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AUTHORITY

ASD ltr, 17 Jun 1971

SUMMARY REPORT

on

DEVELOPMENT OF DIE LUBRICANTS FOR FORGING AND EXTRUDING FERROUS AND NONFERROUS MATERIALS

to

AIR MATERIEL COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

CONTRACT NO. AF 33(600)26272

October 31, 1955

by

H. L. Shaw, F. W. Boulger, and C. H. Lorig

BATTELLE MEMORIAL INSTITUTE
505 King Avenue
Columbus 1, Ohio

April 26, 1956

Commander
Air Materiel Command
Wright-Patterson Air Force Base, Ohio

Attention MCPBIS

Dear Sir:

Contract Number AF 33(600)26272

Enclosed is one (1) copy of the Summary Report on "Development of Die Lubricants for Forging and Extruding Ferrous and Nonferrous Materials". The remaining 49 copies are being sent under separate cover. An additional reproducible copy is also enclosed. This report covers work done from February 1, 1954, through October 31, 1955.

We believe the information in this report is a valuable contribution to the much neglected field of lubrication for hot forging and hot extrusion. The information should be of value to those connected with the Heavy Press Program.

Although no panacea for solving all hot-forging and hot-extruding lubrication problems was discovered, certain procedures were developed for improving metal flow in forging operations, and for lowering pressures in extrusion operations, particularly in working aluminum and magnesium.

Commercial experiments in which an improved method of lubrication was tried, suggested that improvements in die design might be necessary to take full advantage of improved lubricants.

Any comments or suggestions you care to make will be appreciated.

Very truly yours,

Francis W. Boulger
Chief, Division of
Ferrous Metallurgy

FWB:ims
Enc. (1)

cc: Chief, Contract Branch (letter only)
Columbus Air Procurement Office

FOREWORD

This report was prepared by the Battelle Memorial Institute under United States Air Force Contract No. AF 33(600)26272. The contract was administered under the direction of the Manufacturing Methods Branch (MCPBM), Industrial Resources Division, Air Materiel Command, Wright-Patterson Air Force Base, Ohio. Captain Paul J. Wolf acted as Project Monitor. In addition to the authors, other Battelle personnel who contributed to this project were M. J. Wahll, Dr. M. C. Udy, Dr. P. D. Miller, Dr. B. W. King, H. W. Kuhlmann, R. E. Heise, and R. E. Bradford.

This report includes an evaluation of the performance of a number of products for specific applications. Many of the materials tested were not developed or intended by the manufacturer for the conditions to which they were subjected. Any failure or poor performance of a material is therefore not necessarily indicative of the utility of the material under less stringent conditions or for other applications.

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DEVELOPMENT OF DIE LUBRICANTS FOR FORGING AND EXTRUDING FERROUS AND NONFERROUS MATERIALS

by

H. L. Shaw, F. W. Boulger, and C. H. Lorig

SUMMARY

This report summarizes the experimental work conducted during the period February 1, 1954, to October 31, 1955, under Contract No. AF 33(600)26272, sponsored by the Air Materiel Command. Various lubricants and lubricating practices for hot working metals were investigated. It is apparent that improvements in these fields would extend the usefulness of the large presses recently installed by the Air Force. Materials of primary interest in working were aluminum, magnesium, titanium, and steel. For test purposes these materials were represented by 2014 aluminum alloy, AZ80A magnesium alloy, unalloyed titanium, and Type 403 stainless steel.

The principal laboratory-test method for evaluating lubricants was the production of a small T-shaped forging in closed dies. A billet, 1 inch in diameter and 1-5/16 inches long, was pressed into the die cavity under a punch pressure of 46, 000 psi. The depth of penetration into the die cavity was considered a measure of the effectiveness of a lubricant under study. The performance of this test was time consuming because of die reheating and the need for cleaning the dies before changing lubricants.

Therefore, another, simpler, test method was used to screen materials for possible use as lubricants. This method consisted of flattening billets 1 inch in diameter by 1/2 inch in height under a load of 69 tons between flat, parallel dies. The resulting thickness was used to evaluate the effectiveness of a lubricant. Thinner pressings indicated better lubricants, having lower frictional properties. A number of commercial lubricants were evaluated in working each metal to establish a basis for comparing the performance of experimental lubricants or methods of lubrication. Materials or methods of lubrication which gave test results superior to the commercial lubricants may offer advantages in production operations.

<u>Studies With Aluminum</u>. A limited number of experiments indicated that the flow of metal into the forging die cavity can be remarkably improved by increasing the die temperature until it approaches the temperature of the billet. This finding emphasizes the need for improving the

methods for controlling die temperature, particularly when forgings having thin webs and flanges are being produced. Based on these tests, a die temperature of 700 F was used as a standard condition in testing.

Oil-base lubricants produced better die filling than water-base lubricants. It was difficult to make water-carried lubricants stick to the dies at 700 F, particularly if the spray struck the die at an oblique angle. Higher viscosity oil carriers with high flash points gave better die filling than oils with lower flash points. Apparently, higher viscosity oils adhere to the die surface longer before burning, which permits more efficient deposition of the solid portion of the lubricant.

A large number of materials consisting of inorganic and organic materials, organic salts, and mixtures of some of these materials in oils and organic liquids were tried as lubricants in working aluminum. With one exception, these materials showed no improvement in die filling over the best of the commercial products currently in use.

Tetrafluoroethylene resins, when applied to cold dies which were then heated to 700 F, produced better die filling than the commercial lubricants. However, this method of application may not be practical and attempts to apply the resin to hot dies were unsuccessful. Resin primers were also applied to the billets before heating, but die filling was poorer than when the resin was applied to the dies. Even so, die filling was as good or better with the resin than with most of the commercial lubricants studied. This material, if heated to 750 F or higher, produces toxic fumes containing fluorine, as slow decomposition takes place. Perhaps more stable resins could be developed for the application.

Laboratory data showed that remarkable improvements in die filling were produced by pretreating billets with conventional die lubricants. For aluminum, the best billet pretreatment consisted of etching billets in sodium hydroxide then dipping them in aqueous colloidal graphite before heating and forging. This billet pretreatment produced very uniform die filling even when starting with a freshly cleaned die. Untreated billets gave poorer and less uniform die filling when forged with the same die lubricant. The data suggested that the pretreatment might prevent sticking, metal drag, and poor die filling, which account for considerable press down time in starting a run on clean dies in commercial operations.

Pretreated billets used in a commercial forging operation appeared to prevent the sticking and metal drag which occurred with untreated billets. The forging produced was typical of certain airframe components and had thin web sections with deep ribs around the periphery. The dies were of conventional design with a large flash gutter around the periphery of the die cavity. Treated billets appeared to give more lateral metal flow and slightly poorer die filling than untreated billets. Data from these tests indicated that with better lubrication more effort must be taken to restrict lateral movement of metal into the flash trough.

Extrusion experiments were made on aluminum using two die shapes, one a flat-faced die having an included entrance angle of 180 degrees, and the other a conical die having an included entrance angle of 130 degrees. Lubricants which appeared promising in the forging test were studied. Two materials appeared promising as extruding lubricants; one was tetrafluoroethylene resin which was applied to the billet, and the other was an organic grease containing extra-fine flake graphite which was applied to the container and die. These lubricants reduced the extrusion pressure about 50 per cent from that obtained with no lubricant. Conical dies appeared to give lower extrusion pressures than flat dies when good lubrication is attained. Conical dies produced a more uniform macrostructure and appeared to minimize the tendency toward recrystallization and grain growth. In addition, the use of conical dies minimized the tendency for surface cracking and for piping that are sources of trouble in commercial operations.

Studies With Magnesium. Contrary to data obtained for commercial lubricants in forging aluminum, of the group studied water-carried lubricants gave by far the best die filling in working magnesium. The best of these was a mixture of graphite and molybdenum disulfide in water.

As in working aluminum, tetrafluoroethylene resin primers gave better die filling than commercial lubricants. The resin primers may be applied to billets before heating to a forging temperature of 675 F. The material may also be applied to the cold dies before heating, provided the die reaches a temperature of 600 F. However, the experiments indicated that the resin primers could not be reapplied successfully to hot dies. Because of lower temperatures involved in working magnesium, the resin primers are more likely to be useful as forging lubricants for magnesium than for aluminum. The danger from toxic fumes would also be less.

Die filling for magnesium may be greatly improved over that obtained by conventional methods by dipping the billets, having a slightly roughened surface, in an aqueous suspension of colloidal graphite before heating and then forging with conventional lubricants.

As in extrusion tests on aluminum, tetrafluoroethylene resin primers, when applied to magnesium billets, were found to reduce extrusion pressures markedly. The test data showed that a conical die is useful in eliminating or at least minimizing surface cracking, which is one of the chief problems in extruding magnesium in flat-faced dies. The data suggest that conical dies permit higher extrusion speeds.

Studies With Titanium. Regardless of the lubricant, the laboratory tests produced poorer forgings from titanium than from aluminum or magnesium. None of the lubricants used for the lighter metals appeared to be very suitable for titanium. Various types of glasses were investigated but they did not appear to be promising lubricants for forging titanium. Some of the experimental data indicate that a light scale on titanium results in better metal flow and die filling. Billets heated in a salt bath and then forged with a die lubricant containing flake graphite in oil gave the best results. However, salt froze in the corners of the dies and caused some underfilling. Furthermore, the billets seemed to be attacked by the molten salt, which contained barium fluoride and chlorides.

Only two titanium extrusions were made because of experimental difficulties and time limitations. Contrary to the data for aluminum and magnesium, the extrusion pressure for titanium increased from beginning to end of the extrusion stroke. This behavior has been noticed by other investigators. Presumably it occurs because the billet temperature drops during extrusion as a result of the large temperature difference between the billet and the container.

Studies With Steel. Lubricants generally produced much poorer ratings when used in forging steel than when used in working aluminum, magnesium, or titanium. Little difference in die penetration in forging tests was found between commercial and experimental lubricants. Chilling of the billet by the relatively cold die apparently raised the strength of the steel forging to a point where lubricants were relatively ineffective. Increasing die temperature from 700 F to 1100 F appeared to improve die filling, but the effect was much less pronounced than that shown for aluminum.

INTRODUCTION

Closed-die forgings are used for important structural parts in all high-performance aircraft. Since they can be worked close to the desired dimensions, they permit appreciable savings in materials and in machining costs. The closer the approach to the size and shape desired in the finished part, the greater the potential saving offered by forging and extrusion processes. To save weight, aircraft forgings usually consist of a framework of ribs or flanges held together by thinner webs. Unfortunately, precision forgings with thin webs, deep ribs, and narrow draft angles require higher unit forging pressures than parts made to wider dimensional tolerances. To meet more rigid requirements, the U. S. Air Force Heavy Press Program provided industry with larger forging and extrusion presses. These forging presses, with capacities up to 50,000 tons, and extrusion presses, with capacities up to 13,200 tons, permit plastic working of larger articles of conventional design. Alternatively, increasing the available pressure permits the production of parts of conventional size but characterized by thinner ribs, thinner webs, or smaller draft angles.

It is generally recognized that very high pressures are required for press forging parts with thin sections. The factor by which forging pressures exceed the flow stress of the metal being worked depends on friction as well as the area and thickness of the section involved[24, 28, 31, 36]. Since high friction is undesirable, improvements in lubricants for forging and extrusion to lower friction would have the same effect as increasing press capacities.

This research study on die lubricants was conducted by Battelle Memorial Institute under Contract Number AF 33(600)26272. The contract was sponsored and monitored by the Air Material Command at Wright-Patterson Air Force Base. Captain Paul J. Wolf of the MCPBIS office was the Project Monitor.

BACKGROUND

Proper lubrication extends the useful life of forging dies. It is particularly important in the forging of aluminum, magnesium, and stainless steels, which tend to stick to the dies. Lubrication also influences the metal flow in die cavities because it reduces friction between the surfaces of the dies and forging.

Lubricants for hot working metals usually contain a solid, inert material such as graphite in a vehicle such as mineral oil. At forging and extrusion temperatures, the carrier burns or evaporates, leaving a film of solid lubricant. Graphite coatings may be difficult to remove from aluminum and magnesium but give no trouble with steel and most of the nonferrous alloys. Graphite, talc, chalk, lime, mica, and bentonite are common fillers for metalworking lubricants. These materials are ordinarily suspended in

(1) Volatile solvents or aqueous mixtures

(2) Light-viscosity mineral oils

(3) Paraffin-base cylinder oils or heavy fuel oils

(4) Light and heavy petroleum residues.

The amount of filler material combined with such carriers ordinarily ranges from 5 to 40 per cent of the weight of the lubricants.

Some investigators have suggested that vegetable oils and inorganic salts are useful for certain applications. Glasses, of course, have proved to be satisfactory lubricants for hot extrusion of steel at temperatures around 2200 F.

Depending on their viscosity, forging lubricants are usually applied to the dies by spraying or swabbing. Spraying ordinarily results in thinner, more uniform coatings and less smoke. Heavy lubricants, which have to be swabbed, usually have higher flash points and remain on the dies as a film for a longer time. Since it is difficult to coat dies uniformly by swabbing, too much of the lubricant may collect in the recesses. In difficult applications, the blank as well as the die is coated with a lubricant. Ferrous extrusion billets are often coated by dipping in molten glass, by wrapping in glass cloth, or by rolling in powdered glass.

TEST METHODS FOR EVALUATING LUBRICATING MATERIALS

A survey of the literature indicated that no laboratory method for rapidly evaluating the performance of hot-forging and hot-extruding lubricants has met with general acceptance. Usually, new lubricants are given shop trials to evaluate their performance. In development work, especially where many unconventional materials are to be evaluated, shop tests would not be practical. Therefore, it was necessary to develop laboratory tests that were simple, reliable, and required only small quantities of material.

In the course of the investigation, three types of laboratory tests were used. These consisted of (1) a small closed-die forging test, (2) a bulging test, and (3) a pressing test. This nomenclature will be used throughout the report in referring to the type of test used. The three test methods used in the investigation are described below.

Forging Test

The forging test was considered the principal test for evaluating a variety of potential forging lubricants. This test consisted of producing a 2-inch long T-shaped section in a split closed-die arrangement. The complete filling of die cavity produced a forging of the type shown in Figure 1. The photograph also shows the type of billet used for producing the forging. The depth of filling of the die cavity produced by a constant punch load was considered the criterion for rating the various materials used as lubricants. Considering die temperature, a punch load of 115, 000 pounds was selected as the standard press load. This was produced by a line pressure of 2500 psi as determined from press calibrations. A punch load of 115, 000 pounds produced forgings that penetrated the die cavity about two-thirds to three-fourths of the depth for complete filling when conventional commercial lubricants were used at a die temperature of 700 F. Therefore, better lubricants than those currently being used would be expected to show a greater penetration of metal into the die cavity.

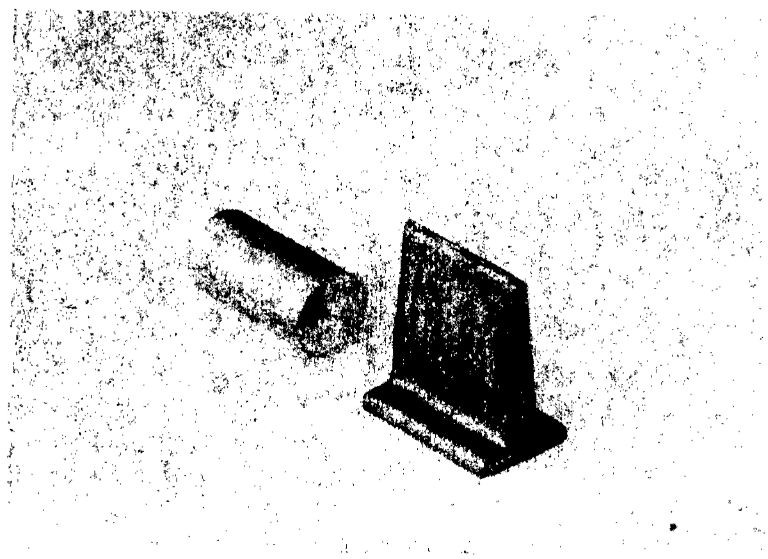

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FIGURE 1. A COMPLETELY FILLED FORGING MADE IN THE EXPERIMENTAL FORGING DIE AND A BILLET OF THE TYPE USED IN THE TEST

A drawing of the die arrangement is shown in Figure A-1 in Appendix A. The cavity for the upright section was 1-7/8 inches deep with a 3-degree taper on all sides. The horizontal section of the "T" was 1-1/4 inches wide. A 1/4-inch radius was used at the entrance to the vertical section. All vertical corners were prepared with a 1/8-inch radius.

Figure 2 shows a photograph of the split-die assembly and punch used in the forging test. In forging, the dies are mated by two dowel pins and are held together by lateral pressure exerted by the 6-degree taper between the die and the retaining block.

Figure 3 shows a photograph of the die arrangement as installed in the press. The die is heated by a gas-fired ring burner placed outside the retaining block. The punch is also heated by a gas-fired burner. Thermocouples, placed in the punch and die, are used to record temperatures.

Most of the billets used in the forging tests were 1 inch in diameter and 1-15/16 inches long. The diameter for unalloyed titanium samples was, however, 0.950 inch. Because of surface imperfections on the as-received 1-inch-diameter bars, the titanium samples were turned to the smaller diameter to eliminate the surface irregularities. The billets were all cut from wrought bar stock, and the ends were faced on a lathe to the proper length.

The forging test appeared to give reliable information. This opinion was supported by experienced forging engineers with whom the subject was discussed. Since the draft angles and die radii were small, and punch pressures were high, the test simulated severe forging conditions.

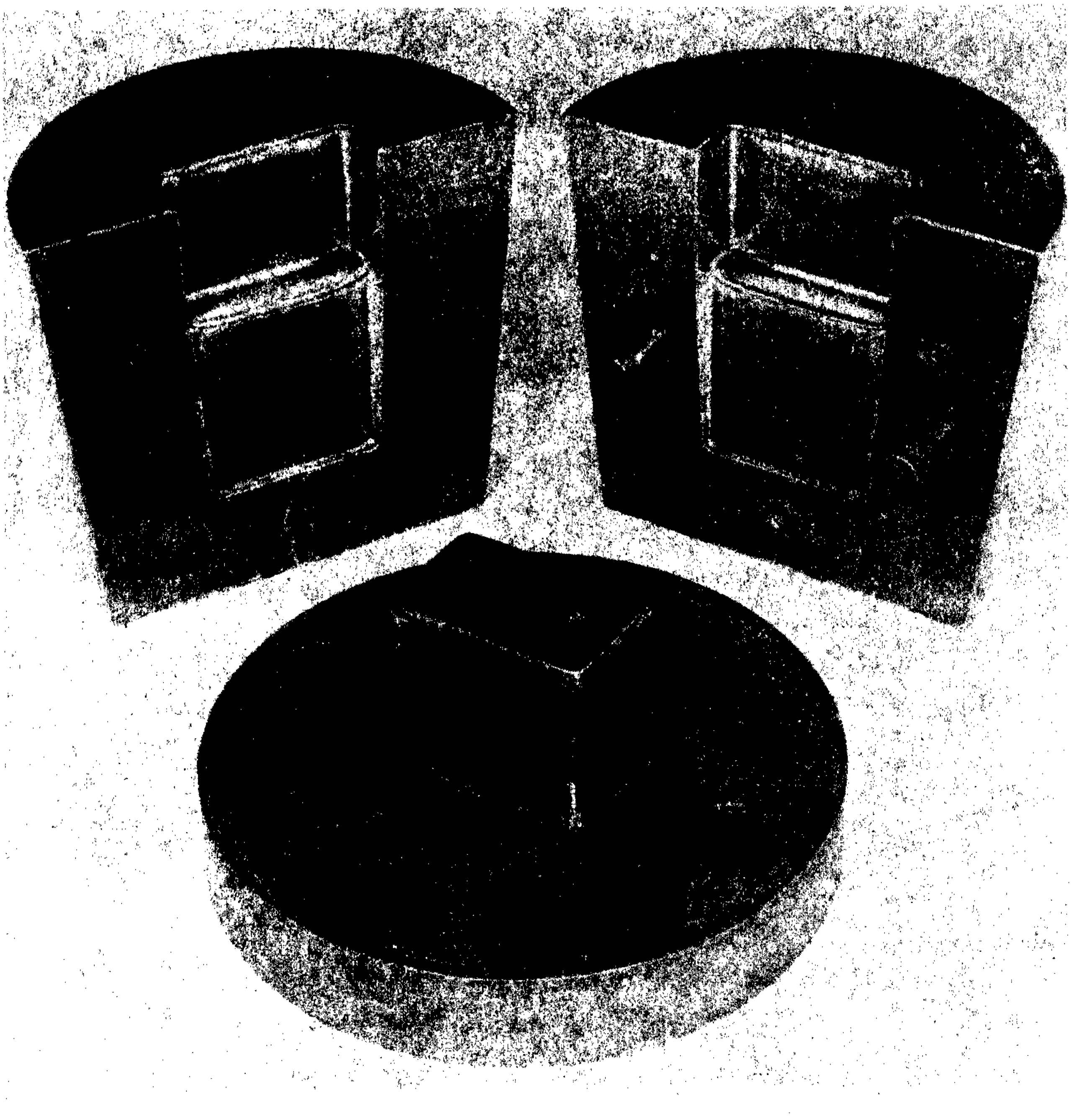

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FIGURE 2. SPLIT-DIE ASSEMBLY AND PUNCH USED IN LABORATORY FORGING TESTS

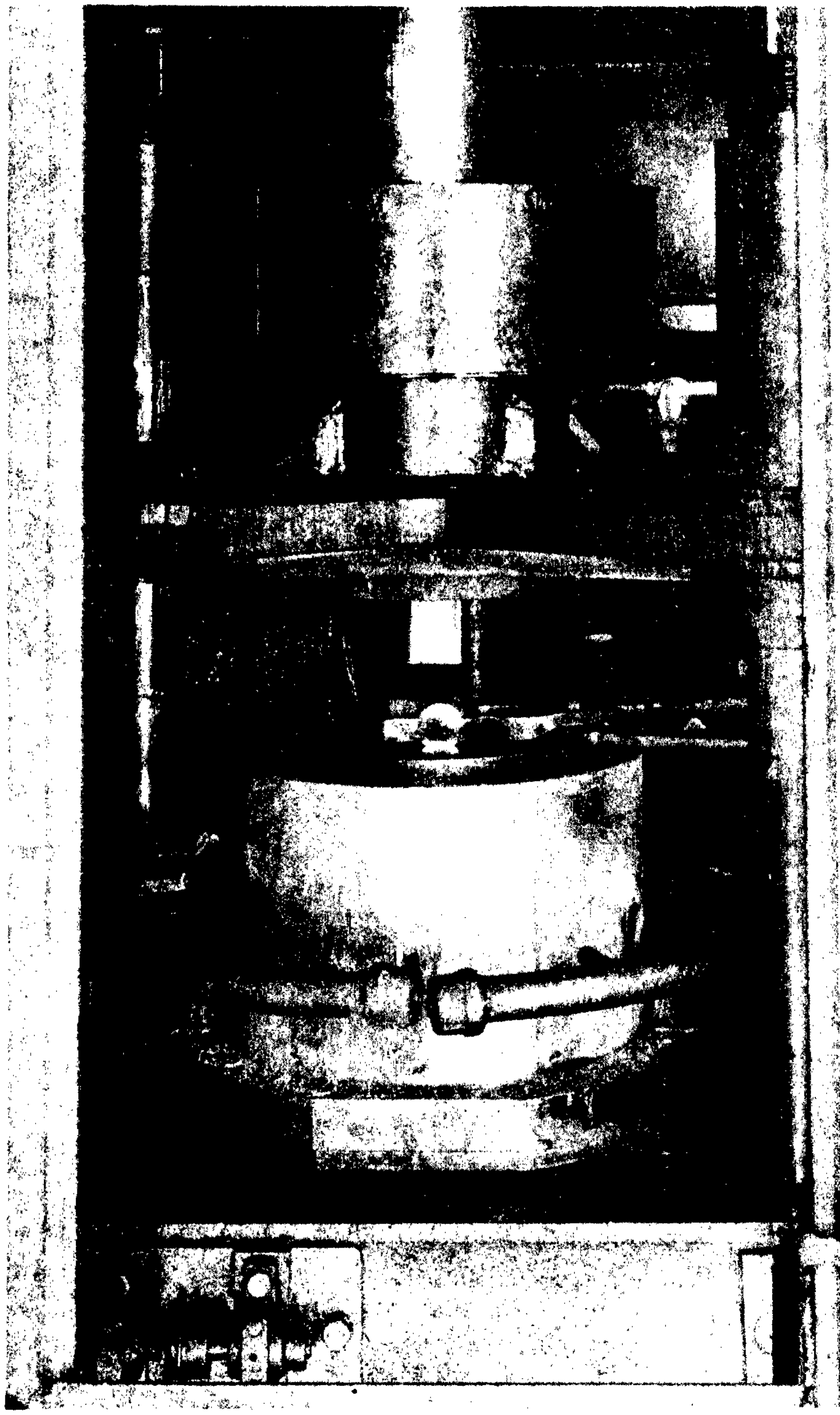

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FIGURE 3. DIE SETUP IN THE PRESS SHOWING A BILLET ABOUT TO BE INSERTED INTO THE CAVITY FOR PRESSING

Bulge Test

The bulge-test method was the initial procedure developed for screening various materials that might be of interest as possible lubricating materials in hot working metals. The reasons for selecting this test for preliminary evaluations are discussed in Appendix B. The bulge test consisted of forging right cylindrical billets between flat parallel dies to a predetermined thickness or reduction in height. The billets, 1 inch in diameter and 1-1/2 inches in height, were pressed 50 per cent of the height to a thickness of 0.750 inch. For these tests the pressing cycle was controlled automatically. The ram travel was automatically reversed by actuating a limit switch that was set to give a predetermined reduction in height. The reduction in height of 50 per cent was controlled within ±1 per cent. A load cell, employing electrical-resistance strain gages, installed under the bottom die, provided a means for recording the loads required for upsetting the billets.

After pressing, the amount of bulging or barreling was measured. This was determined by measuring the diameter at the ends and the diameter at the maximum convexity or concavity of the pressing. The difference between these two diameters was considered the bulge index. A positive index indicated convex sides and a negative index indicated concave sides.

Based on theoretical considerations, larger positive bulge indexes indicate greater friction between the dies and the ends of the test pieces. That is, high friction coefficients restrict lateral movement near the ends and result in barreled specimens.

Preliminary data, described in Appendix B, indicated that the bulge test would be suitable for a rapid screening test. A large number of bulge tests were made on 2014 aluminum and AZ80A magnesium alloy before the small forging die was available. The amount of bulging was very sensitive to variations in die lubricants. For a particular combination of billet temperature and die temperature, the amount of barreling depends on the lubricant used between the dies and the ends of the specimens. Figure 4 shows that bulge indexes ranged from -0.06 to +0.21 inch in tests on aluminum. Figure 5 shows an even wider range for magnesium-alloy specimens which were upset using various lubricants.

The degree to which the sides of the specimens became concave or convex in bulging tests was also sensitive to die temperature. This appeared to indicate that the frictional characteristics of some lubricants changed with temperature. Despite these promising results, it was decided that confidence should not be placed in the bulge test until information was obtained in an actual forging operation.

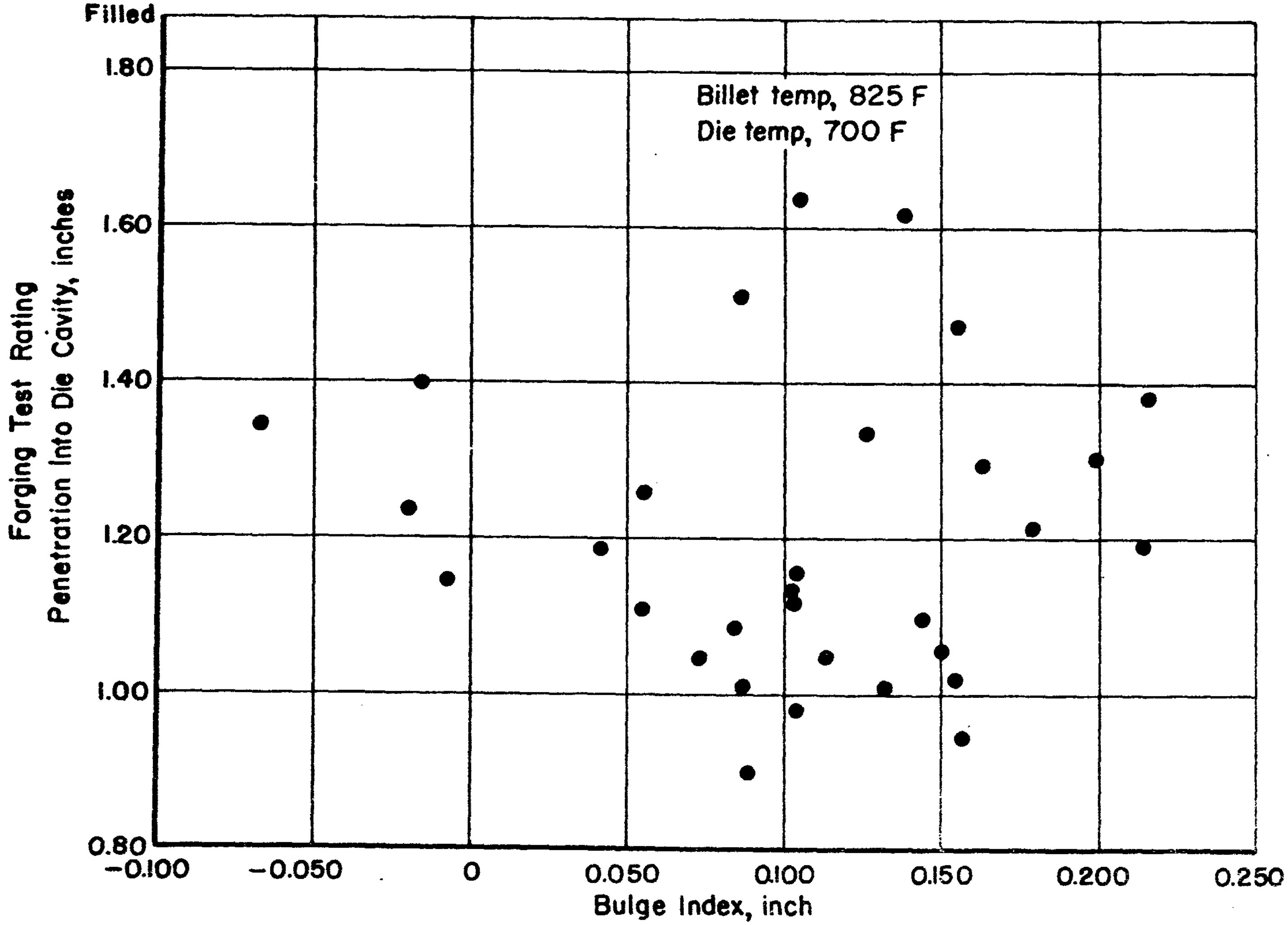

FIGURE 4. POOR CORRELATION BETWEEN RATINGS OBTAINED IN THE BULGE TEST AND THOSE OBTAINED IN THE LABORATORY FORGING TEST FOR A LARGE NUMBER OF LUBRICANTS USED IN WORKING 2014 ALUMINUM ALLOY

A-16855

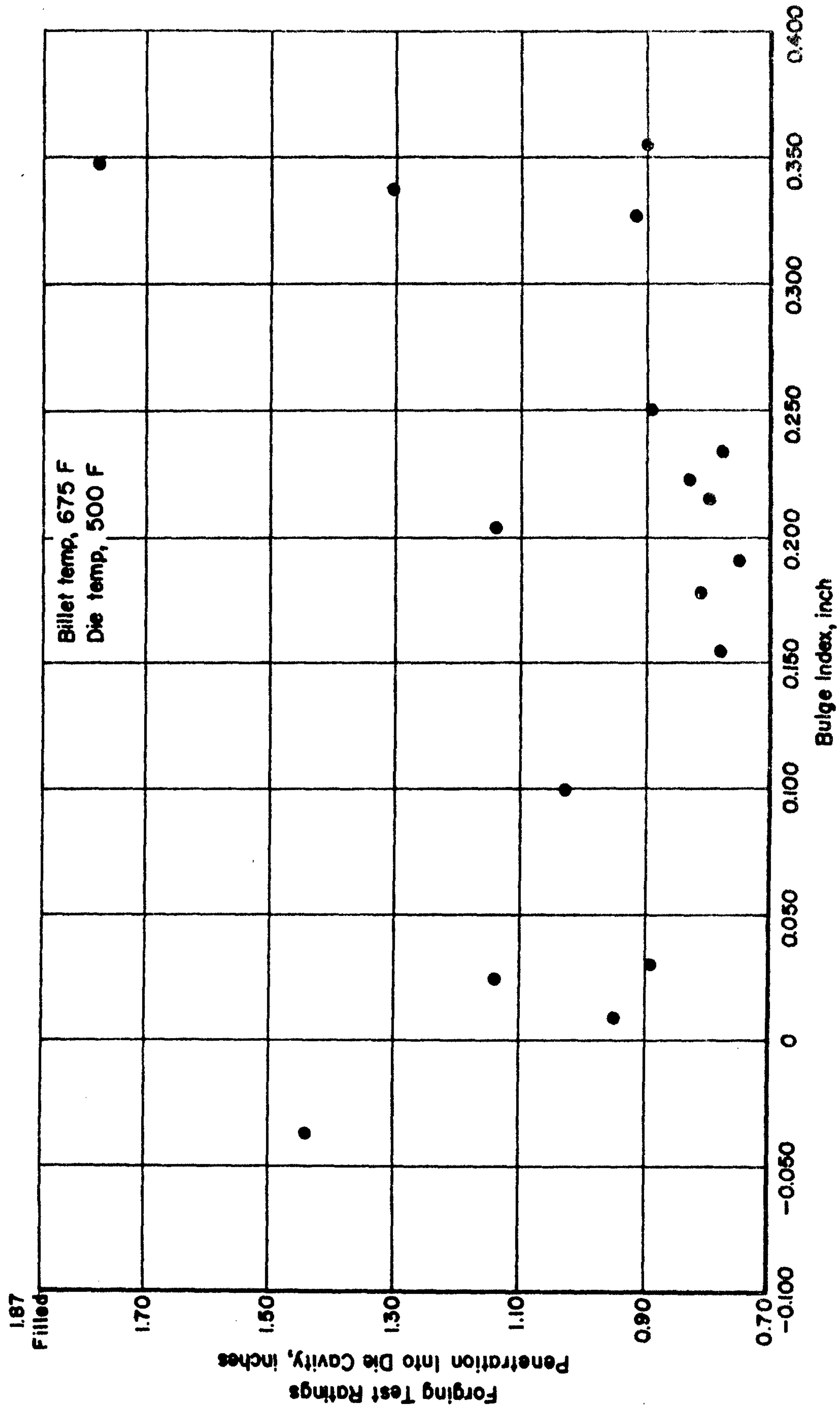

FIGURE 5. LACK OF CORRELATION BETWEEN RATINGS OBTAINED IN THE BULGE TEST AND THOSE OBTAINED IN THE LABORATORY FORGING TEST FOR A NUMBER OF MATERIALS USED AS LUBRICANTS IN WORKING AZ80A MAGNESIUM ALLOY

A-16856

Upon completion of the forging-test equipment, a number of materials that had been used as lubricants in the bulge test were evaluated in the forging test. The forging test did not rate the materials in the same order as the bulge test. Figures 4 and 5 show the lack of correlation between the bulge-test and forge-test ratings for a number of lubricants in working 2014 aluminum and AZ80A magnesium alloys, respectively. The large differences in operating pressures are believed to account for most of the cases of poor agreement between the ratings given by the two test methods. The punch pressure in the forging test was 46,000 psi compared with pressures ranging from 10,000 to 20,000 psi in the bulge test. Probably some lubricants which are suitable for low pressures do not function satisfactorily under more severe conditions.

Negative bulge indexes obtained under certain testing conditions could be interpreted as an indication of unusually good lubrication. Lubricants that gave negative bulge indexes did not produce unusually good die filling in the forging test. Because of this lack of correlation, the bulge test was abandoned as a screening test.

Pressing Test

Because of the lack of correlation between the bulge-test ratings and the forging-test ratings for a large number of lubricants, the bulge test was modified to use thinner billets and higher pressures. This modification, which led to the development of the pressing test, was based on research done by Schroeder and Webster(28) and by Stone(36) on press forging thin sections.

The pressing test consisted of flattening billets 1 inch in diameter by 1/2 inch in height between flat, parallel dies, under a constant load of 69 tons. This produced thin flat pressings having a radius-to-thickness ratio of at least 10. The resulting thickness was used to evaluate the effectiveness of a lubricant. Thinner pressings indicated better lubricants.

Data obtained in the pressing test also permitted estimates of friction coefficients by the following formula:

$$\text{Forging Pressure} = s\left[\frac{e^{\frac{\mu D}{t}} - \frac{\mu D}{t} - 1}{\frac{1}{2}\left(\frac{\mu D}{t}\right)^2}\right]$$

where

s = flow stress of metal at appropriate speed and temperature

μ = coefficient of friction between dies and workpiece

D = diameter of disk being forged

t = thickness of disk being forged

e = base of natural logarithms.

The flow stress, s, used in the calculations was taken as the yield strength of the metal in bulge tests made at the same billet and die temperatures.

Since most pressing tests were made on 1-inch-diameter disks, 1/2 inch high, the equation could be solved by using Figure 6 and the appropriate experimental data. The chart shows that, for a constant billet volume, lower friction coefficients result in thinner pressings and lower forging pressures.

Data obtained while using various materials as lubricants in the pressing test gave better correlation with the forge-test ratings than those obtained in the bulge test. Correlation between pressing-test and forging-test data obtained for a number of different lubricating materials on 2014 aluminum and AZ80A magnesium alloys are shown in Figures 7 and 8, respectively. The correlations are not precise but show, in general, that better die filling in the forging test was obtained with lubricants which gave thinner pressings in the pressing test. Because of the better correlation with the forging test, greater confidence was placed in the pressing test than in the bulge test for screening purposes.

Extrusion Test

Most of the extrusion experiments were made after the bulk of the work had been done on the study of lubricants for forging. Therefore, the data obtained in forging, bulge, and pressing tests served as a severe screening of materials that might hold promise as extrusion lubricants. This limited the number of promising materials that were tried in the extrusion experiments.

Extrusion tests were made on aluminum and magnesium using a reduction in area of 10.3 to 1. One-inch-diameter bar stock, 1-15/16 inches long, was extruded to a 5/16-inch-diameter rod.

An instrument which automatically plotted the hydraulic line pressure against ram travel was used to record the loads during the extrusion cycle. This instrument is known as an H-2CP pressure indicator and is made by Bacharach Industrial Instrument Company. The recorded loads were converted into pressures. The resulting pressures and the surface condition of the extruded bars were used as a means of evaluating the performance of a lubricant.

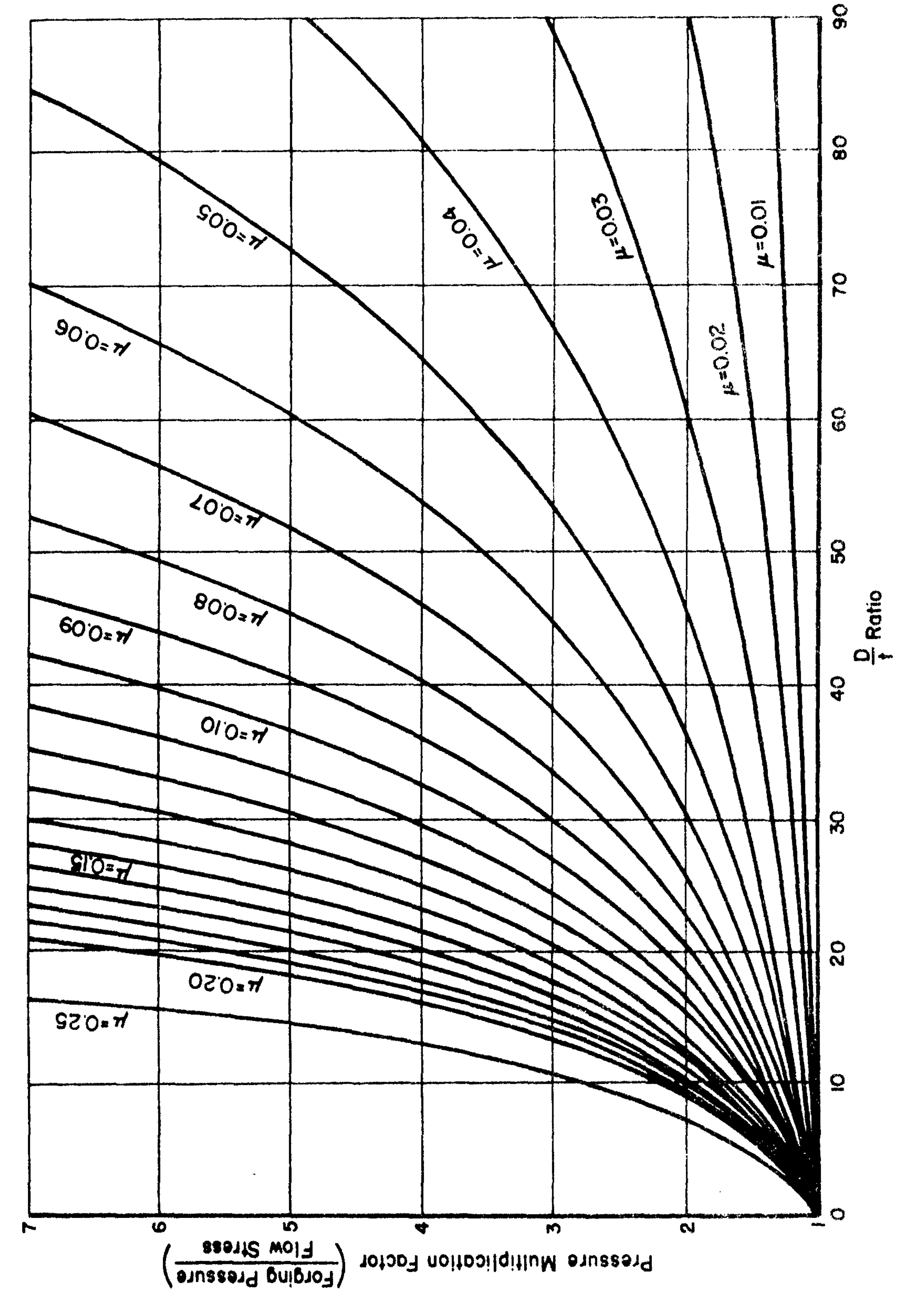

FIGURE 6. COEFFICIENTS OF FRICTION FOR VARIOUS COMBINATIONS OF DIAMETER-TO-THICKNESS RATIOS AND PRESSURE-MULTIPLICATION FACTORS

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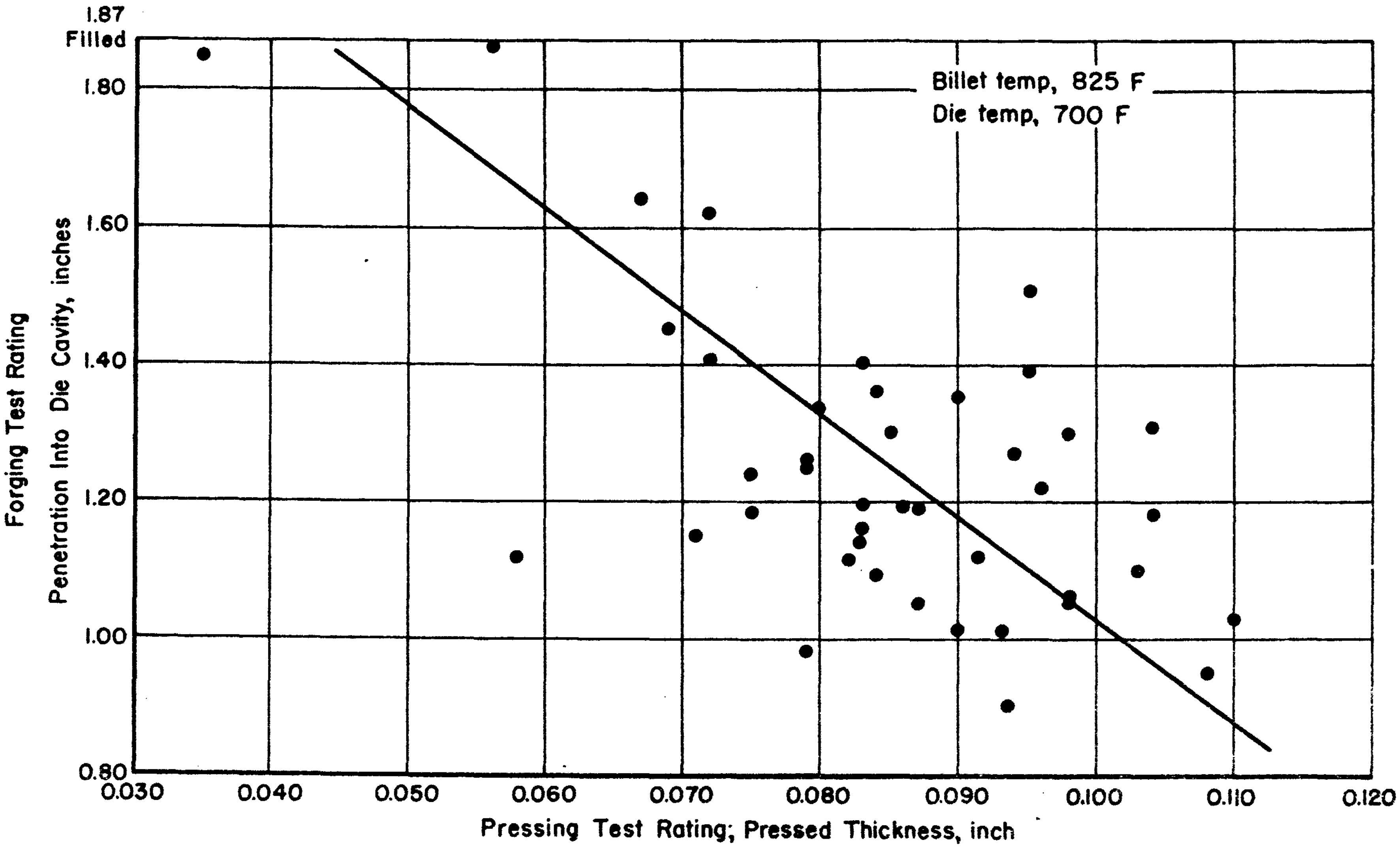

FIGURE 7. CORRELATION BETWEEN RATINGS OBTAINED IN THE PRESSING TEST AND THOSE OBTAINED IN THE LABORATORY FORGING TEST FOR 45 MATERIALS USED AS LUBRICANTS IN WORKING 2014 ALUMINUM ALLOY

A-16858

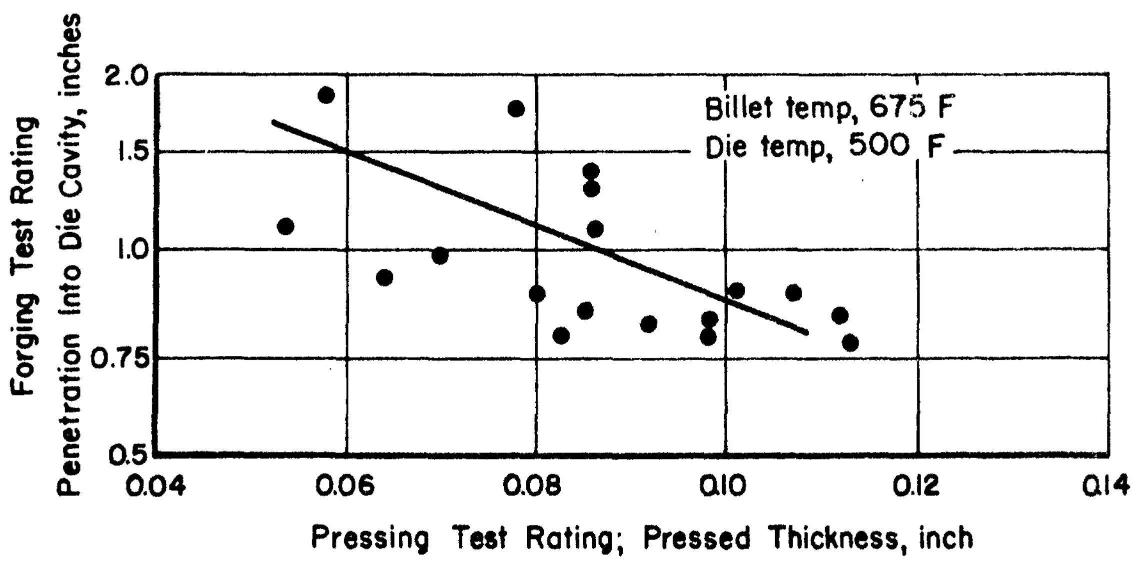

FIGURE 8. CORRELATION BETWEEN TWO LABORATORY TESTS USED FOR EVALUATING 18 MATERIALS AS LUBRICANTS FOR AZ80A MAGNESIUM ALLOY

A-16865

The design of the vertical extrusion equipment used in the experimental press is shown in Appendix C (Figure C-1). This equipment consisted of a die holder, a die, and a container which was seated flat over the die and held down by four 3/4-inch bolts inserted into the die holder.

Two die shapes were used in the equipment. One was a flat die having no entrance angle (180-degree included angle). The other die was constructed with an included entrance angle of 130 degrees. The dies were made from Darwin 93 die steel containing 9 per cent tungsten and 3 per cent chromium. Drawings of the dies are shown in Appendix C (Figure C-2).

The assembly was heated by a gas-fired ring burner. The punch was also heated by a gas flame. Thermocouples were used to record the punch, container, and die temperature.

The punch, die, and container surfaces were cleaned after the use of each different lubricant using 320A-grit Wetordry Ti-M-ite paper made by Minnesota Mining and Manufacturing Company. This grit produced a surface roughness of approximately 10 microinches.

EXPERIMENTAL PRESS AND CHARACTERISTICS

The hydraulic press used for most of the work in this investigation had a capacity of approximately 80 tons. The press could be operated either manually or automatically. The press was equipped with a solenoid-operated pilot-type four-way hydraulic control valve which permitted an automatic cycle of the punch. The length of the downward stroke of the punch was controlled by a limit switch which could be set to give any desired amount of ram travel. The press had a maximum rate of ram travel of about 23 inches per minute and the speed could be controlled.

The bottom platen was equipped with a center hole that made it possible to use the press for vertical extrusion.

The actual ram loads produced by the press at the various line pressures are shown in Figure 9. The calibration was made using a previously calibrated load cell. The line pressure was controlled to give the maximum load desired on the ram in various experiments.

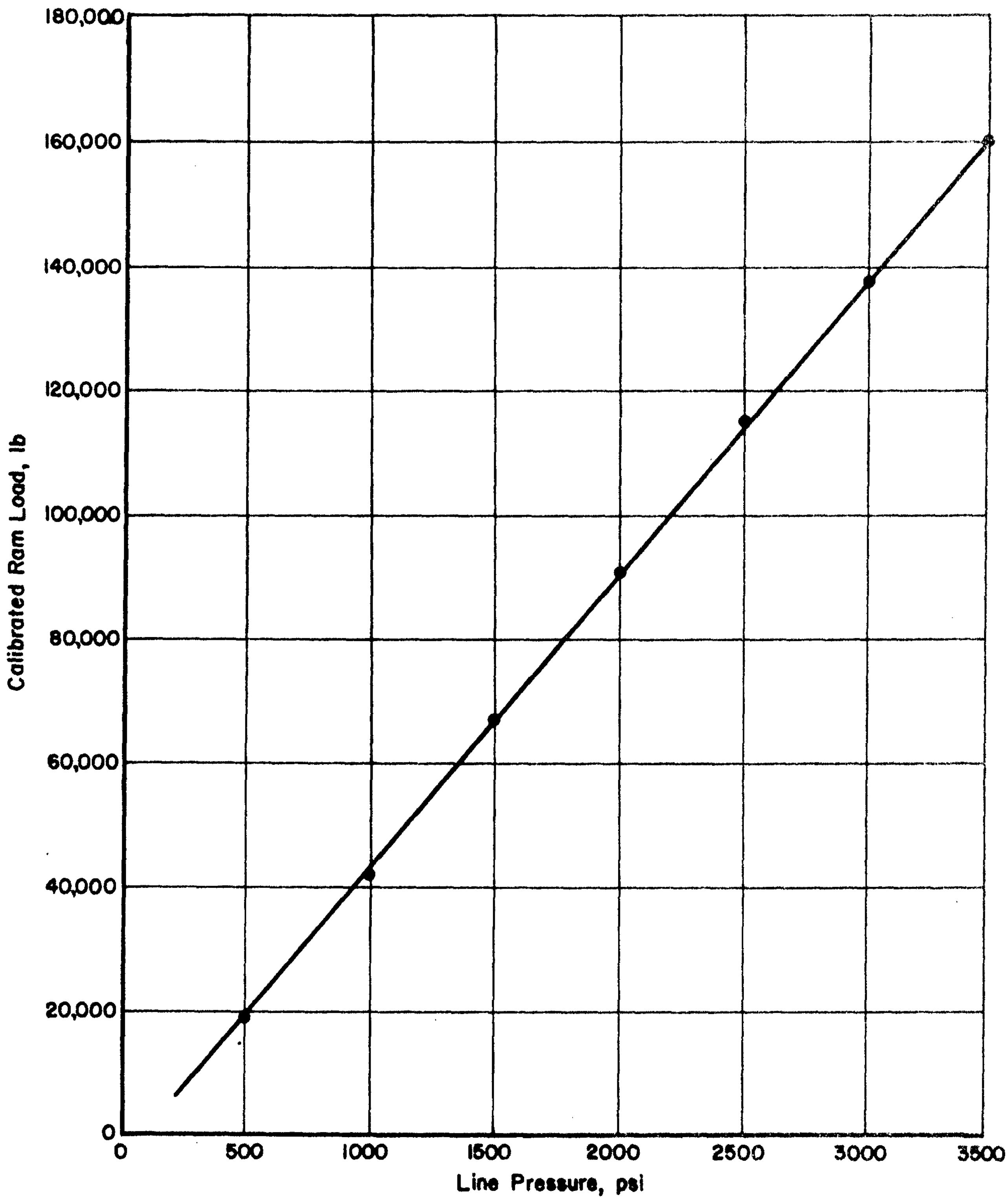

FIGURE 9. RELATIONSHIP BETWEEN LINE PRESSURE AND RAM LOAD OF EXPERIMENTAL HYDRAULIC PRESS

A-16866

STUDIES ON ALUMINUM

Screening and Forging Tests

Aluminum forgings can be made by hammers or by presses actuated either mechanically or hydraulically. The problems of lubricating the stock differ slightly, depending upon the type of machine employed.

Hammers operate intermittently at rather high speed. Because of this factor and because of construction details, it is difficult to heat the dies for forging hammers. Usually the dies operate at temperatures below 400 F. In this range of temperature, solid lubricants suspended in oil or in water appear to be satisfactory, when applied to the dies. Both water-carried and oil-carried lubricants will adhere to the relatively cool dies. Because the die temperatures are low, oil-carried lubricants do not produce flames. However, smoke may be a problem. Hammer forgings are designed with generous draft angles to minimize sticking of the parts in the dies.

Mechanical and hydraulic presses present more severe requirements for metal-working lubricants. The dies in these presses usually operate at temperatures ranging from 400 to 700 F. The higher temperatures make it more difficult to use water-base lubricants. A steam barrier forms on the surface of the hot die and interferes with the production of a smooth, uniform coating. Then too, some lubricants which function satisfactorily at lower die temperatures may not perform as well at higher temperatures. Because of the higher die temperatures in forging presses, oil-carried lubricants produce considerable fume, smoke, and flame.

The trend toward forgings with smaller tolerances and dimensions closer to those of the finished parts means that forgings are being designed with less draft and even no draft. This change in design has resulted in more trouble from forgings sticking in dies. Sticking caused by seizure, or welding, of the stock to the die can be alleviated by better lubrication. However, sticking can be caused by suction between the die and the forging or by contraction of the forging during cooling. In such cases, the problem may have to be solved by changes in die design.

Most aluminum-forging shops use various proprietary lubricants containing graphite in oily or aqueous carriers. For higher die temperatures, most shops generally prefer oil-carried lubricants.

Because a large percentage of the aluminum forging production is of Grade 2014, this alloy was selected for the working stock in all the experimental work. This alloy nominally contains 4.4 per cent copper, 0.8 per cent silicon, 0.8 per cent manganese, and 0.4 per cent magnesium.

One-inch-round bar stock was used for all billets. The tests were designed to use this size in order to reduce the amount of machining necessary to prepare them. Forging, pressing, and bulge-test billets were cut from the bar stock and machined to the proper length. No machining was done on the surface of the samples.

Table E-1 in Appendix E lists all lubricating materials and billet treatments used during the investigation. Each treatment is identified by number. Not all the materials listed were used in tests on aluminum because some were made specifically for working other metals. Commercial lubricants tested are not identified as to brand name.

Complete lists of all data obtained in the forging, pressing, and bulging tests on aluminum are given in Tables F-1, F-2, and F-3, respectively, of Appendix F. Many of the materials screened in the pressing test were not further evaluated in the forging test, because the pressing-test data indicated that they were not promising lubricants. On the other hand, many of the materials evaluated in the forging test were not previously evaluated in the pressing test.

The thickness of the disks produced in standard pressing tests was used as the parameter for screening various lubricating materials. As explained previously, the thickness depended upon the coefficient of friction between the dies and the test piece.

Figure 10 shows the relationship between the diameter-to-thickness ratios and the pressure multiplication factors for a number of lubricants tested under standard conditions. The pressure multiplication factor is equal to the ratio of the forging load divided by the final area of the disk to the flow stress of the metal at the appropriate temperature. The data in Figure 10 are for billets of constant size and volume which were pressed with a load of 138,000 pounds. Therefore, poorer lubricants resulted in thicker pressings, disks with smaller diameter-to-thickness ratios and higher forging pressures. Figure 10 shows that the pressure multiplication factors varied in a threefold range and the diameter-to-thickness ratios ranged from 18 to 90 in tests with 95 lubricants. The apparent friction coefficients varied from 0.018 to 0.25 in these tests on aluminum.

Figure 6 showed the generalized relationship between theoretically calculated friction coefficients, disk dimensions, and pressure multiplication factors. The relationship can be simplified to that shown in Figure 11 for tests on aluminum with standardized loads, billet dimensions, and temperatures. For the standardized experimental conditions, the friction coefficients were determined directly from the thickness measurements, using the trend lines shown in Figure 11.

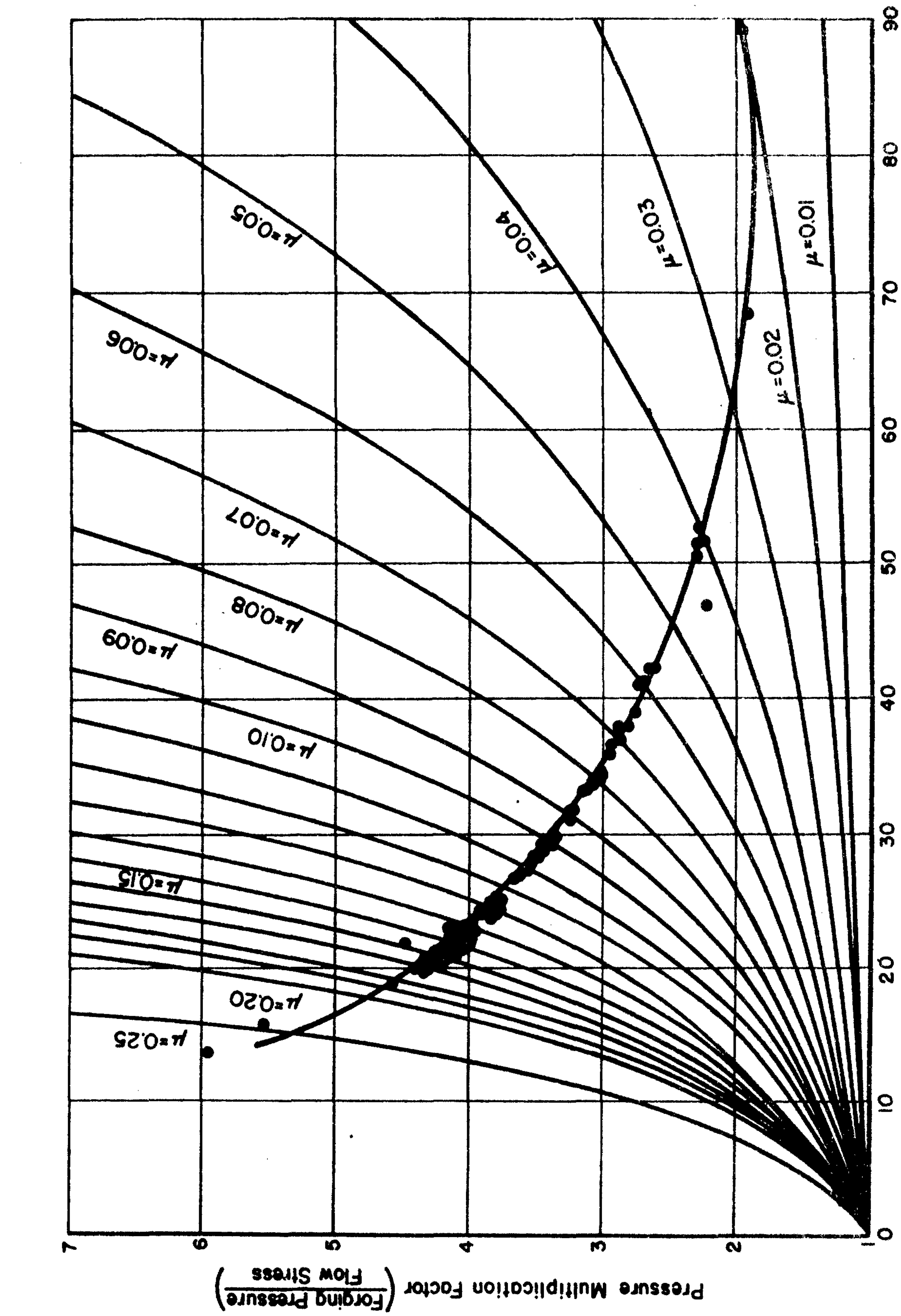

FIGURE 10. INFLUENCE OF DIFFERENT LUBRICANTS ON PRESSURE-MULTIPLICATION FACTORS AND DIAMETER-TO-THICKNESS RATIOS FOR STANDARD PRESSING TESTS

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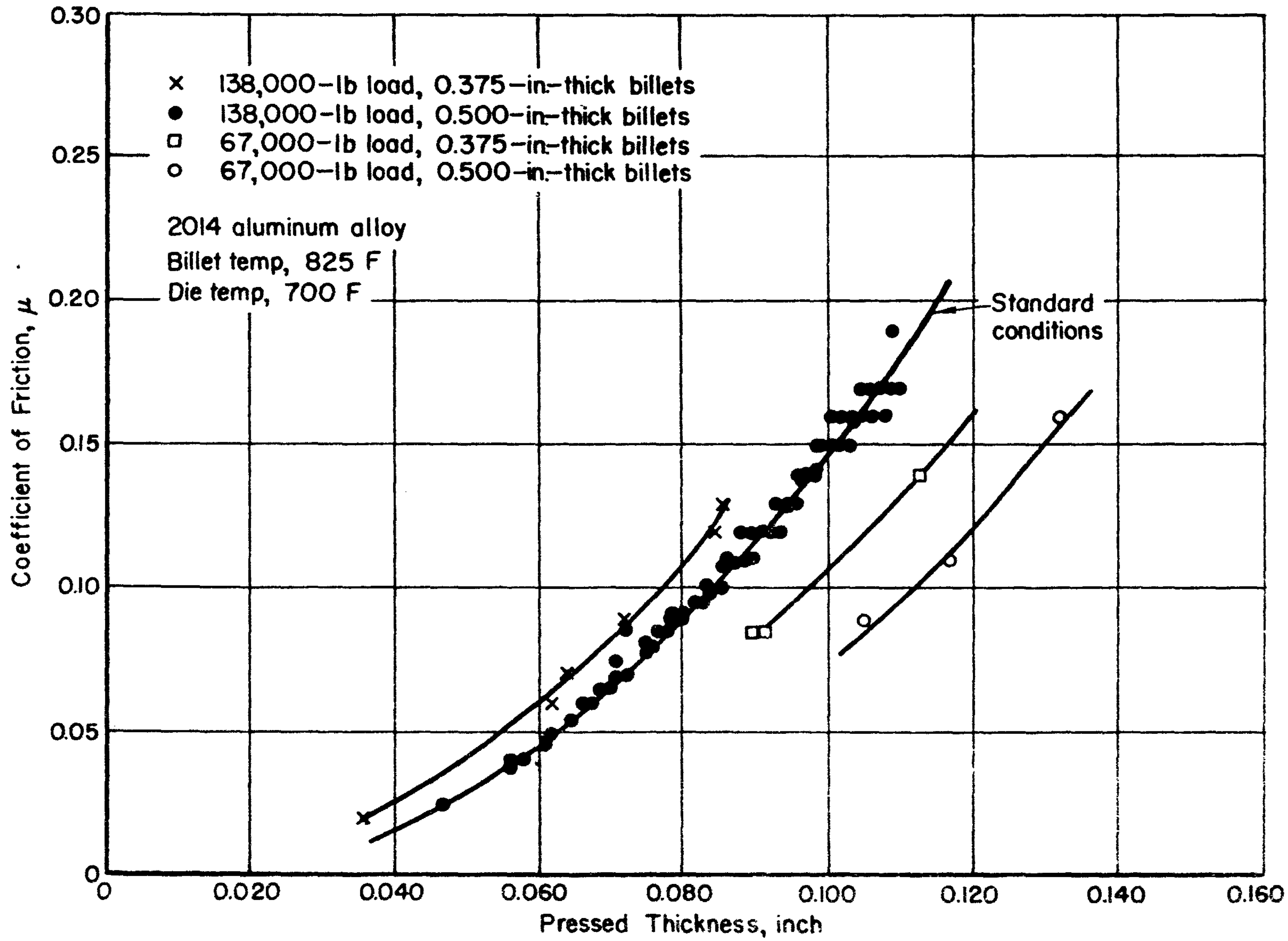


FIGURE 11. RELATIONSHIP BETWEEN THE PRESSED THICKNESS OBTAINED IN THE PRESSING TEST AND THE CORRESPONDING COEFFICIENT OF FRICTON FOR VARIOUS TESTING CONDITIONS USING 1-INCH-DIAMETER 2014 ALUMINUM ALLOY

A-16860

Effects of Forging Pressure
and Die Temperature

Two series of 2014 aluminum billets were forged using four different punch pressures at die temperatures of 500 and 700 F. These tests were made so that a standard punch pressure could be selected that would not completely fill the die cavity when using a potentially good lubricant. Data obtained in these tests are summarized in Figure 12. A photograph of the forgings from the two series of tests is shown in Figure 13. A commercial lubricant (Lubricant 1) used by a large producer of aluminum forgings was applied to the dies in these experiments.

These data show that increasing either the forging pressure or the die temperature improved the depth of fill into the die cavity. Based on these data, a forging pressure of 46, 000 psi was selected as the standard for subsequent tests.

Die temperatures used in press forging aluminum commercially range from about 400 to about 750 F. Because of the size of die blocks and lack of information on the effects of die temperature, only very rough temperature control is practiced. Figure 12 shows that an increase in die temperature from 500 F to 700 F had about the same effect as increasing the forging pressure from 35, 000 to 65, 000 psi at a die temperature of 500 F. At a die temperature of 500 F, a punch pressure of 65, 000 psi produced only a half-filled die. The same punch pressure produced a forging which almost filled the die cavity when the die temperature was maintained at 700 F.

The effects of varying the die temperature when two other commercial lubricants (8 and 59) were applied to the forging dies are shown in Figure 14. Each point on the graph represents average values for tests on three specimens. Raising the die temperature from 500 F to 700 F resulted in remarkably better die filling with either lubricant. Lubricant 49 performed better than 8 at most of the die temperatures investigated in these experiments. With Lubricant 49, results at 700 F were almost as good as those obtained when the die temperature was maintained at 900 F.

Figure 15 shows the results obtained in bulging and pressing tests when Lubricant 8 was tried on dies heated to temperatures ranging from 300 to 900 F. Both screening tests confirm the forging-test data showing the benefits of increasing the die temperature to 700 F. However, the experiments with flat dies suggest that the die lubrication became poorer as the temperature was raised above 700 F. In this respect, Figure 15 disagrees with the data obtained with forging dies showing the effect of raising the die temperature from 700 to 800 F. The studies suggest that some minimum thickness of a lubricating film must be maintained in order to secure satisfactory results at high die temperatures. The area of contact between the stock and dies increased to a greater extent in the bulging and pressing tests than in the forging tests. Consequently, the lubricating

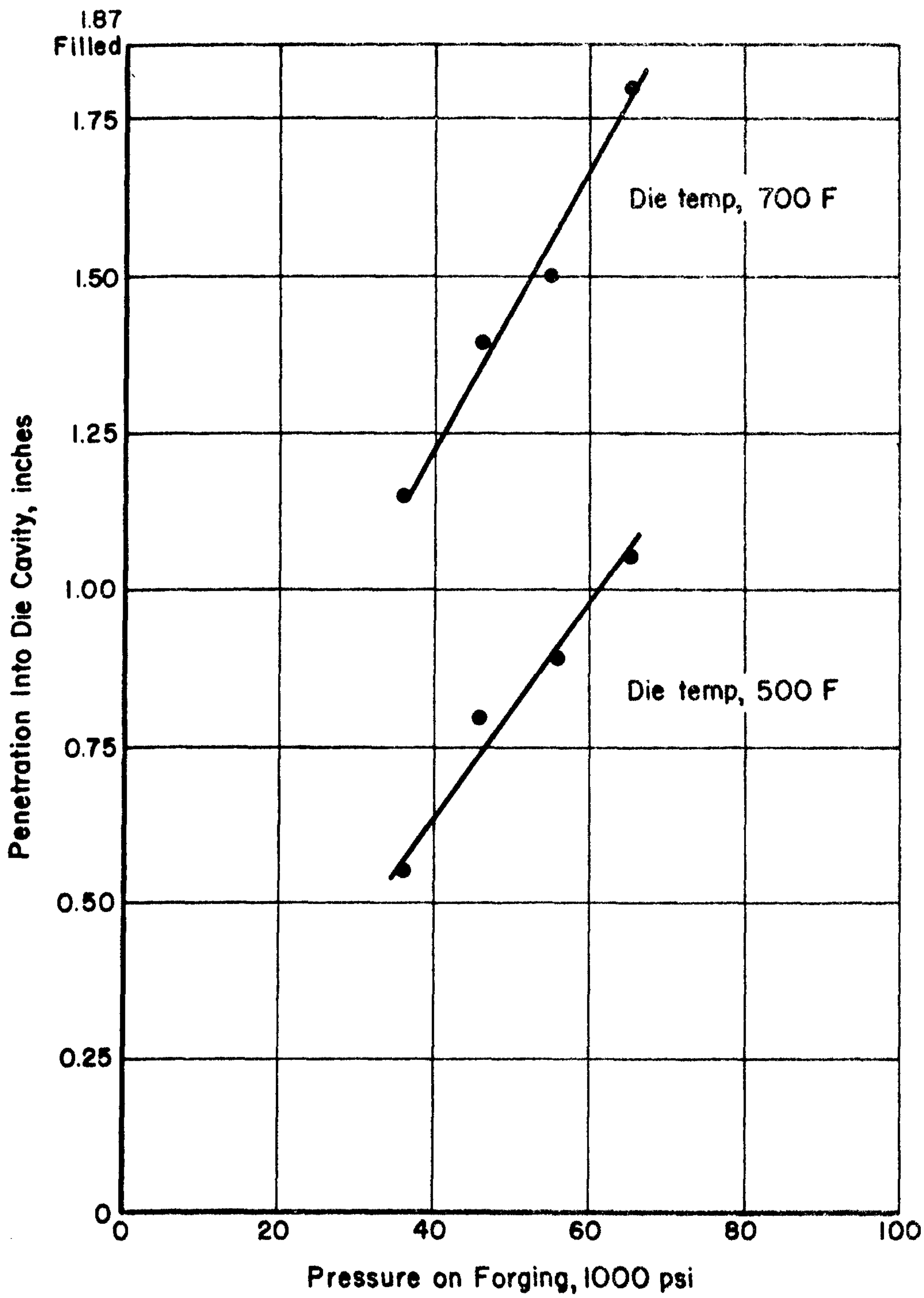
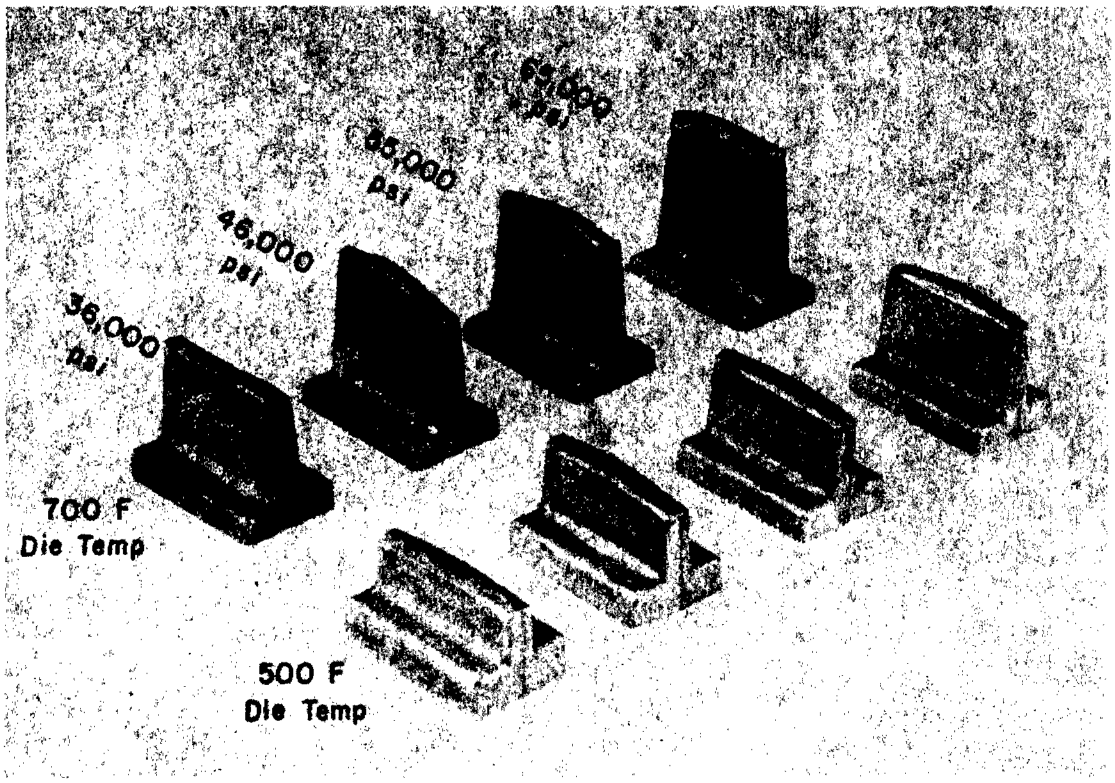


FIGURE 12. EFFECT OF PRESSURE ON PENETRATION OF 2014 ALUMINUM ALLOY INTO FORGING DIE CAVITY USING THE SAME LUBRICANT AT TWO DIFFERENT DIE TEMPERATURES (LUBRICANT I CONTAINING FLAKE GRAPHITE IN AN OIL CARRIER) A-16868



N22124

FIGURE 13. EFFECT OF FORGING PRESSURE AND DIE TEMPERATURE ON THE DEPTH OF PENETRATION INTO THE FORGING DIE CAVITY, USING THE SAME LUBRICANT IN EACH TEST (LUBRICANT 1)

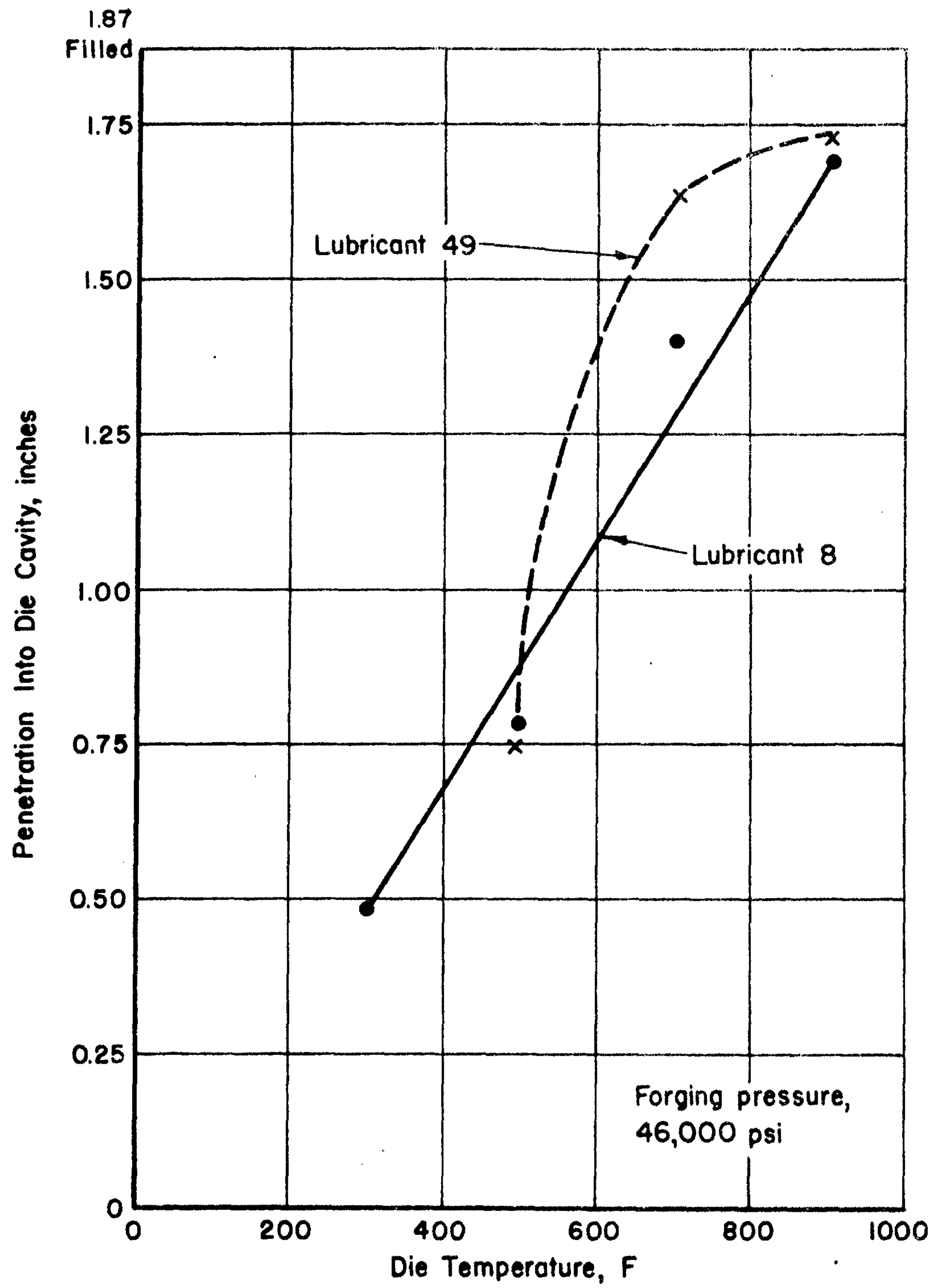


FIGURE 14. EFFECT OF DIE TEMPERATURE ON THE DEPTH OF PENETRATION INTO THE DIE CAVITY IN FORGING TESTS USING LUBRICANTS 8 AND 49 ON 2014 ALUMINUM ALLOY

A-16867

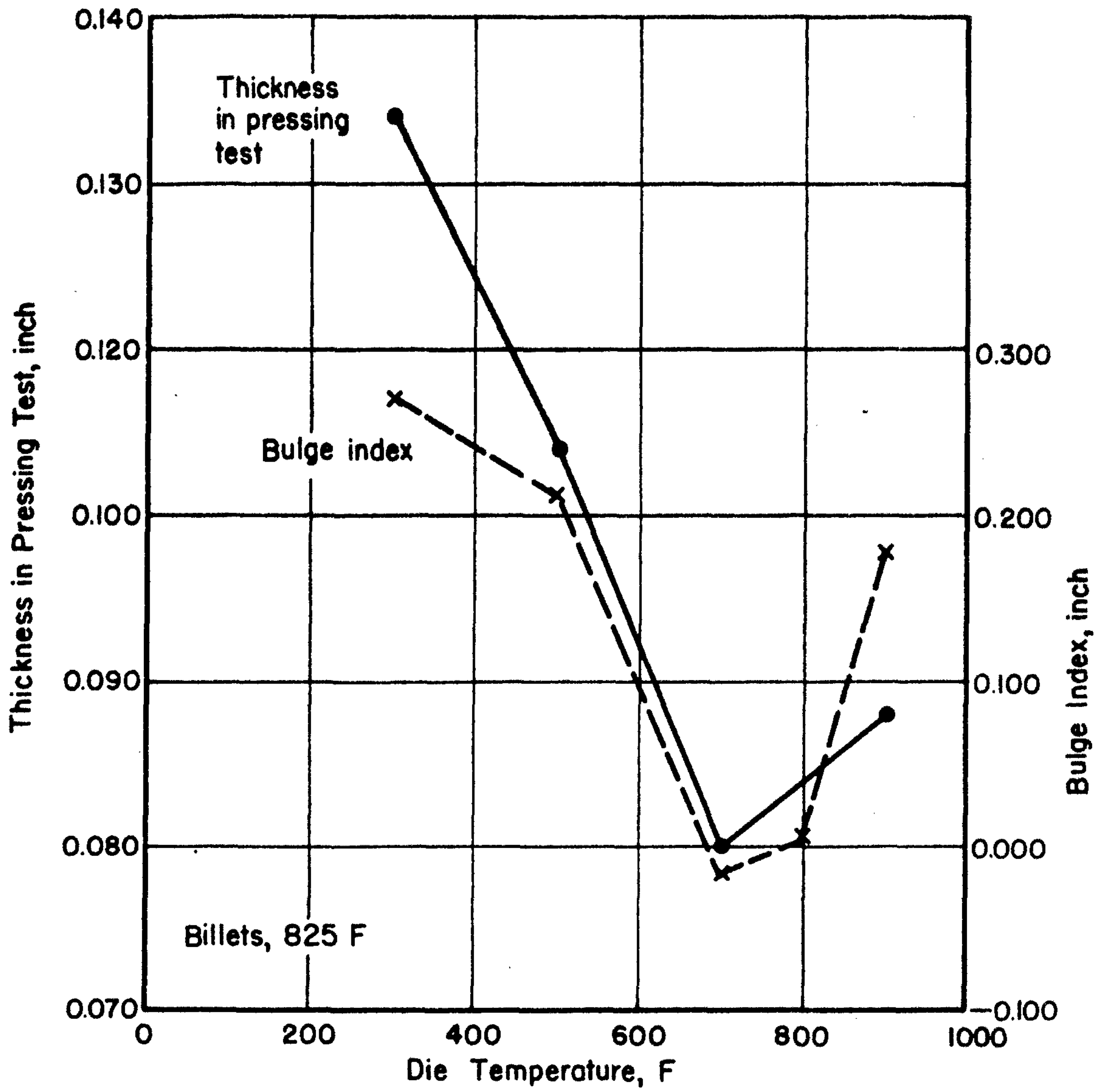


FIGURE 15. EFFECT OF DIE TEMPERATURE ON BULGE AND PRESSING TEST RATINGS FOR TESTS IN WHICH LUBRICANT 8 (COMMERCIAL LUBRICANT CONTAINING GRAPHITE IN AN OIL CARRIER) WAS USED

A-16869

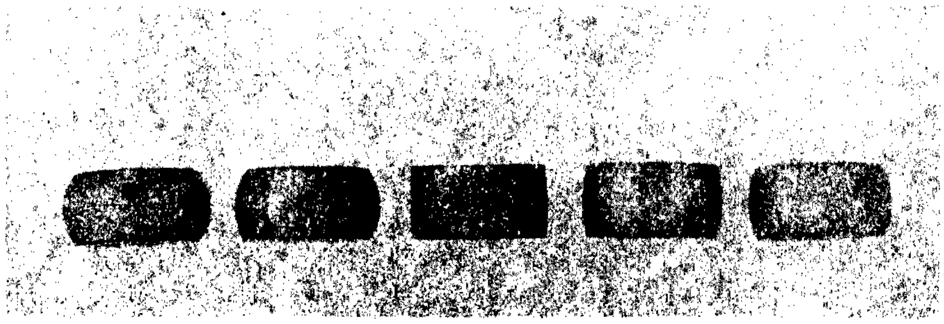
films were thinner in the late stages of deformation in the tests with flat dies than in tests with the forging dies. Probably thinner films and higher die temperatures both increase the likelihood of metal-to-metal contact and seizure. Therefore, it is not surprising that this lubricant did not perform as well at 900 F in the bulging and pressing tests as it did in the forging tests. The lubricant probably has a maximum useful operating temperature that depends to some extent on forging conditions.

Figure 16 is a photograph of representative bulge-test specimens produced at various die temperatures using Lubricant 8. The sample deformed at 700 F is almost cylindrical, indicating that friction was small during testing. The average thickness of specimens subjected to the pressing tests at the same die temperature (Figure 15) was 0.08 inch. This thickness corresponds to a friction coefficient of 0.09.

Figure 17 shows some representative bulge-test specimens pressed with an experimental lubricant compounded in this laboratory. Lubricant 65 consisted of 98 per cent pure boron nitride with ester-type plasticizer as a carrier. So far as bulging is concerned, this material gave the best results of all materials investigated as lubricants for aluminum. This was true for all die temperatures investigated. No seizing or sticking occurred. The photograph shows that considerable lateral flow occurred at the ends of the specimens in tests at 700 F and 900 F. In fact, the friction was so small that the billets developed concave sides. This behavior is very unusual. The heterogeneity of deformation followed a different pattern than it did in specimens which bulged. The concave sides indicate that the deformation was more severe at the ends than at the center of the specimens.

It should be noted, however, that the bulging indexes did not correlate closely with the loads required for upsetting. This indicates, contrary to the common opinion, that heterogeneous deformation sometimes requires less energy than homogeneous flow. This is illustrated by the data for Samples 189 and 461 given in Figures 16 and 17. The sample which necked (Sample 461) required only 70 per cent of the forging load of the sample that maintained its cylindrical shape (Sample 189). Apparently inhomogeneous deformation by bending required less force than more uniform shear deformation to produce the same total reduction in height.

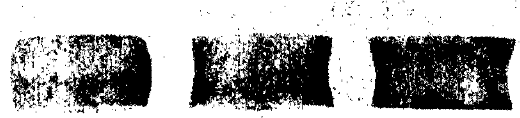
Figure 18 compares the flow patterns on diametral sections of two specimens similar to those shown in Figure 16. They represent samples deformed by dies maintained at 500 and 700 F, coated with Lubricant 8. The deformation was different when bulging occurred than when the specimen remained cylindrical. The etched cross section shows that uniform lateral flow occurred from top to bottom of the slug when the die was heated at 700 F. That is, the flow friction coefficient did not restrict the flow of metal at the end surfaces of the sample. In the other case, the flow of metal at the ends of the original bar was restricted by friction. Consequently, the metal near the center had to be displaced larger distances. The deformation was less uniform in the sample with the larger bulge index.



1/2X					N25416
Die Temperature, F	300	500	700	800	900
Average Bulge Index, inch	0.270	0.213	-0.016	0.007	0.181
Sample	219	143	189	211	419
Forging Load, lb	-	15,900	14,600	-	11,700

FIGURE 16. EFFECT OF LUBRICANT 8 (COMMERCIAL LUBRICANT CONTAINING FLAKE GRAPHITE IN AN OIL CARRIER) ON THE AMOUNT OF BULGING PRODUCED IN THE BULGE TEST AT VARIOUS DIE TEMPERATURES ON 2014 ALUMINUM ALLOY

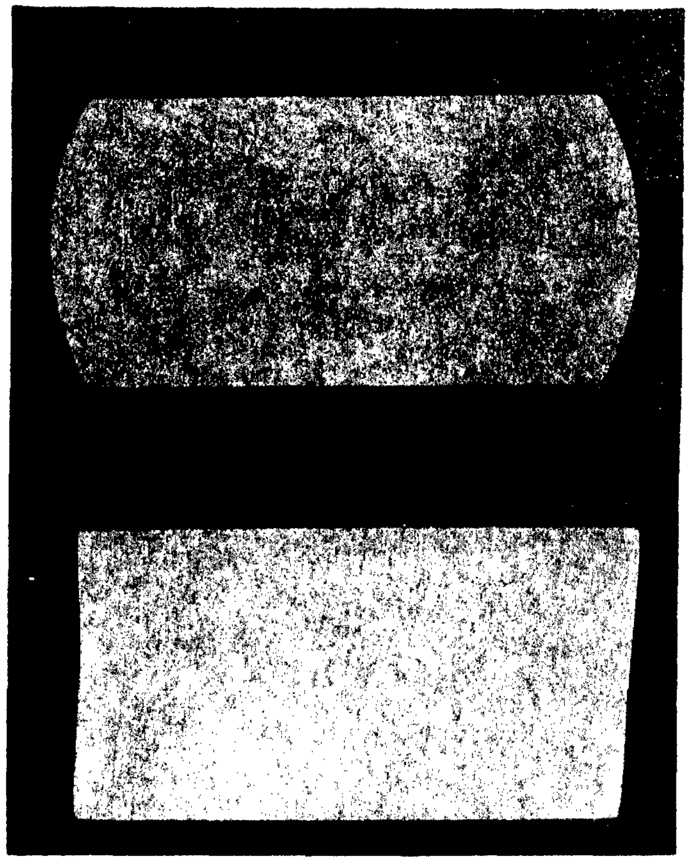
Billets were 1 inch in diameter by 1-1/2 inches in height and were reduced 50 per cent in height by upsetting.



1/2X				N25415
Die Temperature, F	500	700	900	
Average Bulge Index, inch	0.122	-0.066	-0.125	
Sample	437	461	488	
Forging Load, lb	22,100	10,600	12,200	

FIGURE 17. EFFECT OF LUBRICANT 65 (BN IN AN ESTER-TYPE PLASTICIZER) ON THE AMOUNT OF BULGING PRODUCED IN THE BULGE TEST AT VARIOUS DIE TEMPERATURES ON 2014 ALUMINUM ALLOY

Billets were 1 inch in diameter by 1-1/2 inches in height and were reduced 50 per cent in height by upsetting.



2X N25526

	Sample	Die Temperature, F	Bulge Index, inch
Top	142	500	0.213
Bottom	188	700	-0.016

FIGURE 18. FLOW PATTERNS OF 2014 ALUMINUM ALLOY BULGE-TEST SAMPLES FORMED WITH LUBRICANT 8 AT DIE TEMPERATURES OF 500 AND 700 F

The brief study demonstrated the advantages of using dies heated to approximately the same temperature as forging billets. By using heated dies, metal flow can be improved and forging loads can be reduced. These benefits are especially desirable in producing forgings with thin webs and flanges.

Tests on Commercial Lubricants

Before studying experimental lubricants or methods of lubrication, a basis for comparison had to be established. Therefore, a number of commercial lubricants of various types were obtained and compared using the pressing and laboratory forging tests. Materials or methods for lubrication which gave test results superior to the commercial materials may offer advantages in production operations.

The commercial lubricants were received as concentrates and were diluted as recommended for ease of spraying. The lubricants were sprayed with a DeVilbiss Type CM-605 spray gun operating at an air pressure of 60 psi.

Spraying time for the various lubricants was standardized at a total time of five seconds. Because of the lack of clearance between the forging die and punch, spraying had to be done slightly to either side of the punch. Therefore, the die was sprayed for 2-1/2 seconds from each end of the die. Table 1 shows a comparison of forging-test ratings for a number of lubricants sprayed for a total time of 5 and 10 seconds each. Generally, little difference in die filling was noted between the two spraying times. Usually, good die coverage was obtained with oil-carried lubricants even if sprayed from one end. However, water-carried lubricants did not give good coverage if sprayed from one end. This was observed by inspecting the dies after various types of spraying. If sprayed from both ends of the die, good die coverage was observed with the water-carried lubricants. This difference in coverage by method of spraying was reflected in the depth of die filling shown in Table 1 for Lubricants 4 and 10. A total spraying time of 5 seconds was selected because this gave good die coverage with a minimum amount of excess lubricant in the bottom of the die cavity. A spraying time of 10 seconds produced an excess amount of lubricant in the bottom of the die cavity. In most cases, the longer spraying period did not cause significantly better performance in the forging tests.

Forging- and pressing-test ratings obtained on a group of various types of commercial lubricants are listed in Table 2. Lubricants 18 and 19 are not actually used as hot-forging lubricants but were tested merely for comparison.

TABLE 1. EFFECTS OF SPRAYING TIME AND SPRAYING METHOD ON FORGING-TEST RESULTS[a] FOR A NUMBER OF COMMERCIAL LUBRICANTS ON 2014 ALUMINUM ALLOY

Lubricant	Brief Description	Method of Spraying[b]	Penetration Into Die Cavity, inch, for Total Spraying Time Indicated	
			5 Seconds	10 Seconds
1	Flake graphite in oil carrier	A	1.36	1.47
4[c]	Colloidal graphite in water	A	1.19	1.20
		B	0.97	
4A[c]	Colloidal graphite in water	A	1.33	1.53
7	Flake graphite in an oil carrier	A	1.33	1.19
8	Flake graphite in an oil carrier	A	1.44	1.45
10	Graphite in water	A	1.25	1.28
		B	1.06	

(a) Forging tests were made using a die temperature of 700 F, a billet temperature of 825 F, and a forging pressure of 46,000 psi. All values are averages for three specimens.

(b) A - Sprayed from both ends of the die.
B - Sprayed from one end of the die.

(c) Lubricant 4 was diluted 1 to 30 parts of water as recommended by the manufacturer. Lubricant 4A was the same lubricant diluted 1 to 5 parts of water.

TABLE 2. FORGE- AND PRESSING-TEST DATA OBTAINED IN WORKING 2014 ALUMINUM ALLOY WITH VARIOUS COMMERCIAL LUBRICANTS

Lubricant	Brief Description[a]	Depth of Penetration Into Die Cavity in Forge Test[b], in.	Pressing-Test Results[c] Average Pressed Thickness, in.	Pressing-Test Results[c] Coefficient of Friction (μ)
1	Flake graphite in oil carrier	1.36	0.100	0.15
2	Flake graphite in oil carrier	1.32	0.079	0.09
3	Colloidal graphite in oil carrier	1.48	0.094	0.125
4	Colloidal graphite in water carrier	1.20	0.086	0.11
5	Graphite + MoS_2 in oil carrier	1.46	0.080	0.09
6	Graphite + MoS_2 in water carrier	1.17	0.096	0.135
7	Flake graphite in an oil carrier	1.33	0.087	0.11
8	Flake graphite in an oil carrier	1.44	0.080	0.09
9	Flake graphite in an oil carrier	--	0.096	0.14
10	Graphite in a water carrier	1.25	0.075	0.08
13	Flake graphite in an oil carrier	1.31	0.090	0.12
15	MoS_2 in an oil carrier	1.16	0.103	0.16
17	MoS_2 in an oil carrier	1.44	0.092	0.125
18[d]	Diluted E. P. grease with no solid lubricant	0.98	0.108	0.17
19[d]	Diluted soapless grease with no solid lubricant	0.94	0.109	0.17
176	Oil type containing no solid lubricant	1.66	--	--
	Range for commercial lubricants	1.16 to 1.66	0.103 to 0.075	0.085 to 0.16

(a) All oil-base lubricants were diluted according to manufacturers' recommendations with naphthene-base oil having a viscosity of 106 seconds SU at 100 F. The dilution ratios are given in Table E-1 in Appendix E.

(b) Forging tests made using a billet temperature of 825 F, a die temperature of 700 F, and a punch pressure of 46,000 psi. Original data in Table F-1.

(c) Pressing tests were made by pressing billets 1 inch in diameter by 1/2 inch high between flat parallel dies heated to 700 F at a load of 138,000 pounds. Billet temperature was 825 F. Original data in Table F-2.

(d) These lubricants are not actually used as hot-forging lubricants but were tested merely for comparison.

Forging-test data obtained using the commercial lubricants are shown graphically in Figure 19. Penetration into the forging die ranged from 1.16 to 1.66 inches. Of the lubricants tested, one that is marketed as a hot-forging die lubricant that contains no solid lubricating material gave the best penetration. This material was received late in the program and was not used in pressing tests. The oil-carried lubricants containing graphite gave fairly uniform depths of penetration into the die cavity, ranging from 1.31 to 1.48 inches. However, two of them did not perform well in the pressing test. All water-carried lubricants produced poor die filling. This probably resulted from the fact that water-carried lubricants were more difficult to apply to dies at 700 F than oil-carried lubricants. Apparently a steam barrier forms at the die surface which prevents the water-carried lubricant from wetting the die surface. Wetting of the die surface should take place in order to deposit the solid lubricating material suspended in the water. The oil-carried lubricants containing only molybdenum disulfide seemed to be quite erratic. Of the two studied, one had a rating about as good as the best oil-carried lubricant containing graphite. The other was poorer than the graphited lubricants.

Little was known about the exact compositions or the nature of the vehicle for the commercial lubricants. Nevertheless, they were useful for establishing the test values characteristic of lubricants now in use as a basis for comparison.

Data obtained in the pressing test did not rate the lubricants in precisely the same order as the forging test. However, the correlation chart shown in Figure 20 indicates a general agreement between the two tests. As shown in Table 2, the range in thicknesses produced in the pressing test was from 0.103 to 0.075 inch, which corresponds to a range in coefficients of friction of 0.16 to 0.085. These friction coefficients are in the range expected from results reported by other investigators.

Effect of Oil Viscosity, Graphite Size, and Concentration

The effects of viscosity of the carrier and the size and concentration of flake-graphite particles suspended in oil were studied on mixtures of lubricants prepared in the laboratory. These samples were prepared because such information was not available for the commercial lubricants.

Four grades of flake graphite obtained from one source were used in preparing the lubricants. The grades consisted of large, medium, fine, and extra-fine flake graphite.

Various mixtures of the four grades of flake graphite with three different oils were prepared. These mixtures are listed and described in Table 3. Oils A, B, and C, used in these mixtures, may be described as follows:

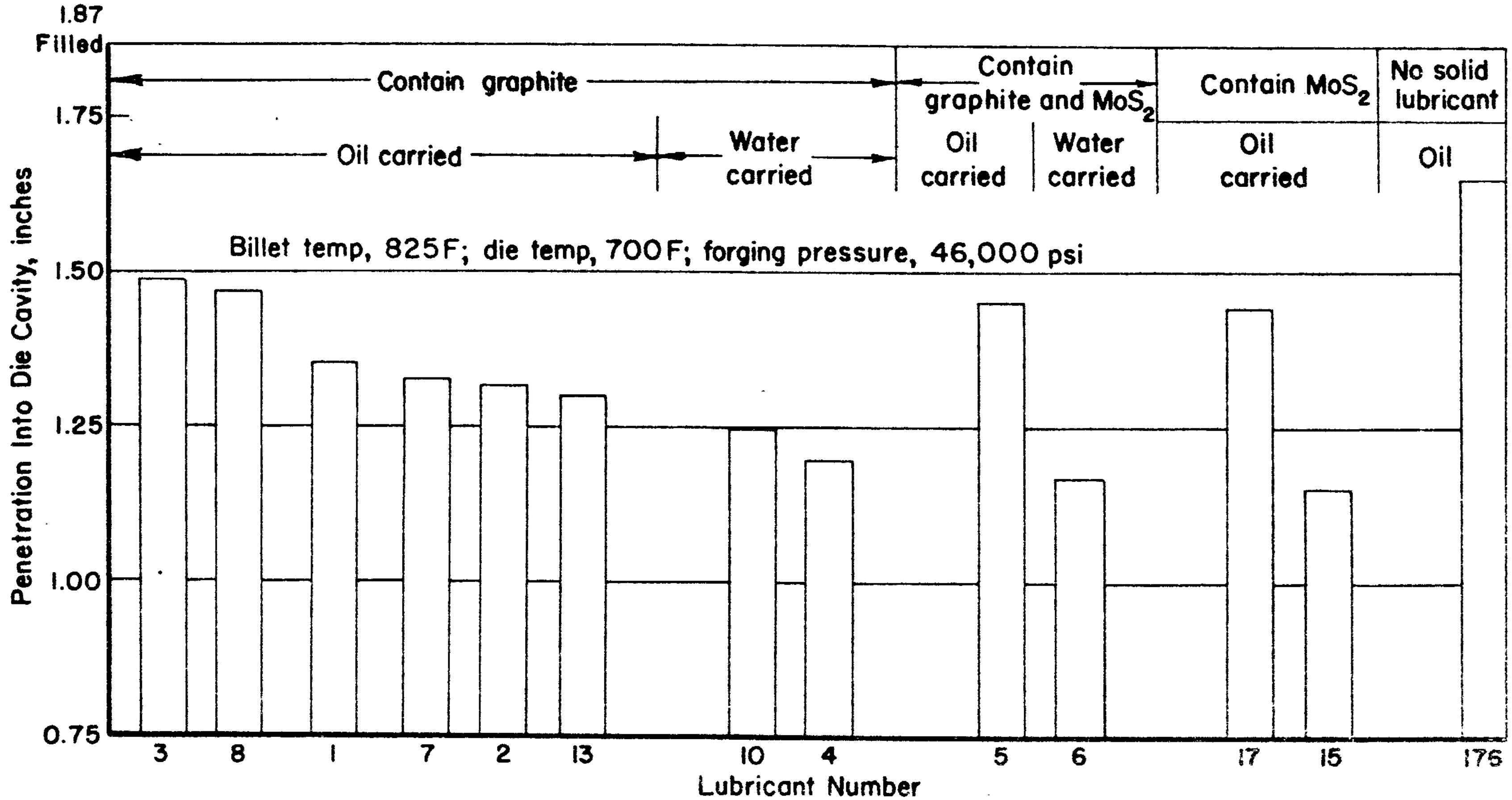


FIGURE 19. FORGING TEST RATINGS FOR COMMERCIAL LUBRICANTS OBTAINED IN WORKING 2014 ALUMINUM ALLOY

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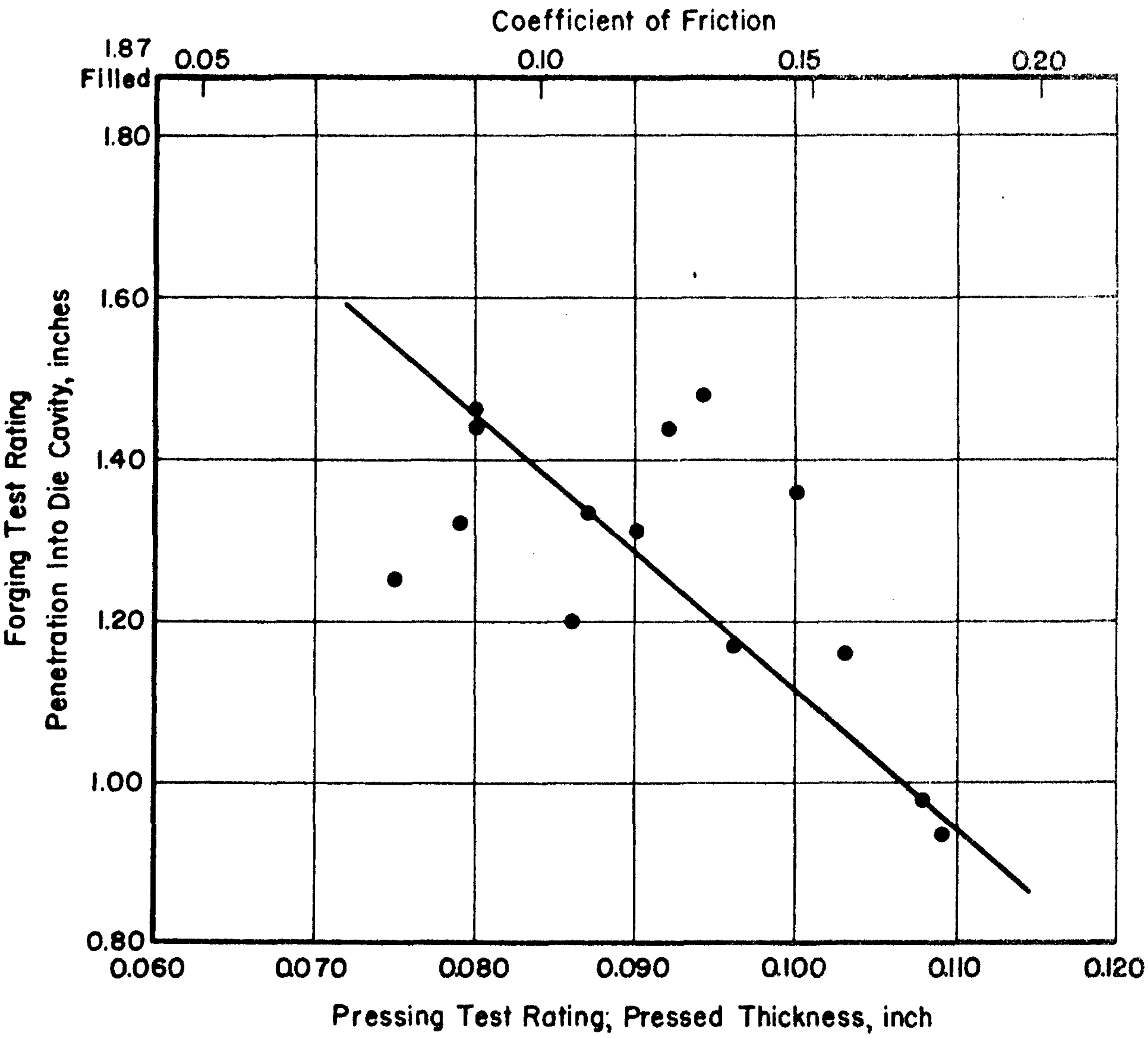

FIGURE 20. CORRELATION BETWEEN PRESSING TEST AND FORGING TEST RATINGS OBTAINED ON COMMERCIAL LUBRICANTS IN FORGING 2014 ALUMINUM ALLOY

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TABLE 3. FORGING- AND PRESSING-TEST DATA SHOWING THE EFFECTS OF GRAPHITE SIZE AND CONCENTRATION IN OIL-CARRIED LUBRICANTS USED IN WORKING 2014 ALUMINUM ALLOY

Lubricant	Description[a]	Average Penetration Into Die Cavity in Forge Test[b], in.	Pressing Test Results[c]	
			Average Pressed Thickness, in.	Coefficient of Friction (μ)
59	Oil B alone	1.05	0.098	0.14
77	20% large flake graphite in Oil B	1.17[d]	0.075	0.075
44	10% medium flake graphite in Oil B	1.39	0.098	0.14
78	20% medium flake graphite in Oil B	1.42	0.094	0.13
155	30% medium flake graphite in Oil B	1.51	--	--
79	20% fine flake graphite in Oil B	1.36	0.084	0.10
156	10% extra-fine flake graphite in Oil B	1.43	--	--
80	20% extra-fine flake graphite in Oil B	1.52	0.072	0.07
157	30% extra-fine flake graphite in Oil B	1.58	--	--
84	20% extra-fine flake graphite in Oil A	1.19	0.104	0.16
83	20% extra-fine flake graphite in Oil C	1.47	--	--

(a) A. Naphthene-base oil having a flash point of 320 F and a viscosity of 106 SUS at 100 F.
B. One-to-one mixture by volume of Oils A and C.
C. 600 W cylinder oil having a flash point of 540 F and a viscosity of 1970 SUS at 100 F.
(b) Forge tests were made using a billet temperature of 825 F, a die temperature of 700 F, and a forging pressure of 46,000 psi.
(c) Pressing tests were made by pressing 1-inch-diameter by 1/2-inch-high billets between flat parallel dies using a billet temperature of 825 F, a die temperature of 700 F, and a pressing load of 138,000 pounds.
(d) Large graphite flakes clogged spray gun.

Oil A – Naphthene-base oil having a flash point of 320 F and a viscosity of 106 SUS at 100 F

Oil B – One-to-one mixture by volume of Oils A and C

Oil C – 600 W cylinder oil having a flash point of 540 F and a viscosity of 1970 SUS at 100 F.

These oils were used throughout the study as vehicles for carrying various types of solids.

Forge-test data for all the mixtures and pressing-test data on some of the lubricants are listed in Table 3. With the exception of the forge-test data on Lubricant 77, a fairly good correlation was shown (Figure 21) for the data obtained in the two types of tests. The large flakes of graphite present in Lubricant 77 clogged the spray gun intermittently and for that reason the forge-test rating is believed to be too low to be typical of the lubricant.

Figure 22 shows the effect of the viscosity of the oil carrier on the forge-test rating. All three lubricants contained 20 per cent by weight of extra-fine flake graphite. All three lubricants were within the range for the commercial lubricants tested. However, the lubricant containing Oil A was near the bottom of the range, while the other two were near the top of the range and were as good as any of the oil-carried commercial lubricants containing graphite.

The low rating for Lubricant 84 containing Oil A is believed to result from the rapidity at which the oil volatilized and changed to dense smoke when it was applied to dies at 700 F. Because of this, poor coverage of the die surface was produced, especially at locations where the spray hit the die surfaces at a very oblique angle. In this respect, this lubricant resembled water-carried lubricants.

Lubricants 80 and 83, containing higher viscosity oils as carriers, gave much higher ratings than Lubricant 84. Lubricant 80, containing Oil B, had a good viscosity for spraying, while Lubricant 83 (containing Oil C) had to be heated to about 200 F in order to reduce the viscosity enough for easy spraying. Both Oils B and C produced much less smoke than Oil A. Better lubricant coverage of the dies before the oil volatilized or burned is believed to be the cause of the better die filling. These experiments indicate that comparatively low viscosities are not necessarily desirable in lubricants for hot working.

Figure 23 shows the effect of graphite flake size on the forge-test rating using 20 per cent by weight each of medium, fine, and extra-fine flake graphite in Oil B. No outstanding differences were noted among the three lubricants. Lubricant 80, containing extra-fine graphite, showed

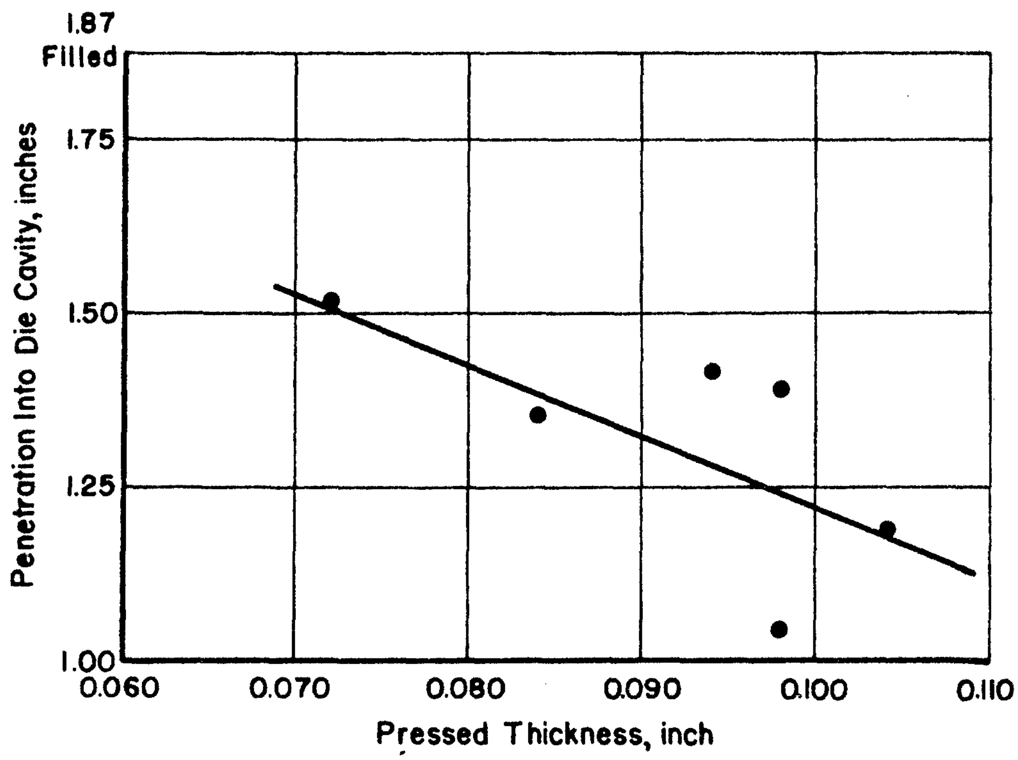

FIGURE 21. CORRELATION BETWEEN PRESSING AND FORGING TEST DATA FOR LUBRICANTS SHOWN IN TABLE 3

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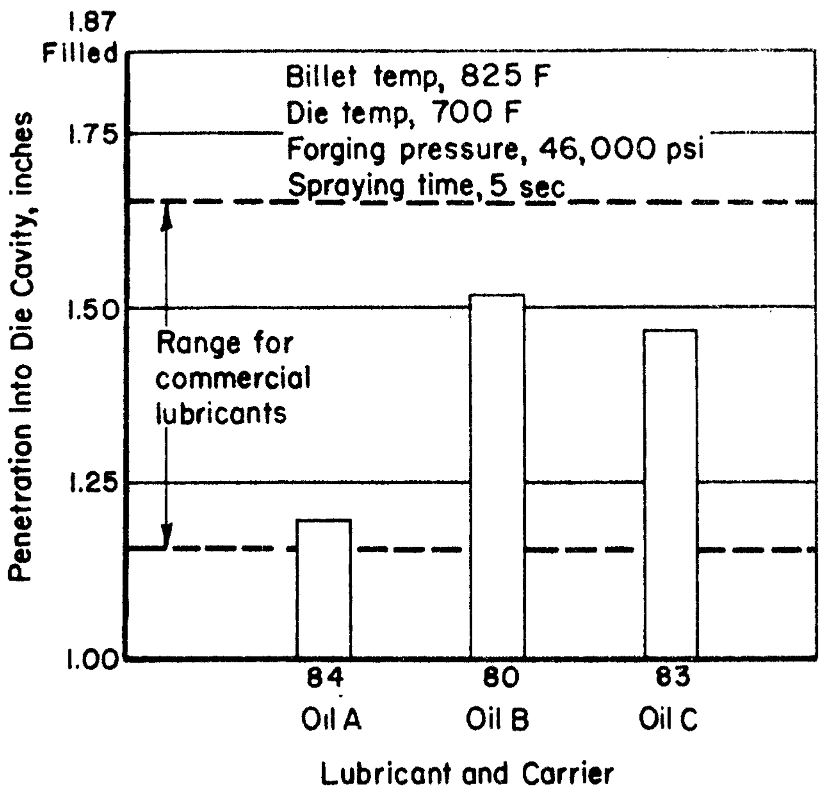

Oil A–Napthene-base oil having a flash point of 320 F and a viscosity of 106 SSU/100 F

Oil B–1 to 1 mixture of oils A and C

Oil C–600W cylinder oil having a flash point of 540 F and a viscosity of 1970 SSU/100 F

FIGURE 22. EFFECT OF CARRIER OIL ON FORGING TEST RESULTS ON 2014 ALUMINUM ALLOY USING LUBRICANTS CONTAINING 20 PER CENT OF EXTRA-FINE FLAKE GRAPHITE

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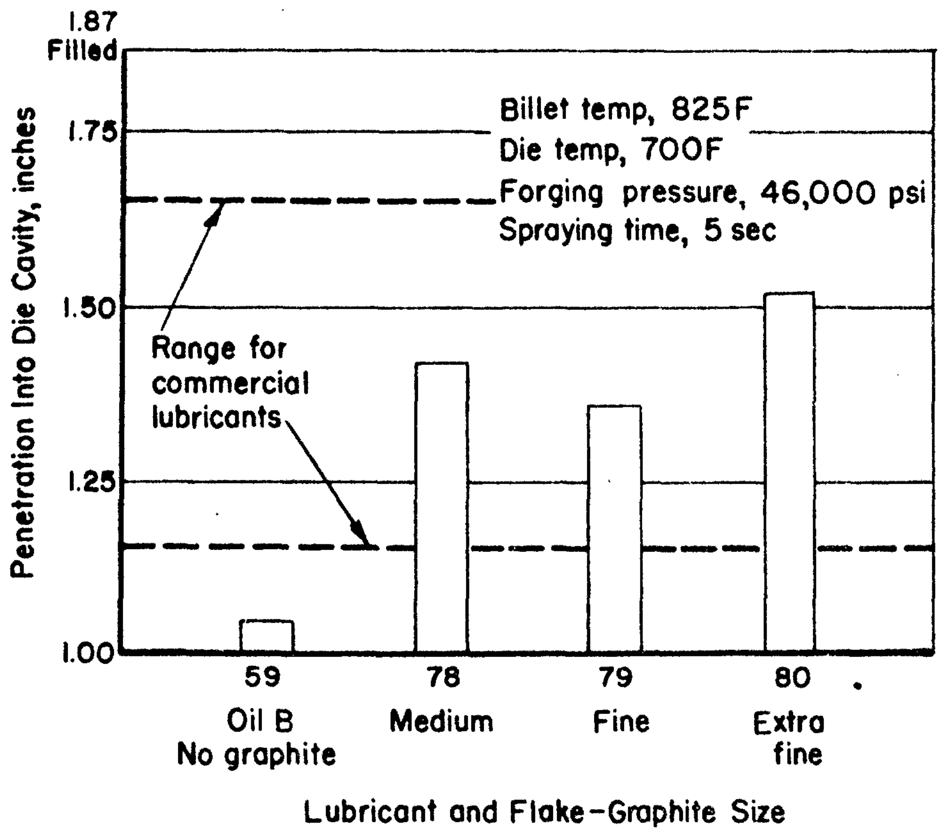

FIGURE 23. EFFECT OF FLAKE-GRAPHITE SIZE ON THE DEPTH OF PENETRATION OF 2014 ALUMINUM ALLOY INTO THE FORGING DIE USING 20 PER CENT OF EACH GRAPHITE IN OIL B

A-16852

the best rating and the improvement in rating over the other two lubricants is believed to be real. The relatively small difference noted between Lubricants 78 and 79 is not believed to be significant.

The effect of concentration of flake graphite in Oil B on the performance in the forging test is shown in Figure 24. Two series of lubricants, containing 10, 20, and 30 per cent by weight each of fine and extra-fine flake graphite, were studied. The data indicate that by increasing the concentration of the graphite from 10 to 30 per cent, the amount of die filling is increased about 10 per cent. These data suggest that the amount of penetration into the forging die depends to a certain extent on the amount of graphite adhering to the die surface, because the dies were sprayed for a uniform length of time. If this is true, then increased spraying time should produce the same effect. However, with increased spraying time, more oil is applied to the dies to get the same die coverage. This would increase the amount of carbonaceous residue from the oil on the dies. The effect of this residue on metal flow is not known but is expected to be beneficial.

The data in Figure 24 also show that the lubricant containing extra-fine flake graphite gave slightly better die filling than the lubricant containing medium flake graphite. This was true for all concentrations investigated and substantiates the effect shown in Figure 23.

Study on Four Experimental Lubricants in Grease Bases

Four experimental lubricants that had been compounded by a lubricant manufacturer were available at Battelle for study. These materials had been used in a study on the extrusion of titanium.[23] They consisted of various amounts of flake graphite and/or molybdenum disulfide in a calcium-base or a bentone grease. All four contained 5 per cent of mica by weight.

In the as-received condition, the consistency of the lubricants was very heavy. Therefore, they were diluted 1 part to 3 parts by volume with Oil A so they could be sprayed.

Table 4 gives a description of the lubricants along with forging- and pressing-test data obtained on them using 2014 aluminum alloy as working stock. The forging- and pressing-test data are shown graphically in Figure 25. The data indicate that the two types of tests rated the four lubricants in the same order. Forging-test ratings showed that they were all within the range for the commercial lubricants tested earlier. Two of them (Lubricants 49 and 51) were as good as the best of the commercial lubricants tested. The pressing test indicated that these two lubricants were better than any of the commercial lubricants. This is considered to indicate that they had better spreading characteristics.

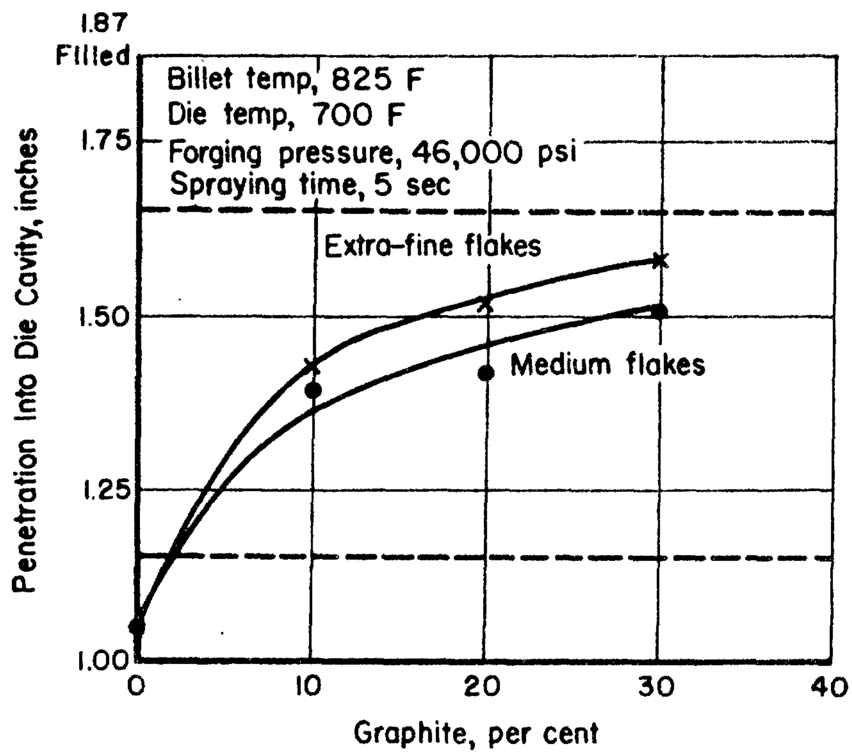

FIGURE 24. EFFECT OF FLAKE-GRAPHITE CONCENTRATION IN OIL B ON THE DEPTH OF PENETRATION OF 2014 ALUMINUM ALLOY INTO THE FORGING DIE

A-16872

TABLE 4. FORGING- AND PRESSING-TEST DATA OBTAINED ON FOUR EXPERIMENTAL LUBRICANTS IN WORKING 2014 ALUMINUM ALLOY

Lubricant	Description(a)	Average Penetration Into Die Cavity in Forge Test(b), in.	Pressing Test Results(c)	
			Pressed Thickness, in.	Coefficient of Friction (μ)
49	35% flake graphite, 5% mica in calcium-base grease	1.64	0.067	0.06
50	25% MoS_2, 5% mica in calcium-base grease	1.51	0.079	0.09
51	25% flake graphite, 15% MoS_2, 5% mica in a calcium-base grease	1.62	0.072	0.085
52	25% flake graphite, 15% MoS_2, 5% mica in a bentone grease	1.39	0.095	0.13
Commercial	Various	1.16 to 1.66	0.103 to 0.075	0.085 to 0.16

(a) The materials listed were diluted one to three parts by volume with Oil A to make them sprayable.
(b) Forge tests were made using a billet temperature of 825 F, a die temperature of 700 F, and a forging pressure of 46,000 psi.
(c) Pressing tests were made by pressing 1-inch-diameter by 1/2-inch-high billets between flat, parallel dies using a billet temperature of 825 F, a die temperature of 700 F, and a pressing load of 138,000 pounds.

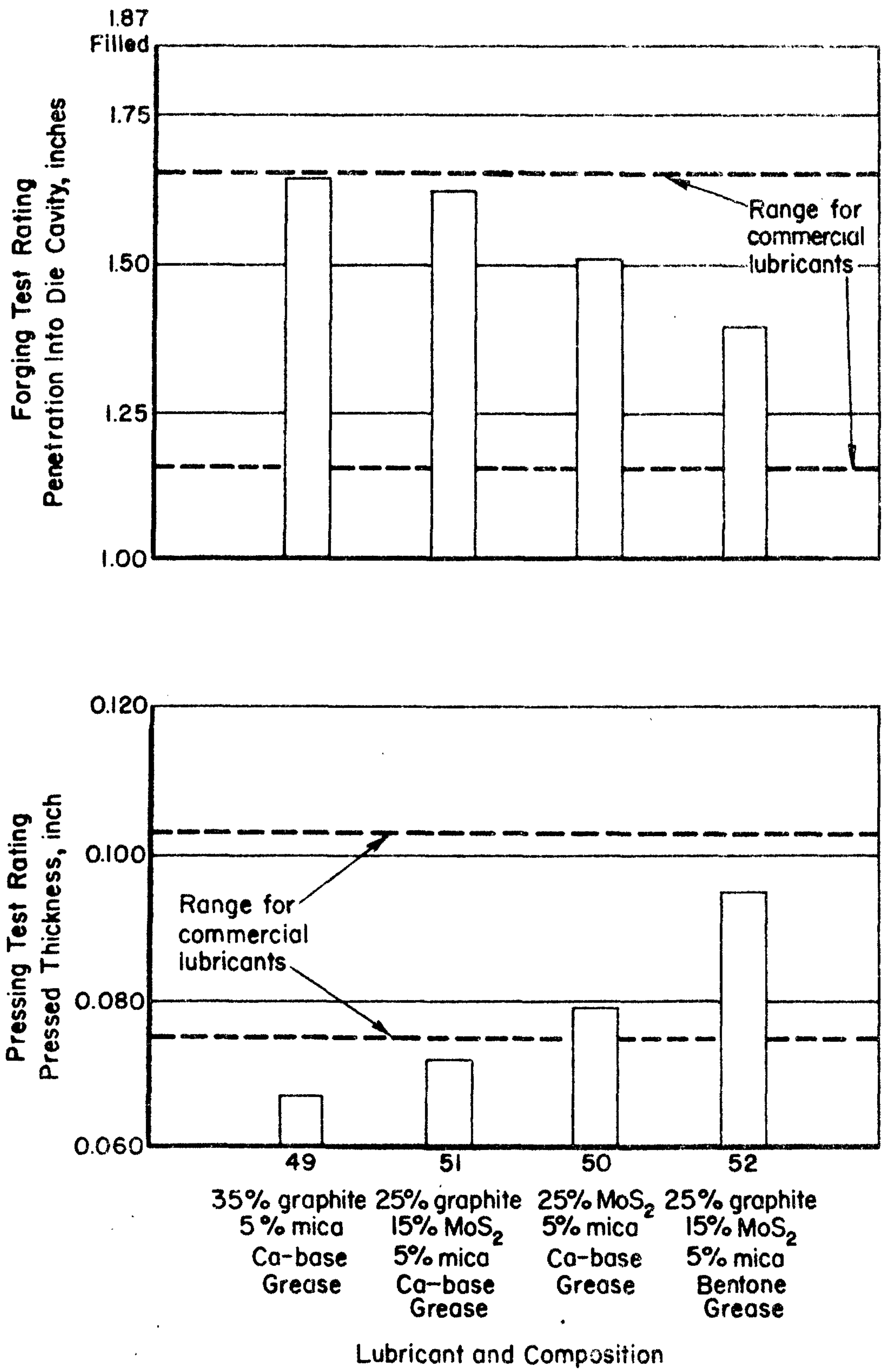

FIGURE 25. PRESSING AND FORGING TEST RATINGS FOR FOUR EXPERIMENTAL LUBRICANTS

The mixtures having the compositions shown were diluted 1 to 3 by volume with Oil A.

A-16849

The two best lubricants (49 and 51) contained comparatively high percentages of graphite in the calcium-base grease; Lubricant 51 contained molybdenum disulfide in addition to the graphite. It is not known whether the slightly poorer rating for Lubricant 51 was the result of the lower graphite content or the presence of the molybdenum disulfide. However, it is suspected that the presence of the molybdenum disulfide may have had a slight deleterious effect because Lubricant 50, which contained only molybdenum disulfide, had a noticeably poorer rating. This lubricant contained the same base as the others.

The ratings for Lubricant 52 indicate that bentone grease is not as desirable a vehicle for carrying the solid lubricants as the calcium-base grease. This is shown by comparing the data for Lubricant 52 with those for Lubricant 51. Both contain identical percentages of graphite and molybdenum disulfide so the variation in performance must be attributed to the different greases.

Studies on Various Inorganic Materials

A large number of various types of inorganic materials were tried as lubricants in working 2014 aluminum alloy. Some of the materials tested were those that are currently being used commercially as lubricants. Others were tried in the search for materials that offer more promise as a lubricating material than those ordinarily used.

Forging-, pressing-, and bulging-test data obtained on some of these materials are given in Table 5. Brief descriptions of the materials are also given in the table. Forge-test data for 10 per cent by weight of the various materials in Oil B as a carrier, when used in forging 2014 aluminum alloy, are shown graphically in Figure 26. All tests were made in triplicate. Graphite gave the best die filling of all the materials tried in these experiments. Talc, molybdenum disulfide, and mica, which are also used either as a solid lubricant or as a filler material in some commercial lubricants, showed much poorer performance than flake graphite in these studies.

Boron nitride, a material having a crystal structure similar to that of graphite, gave much poorer die filling than graphite when used in the same carrier. The boron nitride used had a purity of 98 per cent. It is not known whether the impurities present had any adverse effect on the material when used as a lubricant.

Twenty per cent water solutions of potassium, sodium, ammonium, tin, and lead fluoborates (Lubricants 60, 61, 62, 63, and 64) were tested early in the program by using the bulge test. The tests were made using a die temperature of 500 F. Bulge-test data for these materials used as lubricants in working 2014 aluminum alloy are also listed in Table 5.

TABLE 5. FORGING-, PRESSING-, AND BULGE-TEST DATA FOR A NUMBER OF INORGANIC MATERIALS USED AS LUBRICANTS IN WORKING 2014 ALUMINUM ALLOY

Lubricant	Description	Average Penetration Into Die Cavity in Forge Test(a), in.	Pressing-Test Results(b) Pressed Thickness, in.	Pressing-Test Results(b) Coefficient of Friction (μ)	Bulge Index(c) for Indicated Die Temperature, F 500	Bulge Index(c) for Indicated Die Temperature, F 700
Commercial	Various	1.16 to 1.66	0.103 to 0.075	0.085 to 0.16		
59	Oil B	1.05	0.098	0.14	0.201	0.113
44	10% medium flake graphite in Oil B	1.39	0.098	0.14	0.252	0.110
37	10% medium flake graphite in Oil A	--	--	--	0.260	0.218
45	10% powdered MoS_2 in Oil B	1.08	0.084	0.10	0.250	0.083
36	10% powdered MoS_2 in Oil A	--	--	--	0.270	0.244
43	10% powdered WS_2 in Oil B	1.01	0.090	0.12	0.247	0.032
38	10% powdered WS_2 in Oil A	--	--	--	0.202	0.220
47	10% mica in Oil B	0.90	0.097	0.14	0.265	0.089
46	10% talc in Oil B	1.12	0.093	0.12	0.220	0.103
75	10% boron nitride in Oil B	1.12	--	--	--	--
86	20% boron nitride in Oil B	1.30	0.085	0.10	--	--
76	10% aluminum powder in Oil B	1.11	--	--	--	--
70	20% aluminum powder in Oil B	1.01	0.093	0.13	0.239	0.087
39	20% aluminum powder in Oil A	--	--	--	0.280	--
40	10% indium powder (minus 48 mesh) in Oil A	--	--	--	0.258	--
34	10% aluminum sulfate (minus 100 mesh) in Oil A	--	--	--	0.275	--
35	10% ammonium sulfate (minus 100 mesh) in Oil A	--	--	--	0.279	--
60	20% potassium fluoborate in water	--	--	--	0.285	--

TABLE 5. (Continued)

Lubricant	Description	Average Penetration Into Die Cavity in Forge Test[a], in.	Pressing-Test Results[b] Pressed Thickness, in.	Pressing-Test Results[b] Coefficient of Friction (μ)	Bulge Index[c] for Indicated Die Temperature, F 500	Bulge Index[c] for Indicated Die Temperature, F 700
61	20% sodium fluoborate in water	--	--	--	0.225	--
62	20% ammonium fluoborate in water	--	--	--	0.293	--
63	20% tin fluoborate in water	--	--	--	0.305	--
63A	50% tin fluoborate in water	--	0.105	0.16	--	--
64	20% lead fluoborate in water	--	--	--	0.305	--
93	Fused sodium hydroxide (cp)	--	0.102	0.16	--	--
94	Fused potassium hydroxide (cp)	--	0.097	0.14	--	--
95	Aluminum foil, 0.0015 inch thick; MP, 1215 F	--	0.095	0.13	--	--
96	Copper foil, 0.008 inch thick; MP, 1980 F	--	0.107	0.17	--	--
98	Zinc foil, 0.0005 inch thick; MP, 787 F	--	0.088	0.11	--	--
99	Lead foil, 0.004 inch thick; MP, 620 F	--	0.103	0.16	--	--
100	Tin foil, 0.002 inch thick; MP, 450 F	--	0.107	0.17	--	--
22	Phosphate-type glass	1.11	--	--	--	--

(a) Forge tests were made using a billet temperature of 825 F, a die temperature of 700 F, and a forging pressure of 46,000 psi.
(b) One-inch-diameter by 1/2-inch-high billets were pressed between flat parallel dies using a billet temperature of 825 F, a die temperature of 700 F, and a pressing load of 138,000 pounds.
(c) Bulge index is the maximum concavity or convexity minus the diameter at the end of 1-inch-diameter by 1-1/2-inch-high billets that had been pressed between parallel flat dies to 3/4-inch thickness. Billet temperature was 825 F.

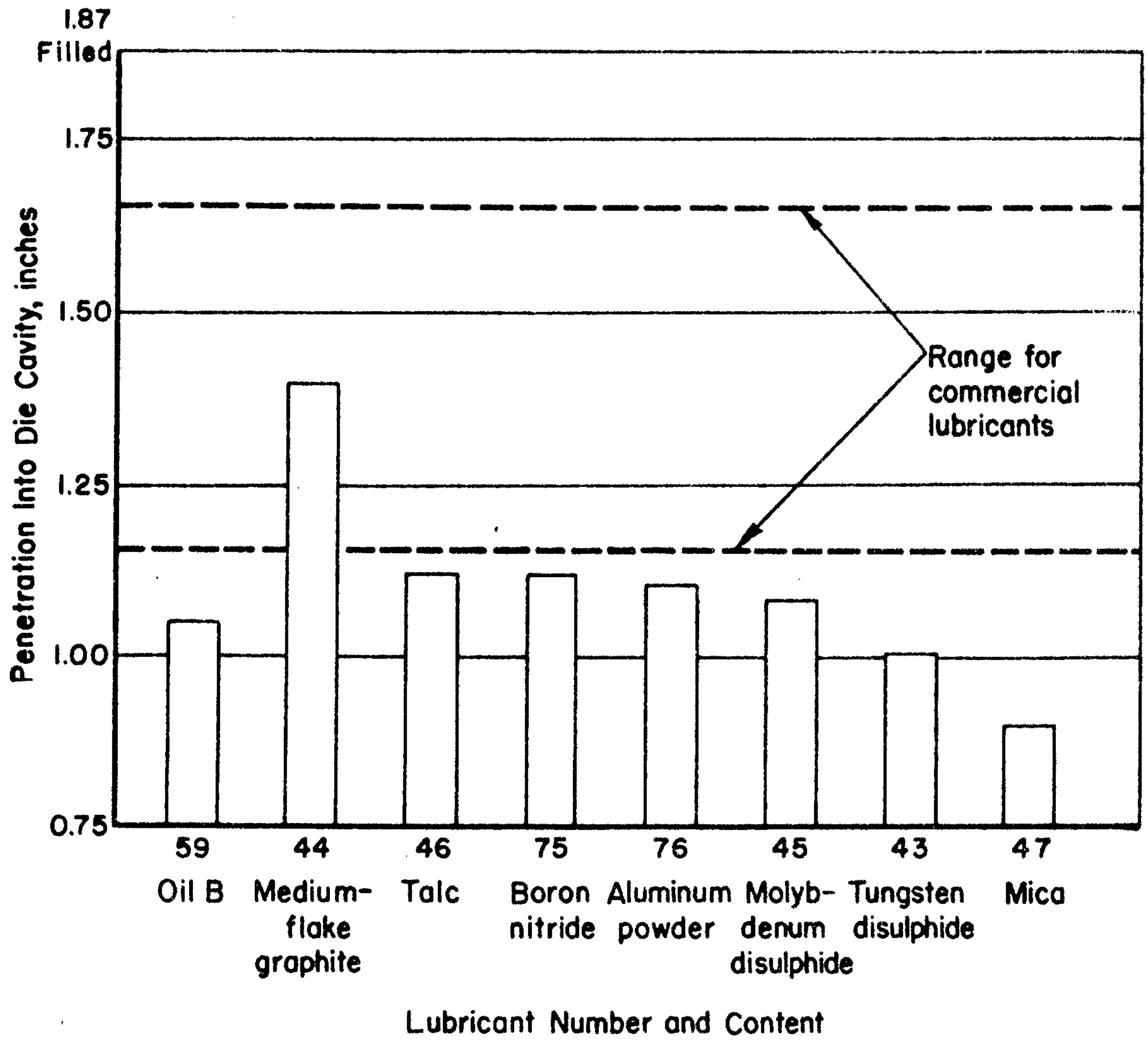

FIGURE 26. RELATIVE FORGING TEST RATINGS FOR 10 PER CENT OF VARIOUS MATERIALS ADDED TO OIL B AS A LUBRICANT IN WORKING 2014 ALUMINUM ALLOY

A-16850

These ratings were not much better than those in which no lubricant at all was used. It was difficult to make the salts stick to the hot dies, probably because of the rapid formation of steam. For these reasons, further tests were not made on these materials. However, a 50 per cent solution of tin fluoborate (Lubricant 63A) was tried as a lubricant in the pressing test. The results were not promising.

Pressing-test data for fused sodium and potassium hydroxides (Lubricants 93 and 94) as lubricants in working 2014 aluminum alloy showed no promise for these materials as lubricants. In using these materials, the billets were immersed in the molten hydroxide at 825°F before pressing. The sodium hydroxide appeared to etch the billet surface slightly and the potassium hydroxide seemed to attack the aluminum to a greater degree.

Metal foils of aluminum, copper, zinc, lead, and tin (Lubricants 95, 96, 98, 99, and 100) when used between the dies and the workpiece in the pressing test were of no value as forging lubricants in working 2014 aluminum alloy. The lead and tin foils melted when applied to the hot dies and billets. Zinc gave the best pressing-test rating of the metal foils. Zinc has a melting point of 787 F, about midway between the die and billet temperatures.

Fourteen experimental glass compositions were made in the laboratory in an effort to develop a glass having a low enough softening range to be useful in working aluminum. In aluminum forging, the glass should be somewhat plastic at the die temperature so that the die would not be scratched by the hard, brittle glass during the forging operation. The compositions are given and some of the properties of the experimental glasses are discussed in Appendix G. Based on these data, one glass composition had a sufficiently low softening range to be considered as a lubricant in working aluminum. This composition is listed as Lubricant 22 and is a phosphate-type glass made from the following oxides: 27.8 per cent Na_2O, 63.6 per cent P_2O_5, and 8.5 per cent ZnO. This glass did not soften appreciably at 800 F, however, it was not brittle at 700 F if sufficient time were allowed for the glass to reach temperature.

The use of this phosphate-type glass as a lubricant in working 2014 aluminum alloy gave poor die penetration in the forging test. The penetration of 1.11 inches listed in Table 5 was slightly poorer than the worst of the commercial lubricants tested. The glass coating was produced by rolling the hot billet in the powdered glass and by touching the ends of the billet in the glass before forging. The forged samples were very difficult to remove from the die because the glass was very tacky. Seizing and tearing of the aluminum at the radii into the die cavity and on the ends were evident on the forgings. Also, the glass tended to remain in the corners of the horizontal section of the T-forging, thus creating an underfilled condition. The glass was very difficult to remove from hot dies. However, this glass would be fairly easy to remove from cold dies because it is water soluble.

Studies on a Group of Temperature-Critical Materials

A group of twenty materials, which were essentially organic or inorganic salts in a carrier of carbon tetrachloride, were used as lubricants in working 2014 aluminum in the pressing test. These materials were studied because they offered a range in melting points. The exact compositions of the materials were not available. They are ordinarily used for indicating the temperature of hot, solid metals because they melt at a particular temperature. Consequently, some of them formed liquid films on the die surfaces.

Pressing-test ratings obtained using these materials as lubricants are given in Table 6. The data show that all but one of these materials gave poor results in the pressing test. One material (Lubricant 92) when first tested gave an exceptionally good rating. Pressings in this test averaged 0.057 inch in thickness and corresponded to a coefficient of friction of 0.04. The same rating was obtained in a second series of tests. However, the exceptionally good ratings could not be obtained again in later tests. Instead, the ratings were quite erratic. The material remained fluid when applied to the dies or billets.

Because of the exceptionally good results obtained in some of the pressing tests using Lubricant 92, forging tests were made using this material as a lubricant. The lubricant was applied to the billets before heating. Very poor die penetration (1.00 inch) was obtained in the forging experiments.

Lubricant 92 was identified as being tetra normal butyl ammonium hexafluophosphate, an organic salt. Because of some of the extremely good ratings shown for this material, additional chemicals in the same general family were either purchased or prepared in the laboratory for testing as lubricants. These materials, along with the pressing test ratings obtained in using them as lubricants in pressing 2014 aluminum, are listed in Table 7. All these materials were in the form of powders or crystals. Lubricant 144 was the same chemical that was the base for Lubricant 92. The hot billets were dipped in the powder to pick up the crystals which adhered and melted on the billet surface before pressing.

None of these organic salts, when used as lubricants in the pressing test, gave promising test results. Therefore, forging tests were not made on these materials.

TABLE 6. PRESSING-TEST RATINGS ON TWENTY TEMPERATURE-CRITICAL MATERIALS[a] USED AS LUBRICANTS IN WORKING 2014 ALUMINUM ALLOY

Lubricant	Melting Point, F	Method of Application	Sample	Pressing-Test Results[b] Pressed Thickness, in.	Pressing-Test Results[b] Coefficient of Friction (μ)	Remarks
91	650	Brushed on billet before heating		0.084	0.10	
92	475	Brushed on billet before heating	184-186	0.057	0.04	Billets heated 15-20 minutes
		Ditto	187-189	0.057	0.04	Billets heated 15-20 minutes
		"	221-223	0.093	0.12	Billets heated 20-25 minutes
		"	224-226	0.077	0.085	Billets heated 10-12 minutes
		Brushed on dies before pressing	227-229	0.075	0.08	Billets heated 15-20 minutes
		Brushed on billet before heating	230-232	0.105	0.16	Billets heated 15-20 minutes
		Brushed on dies before pressing	233-235	0.082	0.095	Billets heated 15-20 minutes
125	338	Brushed on billet before heating and also on dies before forging		0.098	0.14	
126	363	Ditto		0.104	0.16	
127	375	"		0.100	0.15	
128	388	"		0.101	0.16	
129	400	"		0.105	0.17	
130	413	"		0.101	0.15	

TABLE 6. (Continued)

Lubricant	Melting Point, F	Method of Application	Pressing-Test Results(b): Pressed Thickness, in.	Pressing-Test Results(b): Coefficient of Friction (μ)	Remarks
131	425	Brushed on billet before heating and also on dies before forging	0.101	0.15	
132	438	Ditto	0.093	0.13	
133	450	"	0.101	0.15	
134	463	"	0.104	0.16	
135	488	"	0.100	0.15	
136	500	"	0.100	0.15	
137	550	"	0.101	0.15	
138	600	"	0.099	0.15	
139	1150	"	0.101	0.15	
140	1250	"	0.103	0.15	
141	1350	"	0.101	0.15	
142	1450	"	0.101	0.15	

(a) These materials are suspended in a carrier of carbon tetrachloride and have known melting points.

(b) One-inch-diameter by 1/2-inch-high billets were pressed between flat parallel dies using a billet temperature of 825 F, a die temperature of 700 F, and a pressing load of 138,000 pounds.

TABLE 7. PRESSING-TEST RATINGS ON A NUMBER OF ORGANIC SALTS USED AS LUBRICANTS IN WORKING 2014 ALUMINUM

Lubricant	Description	Melting Point, F	Pressing-Test Results[(a)]	
			Pressed Thickness, in.	Coefficient of Friction (μ)
144[(b)]	Tetra-n-butyl ammonium hexafluophosphate	482	0.102	0.15
144	Tetra-n-butyl ammonium hexafluophosphate	482	0.102	0.15
145	Mono-n-butyl ammonium hexafluophosphate	332	0.095	0.13
146	Mono tertiary butyl ammonium hexafluophosphate	--	0.098	0.14
147	Potassium hexafluophosphate	--	0.099	0.14
160	Trimethyl ammonium hexafluophosphate	338	0.100	0.15
161[(c)]	Tetramethyl ammonium fluoborate	788	0.087	0.11
162[(c)]	Tetraethyl ammonium fluoborate	689	0.094	0.13
163[(c)]	Tetra-n-tetraethyl ammonium hexafluophosphate	617	0.085	0.10
164[(c)]	Tetra-n-tetramethyl ammonium hexafluophosphate	>752	0.101	0.15
165[(c)]	Isopropyl tri-n-propyl ammonium hexafluophosphate	365-374	0.106	0.17
166[(c)]	n-Amyl triethyl ammonium hexafluophosphate	320-329	0.101	0.15
167[(c)]	Methyl tri-n-butyl ammonium hexafluophosphate	257	0.113	0.19
168[(c)]	n-Butyl tri-n-triethyl ammonium hexafluophosphate	320	0.116	0.20
169[(c)]	n-Soya trimethyl ammonium hexafluophosphate	329-365	0.105	0.16
170	n-Benzyl tri-n-trimethyl ammonium hexafluo-phosphate	248	0.102	0.15
171	n-Dodecylbenzyl tri-n-trimethyl ammonium hexafluophosphate	354	0.101	0.15

(a) One-inch-diameter by 1/2-inch-high billets pressed between flat parallel steel dies using a billet temperature of 825 F, a die temperature of 700 F, and a pressing load of 138,000 pounds.

(b) Hot billet rolled in powder then reheated for 10 minutes before forging.

(c) These materials were prepared in the laboratory.

Studies on Organic Materials

Since plastics and other organic materials are ordinarily used at room temperature, their properties at higher temperatures are not well established. Most of these materials burn or char to leave a carbonaceous residue when heated at temperatures required for forging aluminum and magnesium. Nevertheless, sixteen organic materials were studied as possible lubricants for hot-working operations. These materials were suggested by organic chemists experienced in research on coatings and plastics. The materials were recommended for study because they were relatively stable at reasonably high temperatures. However, their lubricating properties in the temperature range from 600-800 F were not known. This was also true of some of their other characteristics.

The organic materials studied as lubricants are identified in Table 8. Forging-, pressing-, and bulge-test data, obtained on aluminum specimens using these lubricants, are also listed in the table.

Bulging tests were made early in the program to evaluate some of the organic lubricants. Of the ten materials investigated by that method, Paraplex G62 (Lubricant 24) and the Polyamide Resin 90 (Lubricant 54) gave the best results. That is, they resulted in less bulging, an indication of better flow of metal adjacent to the die surfaces. When this group of materials was used in the pressing test, the same two materials had the best ratings.

Some of the materials tried in the bulge test were not further evaluated by the pressing and forging tests. Lubricants 26 and 27 created considerable spattering when applied to the hot dies. This was considered a disadvantage serious enough to eliminate them from further consideration.

Data obtained in the pressing test indicated that Lubricants 24 (Paraplex G62, an ester-type plasticizer), 56 (Polyamide Resin 90), and 102 (Paraplex G60, an ester-type plasticizer) gave ratings that were as good as some of the best commercial lubricants. Lubricant 143 (nylon powder) gave a pressing-test rating that was slightly better than those obtained on the commercial lubricants.

It should be noted that a tetrafluoroethylene resin produced exceptionally good pressing-test ratings. This material is known to have very low frictional properties at lower temperatures. The resin is marketed in several forms. Three forms of this resin were obtained for study. They are listed in Table E-1 of Appendix E as Lubricants 97, 149, and 150. Because of their interesting possibilities, they are described briefly here:

TABLE 8. FORGING-, PRESSING-, AND BULGE-TEST RATINGS FOR ORGANIC MATERIALS USED AS LUBRICANTS IN WORKING 2014 ALUMINUM ALLOY

Lubricant	Description	Average Penetration Into Die Cavity Forging Test[a], inch	Pressing-Test Results[b] Pressed Thickness, inch	Coefficient of Friction (μ)	Bulge Index[c], inch
23	Monoplex S71 (ester-type plasticizer)	1.03	0.110	0.17	0.153
24	Paraplex G62 (ester-type plasticizer)	1.08	0.087	0.11	0.073
25	550 Fluid (silicone fluid)	—	—	—	0.131
26	Acryloid B-72 (acrylic resin in toluene solvent)	—	—	—	0.162
27	Rhoplex AC-33 (water emulsion of an acrylic polymer)	—	—	—	0.141
53	Silicone Grease No. 41 (diluted 1 part to 8 parts by volume, Oil A)	1.10	0.103	0.16	0.143
54	Polyamide Resin No. 90	0.98	0.079	0.09	0.103
56	Diester synthetic tube oil	—	—	—	0.170
66	Epon 828 (epoxy resin)	0.95	0.108	0.16	0.156
67	Epon RN34 (epoxy resin)	—	—	—	0.150
97	Tetrafluorethylene resin tape (0.010 inch thick)	1.01	0.047	0.025	—
101	Paraplex G50 (ester-type plasticizer)	—	0.092	0.12	—
102	Paraplex G60 (ester-type plasticizer)	—	0.089	0.12	—
143	Nylon powder	0.86	0.072	0.07	—
149	Tetrafluorethylene resin primer for steel	1.84[d]	0.035[d]	0.01	—
149	Tetrafluorethylene resin primer for steel	1.47[e]	—	—	—
149	Tetrafluorethylene resin primer for steel	1.28[f]	0.062[f]	0.05	—
150	Tetrafluorethylene resin primer for aluminum	1.45[e]	0.056[e]	0.04	—
150	Tetrafluorethylene resin primer for aluminum	—	0.066[f]	0.055	—
152	Five per cent coagulated tetrafluorethylene primer for aluminum in Paraplex G62 as a carrier	1.12	—	—	—

(a) Forge tests were made using a billet temperature of 825 F unless otherwise noted, a die temperature of 700 F, and a forging pressure of 46,000 psi.
(b) One-inch-diameter by 1/2-inch-high billets were pressed between flat parallel dies using a billet temperature of 825 F unless otherwise noted, a die temperature of 700 F, and a pressing load of 138,000 pounds.
(c) Bulge index is the maximum concavity or convexity minus the diameter at the end of 1-inch-diameter by 1-1/2-inch-high billets that had been pressed between parallel flat dies to 3/4 inch high. Die and billet temperatures were 700 and 825 F, respectively.
(d) Applied to cold dies which were then heated to 700 F.
(e) Applied to billets which were then heated to 825 F.
(f) Applied to billets which were then heated to 750 F.

Lubricant 97, a tetrafluoroethylene resin tape, 0.010 inch thick.

Lubricant 149, a tetrafluoroethylene resin primer for steel. This is a low-viscosity dispersion of tetrafluoroethylene resin in essentially a water medium. This material is usually applied to ferrous products, dried, then fused at about 750 F and cooled. This produces a coating on the product that has very low frictional properties. The medium for this material apparently is one that, through its reaction with the steel surface, promotes good bonding between it and the resin coating. When this material is applied to aluminum, a somewhat poorer bond is produced.

Lubricant 150, tetrafluoroethylene resin primer for aluminum. This material is similar to Lubricant 149, but the medium is probably somewhat different in order to promote good bonding between the resin coating and the aluminum surface. When this primer coat is applied to steel surfaces, a poor bond results.

When sheets of tetrafluoroethylene tape (Lubricant 97) were placed between the billet and die surfaces in the pressing test, very thin pressed samples resulted. These samples averaged 0.047 inch in thickness and corresponded to a coefficient of friction of 0.025. When the even thinner pressings were obtained, tetrafluoroethylene resin primer for steel was applied to the cold steel dies which were then heated to the forging temperature of 700 F. The pressed thickness was 0.035 inch, which was less than half the thickness produced by the best of the commercial lubricants under identical testing conditions. This thickness corresponded to a coefficient of friction of 0.01.

Tetrafluoroethylene resin primer for aluminum (Lubricant 150), when applied to the aluminum billets before heating to the forging temperature of 825 F, produced fairly thin pressings of 0.056 inch (coefficient of friction 0.04). This was poorer than those produced using the primer recommended for steel. Both resin primers were applied to the aluminum billets before they were heated to 750 F for pressing. This temperature was the recommended fusing temperature and was 75 degrees below the standard working temperature. Under these conditions both lubricants gave comparable results. The pressed thickness was somewhat thicker, probably the result of the lower forging temperature.

The results obtained in the forging test for a number of the organic materials did not agree precisely with the results obtained in the pressing test. Data obtained in the forging test are shown graphically in Figure 27. The forging test showed that the ester-type plasticizers (Lubricants 23 and 24), Polyamide Resin 90 (Lubricant 54), Silicone Grease 41 (Lubricant 53), epoxy resin (Lubricant 66), and nylon powder (Lubricant 143) produced

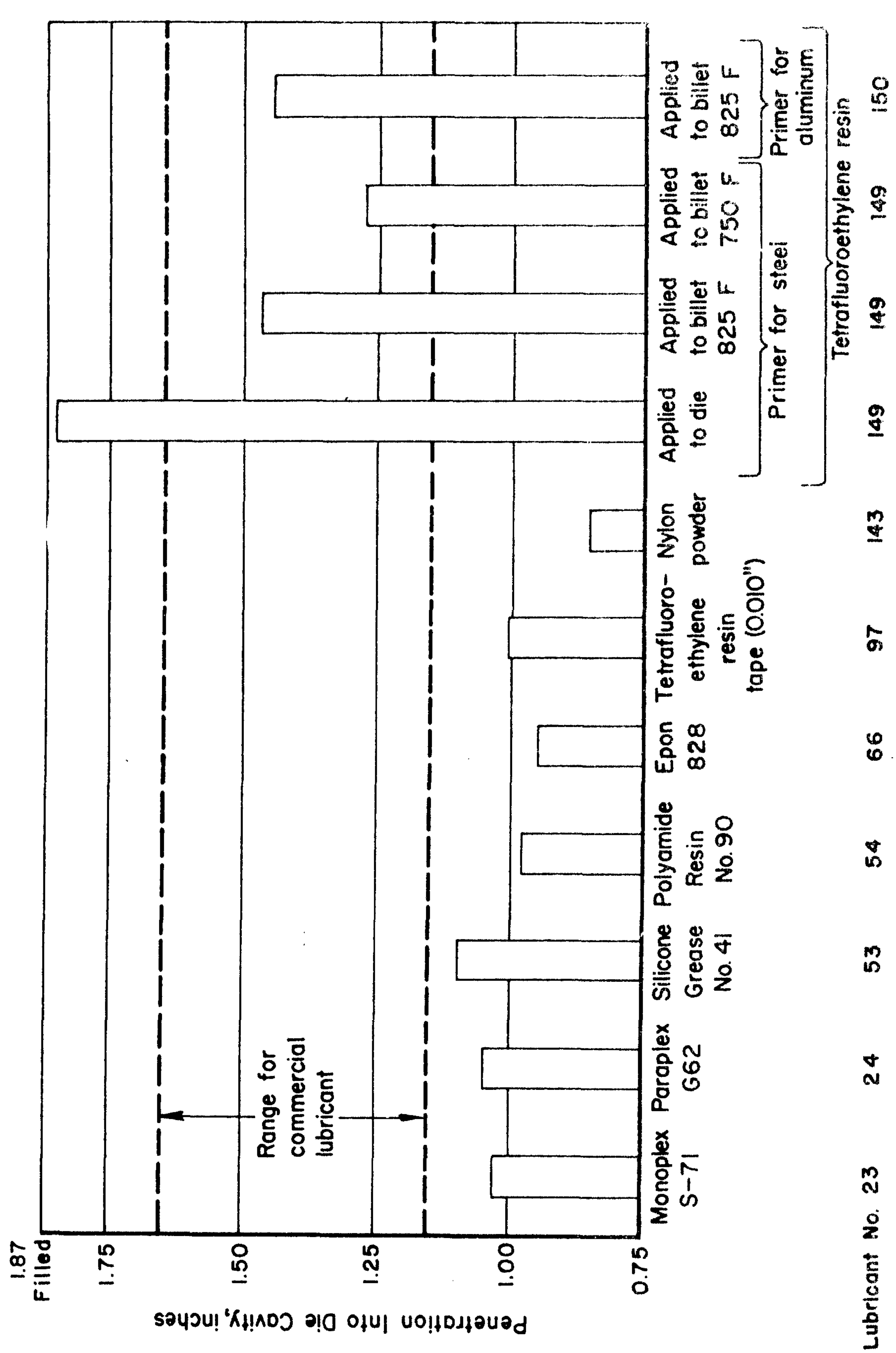

FIGURE 27. RELATIVE PERFORMANCE OF ORGANIC MATERIALS USED AS LUBRICANTS IN THE FORGING TEST USING 2014 ALUMINUM ALLOY

A-17005

poor die filling. Although Lubricants 54 and 143 showed relatively good pressing-test ratings, very poor die filling was obtained when these materials were used as lubricants in the forging test.

Although the tetrafluoroethylene tape (Lubricant 97) worked unusually well in pressing tests, it resulted in poor die filling in the forging test. A sheet of the résin was cut so that the die surfaces would be covered when inserted into the die cavity before the hot billet was inserted for forging. During forging, the resin tape softened and flowed to the corners, thus creating underfilling in the corners of the horizontal sections of the T. Also, the tape apparently separated at the radius, creating billet-to-die contact which allowed seizure to occur and resulted in poor die filling.

The unusually good pressing-test rating obtained on Lubricant 149 was corroborated by unusually good die penetration in the forging test. When the tetrafluoroethylene resin primer for steel was applied to the cold dies that were then heated to 700 F for forging, complete filling of the experimental forging die generally was obtained. When either the resin primer for steel or the primer for aluminum was applied to the billets before heating, poorer die filling resulted. Die filling for the coated billets, however, was within the range for the commercial lubricants.

The value in Table 8 for Lubricant 149 applied to the die is the average for four forgings made immediately after coating and heating the die. The effect of continued service on the lubrication provided by the tetrafluoroethylene primer is also of interest. This was checked by making several forgings without reapplying the primer to the dies. The die-filling measurements for successive forgings made by this practice are shown graphically in Figure 28. The bar chart shows that as many as three satisfactory forgings could be made after one application of the resin primer to the dies. The forgings were judged satisfactory if die filling was as good or better than that obtained with commercial forging lubricants. Figure 29 is a photograph of Forgings 483 through 486 made successively after the die had been coated with the resin primer and heated to 700 F. The forging order is from left to right. The first sample forged showed penetration into the vents and also into the space between the split dies which forms a flashing. The next two showed decreasing amounts of penetration into these areas, but the cavity was still completely filled. The fourth forging showed incomplete die filling. After making the fourth forging on one application of Lubricant 149, an attempt was made to reapply the resin to the dies which were at a temperature of 700 F. Two additional samples were forged but complete filling could not be produced. Ratings for these additional samples are shown in Figure 28. A good bond between the resin and the hot die surface could not be obtained. Apparently bonding between the resin and the steel die surface is promoted by the carrier. When the essentially aqueous carrier was sprayed on the hot die, the carrier was evaporated instantly.

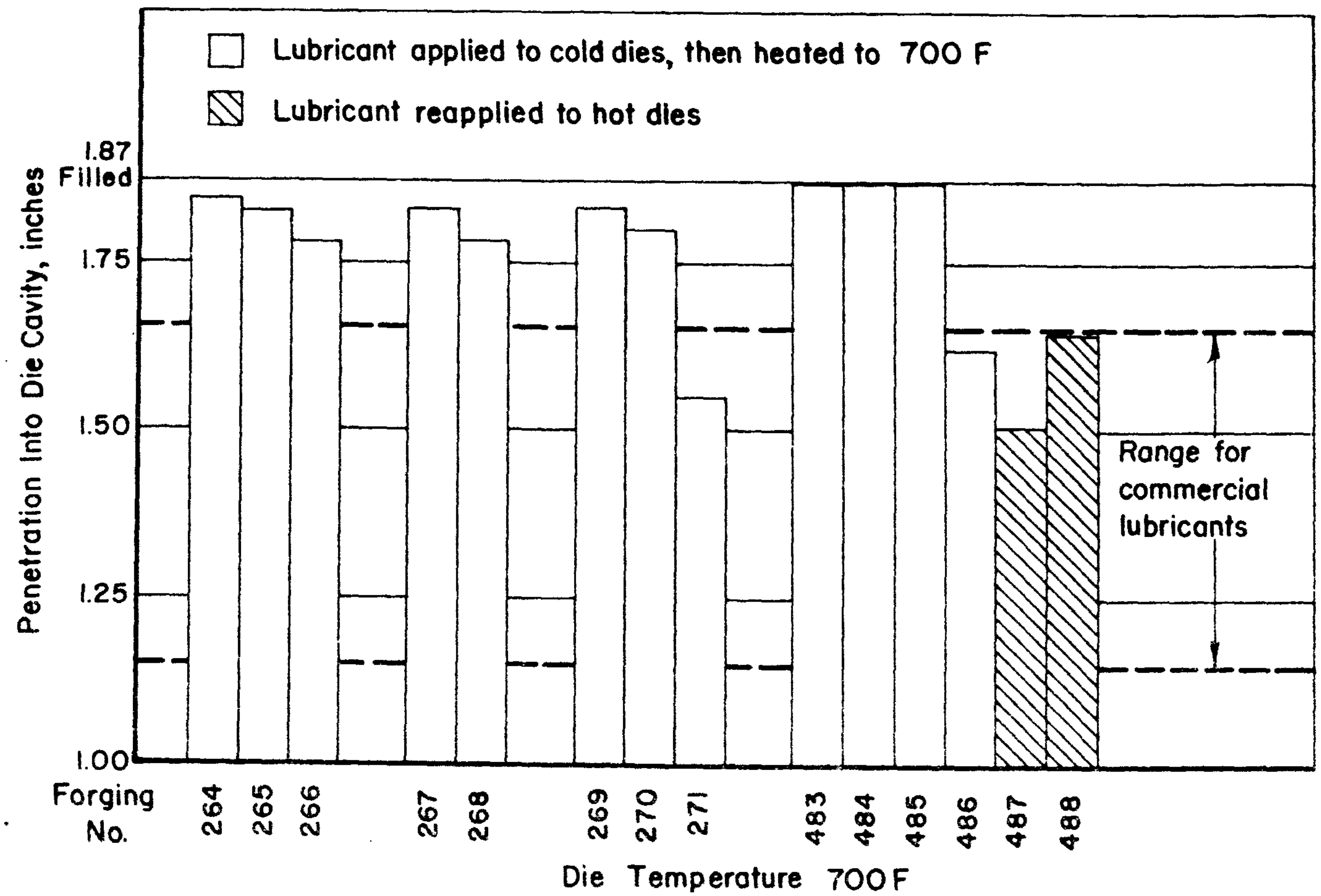

FIGURE 28. DIE FILLING FOR INDIVIDUAL FORGINGS IN FOUR GROUPS OF SAMPLES USING TETRAFLUOROETHYLENE PRIMER FOR STEEL (LUBRICANT 149) AS THE LUBRICANT IN FORGING TESTS ON 2014 ALUMINUM ALLOY

Only one application was made to the cold dies before heating, then each group of specimens was forged.

A-17000

Approx. 1/2X N25417

FIGURE 29. PHOTOGRAPH OF FOUR EXPERIMENTAL 2014 ALUMINUM ALLOY FORGINGS MADE CONSECUTIVELY FROM LEFT TO RIGHT USING ONE APPLICATION OF TETRA-FLUOROETHYLENE RESIN TO THE DIE

An attempt was made to see if the tetrafluoroethylene resin could be applied to the hot dies by dispersing the resin in another type of carrier. Some of the resin (primer for aluminum) was coagulated by freezing, then separated from the carrier by levigation. The coagulated resin was added to an ester-type plasticizer (Paraplex G62) as a carrier. Forging tests using this mixture (Lubricant 152) as a lubricant showed die filling similar to that obtained for the carrier alone (Lubricant 24). Apparently a continuous film of fused resin is necessary to promote good die filling.

The test data indicate that excellent die filling can be obtained when the tetrafluoroethylene resin (primer for steel) is applied to the die to give an adherent, continuous, fused coating. By the test methods used, the metal flow was better than that shown for the best of the commercial lubricants studied. However, the data indicate that with the presently available tetrafluoroethylene resin products, this material cannot be applied directly to hot dies at 700 F.

Although the resin cannot be applied directly to the hot dies, the experiments indicated that it may be applied to the billets before heating as an alternative method of lubrication. However, the data indicated that poorer die filling resulted from this method of application. Even so, die filling was as good or better than most of the commercial lubricants studied.

The use of tetrafluoroethylene resin in commercial operations might have some drawbacks. First, the material is quite expensive. For instance, resin primers for steel and for aluminum are currently priced at about $60 per gallon. Second, the use of tetrafluoroethylene at temperatures in the range for working aluminum may present health hazards because of the toxic decomposition products of the resin. Minute amounts of gaseous fluorine compounds are given off at temperatures above 400 F, and measurable quantities are given off at 600 F or above. These fluorine compounds may be in the form of a sublimate or a finely divided solid. At approximately 750 F, the resin decomposes slowly. The resin finish may be removed from an article by burning at a temperature of 950 F. Therefore, adequate ventilation must be provided where the tetrafluoroethylene resin reaches those temperatures where dangerous amounts of the toxic decomposition products are liberated.

Tetrafluoroethylene resins are inert to all chemicals and solutions of chemicals up to their boiling points, with the exception of molten alkali metals, and fluorine and chlorine trifluoride under special conditions. Therefore, cleaning of forgings to which the resin has adhered cannot be done readily by conventional chemical means to remove the lubricant. The resin would have to be removed mechanically or by burning. In the case of 2014 aluminum alloy, cleaning could be incorporated into the solution heat treatment in which the parts are heated to about 950 F before quenching. At this temperature, the coating would burn. Forged samples to which some of the resin adhered were treated by such a method. After the treatment, the samples were free of the resin and were cleaned and brightened by conventional chemical methods.

Study on Various Carriers for Solid Lubricants

Two types of carriers or vehicles are in general use for depositing a solid lubricating material on the die surface. Solid lubricants, such as graphite or molybdenum disulfide, are mixed with either oil or water to a consistency that may be sprayed on the dies. The chief disadvantage of using water as a carrier, particularly with relatively high die temperature, is that it forms steam when it strikes the die surface. The rapid formation of steam prevents further deposition of the solid lubricant on the die surface. This is particularly true when the spray strikes the die surface at an oblique angle, which is the case in dies with deep rib cavities.

Water-carried lubricants also have the disadvantage of acting as an efficient coolant for the dies. It was demonstrated in earlier laboratory work that better metal flow is obtained if the die temperature is near the billet temperature. Therefore, if the rate of heat extraction by the water of the lubricant is greater than the heat input from the hot billet, the dies will gradually become cooler, giving poorer metal flow. Then it becomes necessary to reheat the dies. This is expensive because it calls for heat from an additional source and also results in press downtime.

An advantage in using water-carried lubricants is their lack of smoking or firing. For this reason, they are frequently used where die temperatures are low enough to permit their use.

Although oil carriers seem to deposit the solid lubricant on the die surface more efficiently and do not cool the dies as rapidly as a water carrier, they still have some disadvantages. Chief among these are flaming or firing and smoking that accompany their use. Flaming is generally more severe with higher die temperatures.

Therefore, an effort was made to determine whether or not certain organic materials might be suitable as carriers for solid lubricants. Several of the liquid organic materials discussed previously were tried as carriers, using 20 per cent by weight of various solid materials mixed with them. The combinations of liquids and solids studied are listed in Table 9. Pressing- and forging-test data obtained using these combinations of materials as lubricants for working 2014 aluminum alloy are also given in the table. For comparison, data are also listed for various solid materials added to Oil B as a carrier. This carrier is believed to be typical of many currently in use. This particular carrier was composed of a 1-to-1 mixture of a naphthene-base petroleum oil having a viscosity of 106 SUS at 100 F and a 600 W cylinder oil having a viscosity of 1970 SUS at 100 F.

TABLE 9. FORGING- AND PRESSING-TEST RATINGS FOR LUBRICANTS CONTAINING DIFFERENT SOLIDS IN VARIOUS MATERIALS AS CARRIERS IN WORKING 2014 ALUMINUM ALLOY

Lubricant	Description[a]	Penetration Into Die Cavity in Forging Test[b], inch	Pressing-Test Results[c]: Pressed Thickness, inch	Pressing-Test Results[c]: Coefficient of Friction (μ)
78	20% medium flake graphite in Oil B	1.42	0.094	0.13
79	20% fine flake graphite in Oil B	1.36	0.084	0.10
80	20% extra-fine flake graphite in Oil B	1.52	0.072	0.07
86	20% boron nitride in Oil B	1.30	0.085	0.10
219	20% MoS_2 in Oil B	1.37	—	—
58	20% medium flake graphite in Paraplex G62	1.15	0.071	0.075
85	20% extra-fine flake graphite in Paraplex G62	1.12	0.058	0.04
57	20% MoS_2 in Paraplex G62	1.11	0.082	0.095
65	20% boron nitride in Paraplex G62	1.20[d]; 1.50[e]	0.090	0.12
71	20% tungsten disulfide in Paraplex G62	1.24	0.075	0.08
74	10% boron nitride + 10% MoS_2 in Paraplex G62	1.25	0.079	0.09
89	10% boron nitride + 10% extra-fine flake graphite in Paraplex G62	1.45	0.065	0.055
90	10% boron nitride + 10% large flake graphite in Paraplex G62	1.34	0.071	0.07
106	20% extra-fine flake graphite in Paraplex G60	1.00	0.067	0.06
103	20% boron nitride in Paraplex G60	—	0.080	0.09
220	20% MoS_2 in Paraplex G60	1.30	—	—
105	20% extra-fine flake graphite in Paraplex G50	1.45	0.069	0.065
104	20% boron nitride in Paraplex G50	1.19	0.083	0.095
153	20% MoS_2 in Paraplex G50	0.94	—	—
69	20% medium flake graphite in Epon 828	1.14	0.083	0.095
68	20% MoS_2 in Epon 828	1.06	0.098	0.14
72	20% tungsten disulfide in Epon 828	1.26	—	—
221	20% boron nitride in Epon 828	1.37	—	—
88	20% extra-fine flake graphite in a 1-to-1 mixture of Silicone Grease, No. 41 and Oil B	1.36	0.070	0.065
87	13% boron nitride in a mixture of 1 part Silicone Grease No. 41 and 2-1/2 parts of Oil B	1.36	0.076	0.08

(a) Paraplexes G62, G60, and G50 are ester-type plasticizers and are described as Lubricants 24, 102, and 101, respectively. Epon 828 is an epoxy resin and is described as Lubricant 66.
(b) Forge tests were made using a billet temperature of 825 F, a die temperature of 700 F, and a forging pressure of 46,000 psi.
(c) One-inch-diameter by 1/2-inch-high billets were pressed between flat, parallel dies using a billet temperature of 825 F, a die temperature of 700 F, and a pressing load of 138,000 pounds.
(d) Lubricant did not flame when applied to dies.
(e) Lubricant flamed when applied to dies.

The pressing-test data indicated that all the carriers which contained extra-fine flake graphite showed good lubricating qualities. Lubricant 85, which contained 20 per cent of extra-fine flake graphite in Paraplex G62 (an ester-type plasticizer), gave the best rating of the group. The same type of graphite added to two other ester-type plasticizers (Paraplexes G60 and G50), gave ratings only slightly poorer, but better than the range for commercial lubricants tested. Combinations of boron nitride and extra-fine flake graphite or large flake graphite in a carrier of Paraplex G62 also produced relatively good pressing-test ratings. Extra-fine flake graphite or boron nitride added to a silicone grease and further diluted with Oil B (Lubricants 88 and 87) produced pressing-test ratings that were about as good as the best of the commercial lubricants tested.

On the basis of the pressing-test ratings, the ester-type plasticizers appeared very promising as carriers for solid lubricants. These materials produced less smoke and were less likely to fire during use than the petroleum oil carrier used. The Paraplexes seemed to remain liquid on the dies longer and did not form a hard carbonaceous residue on the hot dies. With extended heating time they tended to depolymerize and disappear from the die surface.

In spite of the good ratings obtained in the pressing test on some of the combinations of solids and carriers, the performance in the pressing test was not reflected in the forging test. For these lubricants, a very poor correlation in test results was shown for the two types of tests. Lubricants that gave relatively good ratings in the pressing test did not show good ratings in the forging test. The reason for this disagreement is not known. However, the pressures attained in the pressing test were lower than those applied in the forging test. These lubricants apparently functioned adequately at the pressures obtained in the pressing test, but may have allowed seizure at the higher pressures in the forging test. Because of the size and shape of the pressing-test samples, the unit pressures over the die contact area of the pressing are probably fairly uniform. However, in the forging test, actual pressures between the billet and die may vary considerably over the contour of the die surface. Pressures at the radius in the forging die probably exceed the 46,000-psi punch pressure. Lubricant failure at this location would result in poor die filling because of metal drag.

The fact that the Paraplexes remained fluid on the hot die longer than Oil B may have influenced the performance of the lubricants. In the early portion of the forging operation, the fluid containing solid lubricating material may be wiped from one location and pushed to another as pressure increases and metal movement takes place. As the lubricant is wiped away, metal-to-metal contact might occur if the pressure exceeds the strength of the lubricating film. This reasoning appeared to be upheld by the forging data obtained, using Lubricant 65. This lubricant contained 20 per cent by weight of boron nitride in Paraplex G62. Seventeen forgings were made using this lubricant. In twelve of the seventeen experiments, the lubricant burned. Firing did not occur in the other five tests. Better die filling resulted when the lubricant caught fire. The average penetration into the die cavity for the samples forged when the lubricant caught fire was 1.50 inches, while the average penetration for those that were forged when the lubricant did not catch fire was 1.20 inches. This indicates that better die filling results if the solid lubricating material is fixed on the die surface as a result of the carrier burning. Perhaps the residue remaining on the die after the carrier burned had some beneficial lubricating effect. The average die penetration produced by Lubricant 65 when the carrier burned was somewhat better than that noted for the same solid lubricant in Oil B (Lubricant 86). Oil B always caught fire when applied to the dies at 700 F.

Extra-fine flake graphite, which was a solid lubricant common to most of the carriers, gave the best die penetration when used with Oil B. This probably was the result of the carrier burning after it had deposited the solid lubricant on the die surface.

These data indicate that the nature of the carrier for a solid lubricant can have a marked effect on the performance in the forging test. The carrier must have a flash point high enough to permit the carrier to deposit the solid lubricating material on the die surface. It also appears desirable to "fix" the solid lubricant on the die by having the carrier burn.

Studies on Billet Pretreatments

Certain combinations of billet pretreatment and die lubricants were found to be very effective in improving the metal flow. A number of billet pretreatments used in conjunction with two different commercial die lubricants and the corresponding forging-test ratings are given in Table 10. The 2014 aluminum alloy billets were all pretreated before heating for forging.

Data obtained using various billet pretreatments and Lubricant 1 as a die lubricant are shown graphically in Figure 30. Lubricant 1 is a commercial lubricant consisting essentially of flake graphite in mineral oil. Some surface treatments included dipping the treated billet in an aqueous suspension of colloidal graphite before heating them for forging. This suspension consisted of 10 per cent by weight, in distilled water, of a commercial preparation containing 22 per cent colloidal graphite. The temperature of this bath was maintained at 150 F so the warm billets would dry quickly, leaving a uniform coating of colloidal graphite on the surface. The quick drying produced a uniform coating on the billets by preventing the graphite from running on the surface.

The data presented in Figure 30 show that a remarkable improvement in die filling resulted from etching the billets in sodium hydroxide and then dipping them in aqueous colloidal graphite before heating and forging. Lubricant 1 was applied to the dies in these experiments. The sodium hydroxide etching treatment alone, when used with a die lubricant, also produced

TABLE 10. EFFECTS OF VARIOUS BILLET TREATMENTS ON THE FORGE-TEST RATING OF 2014 ALUMINUM ALLOY WHEN USED WITH TWO DIFFERENT DIE LUBRICANTS

Lubricant[a]	Billet Treatment[b] Treatment Number	Billet Treatment[b] Brief Description	Penetration Into Forging-Die Cavity[c], inch
1	—	No billet treatment	1.36
1	182	Billet degreased, aqueous colloidal graphite dip	1.53
1	185	NaOH etch only	1.72
1	186	NaOH etch, aqueous colloidal graphite dip	1.83
1	187	NaOH etch, HNO_3 clean	1.44
1	188	NaOH etch, HNO_3 clean, aqueous colloidal graphite dip	1.55
1	180	Vapor blasted	1.36
1	181	Vapor blasted, aqueous colloidal graphite dip	1.55
1	33	Unsealed Alrok coating	1.40
1	179	Unsealed Alrok coating, aqueous colloidal graphite dip	1.56
1	29	Zincate coating	1.26
3	—	No billet treatment	1.48
3	187	NaOH etch, HNO_3 clean	1.51
3	188	NaOH etch, HNO_3 clean, aqueous colloidal graphite dip	1.69
3	185	NaOH etch only	1.62
3	186	NaOH etch, aqueous colloidal graphite dip	1.75

(a) Lubricant 3 was a commercial lubricant containing colloidal graphite in mineral oil. Lubricant 1 was a commercial lubricant containing flake graphite in mineral oil.
(b) Etching treatment consisted of etching for 5 minutes in a 10 per cent sodium hydroxide solution maintained at 150 F. The nitric acid bath used for cleaning some of the billets was a 10 per cent solution held at room temperature. The aqueous suspension of colloidal graphite consisted of a 10 per cent by weight in distilled water of a commercial preparation containing 22 per cent graphite. The temperature of this bath was maintained at 150 F.
(c) Forging tests were made using a billet temperature of 825 F, a die temperature of 700 F, and a forging pressure of 46,000 psi.

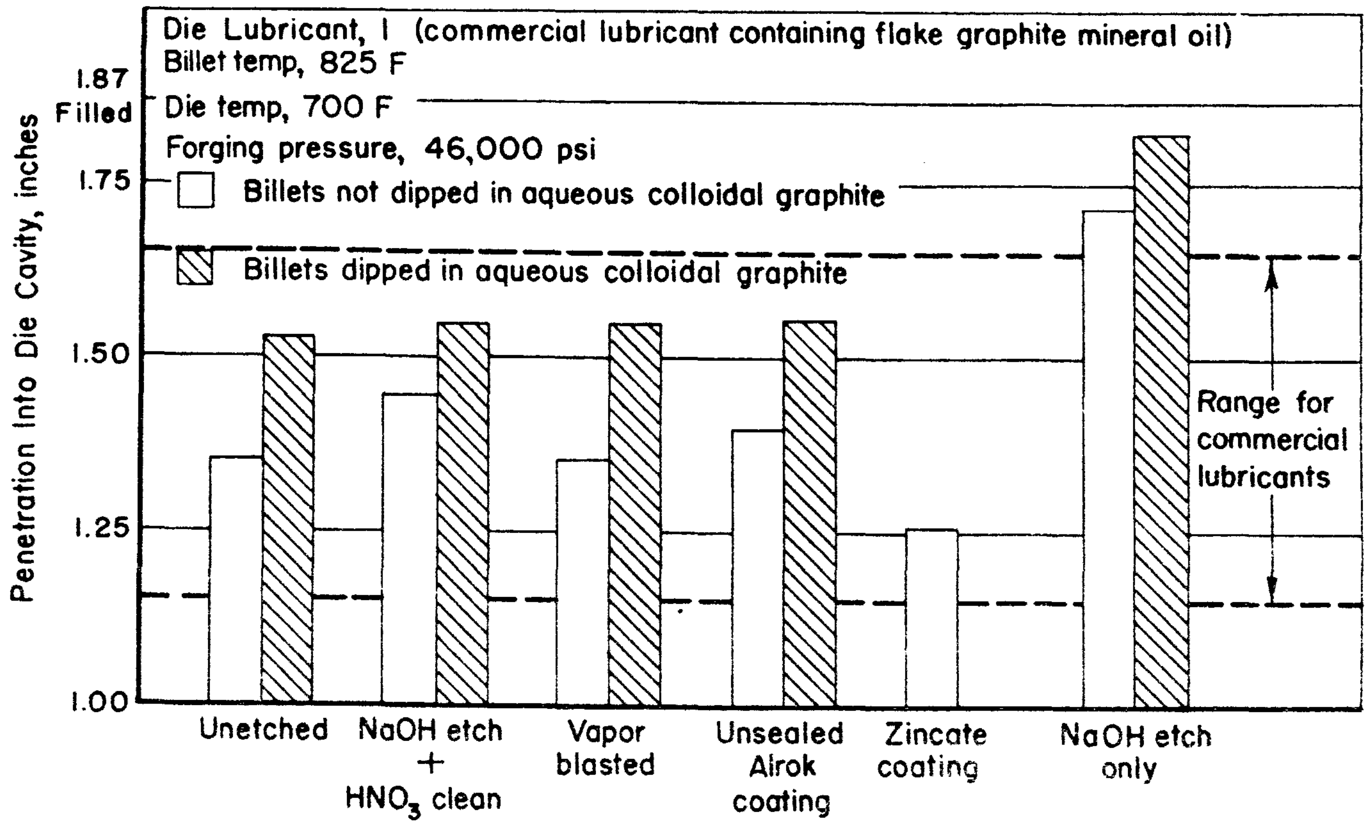

FIGURE 30. EFFECT OF BILLET SURFACE TREATMENTS ON THE DEPTH OF PENETRATION INTO THE FORGING DIE FOR 2014 ALUMINUM ALLOY USING LUBRICANT I ON THE DIE A-17003

exceptionally good die filling compared with the range for commercial lubricants. This indicates that the black residue left on the billet surface after the sodium hydroxide etching treatment has lubricating properties. In addition, the black residue may be rough and porous enough to pick up and hold some of the graphite which may be transferred to the billet surface from the die.

In all cases, dipping in aqueous colloidal graphite produced a marked and consistent improvement in die penetration. The improvement noted was roughly the same for each surface condition. For the billets that were not dipped in aqueous colloidal graphite, vapor blasting and an Alrok coating produced no significant change in die penetration from the levels typical of the untreated billets. Billets etched in sodium hydroxide and further cleaned in nitric acid, a normal commercial treatment, gave slightly better die filling than untreated billets. A zincate coating on the billets gave slightly poorer die filling than the untreated billets. This coating was produced by immersing the billets in a bath consisting of sodium hydroxide and zinc oxide in water (Billet Treatment 29).

The forging-test data obtained with die Lubricant 3 are shown graphically in Figure 31. Lubricant 3 is a commercial preparation consisting of colloidal graphite in mineral oil. Two different billet treatments, each with and without an aqueous colloidal graphite dip, were studied. These treatments were the same as those used in the study in which Lubricant 1 was used on the die. The forging-test ratings for these treatments, using Lubricant 3 on the die, checked the results obtained using Lubricant 1. These data also show the improvement in die filling resulting from a sodium hydroxide etch and the additional benefit gained by dipping the etched billet in a lubricant before heating for forging. The improvement in die filling resulting from etching in sodium hydroxide, or from the subsequent dip in colloidal graphite, was not as marked with Lubricant 3 (colloidal graphite).as with Lubricant 1 (flake graphite).

The marked beneficial effect of treating billets before heating and forging is shown in Figure 32. The bar charts compare the depths of penetration into the die cavity of six untreated and six treated billets. Each group of six billets was forged consecutively starting with a clean die. Lubricant 1 was used on the die in these tests. The untreated billets showed quite nonuniform die filling. The first forging showed the poorest die filling, while the next five showed better die filling, but the results were not uniform from forging to forging. This type of performance is common in the forge plants, especially when starting a production run on clean dies. The treated billets, on the other hand, showed a remarkable improvement in die filling and all forgings filled to a uniform depth. These data suggest that pretreated billets might alleviate the trouble encountered in commercial operations in starting a run on cleaned dies. Generally, the first few forgings made on new or cleaned dies produce considerable press down time as a result of forgings sticking to the dies, metal pickup on the dies,

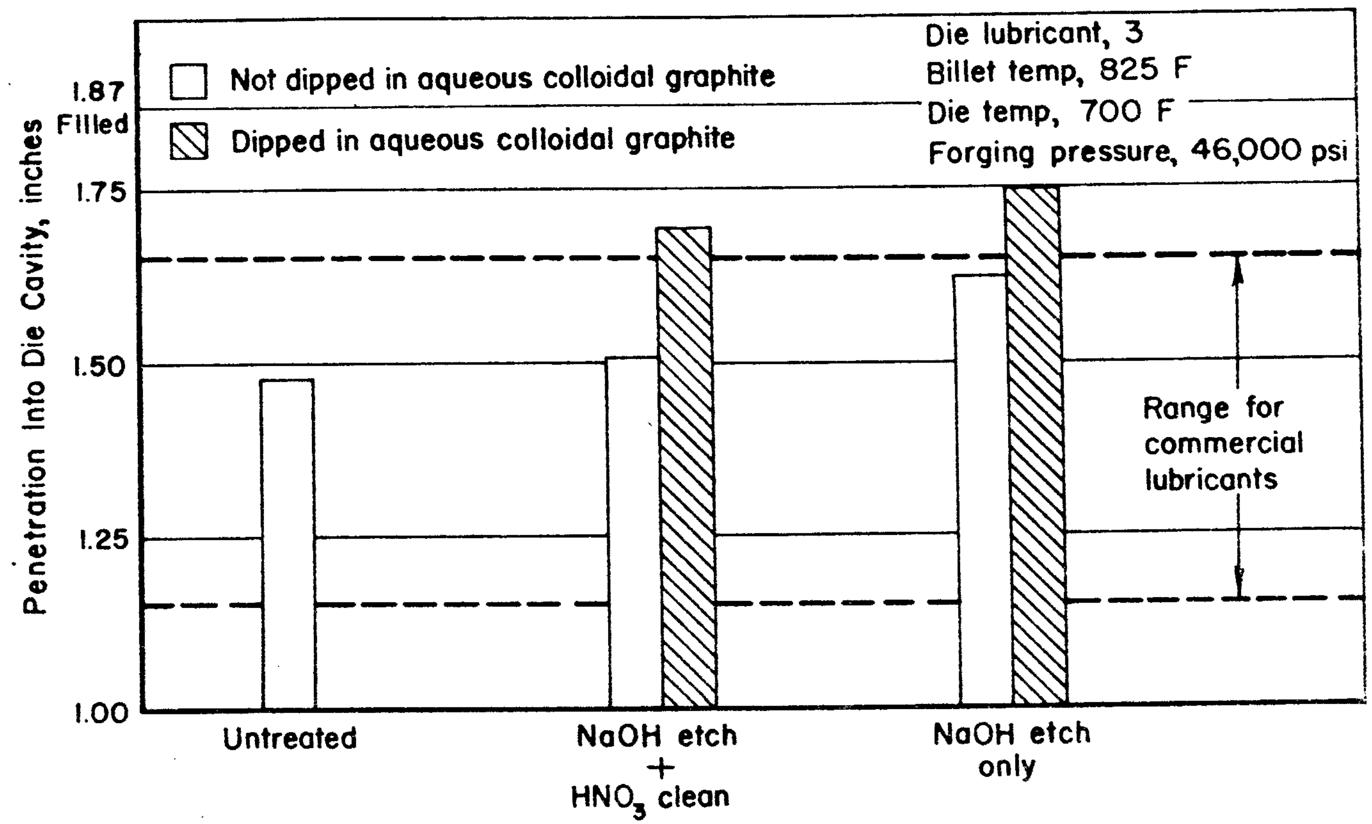

FIGURE 31. EFFECT OF BILLET TREATMENTS ON THE DEPTH OF PENETRATION INTO THE FORGING DIE FOR 2014 ALUMINUM ALLOY USING LUBRICANT 3 ON THE DIE. (A COMMERCIAL LUBRICANT CONTAINING COLLOIDAL GRAPHITE IN MINERAL OIL)

A-17001

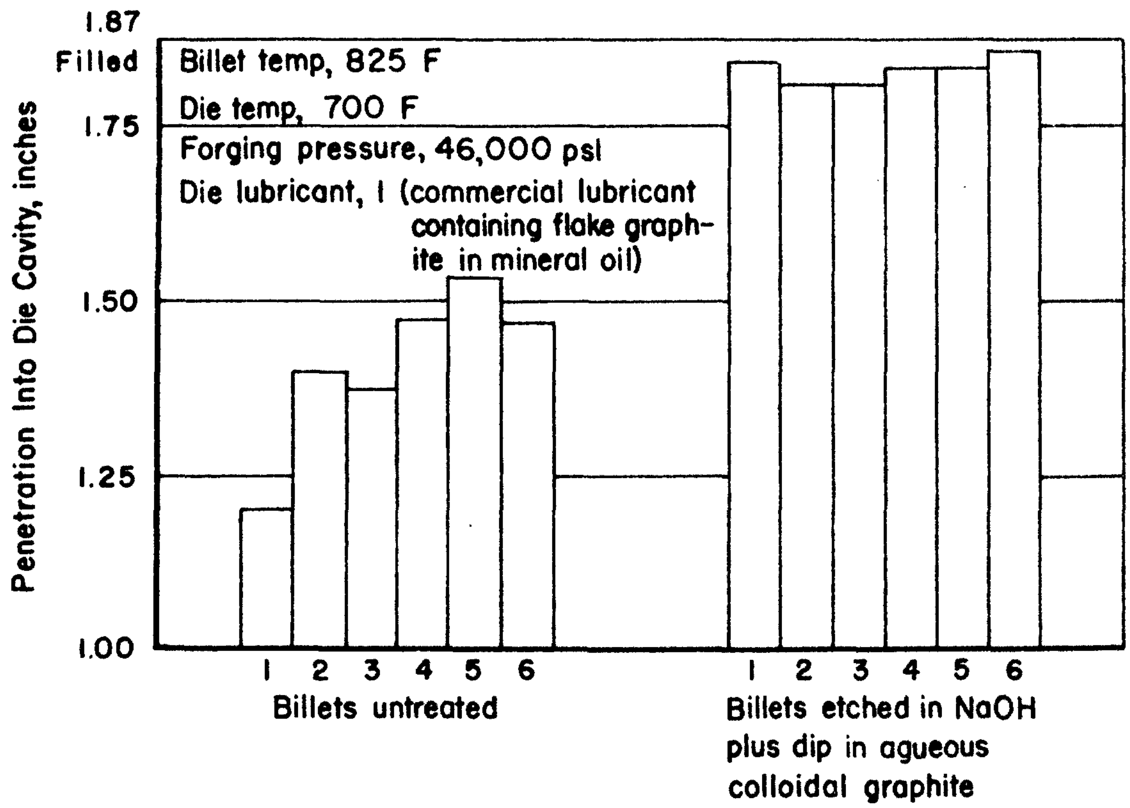

FIGURE 32. EFFECT OF PRETREATING 2014 ALUMINUM ALLOY BILLETS ON DIE FILLING IN FORGING EXPERIMENTS A-17004

and poor die filling. These conditions generally produce forging that must be scrapped, or reconditioned and restruck in the same die.

Because of the promise offered by these billet pretreatments, additional tests were made to study the effects on die filling of several processing variables. Table 10 shows that the pretreated billets gave better die filling than untreated billets with Lubricants 1 and 3 on the dies. Forging tests were also made on treated and untreated billets using three other die lubricants. Forging-test data obtained in these experiments are given in Table 11. Data obtained for Lubricants 1 and 3 are repeated in the table for comparison. The die lubricants and the billet pretreatments are described in the tables.

The forging-test data, presented in Figure 33, show that the billet pretreatment was effective when used with five different types of die lubricants. All pretreated billets produced better die filling than untreated billets used with the best of the commercial lubricants. Data in Table 11 indicate that the billet pretreatment improved the performance of the poorer lubricants more than it helped the better lubricants. Thus, when pretreated billets were used, the relative ratings of the lubricants were not the same as those obtained when untreated billets were used. However, Lubricant 176, a commercial hot-die lubricant containing no solid lubricating material, had the best rating when used with pretreated billets. This lubricant also gave the best rating when used with untreated billets. These data suggest that pretreating billets by etching in sodium hydroxide, followed by dipping in an aqueous suspension of colloidal graphite, will improve the performance of any of the conventional die lubricants now in use. With the exception of one series of tests described in Table 11, the sodium hydroxide etching procedure for pretreating the billets was held constant. The procedure consisted of etching the billets for 5 minutes in a 10 per cent sodium hydroxide solution maintained at a temperature of 150 F. Additional forging tests were made to determine the effects of variations in both temperature and etching time.

Table 12 lists the forging-test ratings for pretreated billets which were etched in a 10 per cent sodium hydroxide solution for 1/2 and 2 minutes at each of two bath temperatures, 150 and 180 F. After etching, the billets were dipped in aqueous colloidal graphite. Lubricant 1 was used on the dies. These data indicate that the etching reaction at a temperature of 150 F is slower than at 180 F. Increasing the etching time from 1/2 to 2 minutes at 180 F produced very little change in test performance. However, the same increase in etching time at 150 F produced a significant improvement in die penetration. An etching time of 2 minutes at a bath temperature of 150 F produced the same die penetration as 1/2 minute at a bath temperature of 180 F. Apparently, at least a minimum amount of etching is required to produce optimum die penetration. As would be expected, this appears to be a function of etching time and bath temperature.

TABLE 11. EFFECT OF PRETREATING BILLETS WITH COLLOIDAL GRAPHITE ON THE FORGE-TEST RATING OBTAINED WITH VARIOUS DIE LUBRICANTS IN WORKING 2014 ALUMINUM ALLOY

Lubricant[a]	Billet Treatment[b] Treatment Number	Billet Treatment[b] Brief Description	Penetration Into Forging-Die Cavity[c], inch	Improvement in Die Filling Resulting From Billet Pretreatment, inch
1	—	None	1.36	—
1	186	NaOH etch, aqueous colloidal graphite dip	1.83	+0.47
3	—	None	1.48	—
3	186	NaOH etch, aqueous colloidal graphite dip	1.75	+0.27
105	—	None	1.45	—
105	186	NaOH etch, aqueous colloidal graphite dip	1.70	+0.25
17	—	None	1.44	—
17	186	NaOH etch, aqueous colloidal graphite dip	1.86	+0.42
176	—	None	1.66	—
176	200	NaOH etch, aqueous colloidal graphite dip	1.87 (die completely filled)	+0.21

(a) Lubricant 1 was a commercial lubricant containing essentially flake graphite in mineral oil. Lubricant 3 was a commercial lubricant containing colloidal graphite in mineral oil. Lubricant 105 was an experimental lubricant containing extra-fine flake graphite in Paraplex G50 (an ester-type plasticizer). Lubricant 17 was a commercial lubricant containing molybdenum disulfide in mineral oil. Lubricant 176 was a commercial lubricant containing no solid lubricating material.

(b) Billet Treatment 186 consisted of etching the billets for 5 minutes in a 10 per cent sodium hydroxide solution maintained at 150 F, rinsed in hot water, then dipped in an aqueous suspension of colloidal graphite at 150 F. The suspension of colloidal graphite consisted of 10 per cent by weight in distilled water of a commercial preparation containing 22 per cent graphite. Billet Treatment 200 was similar to 186, except the billets were etched for 4 minutes at a temperature of 180 F.

(c) Forging tests were made using a billet temperature of 825 F, a die temperature of 700 F, and a forging pressure of 46,000 psi.

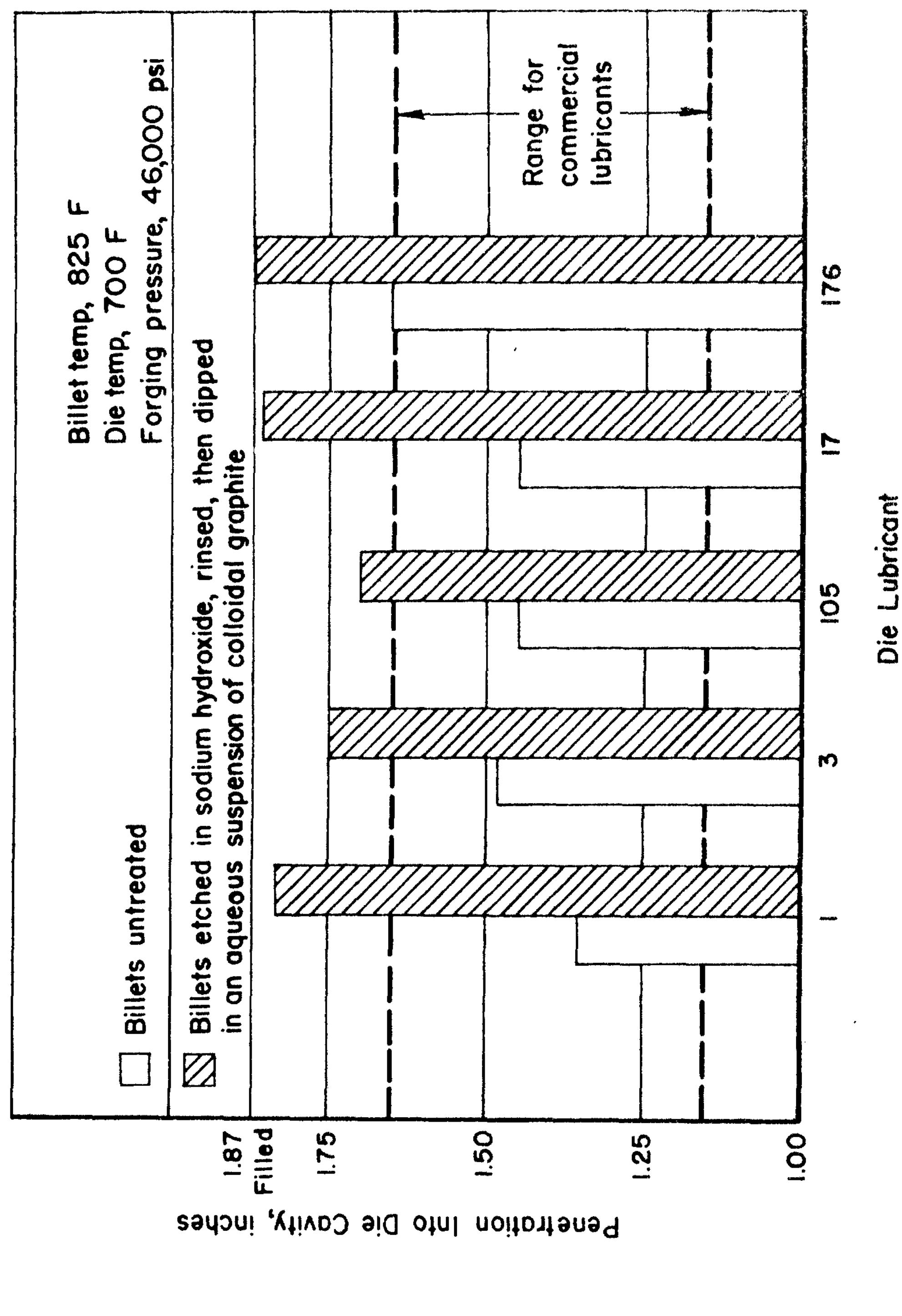

FIGURE 33. EFFECT OF BILLET PRETREATMENT ON THE DIE PENETRATION IN FORGING 2014 ALUMINUM ALLOY WITH FIVE DIFFERENT DIE LUBRICANTS

A-17002

TABLE 12. EFFECT OF TIME AND TEMPERATURE OF BILLET PRETREATMENTS ON FORGING-TEST RATINGS FOR 2014 ALUMINUM

	Billet Treatment(a)				
Lubricant	Treatment Number	Etchant	Etching Temperature, F	Etching Time, minutes	Penetration Into Forging-Die Cavity(b), inch
1	183	10% NaOH	150	1/2	1.69
1	184	10% NaOH	150	2	1.80
1	198	10% NaOH	180	1/2	1.80
1	199	10% NaOH	180	2	1.84

(a) Billets were etched as indicated, then dipped in an aqueous suspension of colloidal graphite maintained at a temperature of 150 F. The suspension of colloidal graphite consisted of 10 per cent by weight in distilled water of a commercial preparation containing 22 per cent graphite.

(b) Forging tests were made using a billet temperature of 825 F, a die temperature of 700 F, and a forging pressure of 46,000 psi.

In order to determine more precisely the effects of etching time on the forging-test rating, two series of 2014 aluminum alloy billets were etched for various lengths of time in a 10 per cent sodium hydroxide solution maintained at 180 F. After etching, one series of billets was dipped in an aqueous suspension of colloidal graphite maintained at 150 F. The other series was not dipped in the graphite suspension. All billets were then forged under standard testing conditions using Lubricant 1 on the dies. The forge-test data obtained are listed in Table 13. The average distance along the bottom of the forging which touched the base of the die cavity is also listed in the table.

The forging-test data listed in Table 13 are shown plotted as a function of etching time in Figure 34. The data indicate that at a bath temperature of 180 F an etching time of 2 minutes is sufficient to produce optimum die penetration. The data also show that in the etched condition only, die penetration improves with increasing time up to about 1/2 minute. Additional etching time did not show any significant improvement. The die filling for the as-etched billets appeared to be improved a constant amount by dipping them in the aqueous suspension of colloidal graphite.

In many shop operations, because of delays, billets are sometimes left in the heating furnace for extended periods of time. To estimate the effect of such practice, two series of etched and colloidal graphite-dipped 2014 aluminum alloy billets were heated for 6 and 10 hours before forging. The samples were heated in an electric muffle furnace having no protective atmosphere. The object of the tests was to determine whether or not long heating periods would destroy the effectiveness of the billet coating.

Forging-test data obtained on the treated billets, using Die Lubricant 1, are listed in Table 14. Data for samples heated for the normal heating period are also listed for comparison. The data indicate that heating periods up to 10 hours had no adverse effect on the effectiveness of the billet coating.

In aluminum forge plants a caustic bath (sodium hydroxide) is used in the normal cleaning procedure. In using straight sodium hydroxide, foaming and the formation of a heavy sludge in the bottom of the etching tank produce operating problems. Therefore, several proprietary caustic etchants are available that suppress foaming and prevent the formation of sludge. These products are used in many shops.

Therefore, forging tests were made to determine whether these proprietary etchants produced the same results as sodium hydroxide when used in conjunction with the aqueous colloidal graphite dip.

Two different commercial proprietary etchants were used at two concentrations. Concentrations used were 2.5 and 6.0 ounces per gallon. Although the higher concentration is recommended by the manufacturer, the basicity occasionally drops to about 2.5 ounces per gallon during use because

TABLE 13. FORGING-TEST RATINGS FOR 2014 ALUMINUM ALLOY BILLETS ETCHED IN A 10 PER CENT SOLUTION OF SODIUM HYDROXIDE FOR VARIOUS LENGTHS OF TIME

Lubricant	Billet Treatment: Treatment Number	Billet Treatment: Etchant	Billet Treatment: Etching Time	Dip After Etching	Penetration Into Forging-Die Cavity[a], in.	Distance Along Bottom of Forging Which Touched Base of Die Cavity[b], in.
1	--	None	--	None	1.36	0.0
1	192	Sodium hydroxide[c]	10 sec	None	1.56	0.0
1	193	Ditto	30 sec	None	1.67	0.0
1	194	"	2 min	None	1.67	0.0
1	195	"	4 min	None	1.67	0.0
1	196	"	5 min	None	1.75	0.0
1	182	None	--	Dipped in colloidal graphite[d]	1.53	0.0
1	197	Sodium hydroxide[c]	10 sec	Colloidal graphite[e]	1.72	0.0
1	198	Ditto	30 sec	Colloidal graphite	1.80	0.28
1	199	"	2 min	Colloidal graphite	1.83	1.25
1	200	"	4 min	Colloidal graphite	1.845	1.51

(a) Forging tests were made using a billet temperature of 825 F, a die temperature of 700 F, and a forging pressure of 46,000 psi.

(b) Maximum length was 1.75 inch. This indicated complete filling.

(c) The billets were etched for the time indicated in a 10 per cent solution of sodium hydroxide maintained at a temperature of 180 F. After etching, the billets were rinsed in hot water and dried.

(d) Unetched billets were cleaned with acetone then treated as in Footnote (e).

(e) The etched, rinsed, and dried billets were dipped in a water suspension of colloidal graphite maintained at a temperature of 150 F. After dipping, the billets were dried then heated for forging. The suspension of colloidal graphite consisted of 10 per cent by weight in distilled water of a commercial preparation containing 22 per cent graphite.

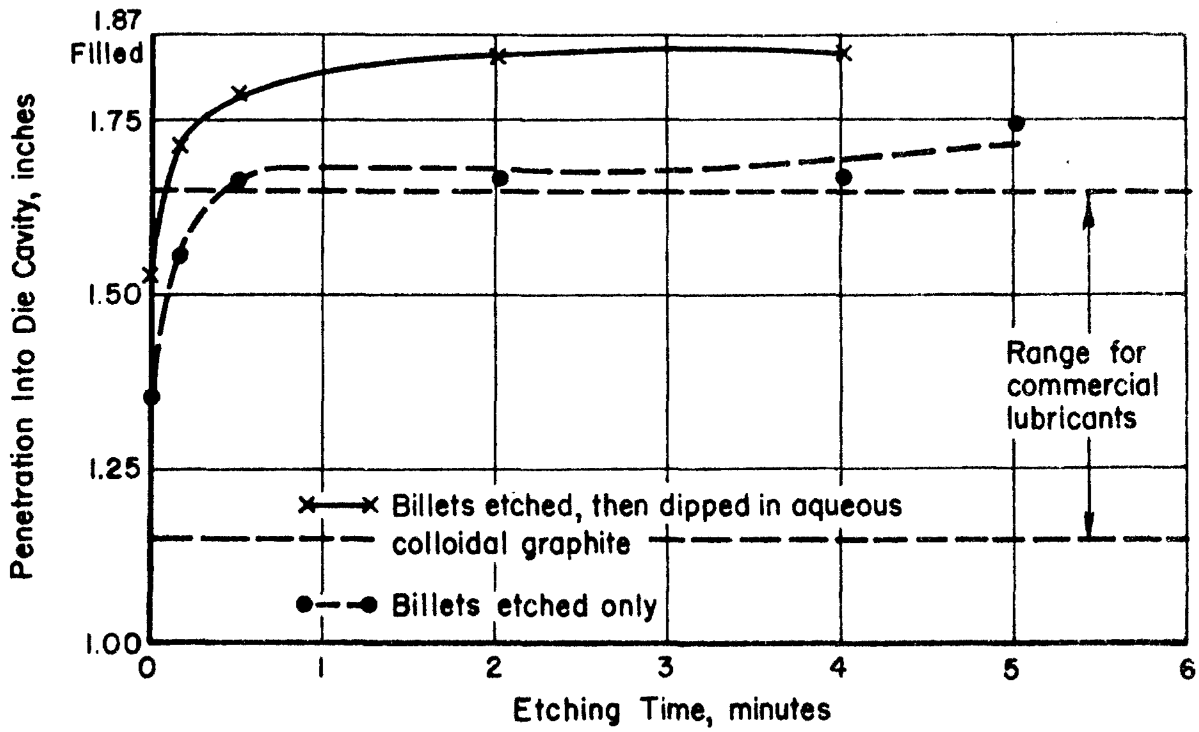

FIGURE 34. EFFECT OF ETCHING TIME ON THE DEPTH OF PENETRATION INTO THE FORGING DIE FOR 2014 ALUMINUM ALLOY BILLETS THAT WERE ETCHED IN 10 PER CENT SODIUM HYDROXIDE AT 180 F AND EITHER DIPPED OR NOT DIPPED IN A SUSPENSION OF COLLOIDAL GRAPHITE BEFORE HEATING AND FORGING

Commercial Lubricant I was used on the die. A-16999

TABLE 14. EFFECT OF HEATING PRETREATED BILLETS FOR EXTENDED PERIODS OF TIME ON FORGING-TEST RATINGS FOR 2014 ALUMINUM ALLOY

Lubricant	Billet Treatment	Billet Heating Time, hr	Penetration Into Forging-Die Cavity[a], in.
1	200[b]	1/3 to 1	1.84
1	200[b]	6	1.81
1	200[b]	10	1.83

(a) Forging tests were made using a billet temperature of 825 F, a die temperature of 700 F, and a forging pressure of 46,000 psi. Lubricant 1 was used in all tests.

(b) Billets etched for 4 minutes in 10 per cent sodium hydroxide at 180 F, rinsed in hot water, then dipped in an aqueous suspension of colloidal graphite maintained at a temperature of 150 F. The suspension of colloidal graphite consisted of 10 per cent by weight in distilled water of a commercial preparation containing 22 per cent graphite.

the caustic is depleted. Billets were etched for 2 and 4 minutes at each concentration while the bath was maintained at a temperature of 180 F. After etching, the billets were dipped in an aqueous suspension of colloidal graphite, then heated and forged using Lubricant 1 on the dies. Data obtained in these tests are given in Table 15.

Using a concentration of 6 ounces per gallon, billets etched in both preparations showed complete die filling when etched for either 2 or 4 minutes. When a concentration of 2.5 ounces per gallon was used for an etching time of 4 minutes, the billets etched with the product representing Producer B gave better die filling than those etched with the product representing Producer A. However, when the billets were etched for 2 minutes, both preparations gave similar results. The forging-test results indicate that the commercial preparations are as good as, or slightly better than, pure sodium hydroxide for etching aluminum as a part of the billet pretreatment.

Tests were also made to determine whether molybdenum disulfide powder or boron nitride would be good substitutes for the colloidal graphite coating on etched billets. The billets were all etched for 5 minutes in a 10 per cent sodium hydroxide solution maintained at a temperature of 150 F. After etching and rinsing, the billets were either dipped in the aqueous colloidal graphite, or dusted with powdered molybdenum disulfide or boron nitride. After treating, the billets were forged using three different commercial lubricants on the die. Billets dusted with boron nitride were forged using only one of the three die lubricants.

Data obtained in these tests are listed in Table 16. Data for untreated billets are also included for comparison. The data show that for each die lubricant used, significantly poorer die penetration was obtained with the molybdenum disulfide-coated billets than with the colloidal graphite-coated billets. The use of a boron nitride coating on the billets produced an adverse effect on die filling when used with Lubricant 3 on the die. The die penetration was poorer than that obtained on untreated billets using the same die lubricant.

Plant Forging Tests

The laboratory pressing and forging tests suggested that two novel lubricating practices were likely to improve die filling when forging aluminum alloys. These two processing treatments are:

(1) Coating the dies or billets with tetrafluoroethylene resin

(2) Etching the billets in a hot solution of sodium hydroxide, rinsing, dipping in an aqueous suspension of colloidal graphite, drying, and then heating and forging the billets using a conventional die lubricant.

TABLE 15. FORGING-TEST RATINGS FOR 2014 ALUMINUM-ALLOY BILLETS ETCHED IN COMMERCIAL CAUSTIC PREPARATIONS

Lubricant	Billet Preparation[a] Treatment Number	Etchant[b]	Concentration[c], oz per gal	Etching Time, min	Etching Temperature, F	Penetration Into Forging-Die Cavity[d], in.
1	201	Commercial caustic (Producer A)	2.5	2	180	1.83
1	202	Commercial caustic (Producer A)	2.5	4	180	1.80
1	203	Commercial caustic (Producer A)	6.0	2	180	1.87
1	204	Commercial caustic (Producer A)	6.0	4	180	1.87
1	205	Commercial caustic (Producer B)	2.5	2	180	1.81
1	206	Commercial caustic (Producer B)	2.5	4	180	1.87
1	207	Commercial caustic (Producer B)	6.0	2	180	1.87
1	208	Commercial caustic (Producer B)	6.0	4	180	1.87

(a) Billets were etched as indicated, rinsed in hot water, then dipped in a water suspension of colloidal graphite maintained at a temperature of 150 F. The suspension of colloidal graphite consisted of 10 per cent by weight in distilled water of a commercial preparation containing 22 per cent graphite.

(b) The two etchants listed are commercial caustic etchants that are prepared for etching aluminum. These proprietary materials are especially designed to prevent foaming and sludging during use.

(c) 6.0 ounces per gallon is the recommended concentration. A concentration of 2.5 ounces per gallon is considered a low working concentration that is occasionally attained as the caustic is depleted.

(d) Forging tests were made using a billet temperature of 825 F, a die temperature of 700 F, and a forging pressure of 46,000 psi. Lubricant 1 was used on the dies in all tests.

TABLE 16. EFFECTS OF VARIOUS BILLET TREATMENTS AND DIE LUBRICANTS ON THE FORGE-TEST RATING OF 2014 ALUMINUM ALLOY

Lubricant[a]	Billet Treatment[b] Treatment Number	Billet Treatment[b] Brief Description	Penetration Into Forging-Die Cavity[c], in.
1 (flake graphite in mineral oil)	--	Untreated	1.36
	186	NaOH etch, aqueous colloidal graphite dip	1.83
	191	NaOH etch, billets dusted with MoS_2 powder	1.75
3 (colloidal graphite in mineral oil)	--	Untreated	1.48
	186	NaOH etch, aqueous colloidal graphite dip	1.75
	191	NaOH etch, billets dusted with MoS_2 powder	1.61
	189	NaOH etch, billets dusted with boron nitride	1.37
17 (molybdenum disulfide in mineral oil)	--	Untreated	1.44
	186	NaOH etch, aqueous colloidal graphite dip	1.81
	191	NaOH etch, billets dusted with MoS_2 powder	1.72

(a) Commercial lubricants were used on the dies.
(b) All billets were etched for 5 minutes in a 10 per cent sodium hydroxide solution maintained at 150 F, rinsed in hot water, then given the indicated additional treatment.
(c) Forging tests were made using a billet temperature of 825 F, a die temperature of 700 F, and a forging pressure of 46,000 psi.

No plant trials were made with tetrafluoroethylene because the resin could produce toxic fumes when heated to forging temperatures. Furthermore, no suitable method for applying a resin coating on hot dies was known.

The practice of pretreating billets, by etching in caustic and then coating them with colloidal graphite, was simple and promising enough to justify plant experiments. Therefore, arrangements were made with several plants to evaluate the performance of pretreated billets in making aluminum forgings.

Production of Boeing Part No. 5-48951-3

The production of Boeing Part No. 5-48951-3 was suggested and tried by a large aluminum forging plant as a typical forging that might serve to evaluate the performance of pretreated billets compared with that of untreated billets. A photograph of the Boeing part is shown in Figure 35. Both top and bottom sides of the forging were symmetrical around the center line. The part was produced from 2014 aluminum alloy.

The forging was made in three steps consisting of two blocking and one finishing operation. The first blocking operation consisted of pressing a 4-3/4-inch-diameter by 30-inch-long billet to the general shape of the finished part. The ends of the billets were beveled to eliminate the sharp corners. In the second blocking operation, the general shape produced in the first blocking operation was carried a step farther so that the finished part could be made in one additional operation in the finishing dies.

The tests were planned to produce the fitting, using two groups of 15 samples each. One group was given the suggested pretreatment before each operation; the other was forged using conventional lubrication methods. The differences in die filling, sticking, and surface characteristics produced by the two methods were to be a measure of the effectiveness of the billet pretreatment.

The plant's regular proprietary die lubricant, which consisted essentially of graphite in an oil carrier, was sprayed on the dies for forging both treated and untreated billets.

The forging operations were performed on a 15,000-ton hydraulic press, using a load of 10,000 tons for all operations. In planning the experiments, Samples 14 and 15 in each group were to be pressed in the second blocking dies at a reduced load of 5000 tons. Also, Samples 12 and 13 in each group were to be pressed in the finish die at the reduced load. These tests were expected to show the difference in die filling between treated and untreated samples, provided the dies did not completely close.

The billet pretreatment consisted of etching in a commercial proprietary caustic etchant at a concentration of about 4 ounces per gallon for

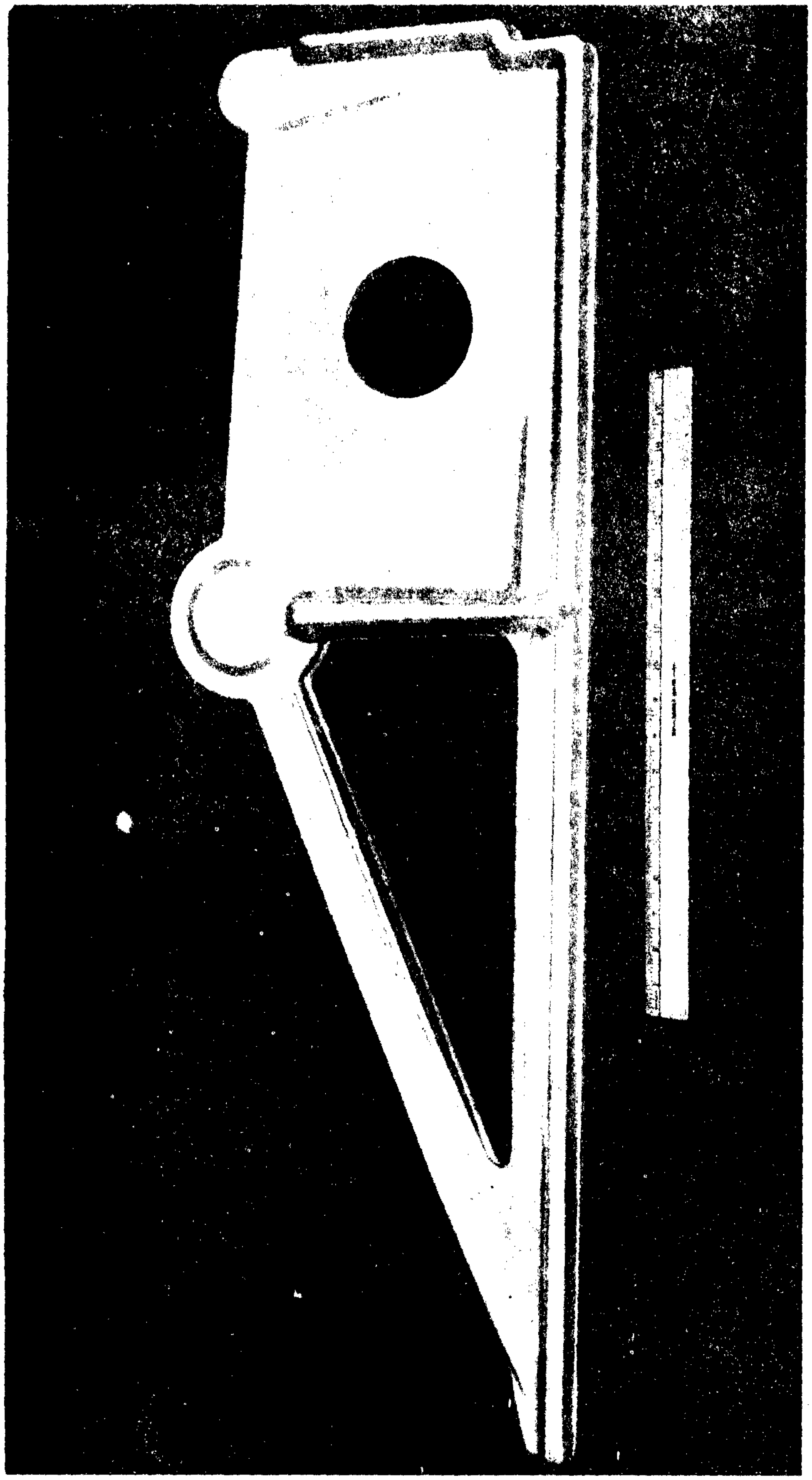

FIGURE 35. PHOTOGRAPH OF BOEING PART NO. 5-48951-3 MADE IN PLANT EXPERIMENTS

4 minutes at a temperature of 185 F. The billets were charged cold into the solution. After etching, they were rinsed in cold water, then dipped for 2 minutes in an aqueous suspension of colloidal graphite maintained at a temperature of 160 F, then allowed to air dry. The graphite suspension consisted of 10 per cent in water of a commercial preparation containing 22 per cent by weight of graphite. After the first and second blocking operations, both groups of forgings were cleaned and prepared for the next operation in the usual manner. In addition, the treated samples were given another pretreatment.

Billet and die temperatures were maintained at 800 F and 700 F, respectively, for all experiments. A clean die was used to begin each operation. During each operation, the dies were cleaned between runs on the treated and untreated series of samples, so that the first forging of each group was made on a clean die. Pertinent information obtained in each of the three operations is discussed below.

First Blocking Operation. For this operation, the 15 untreated billets were forged first, the dies were then cleaned and reheated, then the 15 treated billets were forged. As originally planned, the first five forgings of each group were to be "wasters" and were not to be used for comparison. This plan had to be abandoned because none of the first six untreated billets filled the die cavity at the pointed end of the forging. Before trying the seventh billet, the pointed end of the die was given spot lubrication in addition to the usual spray application. This practice, which resulted in better die filling at the critical location, was followed for the rest of the billets. After fifteen untreated billets had been blocked, the dies were cleaned. No particular trouble was encountered on any of the treated billets, even the first.

A photograph of the forging after the first blocking operation is shown in Figure 36. After the operation, various measurements were made on the blocked forgings at the locations shown in the sketch in Figure 37. These measurements and evaluations are listed in Table 17. The flash thickness was measured at the same location for all forgings just outside Position 4 in the sketch.

The data indicated that the treated billets produced thinner webs and a thinner flash than the untreated billets. These measurements averaged about 0.012 inch thinner for the forgings made from the treated billets.

Very little difference in die filling was shown between the treated and untreated samples at Positions 2, 3, and 4. At these positions, metal flow was always good. The flash trough filled, thus preventing lateral flow of metal and causing the metal to fill the die cavities.

All forgings showed some underfilling at Position 1. This can be seen in Figure 36. The untreated billets gave slightly better filling than the

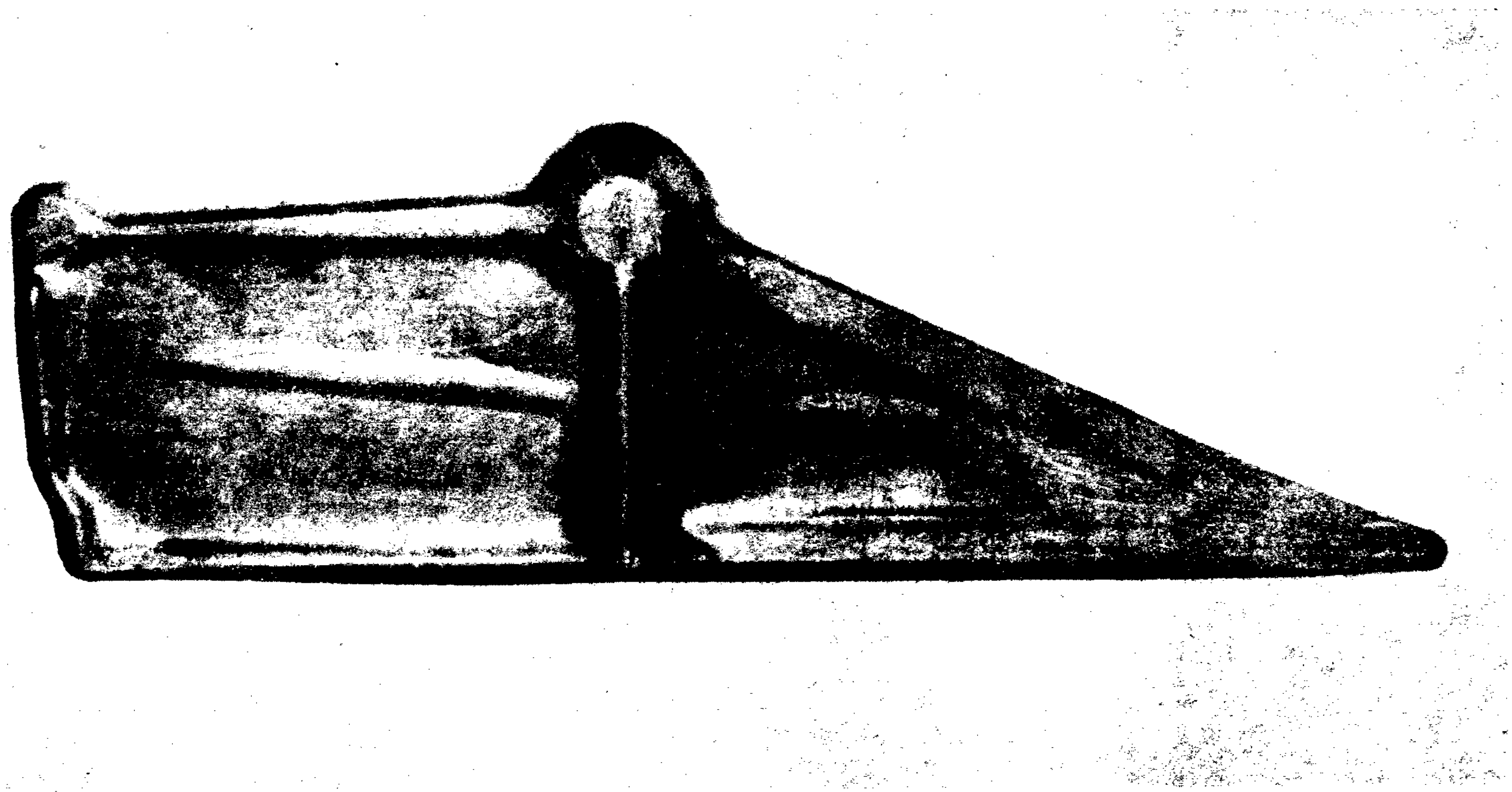

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FIGURE 36. PHOTOGRAPH OF BOEING PART NO. 5-48951-3 AFTER THE FIRST BLOCKING OPERATION

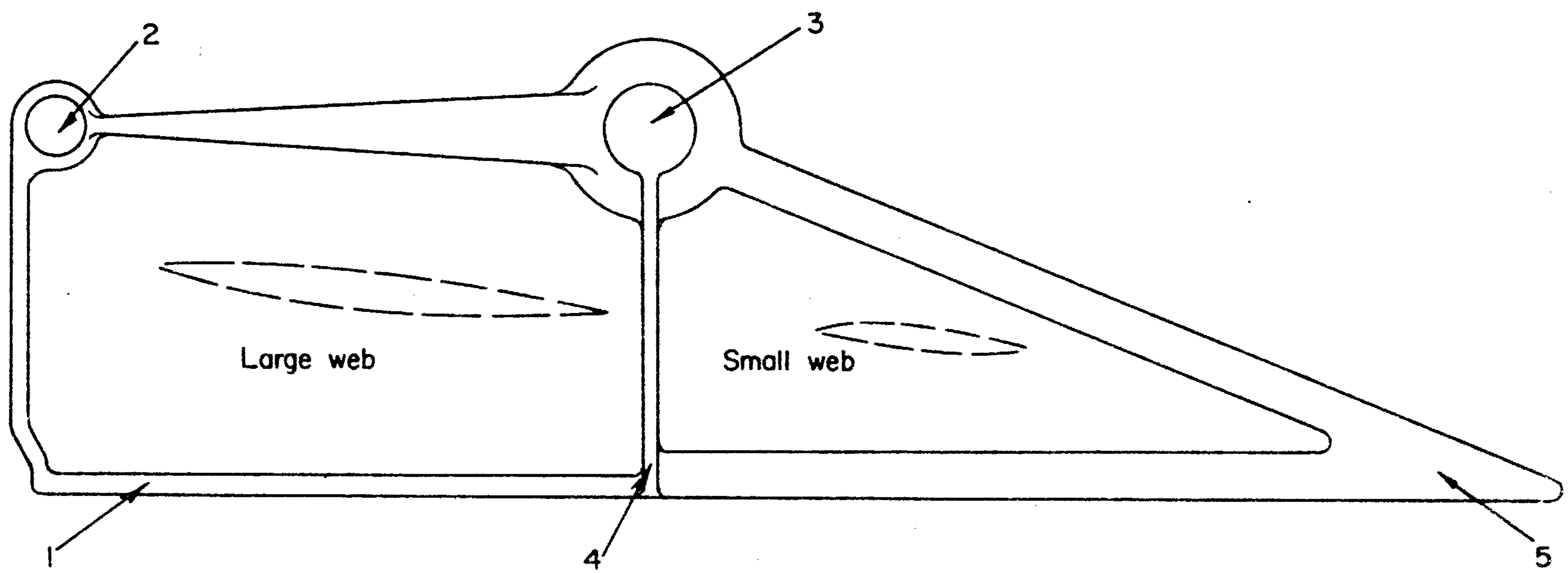


FIGURE 37. LOCATION OF MEASUREMENTS ON BOEING PART NO. 5-48951-3 AFTER THE FIRST BLOCKING OPERATION

A-18035

treated billets at this location. Insufficient metal was available to adequately fill the flash trough at this corner. Because of this, lateral flow of metal was not slowed up enough at the flash to build up enough pressure to fill the rib section before the dies completely closed. The reason for the slightly better filling at this corner for the untreated billets appeared to be caused by the difference in lubrication in the flash cavity. The flash cavity was not spray lubricated; therefore, the untreated billets showed some drag in the flash cavity while the treated billets showed less drag in the flash cavity. For this operation, some drag appeared to be desirable. Poorer lubrication in the flash trough, in the case of untreated billets, apparently restricted lateral flow enough that more metal was available to give better filling in the rib.

The forgings made from the treated billets all showed considerably better filling in the last 3 or 4 inches of the rib section at the point end, Position 5. More drag appeared in the last third of the dart end of the forgings made from the untreated billets than for those made from the pretreated billets. This drag was slight and not great enough to create seizing. The difference in drag noted between the treated and untreated samples, however, may have caused the difference in the degree of filling at the dart end.

No gross differences in surface finish resulted from using the two lubrication practices. The finish could not be measured quantitatively; therefore, each pair, e.g., Samples 6 and 6C, were compared visually with each other. These comparisons are also given in Table 17. The treated samples appeared to produce a slightly better surface than the untreated samples.

Second Blocking Operation. Blanks used for this operation had been flash trimmed, cleaned in the normal manner, and conditioned by chipping or grinding where necessary. The previously treated billets were treated again before forging.

The 15 pretreated samples were forged first, the dies cleaned and reheated, then the 15 untreated samples were forged. The last two samples of each group, 14 and 15, were forged at a reduced load of 5000 tons to see if any difference in die filling resulted from the pretreatment.

After forging, the two groups of samples were evaluated. A rough sketch of the part showing the location of the measurements obtained is shown in Figure 38. Various measurements and evaluations are given in Table 18. The web thicknesses were measured at the same location on each forging. Generally, any nonfilling had to be rated qualitatively rather than quantitatively.

TABLE 17. MEASUREMENTS OBTAINED AFTER THE FIRST BLOCKING OPERATION USING TREATED

Forging Sample[(a)]	Thickness, in. Large Web	Small Web	Flash	Fill at Various Top Die 1	2	3	4	5
6	0.615	0.360	0.790	1-5/16 x 2-5/8	OK	OK	OK	(c)
6C	0.590	0.340	0.765	1-5/16 x 3-1/4	VSNF	OK	SNF	OK
7	0.600	0.350	0.775	1-1/8 x 2-1/4	OK	OK	OK	2-5/8 x 3/4
7C	0.585	0.335	0.770	1-5/8 x 3-1/8	OK	OK	SNF	OK
8	0.590	0.345	0.770	3/4 x 1-1/8	SNF	OK	OK	SNF
8C	0.585	0.335	0.760	1-1/4 x 2-3/4	SNF	OK	SNF	OK
9	0.590	0.340	0.770	SNF	OK	OK	OK	3/4 x 2-3/4
9C	0.585	0.330	0.760	3/4 x 3-1/16	OK	OK	OK	OK
10	0.600	0.345	0.770	1-1/4 x 2-3/4	VSNF	OK	OK	3/4 x 2-7/8
10C	0.585	0.335	0.760	7/8 x 2-5/8	SNF	OK	SNF	OK
11	0.595	0.345	0.770	1-1/4 x 2	OK	OK	OK	SNF
11C	0.570	0.325	0.750	1-5/16 x 2-7/8	SNF	OK	SNF	OK
12	0.600	0.355	0.780	1-3/8 x 2-3/4	OK	OK	OK	3/4 x 3-3/4
12C	0.590	0.355	0.775	1-1/2 x 4	SNF	OK	OK	OK
13	0.595	0.345	0.770	VSNF	OK	OK	OK	VSNF
13C	0.585	0.330	0.765	2-1/8 x 2-5/16	SNF	OK	SNF	OK
14	0.595	0.335	0.775	1-5/16 x 2-13/16	SNF	OK	OK	OK
14C	0.590	0.325	0.765	1-1/4 x 3-3/16	SNF	OK	OK	OK
15	0.590	0.330	0.755	1-1/8 x 3-1/8	SNF	OK	OK	OK
15C	0.585	0.325	0.765	1-1/8 x 3-1/8	SNF	OK	OK	OK

(a) Suffix C indicated treated billets.

(b) For Positions 1 and 5, the maximum length and width of the underfill was measured. VSNF = very slight nonfill; SNF = slight nonfill; NF = nonfill.

(c) Metal did not flow all the way to the tip. Improper spotting of the billet was believed to be the cause.

AND UNTREATED BILLETS IN PRODUCING BOEING PART NO. 5-48951-3

Locations(b)						
Bottom Die					Comparison of Surfaces	
1	2	3	4	5	Top	Bottom
1-5/8 x 2-1/4	OK	OK	OK	(c)	--	--
1-1/4 x 2-3/8	VSNF	OK	NF	2-3/16 x 7/8	Better than Sample 6	Better than Sample 6
1-1/16 x 3-1/8	VSNF	OK	OK	2-3/16 x 7/8	Better than Sample 7A	Same
1-3/16 x 2-1/2	VSNF	OK	SNF	SNF	Lap and seam in metal	
7/8 x 1-1/4	OK	VSNF	VSNF	1-1/2 x 3/4	Same	Same
2-1/4 x 3-1/8	SNF	SNF	SNF	OK		
SNF	OK	OK	OK	2-5/16 x 5/8	Same	Same
1 x 2-1/2	SNF	SNF	OK	OK		
13/16 x 2	VSNF	OK	OK	7/8 x 3-1/8	Same	--
1-1/4 x 2-5/16	SNF	OK	OK	3/4 x 1-5/16		Better than Sample 10
VSNF	OK	OK	OK	3/4 x 2-1/8	Same	Same
1 x 1-1/2	SNF	SNF	SNF	OK		
1-1/4 x 2-1/2	OK	OK	OK	3/4 x 2-3/4	Same	Same
1-3/8 x 3-1/4	SNF	OK	OK	OK		
7/8 x 1-1/2	OK	OK	VSNF	7/8 x 2-3/16	Same	Same
1-1/4 x 2-1/4	SNF	OK	VSNF	OK		
1-1/4 x 3-3/16	SNF	OK	SNF	7/8 x 2-7/8	Same	Same
1-5/16 x 2-3/16	SNF	OK	SNF	3/4 x 2-3/16		
1-1/8 x 3-1/4	SNF	OK	OK	3/8 x 3	--	Better than Sample 15A
1-1/8 x 3-1/8	SNF	OK	OK	5/8 x 2-1/4	Better than Sample 15	--

TABLE 18. MEASUREMENTS OBTAINED AFTER THE SECOND BLOCKING OPERATION USING

Forging Sample[(a)]	Thickness, in. Large Web	Thickness, in. Small Web		Fill at Various 1	2	3[(c)]	4
6	0.495	0.245	Top	VSNF	OK	VSNF, VSNF	OK
			Bottom	VSNF	OK	SNF, SNF	VSNF
6C	0.465	0.230	Top	VSNF	OK	SNF, SNF	VSNF
			Bottom	VSNF	OK	VSNF, VSNF	OK
7	0.480	0.235	Top	VSNF	OK	VSNF, SNF	OK
			Bottom	VSNF	OK	VSNF, SNF	OK
7C	0.475	0.235	Top	VSNF	OK	SNF, SNF	VSNF
			Bottom	VSNF	OK	VSNF, VSNF	OK
8	0.460	0.220	Top	VSNF	OK	SNF, SNF	VSNF
			Bottom	VSNF	OK	SNF, SNF	OK
8C	0.475	0.235	Top	VSNF	OK	SNF, SNF	VSNF
			Bottom	VSNF	OK	VSNF, VSNF	OK
9	0.465	0.230	Top	VSNF	OK	VSNF, SNF	VSNF
			Bottom	VSNF	OK	VSNF, SNF	OK
9C	0.470	0.230	Top	VSNF	OK	SNF, VSNF	VSNF
			Bottom	VSNF	OK	VSNF, SNF	OK
10	0.480	0.230	Top	VSNF	OK	VSNF, SNF	OK
			Bottom	VSNF	OK	SNF, VSNF	OK
10C	0.465	0.225	Top	VSNF	OK	SNF, VSNF	VSNF
			Bottom	VSNF	OK	VSNF, VSNF	OK
11	0.470	0.230	Top	VSNF	OK	SNF, SNF	VSNF
			Bottom	VSNF	OK	VSNF, VSNF	OK
11C	0.470	0.225	Top	VSNF	OK	SNF, SNF	VSNF
			Bottom	VSNF	OK	VSNF, VSNF	OK
12	0.470	0.225	Top	VSNF	OK	SNF, SNF	VSNF
			Bottom	VSNF	OK	VSNF, VSNF	OK
12C	0.480	0.235	Top	VSNF	OK	SNF, SNF	VSNF
			Bottom	VSNF	VSNF	VSNF, VSNF	OK
13	0.470	0.225	Top	VSNF	OK	SNF, SNF	OK
			Bottom	VSNF	OK	VSNF, VSNF	OK
13C	0.475	0.225	Top	VSNF	OK	SNF, SNF	VSNF
			Bottom	VSNF	OK	VSNF, VSNF	OK

TREATED AND UNTREATED BILLETS IN PRODUCING BOEING PART NO. 5-48951-3

Rib Locations(b) 5A(d)	5B	6A	6B	Fill at Bosses	Surface
NF, VSNF	OK	SNF	VSNF	--	Tearing in large web
NF, OK	OK	SNF	VSNF	--	--
VSNF, SNF	OK	SNF	VSNF	--	--
VSNF, VSNF	OK	VSNF	VSNF	--	--
VSNF, VSNF	OK	SNF	VSNF	--	--
VSNF, VSNF	OK	VSNF	VSNF	--	--
VSNF, VSNF	OK	SNF	VSNF	--	--
VSNF, VSNF	OK	VSNF	VSNF	--	--
VSNF, VSNF	OK	SNF	VSNF	VSNF, Boss 3	Tearing in small web
VSNF, VSNF	OK	VSNF	VSNF	--	--
VSNF, VSNF	OK	SNF	VSNF	--	--
VSNF, VSNF	OK	VSNF	VSNF	--	Very slight tearing in large web
VSNF, VSNF	OK	SNF	VSNF	VSNF, Boss 3	--
VSNF, VSNF	OK	SNF	SNF	--	Tearing in large web
VSNF, VSNF	OK	SNF	VSNF	--	--
VSNF, VSNF	OK	VSNF	VSNF	--	--
VSNF, 1/2 x 1-1/8	OK	SNF	VSNF	--	Slight tearing in large web
OK, 3/8 x 1	OK	VSNF	VSNF	VSNF, Boss 3	
OK, VSNF	OK	SNF	VSNF	--	--
VSNF, VSNF	OK	VSNF	VSNF	--	--
VSNF, SNF	OK	SNF	VSNF	--	--
VSNF, VSNF	OK	VSNF	VSNF	VSNF, Boss 3	--
VSNF, SNF	OK	SNF	VSNF	--	--
VSNF, SNF	OK	VSNF	VSNF	--	--
SNF, 5/8 x 2-1/8	OK	SNF	VSNF	--	--
VSNF, 5/8 x 2	OK	SNF	VSNF	VSNF, Boss 3	Tearing in large web
VSNF, SNF	OK	SNF	VSNF	--	--
VSNF, VSNF	OK	SNF	VSNF	--	--
VSNF, SNF	OK	SNF	VSNF	--	--
VSNF, VSNF	OK	SNF	VSNF	--	--
VSNF, VSNF	OK	SNF	VSNF	--	--
VSNF, SNF	OK	VSNF	VSNF	--	--

TABLE 18.

Forging Sample[a]	Thickness, in. Large Web	Small Web		Fill at Various 1	2	3[c]	4
14[e]	0.520	0.275	Top	VSNF	OK	SNF, 1/2 x 5/8	SNF
			Bottom	VSNF	OK	VSNF, SNF	OK
14C[e]	0.510	0.265	Top	VSNF	OK	SNF, 1/2 x 5/8	VSNF
			Bottom	VSNF	OK	VSNF, VSNF	OK
15[e]	0.510	0.260	Top	VSNF	OK	SNF, 1/2 x 3	VSNF
			Bottom	VSNF	OK	VSNF, 1/2 x 3/4	OK
15C[e]	0.510	0.260	Top	VSNF	OK	OK, SNF	SNF
			Bottom	VSNF	OK	OK, VSNF	OK

(a) Suffix C = treated forgings.
(b) VSNF = very slight nonfill
SNF = slight nonfill
NF = nonfill (dimensions are width and length of nonfilled areas in inches).
(c) First value is near Boss 3.
Second value is near Ribs 4 and 5A.
(d) First value is at the dart end of Rib 5A.
Second value is at about the center portion of Rib 5A.
(e) Pressed with a load of 5000 tons; all others were pressed with a load of 10, 000 tons.

(Continued)

Rib Locations(b)				Fill at	
5A(d)	5B	6A	6B	Bosses	Surface
VSNF, 5/8 x 6-3/4	OK	3/8 x 4	SNF	--	--
VSNF, 5/8 x 6	OK	SNF	VSNF	--	--
VSNF, 5/8 x 5-1/2	OK	3/8 x 3-1/8	SNF	--	--
VSNF, 5/8 x 5-1/2	OK	SNF	VSNF	--	--
NF, 5/8 x 7	OK	3/8 x 4-1/2	SNF	--	--
SNF, 5/8 x 7	OK	SNF	VSNF	--	--
VSNF, 5/8 x 4-1/2	OK	3/8 x 3	SNF	--	--
VSNF, 5/8 x 4-3/4	OK	VSNF	VSNF	--	--

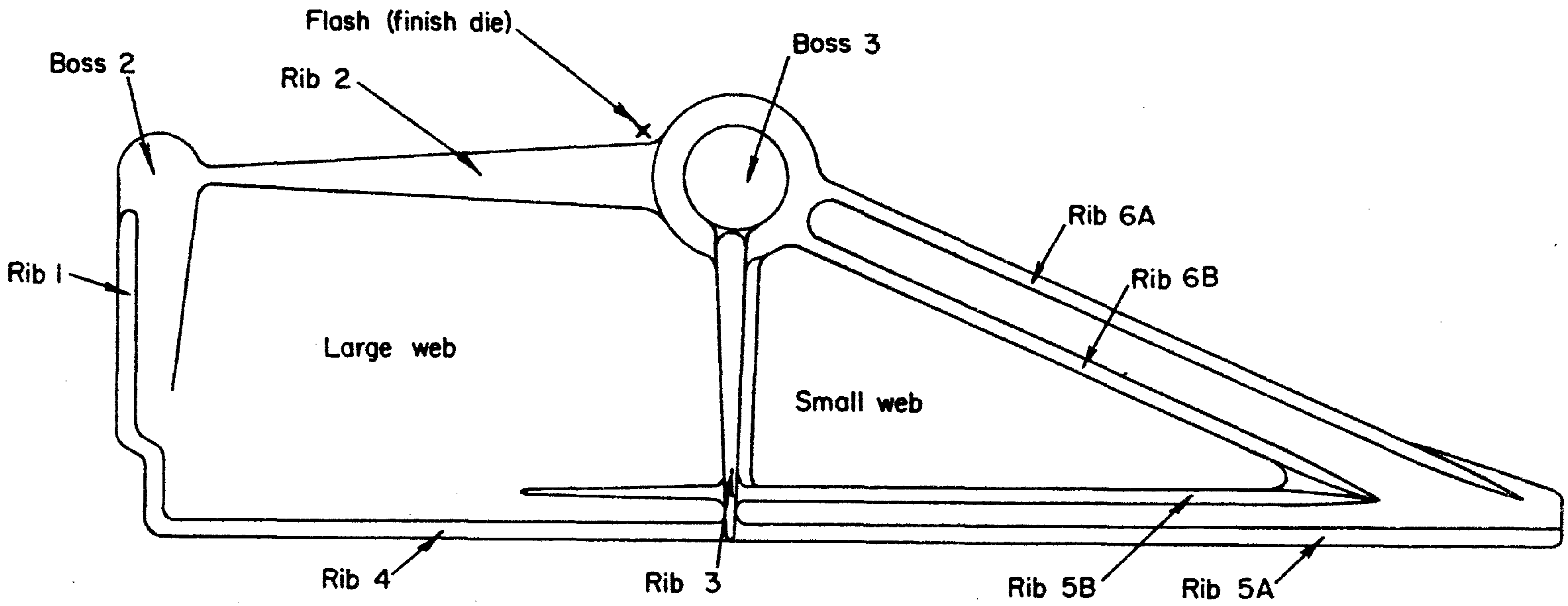


FIGURE 38. LOCATION OF MEASUREMENTS AFTER THE SECOND BLOCKING AND FINISHING OPERATIONS ON FORGING NO. 5-48951-3 FOR BOEING

A-18036

Although some variations were noted in the thicknesses of the webs, no significant difference in thickness was shown between the average values for the two series of samples. The samples that were pressed at the reduced load of 5000 tons showed about 0.025 inch thicker webs than those pressed at 10,000 tons. However, no significant difference in thickness was found between the treated and untreated samples.

Generally, differences in filling were slight, and most nonfilling noted would ordinarily pass inspection. However, the treated samples showed slightly better filling than the untreated samples when the rib filling for each pair of samples was compared at the various locations. In addition, five of the ten untreated samples that were compared showed very slight nonfilling on the boss at Position 3. None of the treated samples showed nonfilling at this location.

An important difference between the treated and untreated samples was in the surface appearance. Five of the ten untreated samples showed tears in at least one of the web sections. Only one treated sample showed this type of surface defect. These defects apparently resulted from insufficient lubrication.

Finishing Operation. Before the finishing operation, the forgings produced in the second blocking operation had been flash trimmed, cleaned, and chipped to remove any surface imperfections. The previously pretreated samples were again treated.

The 15 pretreated samples were forged first, the dies cleaned and reheated, then the 15 untreated billets were forged. As originally planned, the first five forgings of each group were to be wasters and were not to be used for comparison. Also in this operation, Samples 12 and 13 of each series were to be forged at a reduced load of 5000 tons, the remainder to be forged at a load of 10,000 tons. In these tests, the samples were forged in numerical order, except that Samples 12 and 13 were forged last in each series to minimize the number of press adjustments.

Previous experience in making this forging had shown that sticking in the finishing die had been a source of trouble. Time spent in freeing the forgings from the die impaired the production rate. Data in Table 19 show that 7 of the 15 untreated samples gave varying degrees of sticking in the die. On the other hand, none of the treated forgings stuck in the dies.

Various measurements obtained on the forged samples are listed in Table 20. The measurements were obtained at the locations shown in the sketch shown in Figure 38.

The difference in surface characteristics between the treated and untreated samples appeared to be the most striking difference between the two

TABLE 19. STICKING CHARACTERISTICS FOR TREATED AND UNTREATED SAMPLES USED IN PRODUCING BOEING PART NO. 5-48951-3 IN THE FINISHING DIE

Sample	Sticking, Treated Samples	Sticking, Untreated Samples
1	No	Stuck badly bottom die
2	No	Stuck slight top die, restrike, stuck slightly bottom die
3	No	No sticking
4	No	No sticking
5	No	No sticking
6	No	No sticking
7	No	No sticking
8	No	No sticking
9	No	No sticking
10	No	Stuck slightly
11	No	Stuck worse than Sample 10, had to hit forging with hammer while prying
12	No	Stuck, had to hit forging with hammer while prying
13	No	Stuck slightly
14	No	No sticking
15	No	Very slightly

TABLE 20. MEASUREMENTS OBTAINED ON FORGINGS AFTER THE FINISH-DIE OPERATION USING TREATED AND UNTREATED BILLETS IN PRODUCING BOEING PART NO. 5-48951-3

Sample[a]	Thickness, in. Large Web	Flash		Nonfilling at Various Rib Locations	Surface
6	0.410	0.115	Top	VSNF Ribs 1, 3, 5B, 6B	Slight drag on radius, Ribs 1 and 5B
			Bottom	VSNF Ribs 4, 6A	OK
6C	0.420	0.125	Top	VSNF Ribs 3, 4, 5A, 6B	OK
			Bottom	VSNF Ribs 1, 3, 4, 5A	OK
7	0.410	0.115	Top	VSNF Ribs, 3, 5A, 6B	Slight drag on radius, Rib 1
			Bottom	VSNF Ribs, 3, 5B, 6A	OK
7C	0.420	0.130	Top	VSNF Ribs 3, 5A, 5B, 6B	OK
			Bottom	VSNF Ribs 1, 3, 4, 5B, 6A	OK
8	0.410	0.125	Top	VSNF Ribs 3, 4, 5A, 6B	Slight drag on radius, Rib 1
			Bottom	VSNF Ribs 3, 5A, 6A	OK
8C	0.420	0.135	Top	VSNF Ribs 4, 5A, 6B	OK
			Bottom	VSNF Ribs 3, 4, 5A, 6B	OK
9	0.410	0.120	Top	VSNF Ribs 3, 4, 5A, 6B	Slight drag on radius, Rib 1
			Bottom	VSNF Ribs 3, 6A	Slight drag on radius, Rib 1
9C	0.435	0.130	Top	VSNF Ribs 3, 4, 5A	OK
			Bottom	VSNF Ribs 3, 4, 5A; SNF 6A	OK
10	0.415	0.140	Top	VSNF Ribs 3, 4, 5A, 6A	Slight tearing on radius, Rib 1
			Bottom	VSNF Ribs 4, 5A, 6A	Slight tearing on radius, Rib 1
10C	0.420	0.135	Top	VSNF Ribs 3, 4, 5A, 5B, 6B	OK
			Bottom	VSNF Ribs 2, 4, 5A, 5B, 6A	OK

TABLE 20. (Continued)

Sample[a]	Thickness, in. Large Web	Thickness, in. Flash		Nonfilling at Various Rib Locations	Surface
11	0.410	0.120	Top	VSNF Ribs 1, 2, 3, 4, 5A	Slight tearing on radius, Ribs 1 and 4; between Ribs 6A and 6B
			Bottom	VSNF Ribs 1, 2, 4, 6A	Slight drag on radius, Rib 1
11C	0.430	0.125	Top	VSNF Ribs 1, 2, 3, 5	OK
			Bottom	VSNF Ribs 1, 2, 5A	OK
12	0.430	0.155	Top	VSNF Ribs 4, 5A	Very slight drag on radius, Rib 1
			Bottom	VSNF Ribs 2, 3, 5A, 6B	Very slight tearing on radius, Rib 1
12C	0.470	0.180	Top	VSNF Ribs 1, 4, 5A, 5B	OK
			Bottom	VSNF Ribs 3, 5A, 5B, 6A; SNF Ribs 1, 2, 4	OK
13[b]	0.425	0.150	Top	VSNF Ribs 4, 6B	Slight drag on radius, Rib 1
			Bottom	VSNF Ribs 3, 4, 5A	Slight drag on radius, Rib 1
13C[b]	0.465	0.175	Top	VSNF Ribs 1, 2, 4, 5A, 6B	OK
			Bottom	VSNF Ribs 1, 3, 4, 5B, 6A; SNF Rib 6B	OK
14[b]	0.440	0.130	Top	VSNF Ribs 5A, 6A	Slight drag on radius, Rib 1
			Bottom	VSNF Ribs 3, 5A, 6B	Slight drag on radius, Rib 1
14C[b]	0.430	0.150	Top	VSNF Ribs 3, 4, 5A, 6A; SNF Rib 1	OK
			Bottom	VSNF Ribs 3, 5A, 6B	OK
15	0.420	0.130	Top	VSNF Ribs 3, 5A	Slight drag and tearing on radius, Rib 1
			Bottom	VSNF Rib 5A	Slight tearing on radius, Rib 1
15C	0.440	0.140	Top	VSNF Ribs 3, 5A, 6B	OK
			Bottom	VSNF Ribs 4, 5A	OK

(a) Suffix C indicates treated billets.
(b) Samples forged at a load of 5000 tons, all others forged at a load of 10,000 tons. Billet temperature was 820-840 F; die temperature was 700 F.

groups. All of the untreated samples showed various degrees of drag or tearing. None of the treated samples showed this surface condition. This drag or tearing occurred generally at the radius between Rib 1 and the large web. Figure 39 illustrates the type of surface condition noted for the untreated samples. This drag or tearing condition probably was the chief cause of sticking noted in forging the untreated samples.

Measurements on the rib showed that the untreated samples had fewer nonfilled areas than the treated samples. However, the nonfilling was very slight and the forgings were all acceptable by the inspector. The first six untreated samples that had large nonfilled areas at the pointed end of Rib 5A in the first blocking operation filled in the finish die to the satisfaction of the inspector. Also, the samples that were run at the reduced load in the second blocking operation filled satisfactorily.

The forgings made from untreated billets were slightly thinner, about 0.01 inch, in the web and flash areas. This difference was a little more noticeable among samples made with the lower load. It was also noted that pretreated billets gave forgings with more metal outside the gutter than did regular billets. This metal encroached on the flat portions of the dies which should meet to control the thickness of the forgings. These observations are interpreted as evidence that the billet pretreatments minimized the friction which restricted metal from flowing laterally.

Apparently, in both blocking and finishing dies, considerable lateral flow took place before the metal filled the vertical or rib sections. Therefore, the difficulty of filling the ribs was accentuated by better lubrication. Probably die designs should be varied slightly, depending on the lubricating conditions. With a better lubricant, more care is required in order to prevent metal from spreading beyond the flash cavity. If the metal is not restricted to the flash cavity, the dies cannot close and the ribs will not have the proper dimensions.

A forging made by regular practice and one which had received the lubricating pretreatments were cleaned in the normal fashion. That is, they were etched in a caustic solution and brightened by a dip in nitric acid. Both samples developed a satisfactory finish, indicating that the pretreatments caused no difficulty in cleaning.

Production of Boeing Part No. 5-86631-1

The performance of pretreated billets was also compared with that of untreated billets in the production of Boeing Part No. 5-86631-1. This part was made in a different plant than the one that produced Boeing Part No. 5-48951-3. A sketch of this part is shown in Figure 40. This part is a canister-type forging made from 2014 aluminum alloy. The walls are produced with no draft. The part is made in two steps, one blocking operation and a finishing operation. Comparisons between treated and untreated preblocked forgings were made only in the finishing operation.

FIGURE 39. DRAG OR TEARING ENCOUNTERED IN USING UNTREATED BILLETS IN PRODUCING BOEING PART NO. 5-48951-3 IN THE FINISHING DIE

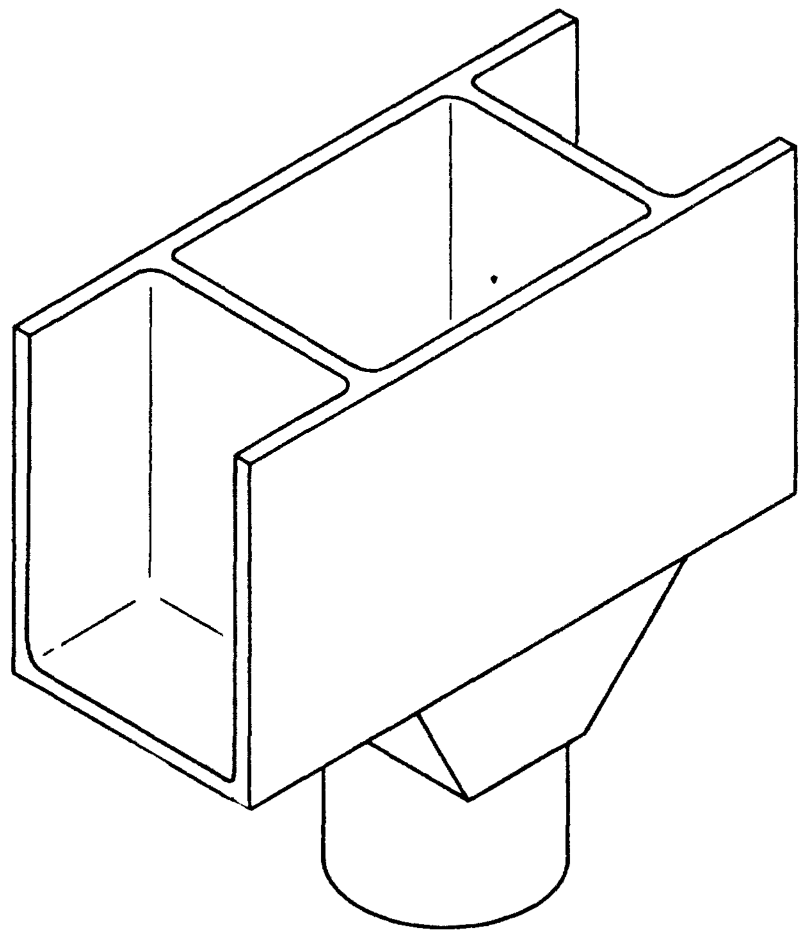


FIGURE 40. SKETCH OF FINISHED FORGING IDENTIFIED AS BOEING PART NO. 5-86631-1

A-18037

The walls of the forging were about 4-1/2 inches high and 3/16 inch thick. The walls are essentially extruded into the punch in a closed-die operation. The cavities in the punch were so deep the walls of the forgings did not bottom when the dies were completely closed. After forging, the walls are sawed to a length of 3.96 inches. The forging was made on a 2000-ton hydraulic press. A knockout pin was used to eject the forging from the bottom die.

Previous attempts at making good saleable forgings of this part with the plant's normal lubricating procedure were unsuccessful. The forgings had been characterized by severe scoring on the walls and rounded corners at the outside base of the can.

Twenty precoated and twenty-five conventional blanks were prepared for the test. The coated blanks were etched in a 10 per cent sodium hydroxide solution at 180 F for 2 minutes. Following that treatment, the samples were rinsed in hot water, then dipped in a suspension of colloidal graphite in water.

The dies were completely refinished to a surface roughness of 6 microinches to begin the test series. At the beginning of the run, the punch and die temperatures were 600 F and the stock temperature was maintained at 800 F. The coated samples were run first to see whether or not the forging could be produced satisfactorily by this method.

The first two samples were run using the regular lubricant, a suspension of colloidal graphite in water, on the dies. These samples showed some scoring on the walls and also showed rounded corners at the base of the can. This rounding of the corners seemed to be caused by a shear action similar to that encountered in the extrusion process in which flat-faced dies are used. Because these first two parts showed defects, the die lubricant was changed to one consisting of white lead in an oil carrier. Two additional forgings were then made. The second of these showed a little less rounding of the corners at the base of the can. Since these two forgings were not satisfactory, the die lubricant was changed again, this time to an oil-type commercial lubricant containing no solid lubricating material. This lubricant had not been used before in the plant. This particular lubricant is identified as Lubricant 176 in this report. After running four forgings with this lubricant, the inspector decided that the forgings were satisfactory. Therefore, the remainder of the precoated samples were forged using this die lubricant.

After finishing the treated samples, the untreated samples were forged using the same die lubricant that appeared to be successful on the treated samples. No particular trouble was encountered; therefore, all 25 untreated samples were forged. The dies were not cleaned between the treated and untreated series of samples. The die temperature at the end of the run on the treated samples was between 450 and 500 F. At the end of the run on the untreated samples, the die temperature had dropped to 400 F.

Because of the success in making this forging, the plant superintendent decided to continue running the forging as long as stock blanks were available. The eighth, sixteenth, and twentieth forgings made from treated blanks, and the eighth, sixteenth, and twenty-fifth, and the last forging of the run on untreated blanks were examined.

The most significant difference between the treated and untreated samples was in the uniformity of metal flow. The contours of the sides of the seven forgings examined in the laboratory are shown in Figures 41 and 42. The sketches were traced to scale, then reduced in reproduction. The dotted line near the top of each drawing indicates the location of the trimming line. The sketches show that the forgings made from pretreated blanks were more uniform in height. All three of these forgings provided ample stock for trimming. Two of the four untreated forgings, however, were barely long enough to give the proper dimensions after sawing. The greater dimensional uniformity in the walls of the forgings given the special pretreatment is considered an advantage.

The sketches show that all forgings had four points of maximum length. These high spots occurred at the junctions of the side walls with the two transverse ribs. The metal flowed easier at these locations because of the greater section dimensions.

In these experiments, the punch pressure was sufficient to close the dies in each forging operation. Consequently, the web thickness was controlled by the die dimensions and the average height in the walls of the forgings was controlled by the volume of the blanks. For these reasons, no significant difference in dimensions, except uniformity of wall height, was found among samples representing the two methods of lubrication. Unfortunately, it was impossible to conduct experiments with punch loads too small to close the die. Perhaps such experiments would show greater differences between forgings made with and without the pretreatment.

Larger Scale Pressing Tests

Larger scale pressing tests were performed on treated and untreated 2014 aluminum alloy billets using a 700-ton hydraulic press available at Battelle. These tests were made to determine the effect of the billet pretreatment on forging pressures required for simple compression between flat parallel dies.

Billets 1-1/2 and 1 inch in length by 3 inches in diameter, were machined from hot-rolled bar stock on a lathe. Several billets of each size were given Billet Treatment 200, which consisted of etching the billets in a 10 per cent sodium hydroxide solution at 180 F for 4 minutes. After etching and rinsing, the billets were dipped in a warm aqueous suspension of colloidal graphite.

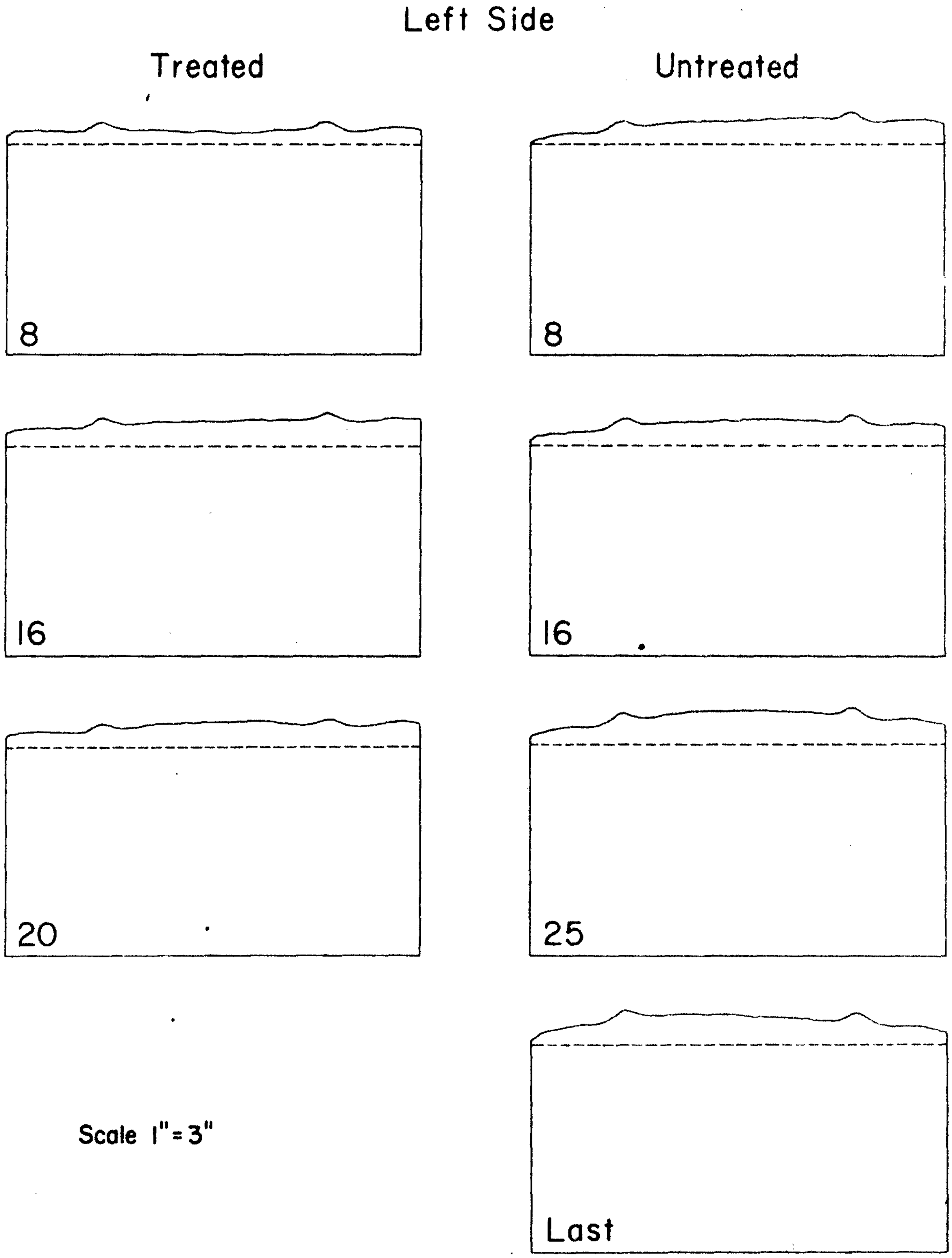


FIGURE 41. REPRODUCTION OF THE LEFT SIDE OF BOEING PART NO. 5-86631-1 AFTER FORGING TREATED AND UNTREATED BLANKS

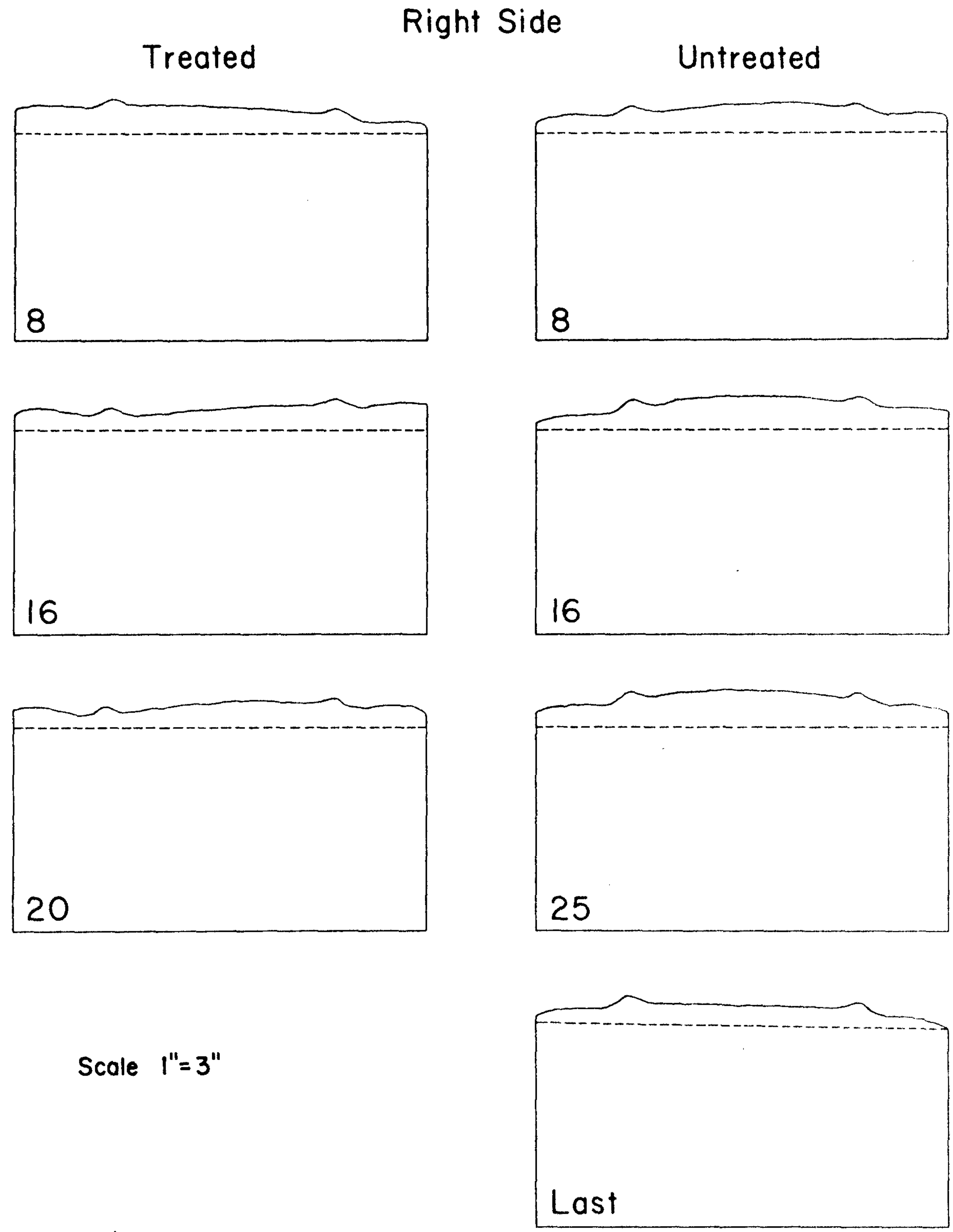


FIGURE 42. REPRODUCTION OF THE RIGHT SIDE OF BOEING PART NO. 5-8663-1 AFTER FORGING TREATED AND UNTREATED BLANKS

Treated and untreated billets of each length were upset between flat dies at a load of 600 tons using Lubricant 1 on the dies. The dies were heated to a temperature of 300 F. A dwell time of 5 seconds was used for each pressing experiment.

Pertinent measurements obtained on the pressed samples are given in Table 21. The billet pretreatment resulted in thinner pressings because it lowered the friction coefficient between the work and the dies. The differences in thickness, and in final area, resulting from pretreating the billets ranged around 20 per cent. Specifically, the billet pretreatments had the following effects in these experiments:

(1) In pressing 1-1/2-inch-high billets, pretreating the billets increased the final diameter by 11.5 per cent and the final area by 24.1 per cent, and decreased the final thickness by 19.4 per cent.

(2) In pressing 1-inch-high billets, pretreating the billets increased the final diameter by 8.5 per cent, and the final area by 17.7 per cent, and decreased the final thickness by 15.3 per cent.

These data confirm the results obtained on much smaller specimens. Figures 43 and 44 show representative pressings, made by both lubrication practices, from 1-1/2 and 1-inch-high billets, respectively.

Improvements in lubrication permit metal to flow at lower die pressures. Table 21 shows that pretreating the billets lowered the friction coefficient about 25 per cent and the final forging pressure about 16 per cent in these experiments. Such benefits increase the limiting size of the forging which can be made on a particular press. For instance, the 600-ton load produced a 6.58-inch-diameter pressing from the larger pretreated billet. It was calculated from data in Table 21 that a load of approximately 745 tons would have been required to produce a pressing of the same size from a conventional, untreated billet. This improvement seems large enough to be important for some commercial forging operations.

Extrusion Experiments on Aluminum

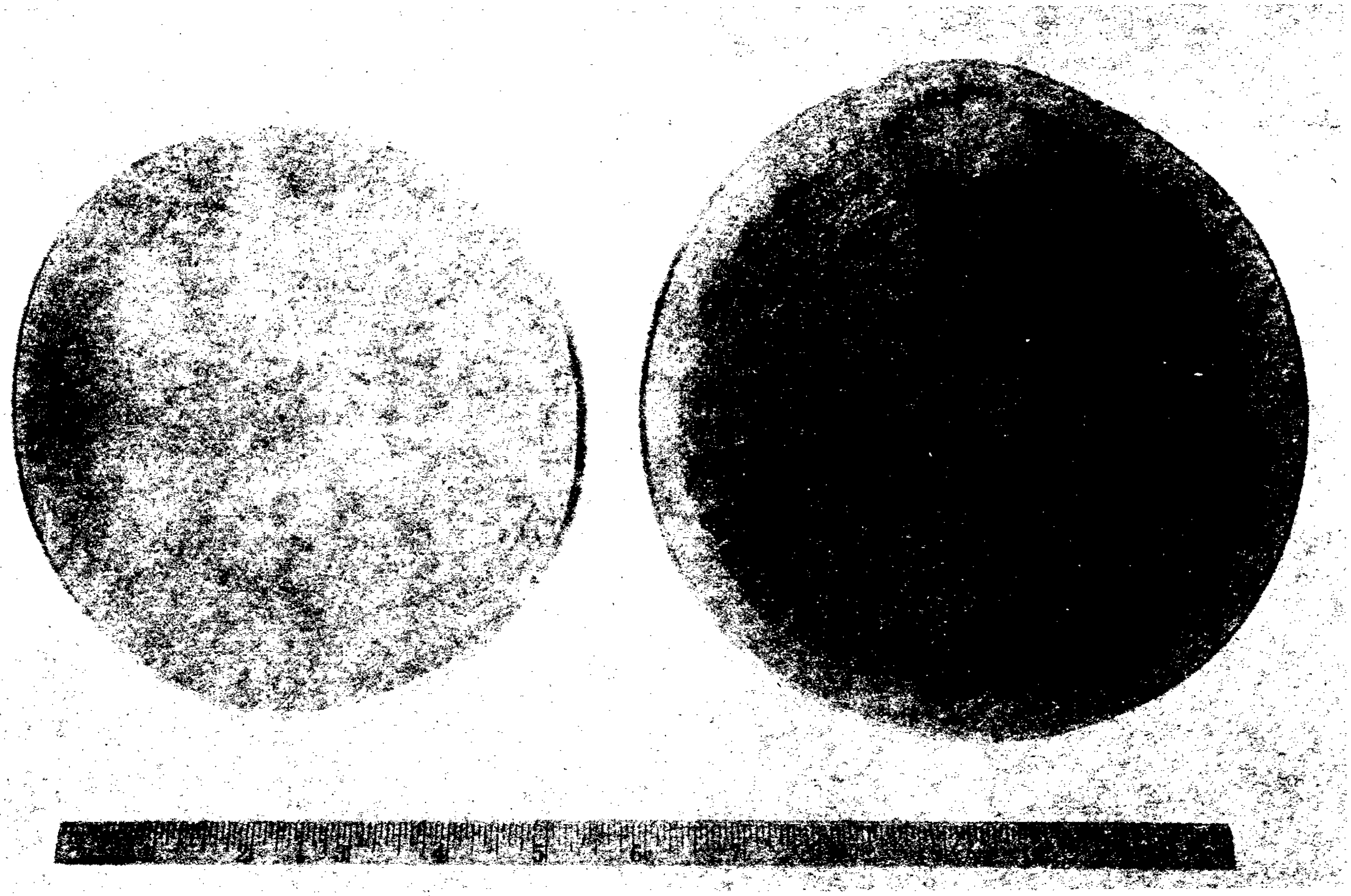
The use of lubricants in extruding aluminum shapes has not been generally accepted in the aluminum-extruding industry. Some extruders use lubricants on both billets and dies, others use lubricants just on the dies, and others use none at all.

Generally, flat extrusion dies having no entrance angle are used. Such dies produce flow by shear, causing a "dead" metal region in the corner at the intersection of the die and container. By this practice, billet surface imperfections are less likely to be carried through to form

TABLE 21. DATA OBTAINED IN PRESSING 2014 ALUMINUM ALLOY BILLETS UNDER A LOAD OF 600 TONS BETWEEN FLAT DIES

Sample	Billet Size[a], in. Diameter	Billet Size[a], in. Height	Billet Treatment	Lubricant[c]	Pressing Load, tons	Pressed Thickness, in.	Average Pressed Diameter, in.	Average Area, sq in.	Average Pressure, psi	Coefficient of Friction[d] (μ)
L2	3	1-1/2	None	1	600	0.384		27.6		
L3	3	1-1/2	None	1	600	0.391		27.1		
L4	3	1-1/2	None	1	600	0.385		27.5		
						Avg 0.387	5.92	27.4	43,500	0.22
L5	3	1-1/2	200[b]	1	600	0.321		33.0		
L6	3	1-1/2	200[b]	1	600	0.305		34.8		
L7	3	1-1/2	200[b]	1	600	0.311		34.1		
						Avg 0.312	6.58	34.0	35,300	0.13
L8	3	1	None	1	600	0.325		21.8		
L9	3	1	None	1	600	0.286		24.7		
						Avg 0.306	5.44	23.2	51,750	0.20
L10	3	1	200[b]	1	600	0.255		27.7		
L11	3	1	200[b]	1	600	0.262		27.0		
						Avg 0.259	5.90	27.3	44,000	0.15

(a) The billets were prepared from 3-inch-diameter hot-rolled bar stock.
(b) Billets were etched in 10 per cent sodium hydroxide solution at 180 F for 4 minutes. After etching, the billets were dipped in aqueous colloidal graphite and dried before heating for forging.
(c) Lubricant 1 was a commercial product containing flake graphite in mineral oil.
(d) Friction coefficients were calculated according to the formula given in Appendix D.
Billet temperature - 825 F
Die temperature - 300 F.

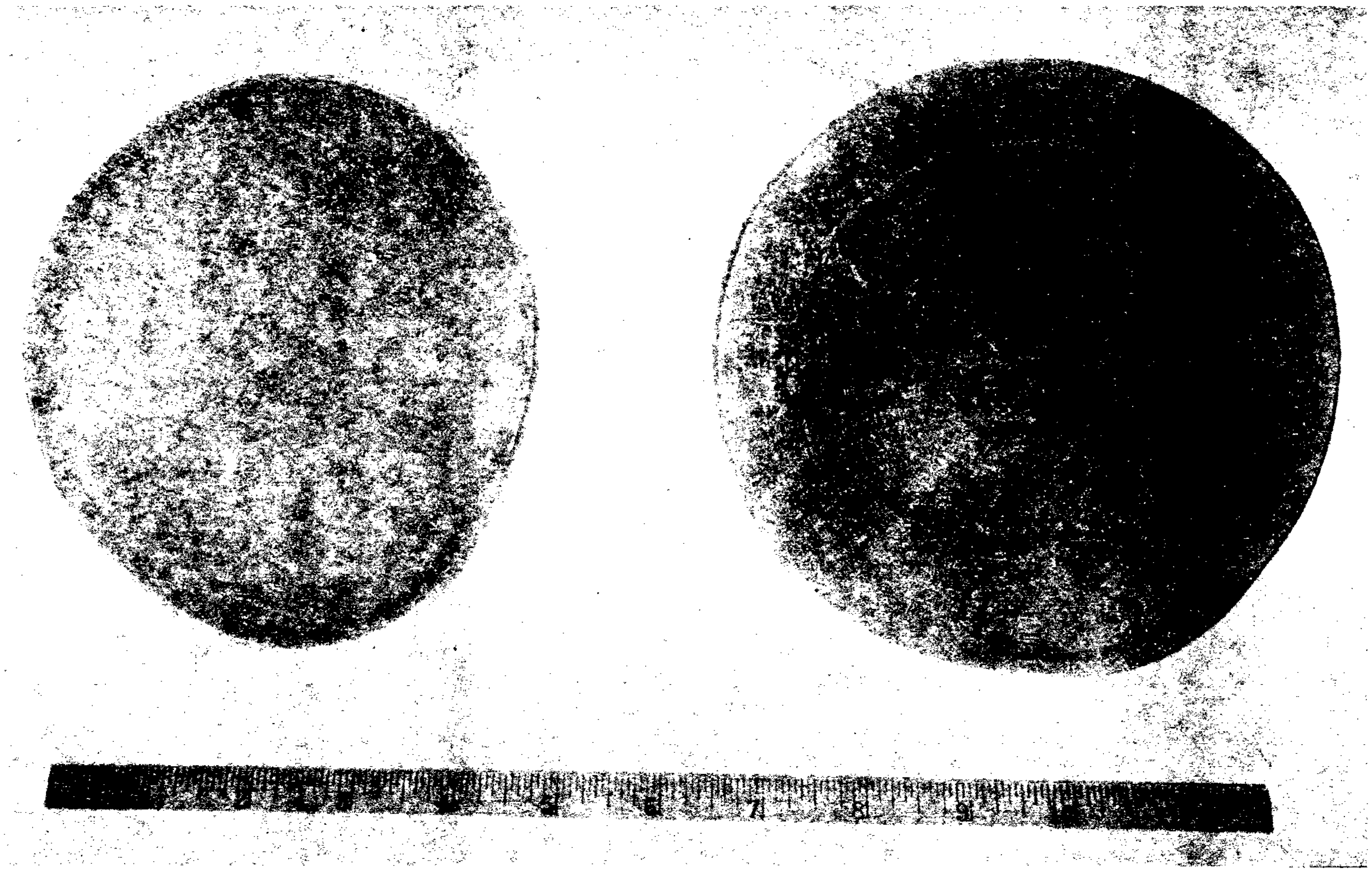


N25433

Untreated, Lubricant 1 Only

Treated, Plus Lubricant 1

FIGURE 43. COMPARISON OF UNTREATED AND TREATED BILLETS, 3 INCHES IN DIAMETER BY 1-1/2 INCHES HIGH, AFTER PRESSING BETWEEN FLAT DIES UNDER A LOAD OF 600 TONS



Untreated, Lubricant 1 Only

Treated, Plus Lubricant 1

FIGURE 44. COMPARISON OF UNTREATED AND TREATED BILLETS, 3 INCHES IN DIAMETER BY 1 INCH HIGH, AFTER PRESSING BETWEEN FLAT DIES UNDER A LOAD OF 600 TONS

imperfections on the extrusions. It is generally conceded that extruding without lubricants through flat dies requires higher extrusion pressures, but the quality of the extrusion is good with a bright surface with no need for removing a lubricant that might adhere to the extrusion.

However, any reduction in friction between the billet and the die and container would increase the effective capacity of extrusion presses. That is, smaller frictional work requirements would lower extrusion pressures and permit larger extrusions to be made.

Therefore, the extrusion tests on aluminum were designed to determine the effectiveness of various lubricants in reducing the extrusion pressure. The forging and pressing tests made on 2014 aluminum alloy served as a severe screening test for the evaluation of lubricants to be tried in extruding aluminum. Based on these data, the number of promising lubricants tried was limited.

The extrusion experiments were made on 2014 aluminum alloy using a reduction in area of 10.3 to 1. One-inch-diameter bar stock, 1-15/16 inches long, was extruded to a 5/16-inch rod using the experimental tooling arrangement described in Appendix C. Two die shapes were used in the extruding experiments; one was a flat die having an included angle of 180 degrees, the other was a conical die having an included angle of 130 degrees. For extrusion, the die and container were heated to 800 F and the billets were heated to 825 F. An instrument which automatically plotted the hydraulic line pressure against ram travel was used to record the loads during the extrusion cycle. An exit extrusion rate of 22.3 feet per minute was used for the tests. After the extrusion cycle, the skull was cut off with bolt cutters and the extrusion knocked through the die with a punch.

Data obtained in the extrusion experiments on 2014 aluminum alloy using various lubricants and two different die shapes are summarized in Table 22. The original data obtained in the experiments are given in Table F-4 of Appendix F. Extrusion pressures for front, middle, and back positions were calculated from the line-pressure versus ram-travel charts obtained for each extrusion. Most of the extrusion pressures listed in Table 22 are averages of the values obtained for three extrusions made consecutively, beginning each group with a clean container and a clean die.

The pressure necessary to extrude without a lubricant was used as a basis for comparing the effectiveness of the various lubricants studied. With no lubricant, using the flat die (180-degree entrance angle), a pressure of 72,000 psi was required to start extruding; this decreased to 38,000 psi at the back end of the extrusion. The pressures required for extruding through the conical die (130-degree entrance angle) were 14 per cent greater at the front and 12 per cent greater at the back end than those required for extruding through the flat die. The difference in extrusion pressures between the beginning and the end of the extrusion cycle indicates that, for the particular extrusion studied, the pressure necessary to overcome friction between the billet and container wall was about the same as that required to actually extrude the metal through the die. This means that the container friction roughly doubled the pressure required to produce the extrusion.

The lubricants studied were not rated in the same order by the two dies used. With lubricants that required relatively high pressures for extruding, the flat die seemed to require the least pressure. However, for the better lubricants which required relatively low pressures for extruding, lower pressures were required to extrude through the conical die.

With one exception, lubricants lowered the pressures required for extruding. This was true for both types of dies. The degree to which the starting extrusion pressure was lowered by using the various lubricants was not always reflected in a similar reduction of pressure at the back end of the extrusion. This would be expected because container friction practically disappears at the end of the extrusion cycle. Considering these factors, Lubricants 150 and 149 (tetrafluoroethylene resins that were applied to the billets) appeared the most promising in reducing friction during extrusion. Using these materials as lubricants, the starting pressures were decreased about 45 per cent from those obtained with no lubricant, while the pressure at the end of the extrusion cycle was lowered about 25 per cent. For comparison, two commercial materials, Lubricants 1 and 3, showed a reduction in pressure of about 15 per cent at the start and no reduction at the end of the extrusion cycle.

Lubricant 123, which consisted of extra-fine flake graphite in a sodium Paraplex G60 grease, also showed considerable promise in lowering extrusion pressures when used with both types of dies. It produced poor surfaces, however. Boron nitride, when added to the same grease as a carrier (Lubricant 124), also appeared to be effective in reducing the pressures required for extruding through the flat die. It was not so effective when used with the conical die. Boron nitride in a carrier of Paraplex G62 (Lubricant 65) was also quite effective in reducing the extrusion pressures, especially when using a flat die.

Representative pressure versus ram-travel curves for four lubricants used in extruding 2014 aluminum alloy are shown in Figure 45. These curves illustrate how the extrusion pressure may be materially reduced by the use of Lubricants 123 and 150. The flat curves for Lubricants 123 and 150 show that these lubricants drastically reduced friction between the billet and container. At the same time, the friction between the die and the extrusion was lowered, as reflected by the lower pressure required at the back ends of the extrusions.

ALUMINUM ALLOY USING VARIOUS LUBRICANTS AND TWO DIFFERENT DIE SHAPES

(180-Degree Included Angle)		Conical Die (130-Degree Included Angle)				
		Extrusion Pressure, 1000 psi				
Surface Rating[a]	Segmentation[b]	Front	Middle	Back	Surface Rating[a]	Segmentation[b]
F, F, F	3 to 4 in.	82.0	56.8	42.5	VG, VG, VG	None
VG, VG, VG	1 in.	67.2	56.9	42.0	F, F, G	None
VG, VG, VG	3/4 in. on Samples 20 and 21	79.1	53.1	39.9	G, G, G	None
VG, G, G	2 in. on Samples 13 and 14	42.5	42.6	38.8	G, G, G	None
VG, VG, VG	1 in.[d]	76.5	59.2	44.8	G, G, G	None
VG, F, F	None	36.5	34.0	29.4	F, F, F	None
F, F, F	1 in. on Sample 32[e]	35.1	35.5	34.5	F, F, F	None
G, G, G	1 in.	38.4	32.8	40.8	F, VG, VG	None
F, F, F	2 in. on Sample 48, 1 in. on Sample 49	52.1	40.0	36.3	VG, G, G	None
F, G, F	1 in. on Samples 55 and 56	47.2	43.6	35.3	G, F, G	None
G, F, G	1 in.[f]	39.7	41.2	37.4	F, F, F	None
P, F	3-1/2 in.[g]	55.5	50.4	42.1	VP, VP, VP	Entire length on 40
VP, F, P	1/2 in.[h]	59.8	50.8	41.0	VP, VP, P	None
F, VG, VG	2 in. on Sample 60	42.5	40.8	36.3	G, G, F	None

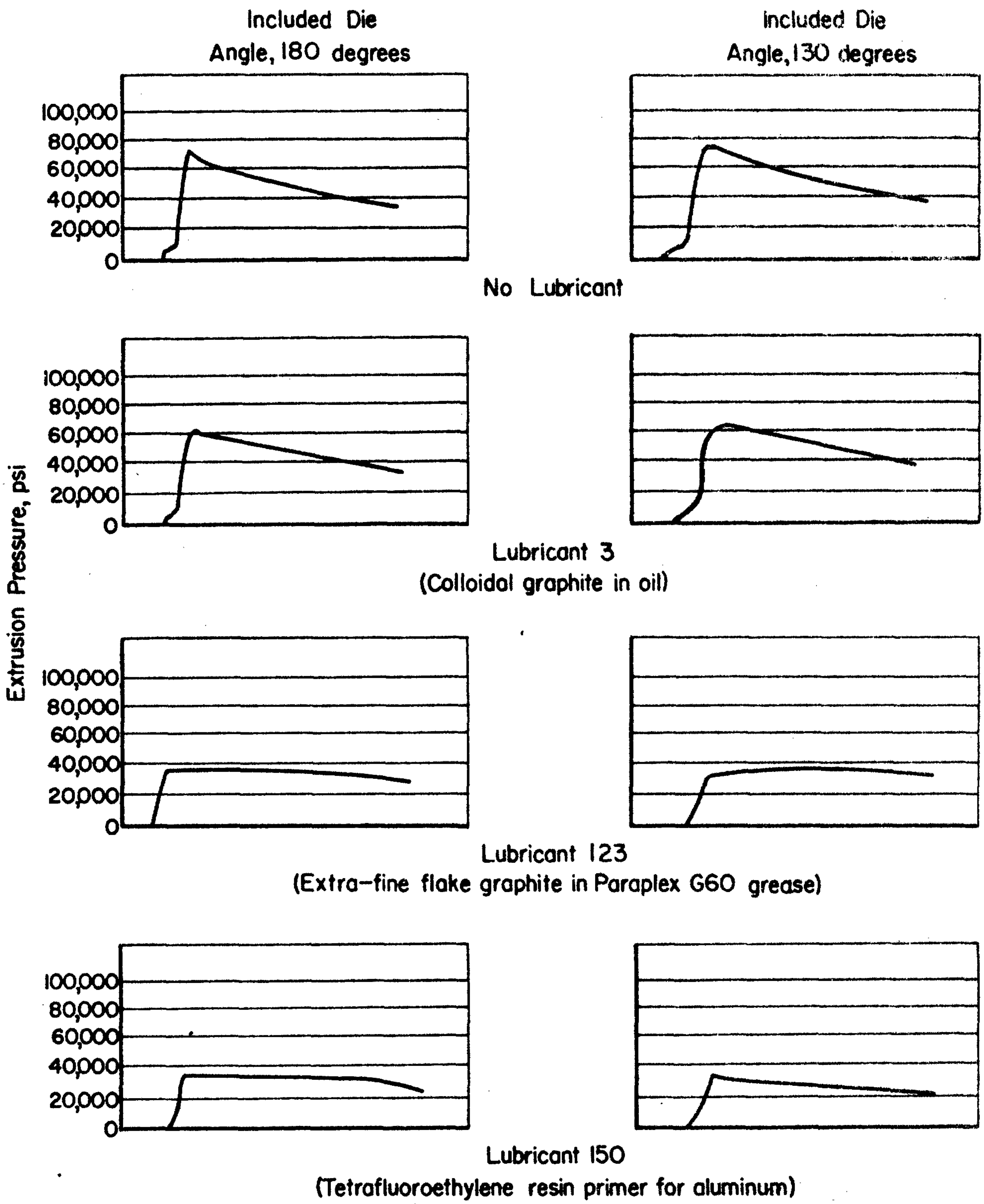


FIGURE 45. REPRESENTATIVE PRESSURE VERSUS RAM-TRAVEL CURVES FOR SELECTED LUBRICANTS USED IN EXTRUDING 2014 ALUMINUM ALLOY

A-18038

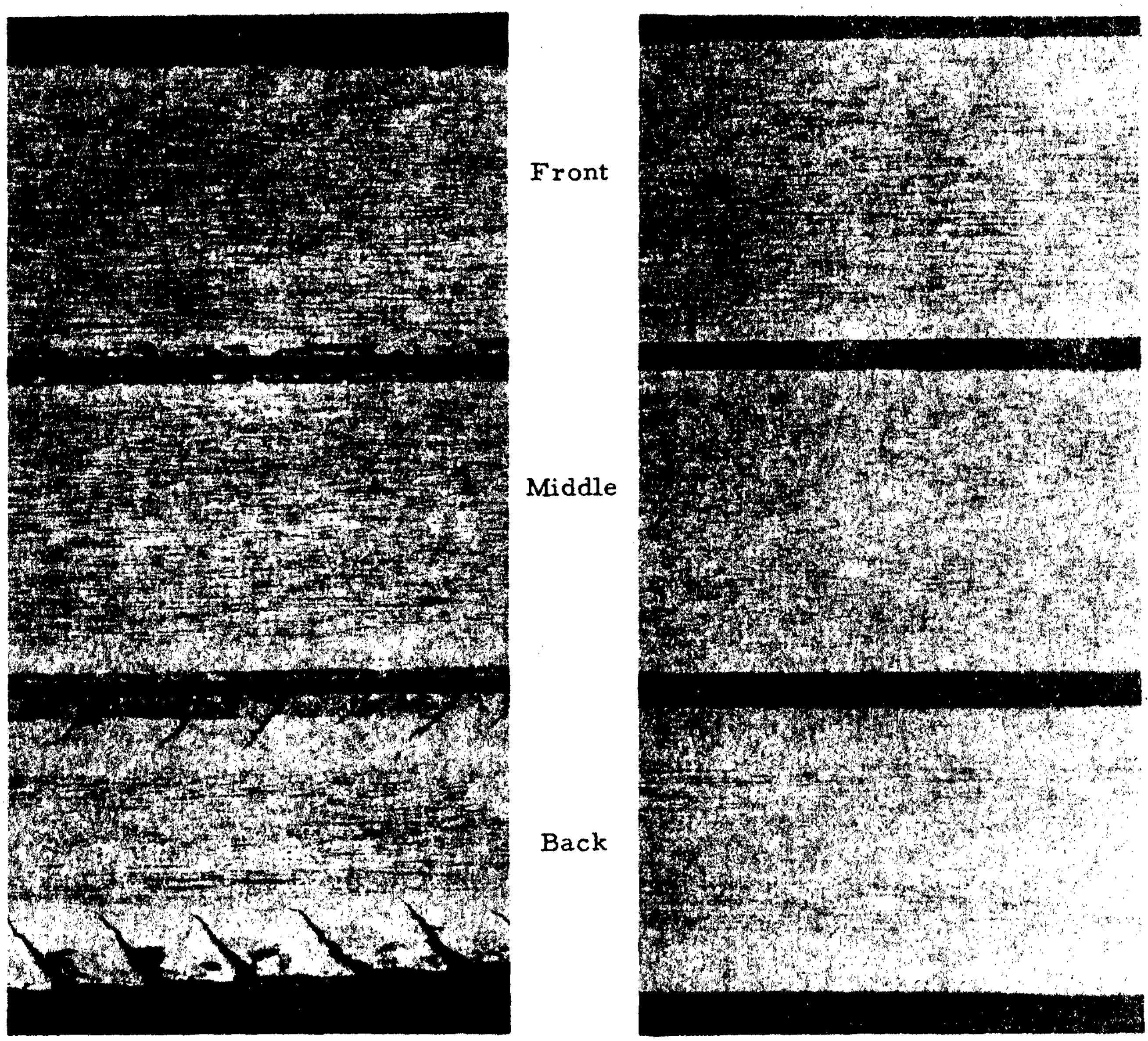
A billet treatment in which the billets were etched in sodium hydroxide, then dipped in an aqueous suspension of colloidal graphite before heating and extruding with a conventional die lubricant, was not as effective in reducing the extruding pressures as Lubricants 149, 150, or 123. However, the treatment was more effective when used with conical dies than when used with flat dies. This suggests that a particular lubricant may require a particular die shape to produce optimum effectiveness in reducing friction during extrusion.

Some of the extrusions were examined macroscopically to determine whether there were any significant differences in metal flow between lubricated and unlubricated extrusions and also between those made using flat and conical dies. Such a study was made on extrusions representing those produced without a lubricant, with Lubricant 123, and with Lubricant 149. Representative macrostructures are shown in Figures 46, 47, and 48, respectively. Structures representing the front, middle, and back portions of each extrusion are shown for each condition.

Two significant differences are shown when the macrostructures in Figures 46, 47, and 48 are compared. First, grain growth, which occurred around the periphery of the extrusion made with the flat die (180-degree included entrance angle) without a lubricant, was eliminated or reduced by the use of lubricants or a conical die. Second, the conical die (130-degree included entrance angle) produced a more uniform macrostructure than did the flat die (180-degree included entrance angle). This appeared to be true for unlubricated and lubricated extrusions. Apparently, the conical die produces a more homogeneous reduction across the cross section than the flat die.

Grain growth encountered in extruding aluminum is caused by the temperature of the extruded metal being raised above its recrystallization temperature. If the billet temperature is not too high, the heat of working and the heat of friction may be sufficient to raise the temperature of the metal above the recrystallization temperature. This effect can be controlled to a certain extent by the rate of extrusion. Slow rates of extrusion allow heat generated by friction and work to dissipate into the surrounding mass of tooling. Also, the degree of work on the aluminum during extrusion affects the temperature at which recrystallization and grain growth takes place. The greater the degree of work on the aluminum, the lower will be the recrystallization temperature. For the particular conditions of extrusion in this laboratory work, the photomacrographs indicate that the flat die produced a greater amount of heat than the conical die either through work in deforming the metal or in friction between tools and workpiece. This is evidenced by the amount of grain growth which occurred when a lubricant was not used. The amount of heat generated during extrusion appears to be minimized by using lubricants or a conical die.

Included Die Angle, 180 degrees | Included Die Angle, 130 degrees

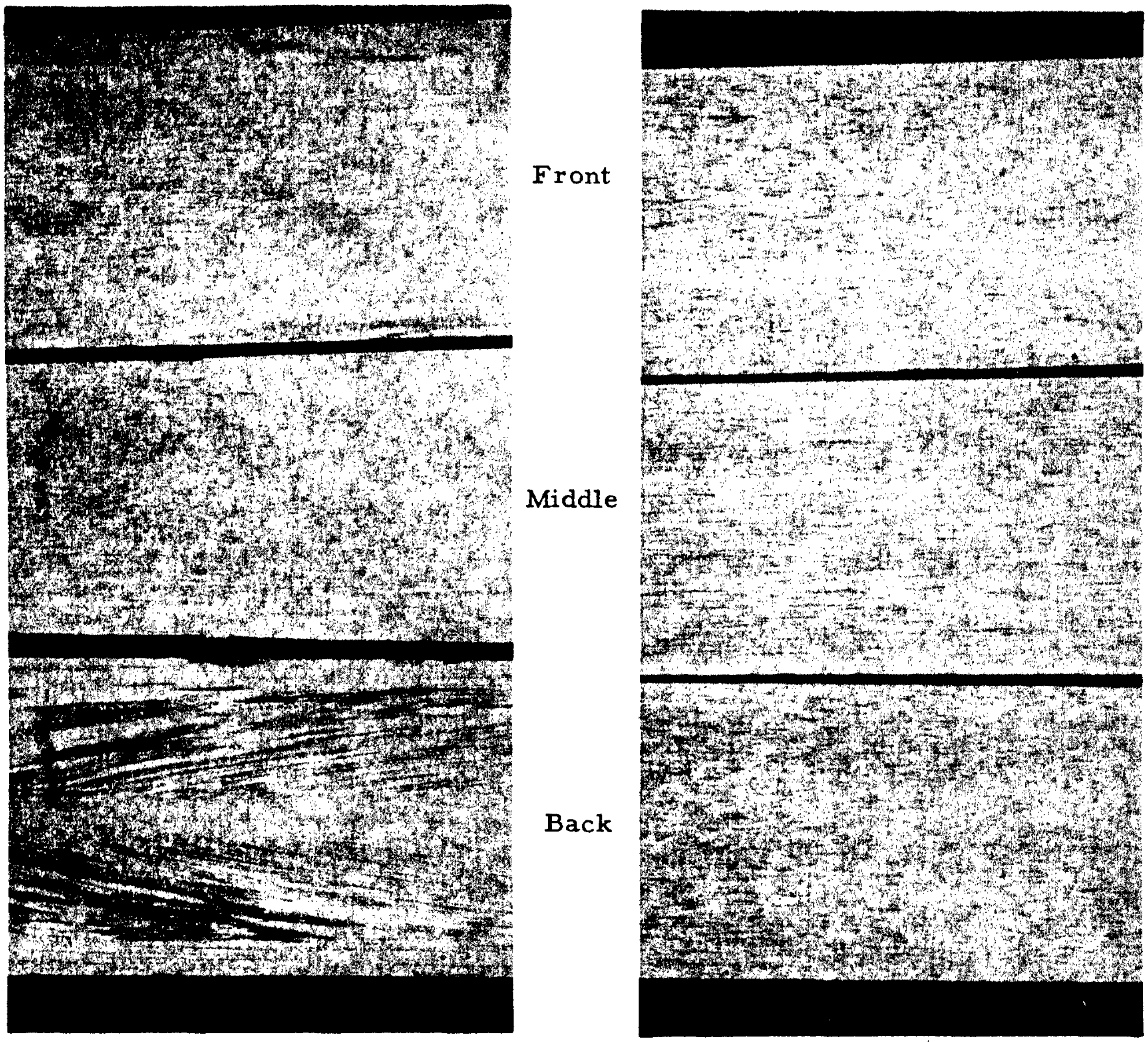


6X N25482 | 6X N25483

Flick's Etch

FIGURE 46. REPRESENTATIVE MACROSTRUCTURE OF 2014 ALUMINUM ALLOY EXTRUSIONS MADE USING NO LUBRICANT (LONGITUDINAL SECTION)

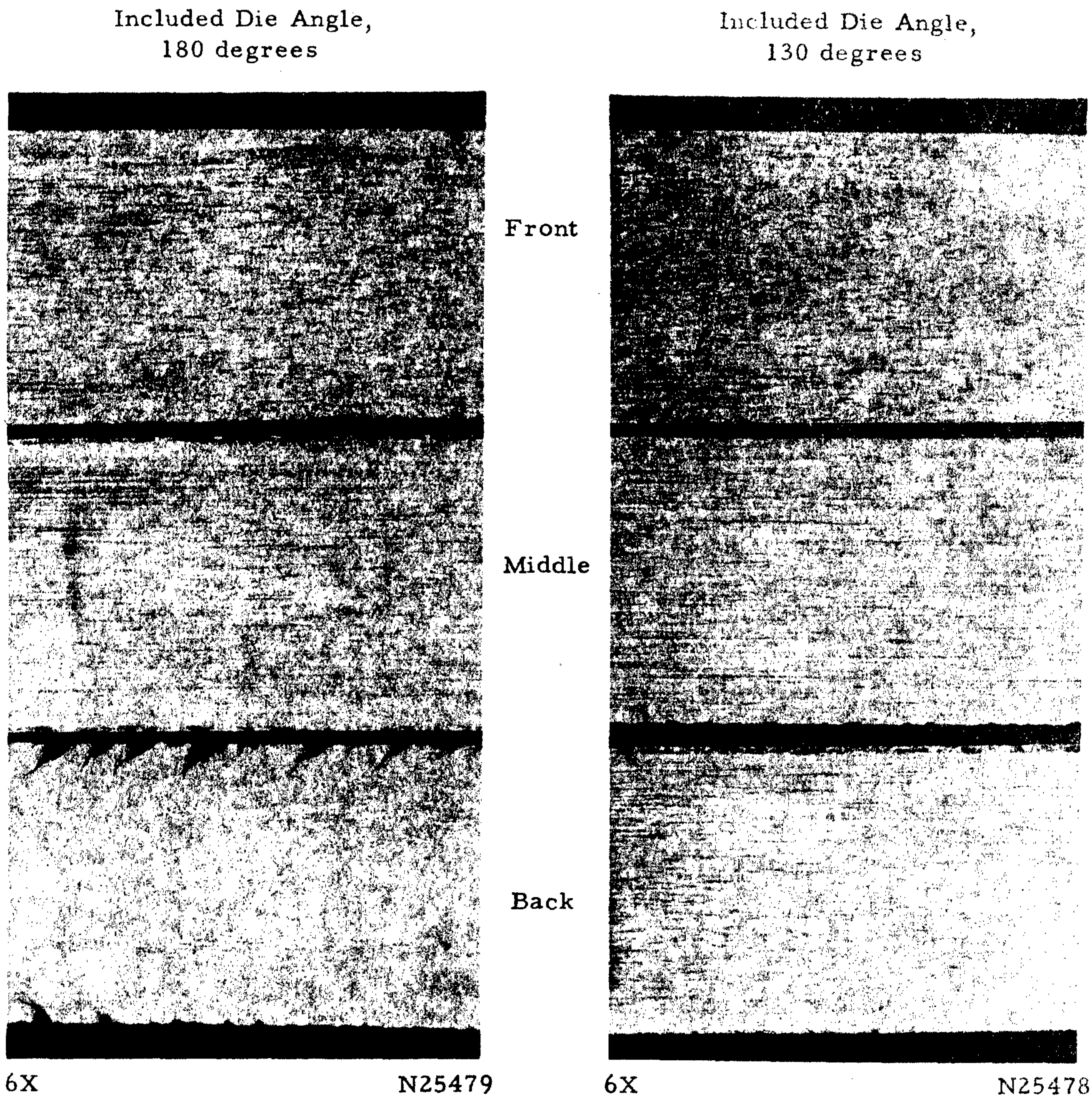
Included Die Angle, 180 degrees | Included Die Angle, 130 degrees



6X N25481 | 6X N25480

Flick's Etch

FIGURE 47. REPRESENTATIVE MACROSTRUCTURES OF 2014 ALUMINUM ALLOY EXTRUSIONS MADE USING LUBRICANT 123 (EXTRA-FINE FLAKE GRAPHITE IN PARAPLEX G60 GREASE) WHICH WAS APPLIED TO THE DIE AND CONTAINER (LONGITUDINAL SECTION)



Flick's Etch

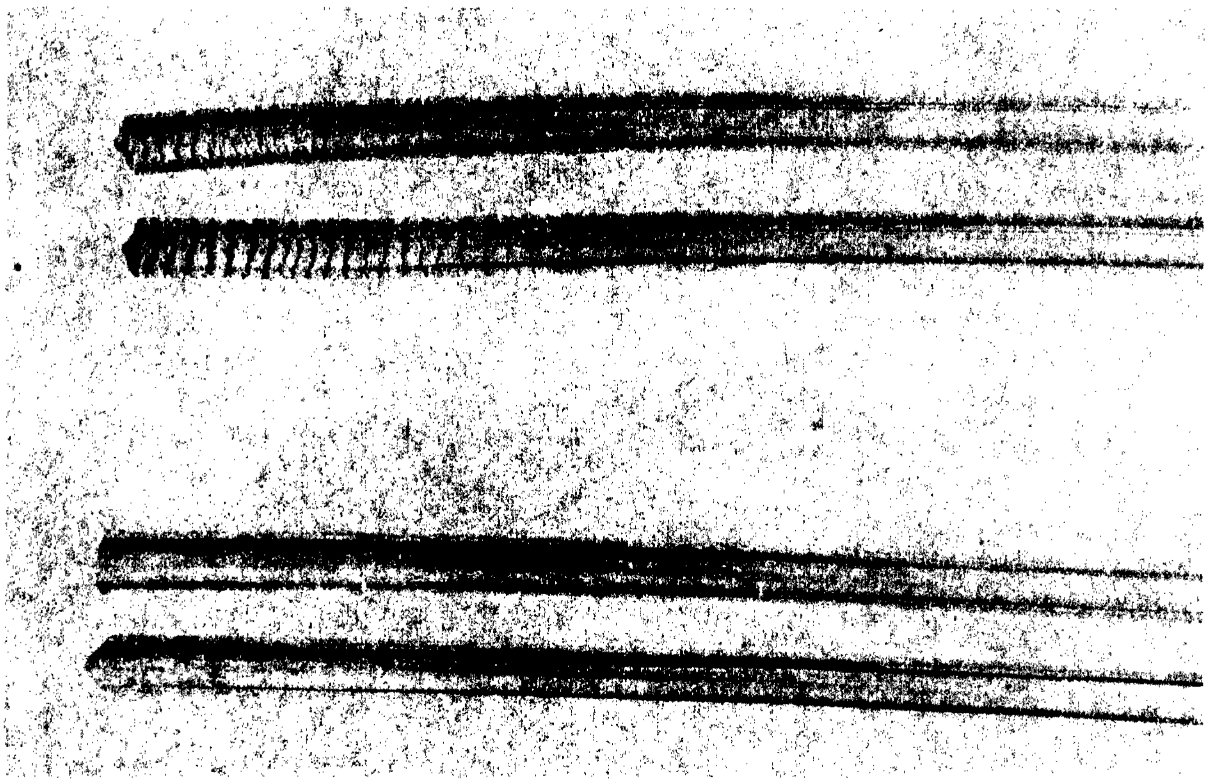
FIGURE 48. REPRESENTATIVE MACROSTRUCTURES OF 2014 ALUMINUM ALLOY EXTRUSIONS MADE USING LUBRICANT 149 (TETRAFLUOROETHYLENE RESIN PRIMER FOR STEEL) WHICH WAS APPLIED TO THE BILLET (LONGITUDINAL SECTION)

Additional evidence is shown by the data in Table 22 that the amount of heat generated by working in the flat die was greater than that produced by the conical die. The data show that segmentation was generally produced at the back ends of the extrusions made using the flat die. With the exception of one extrusion, this "rattlesnake" defect did not occur when the conical die was used. This difference was noted even when lubricants were used. The difference in segmentation noted between flat and conical dies is illustrated in Figures 49 and 50. When lubricants were used, the number of and the distance between segments appeared to be reduced. This is also illustrated by comparing the segmentation of the extruded rods shown in Figures 49 and 50.

Segmentation generally occurs when the temperature of the extrusion is raised, as a result of heat produced by metal working, to a temperature where hot ruptures develop. This generally can be controlled by the speed of extrusion. Slower speeds allow the heat generated to be dissipated into the tooling mass. The data suggest that higher extruding speeds can be used with conical dies than with flat dies without encountering transverse cracks or "rattlesnake" defects.

Another disadvantage of the flat die is the susceptibility to a fault known as piping. Data given in Table 22 show that piping took place only in samples extruded through a flat die. For the samples examined, the piping was not severe. Piping is generally believed to result from reverse flow of the billet surface metal in the final stages of extruding through flat dies. The surface portion of the billet flows backwards to the punch, then is deflected into the center portion of the extrusion, taking the form of a funnel closing in from the corners and continuing into the die as a tubular fault. The condition seems to be exaggerated when better lubricants are used between the container and billet.

The limited experimental extrusion data obtained on 2014 aluminum alloy showed that the extrusion pressures can be markedly reduced by the use of certain lubricants. Although only two die angles were studied, the data indicated that conical dies give lower pressures than flat dies when good lubrication is obtained. The conical die having an entrance angle of 130 degrees produced a more uniform extruded structure and appeared to minimize the tendency toward recrystallization and grain growth. In addition, the use of the conical die minimized the tendency for segmentation and piping that are sources of trouble in commercial operations.

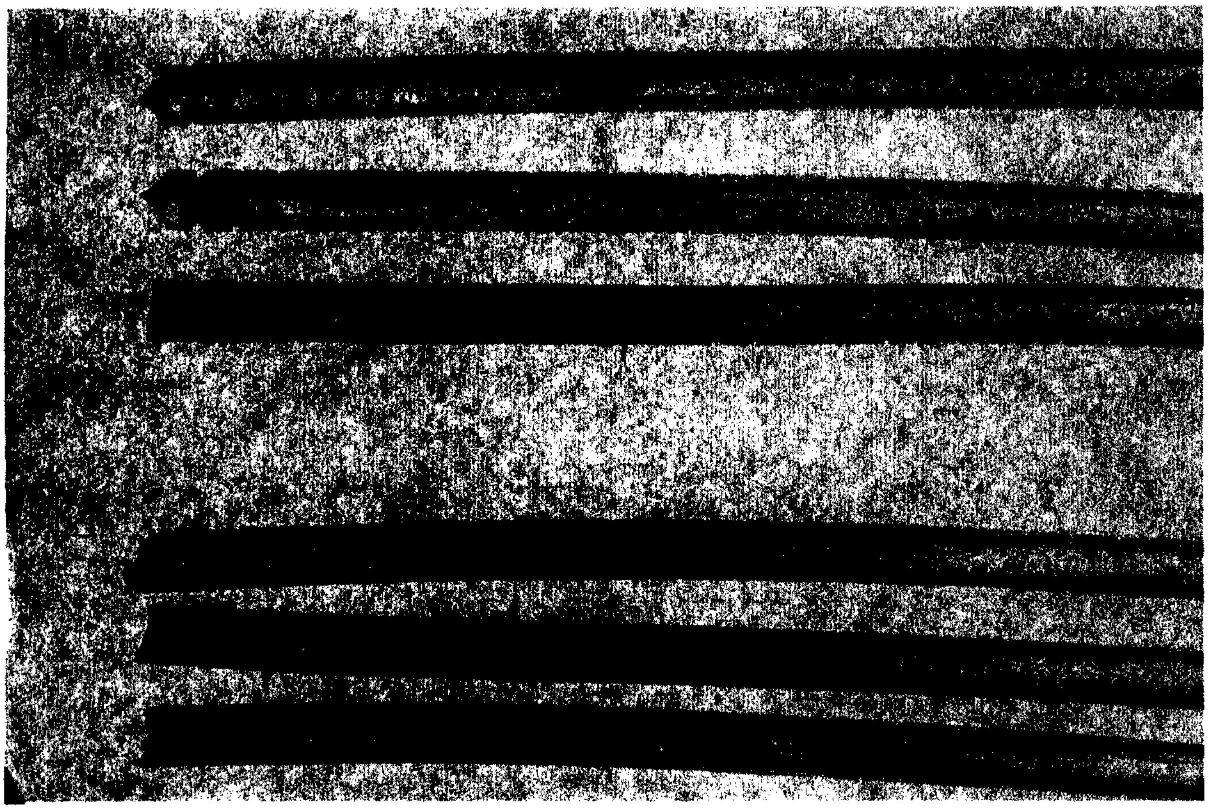


1X N25714

Top group – Extruded through a flat die having an entrance angle of 180 degrees

Bottom group – Extruded through a conical die having an entrance angle of 130 degrees

FIGURE 49. BACK ENDS OF 2014 ALUMINUM ALLOY EXTRUSIONS MADE USING NO LUBRICANT AT AN EXIT SPEED OF 22.3 FEET PER MINUTE



1X N25715

Top group – Extruded through a flat die having an entrance angle of 180 degrees

Bottom group – Extruded through a conical die having an entrance angle of 130 degrees

FIGURE 50. BACK ENDS OF 2014 ALUMINUM ALLOY EXTRUSIONS MADE USING LUBRICANT 65 (BN IN PARAPLEX G62) AT AN EXIT SPEED OF 22.3 FEET PER MINUTE

STUDIES ON MAGNESIUM

Screening and Forging Tests

The practice for forging magnesium is essentially the same as that used in forging aluminum. The chief difference is in the temperatures used. Magnesium-alloy stock is usually heated to approximately 700 F for forging; however, this depends on the alloy. A die temperature of 550 to 650 F is generally considered a good operating temperature in blocking dies. This allows thin sections to be made without cracking and underfilling caused by excessive cooling. The finishing die may be operated at lower temperatures to take advantage of improvements in strength from strain hardening.

Dies for forging magnesium are usually lubricated with graphite, either in flake or colloidal form, suspended in a light mineral or animal oil or suspended in water. Graphite, which adheres to the magnesium forging, is difficult to remove by chemical action. If the lubricant which adheres to the forging is relatively heavy, severe pitting may result before the lubricant is completely removed from the surface of the forging. Therefore, at times, the lubricant must be removed by some mechanical means such as sandblasting.

Grade AZ80A magnesium alloy was selected as working stock for the experimental work in the study of lubricants for working magnesium. This alloy contains 8.5 per cent aluminum, 0.5 per cent zinc, and 0.15 per cent manganese. Forging-, pressing-, and bulge-test billets were prepared from 1-inch-diameter bar stock and machined to proper length. No machining was done on the periphery of the samples.

Lubricants used in tests on magnesium are listed in Table E-1 of Appendix E. This table lists all materials and billet treatments used for the entire investigation. Not all materials listed were used in tests on magnesium because some were tried specifically for other metals. Each lubricant or treatment is identified by number. Commercial lubricants tested are not identified as to brand name.

Complete lists of all data obtained in the forging, pressing, and bulging tests on magnesium are given in Tables H-1, H-2, and H-3, respectively, of Appendix H. Some of the materials screened in the pressing test were not further evaluated in the forging test, because the pressing-test data indicated that they were not promising lubricants. On the other hand, some of the materials evaluated in the forging test were not previously evaluated in the pressing test.

The thickness of the disks produced in the standard pressing test was used as the parameter for screening various lubricants. Coefficients of friction for the magnesium pressings were not calculated. It was shown in pressing tests on aluminum that a direct relationship between the pressed thickness and the coefficient of friction existed. A similar relationship should hold true for magnesium.

The bulge-test data given in Table H-3 of Appendix H were not used in evaluating the various lubricants tried on magnesium. These data were obtained early in the program and the ratings obtained in this test did not correlate very well with data obtained in the pressing and forging tests. The latter two test methods were believed to be more reliable.

Tests on Commercial Lubricants

Pressing and forging tests were made on a number of commercial lubricants to establish a basis for comparing the performance of experimental lubricants or methods of lubrication. Materials or methods of lubrication which gave test results superior to the commercial material may offer advantages in production operations.

The commercial lubricants were received as concentrates and were diluted as recommended by the manufacturers for ease of spraying. As in the tests on aluminum, the lubricants were sprayed for a standard total time of 5 seconds, 2-1/2 seconds from each end of the die.

A list of lubricants used and the pressing- and forging-test data obtained on them are given in Table 23. A fair correlation existed between the pressing- and forging-test data. Generally, lubricants that produced thin pressings gave good penetration into the forging die.

The forging-test data indicated that the type of carrier in the lubricant markedly influenced the amount of die filling by the metal. Water-carried lubricants gave by far the best ratings, and the kerosene-carried lubricants gave the poorest ratings. Oil-carried lubricants produced slightly better die filling than the kerosene-carried lubricants.

Of the two water-carried materials (Lubricants 4 and 6), Lubricant 6, which contained graphite and molybdenum disulfide, produced a much greater die penetration than Lubricant 4, which contained colloidal graphite. The superiority of the water dilution over the oil dilution is shown by comparing the data for Lubricant 6 with those for Lubricant 5. Both lubricants were made by the same manufacturer and reportedly had the same proportions of solid ingredients. Also, the superiority of water dilution over oil or kerosene dilutions of colloidal graphite may be seen by comparing Lubricant 4 with Lubricants 3 and 12. Lubricants 3 and 12 were prepared from the same oil base mixture. These two lubricants were also prepared by the same manufacturer.

TABLE 23. FORGING- AND PRESSING-TEST DATA OBTAINED IN WORKING AZ80A MAGNESIUM ALLOY WITH VARIOUS COMMERCIAL LUBRICANTS

Lubricant[a]	Brief Description	Penetration Into Die Cavity in Forging Test[b], in.	Pressed Thickness After Pressing Test[c], in.
1	Flake graphite in oil	1.11	0.076
2	Flake graphite in oil	0.95	0.065
3	Colloidal graphite in oil	0.92	0.101
4	Colloidal graphite in water	1.44	0.086
5	Graphite and powdered MoS_2 in oil	1.01	0.085
6	Graphite and powdered MoS_2 in water	1.62	0.078
8	Flake graphite in oil	1.14	0.055
12	Colloidal graphite-oil mixture diluted with kerosene	0.90	0.107
14	MoS_2-oil mixture diluted with kerosene	0.78	0.098
16	MoS_2-oil mixture diluted with kerosene	0.80	0.098

(a) All oil-base lubricants were diluted according to manufacturers' recommendations with a naphthene-base oil having a viscosity of 106 SUS at 100 F. The dilution ratios for all lubricants are listed in Table E-1 of Appendix E.

(b) Forging tests were made using a billet temperature of 675 F, a die temperature of 500 F, and a punch pressure of 46,000 psi.

(c) Pressing tests were made by pressing billets 1 inch in diameter by 1/2 inch in height between flat parallel dies heated to 500 F at a load of 138,000 pounds. The billet temperature was 675 F.

The superiority of water-carried lubricants over oil-carried lubricants in forging magnesium is the reverse of that found in forging aluminum. The difference in die temperatures appears to be the chief reason for the different behaviors of water- and oil-carried lubricants. When forging aluminum, using a die temperature of 700 F, it was difficult to make water-carried lubricants stick to the die. However, in forging magnesium using a die temperature of 500 F the water-carried lubricants adhered to the die.

Studies on Organic Materials

Twelve organic materials were selected for study as lubricants in working AZ80A magnesium alloy. These materials were tried because they were fairly stable to reasonably high temperatures. These materials had also been evaluated as lubricants in earlier experiments on the 2014 aluminum alloy.

The organic materials studied are listed and briefly described in Table 24. Available forging- and pressing-test ratings for these materials are also given in the table.

Both forging and pressing tests made on most of these materials showed relatively poor ratings. The forging-test ratings for all but one of the materials were as poor or poorer than the poorest of the commercial lubricants.

Tetrafluoroethylene resin primers, which were not studied in the pressing test, however, showed extremely good die penetration when used under certain conditions in the forging test. This agreed with forging data obtained on 2014 aluminum alloy using these resins as lubricants. The data show that these tetrafluoroethylene resin primer coats may be applied to the billets before heating at 675 F to produce almost complete die filling. The material may also be applied to the cold dies before heating, provided the die reaches a temperature of at least 600 F. However, test data indicated that the resin could not be reapplied successfully to the hot dies.

At high temperatures these resins give off toxic fumes or decomposition products. Minute amounts of gaseous fluorine compounds are given off at temperatures around 400 F, and measurable quantities are given off at 600 F or above. At approximately 750 F the resin decomposes slowly. Therefore, if the resins are to be used at such temperatures, adequate ventilation must be provided.

Because the temperatures are lower, tetrafluoroethylene resins are more likely to be useful in forging magnesium than in forging aluminum, partly because the danger from toxic fumes is less at lower working temperatures. The plastic primer intended by the manufacturer for use on steel gave better results as a forging lubricant than the primer sold for coating aluminum.

TABLE 24. FORGING- AND PRESSING-TEST RATINGS OBTAINED FOR VARIOUS ORGANIC LUBRICANTS IN WORKING AZ80A MAGNESIUM ALLOY

Lubricant	Brief Description	Penetration Into Cavity in Forging Test[a], in.	Pressed Thickness After Pressing Test[b], in.
--	Commercial lubricants	0.80 to 1.62	0.055 to 0.107
23	Ester-type plasticizer (Monoplex S-71)	--	0.105
24	Ester-type plasticizer (Paraplex G62)	--	0.110
25	550 fluid (silicone)	--	0.098
26	Acrylic resin in toluene solvent (Acryloid B72)	--	0.090
27	Acrylic polymer, water emulsion (Phoplex AC33)	0.81	0.092
53	Silicone Grease 41 (diluted 1 part to 8 parts by volume of Oil A[c]	0.83	0.112
54	Polyamide Resin 90	0.89	0.080
56	Diester synthetic turbo oil	0.75	0.113
143	Nylon powder	0.72	--
144	Mono-n-butylammonium hexafluophosphate	0.70	--
149	Tetrafluorethylene resin (primer for steel)	1.51[d]	--
		1.87[e] (filled)	--
		1.87[f] (filled)	--
		1.83[f]	--
		1.84[g]	--
150	Tetrafluorethylene resin (primer for aluminum)	1.75[g]	--

Footnotes appear on the following page.

Footnotes to Table 24.

(a) Forging tests were made using a billet temperature of 675 F, a die temperature of 500 F unless otherwise indicated, and a punch pressure of 46,000 psi.
(b) Pressing tests consisted of pressing billets 1 inch in diameter by 1/2 inch in height between flat parallel dies heated to 500 F, using a load of 138,000 pounds. The billet temperature was maintained at 675 F.
(c) Oil A was a naphthene base oil having a viscosity of 106 SUS at 100 F.
(d) Applied to cold die before heating to 500 F for forging.
(e) Applied to cold die, heated to 700 F, then cooled to 500 F for forging.
(f) Applied to cold die before heating to 600 F for forging.
(g) Applied to billets before heating to 675 F for forging.

The tetrafluoroethylene resin coatings are difficult to remove from the forged surface. Because the material is inert to practically all chemicals, it cannot be removed by chemical means. The resin can be removed by heating to a temperature of about 950 F, but, because magnesium forgings are not ordinarily heated to this temperature, this method of removal is not feasible for magnesium. Therefore, any resin that adheres to the forging must be removed by mechanical means such as sandblasting or vapor blasting.

Study on Inorganic Materials in Various Carriers

Several lubricants containing various inorganic materials in different carriers were also studied in working AZ80A magnesium alloy. The lubricants are listed and briefly described in Table 25. The forging-test ratings for all lubricants and the pressing-test ratings for three of the lubricants are also given in the table. The range in ratings for commercial lubricants studied are also listed for comparison.

The forging-test data indicated that mica or boron nitride in a carrier of Oil B, medium flake graphite or boron nitride in a carrier of Paraplex G62, or extra-fine flake graphite in Paraplex G60 or G50 as carriers, gave die filling as good as the commercial lubricants diluted with oil or kerosene. The die filling obtained with mica in Oil B as a carrier was almost as good as the best of the commercial preparations diluted with oil.

In the study on commercial lubricants in working magnesium, it was found that Lubricant 6 produced by far the best die penetration in the forging test. This lubricant produced a die penetration of 1.62 inch. It is a dispersion of graphite and molybdenum disulfide in water. In using it, the heavy mixture was diluted 1 part to 20 parts of water. The percentage of solids in the original mixture was not known precisely. On the assumption that the original mixture contained 50 per cent solids, the diluted mixture prepared for use would contain 2.5 per cent solids. Thus, if equal weights of graphite and molybdenum disulfide were used in the original mixture, then the diluted mixture would contain 1.25 per cent of each solid constituent.

Two mixtures of graphite and powdered molybdenum disulfide in water were prepared in the laboratory to the above-mentioned dilution. One of the mixtures contained colloidal graphite and the other contained an extra-fine flake graphite which had a larger particle size. These preparations are identified as Lubricants 158 and 159, respectively, in Table 25.

TABLE 25. FORGING- AND PRESSING-TEST DATA OBTAINED IN WORKING AZ80A MAGNESIUM ALLOY USING VARIOUS INORGANIC MATERIALS IN DIFFERENT CARRIERS

Lubricant	Brief Description	Penetration Into Die Cavity in Forging Test[a], inch	Pressed Thickness After Pressing Test[b], inch
--	Commercial lubricants	0.80 to 1.62	0.055 to 0.107
47	10% mica in Oil B[c]	1.09	--
55	5% boron nitride in Oil B[c]	0.89	0.085
58	20% medium flake graphite in Paraplex G62	1.03	0.070
65	20% boron nitride in Paraplex G62	0.78	0.083
105	20% extra-fine flake graphite in Paraplex G50	0.92	--
106	20% extra-fine flake graphite in Paraplex G60	0.98	--
158	1.25% colloidal graphite + 1.25% powdered MoS_2 in distilled water	1.58	--
159	1.25% extra-fine graphite + 1.25% powdered MoS_2 in distilled water	0.92	--

(a) Forging tests were made using a billet temperature of 675 F, a die temperature of 500 F, and a punch pressure of 46,000 psi.

(b) Pressing test consisted of pressing billets 1 inch in diameter by 1/2 inch in height between flat parallel dies heated to 500 F, using a load of 138,000 pounds. Billet temperature was 675 F.

(c) Oil B is a 1-to-1 mixture of a naphthene-base oil having a flash point of 320 F and a viscosity of 106 SUS at 100 F and a 600 W cylinder oil having a flash point of 540 F and a viscosity of 1970 SUS at 100 F.

Lubricant 158, which contained colloidal graphite and powdered molybdenum disulfide, produced a die penetration of 1.58 inch in the forging test. This value was comparable to that of 1.62 inch obtained for commercial Lubricant 6. When the colloidal graphite was replaced with an extra-fine flake graphite (Lubricant 159), much poorer die filling resulted.

These limited data indicated that certain combinations of graphite and powdered molybdenum disulfide in a water carrier serve as exceptionally good die lubricants in forging magnesium. Colloidal graphite was found to be superior to flake graphite when used in the mixture. Additional information should be obtained to determine the effects of the size of the molybdenum disulfide and also the effects of varying the relative percentages of the two solid constituents. In addition, the maximum die temperature to which such water-carried lubricants can be applied should be determined.

Studies on Billet Pretreatments

Previous data obtained on aluminum showed that certain billet pretreatments, when used with conventional die lubricants, gave improved performance in laboratory forging tests. The best of these treatments consisted of etching the billets in sodium hydroxide, then dipping them in an aqueous suspension of colloidal graphite before heating and forging.

Because of these improvements in die filling, a study was made to determine whether or not similar types of treatments would be useful in forging magnesium. However, magnesium is quite resistant to attack by most sodium hydroxide solutions. Therefore, several other treatments were tried.

Table 26 lists a group of billet treatments used in forging tests on AZ80A magnesium alloy. The forging tests were made on billets given each treatment with and without a subsequent dip in a suspension of colloidal graphite. The billets were forged using Lubricant 1 on the dies. This lubricant is a commercial preparation consisting essentially of flake graphite in an oil medium. The forging-test data obtained using the various pretreatments are listed in Table 26 and shown graphically in Figure 51.

These data show that all of the billet treatments were beneficial when used with die Lubricant 1. Vapor blasting, etching in acetic acid, or etching in acetic acid followed by an HNO_3 brightening dip, produced the best results. Etching in HF followed by a dichromate treatment was not so effective as the other three treatments.

The most striking effect shown in Figure 51 is that die filling was markedly improved by coating the billets with colloidal graphite before heating them for forging. This was accomplished by dipping the previously

TABLE 26. FORGING-TEST DATA FOR AZ80A MAGNESIUM ALLOY USING VARIOUS BILLET TREATMENTS IN COMBINATION WITH LUBRICANT 1 ON THE DIES

Lubricant	Billet Treatment	Penetration Into Die Cavity[a], inch
1	None	1.11
1	182 (degreased, dipped in colloidal graphite)	1.77
1	180 (vapor blasted)	1.26
1	181 (vapor blasted, dipped in colloidal graphite)	1.86
1	209 (acetic acid etch)	1.30
1	212 (acetic acid etch, dipped in colloidal graphite)	1.86
1	210 (acetic acid etch + HNO_3 etch)	1.28
1	211 (acetic acid etch + HNO_3 etch, then dipped in colloidal graphite)	1.62
1	215 (HF etch + boil in sodium dichromate saturated with CaF_2)	1.19
1	216 (same as 215 above, but further dipped in colloidal graphite)	1.33

(a) Forging tests were made using a billet temperature of 675 F, a die temperature of 500 F, and a punch pressure of 46,000 psi.

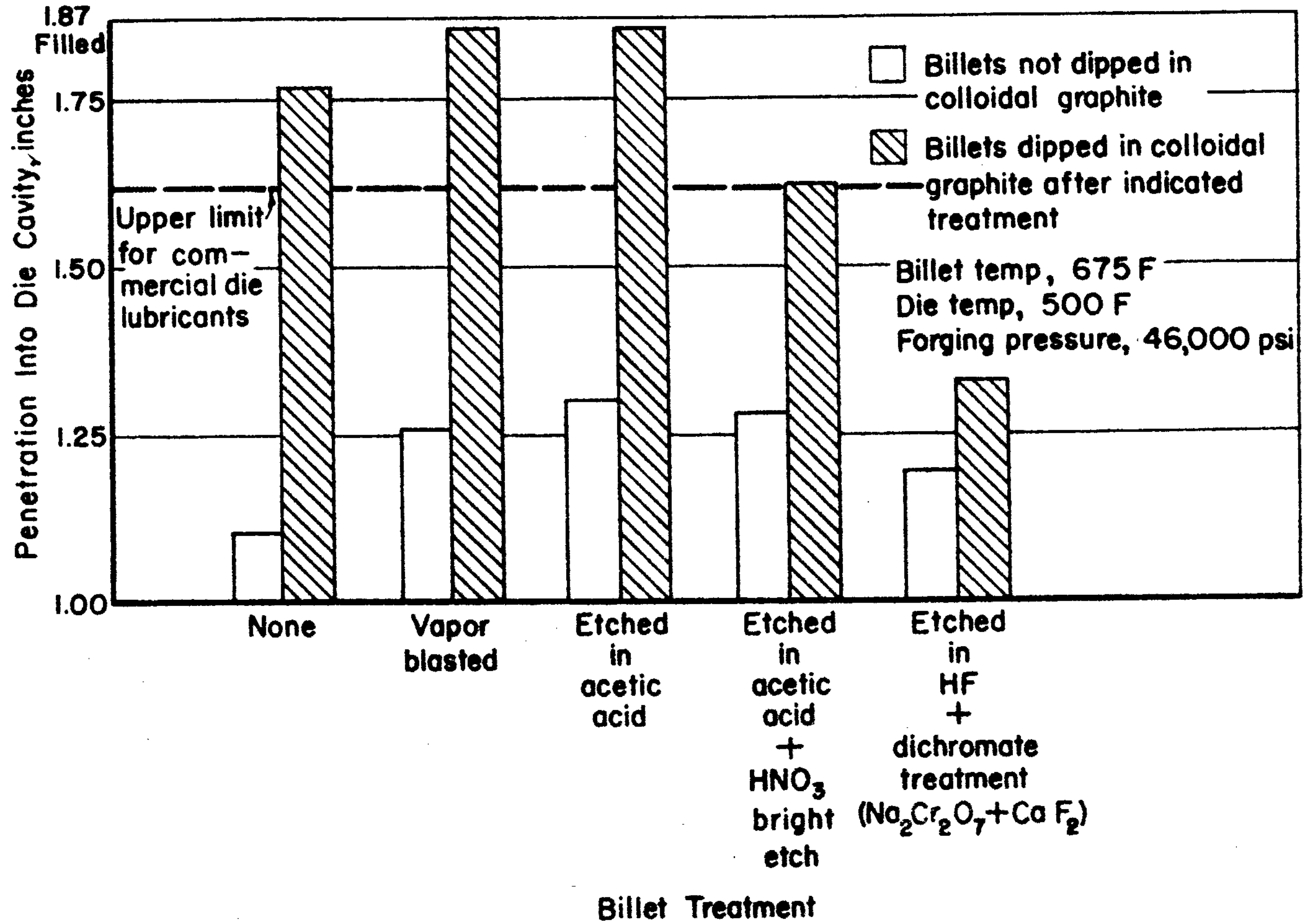


FIGURE 51. EFFECT OF BILLET SURFACE TREATMENT ON DEPTH OF PENETRATION INTO THE FORGING DIE FOR AZ80A MAGNESIUM ALLOY USING COMMERCIAL LUBRICANT I ON THE DIE

A-16847

treated billets into a warm aqueous dispersion of colloidal graphite. The extent to which the coating of colloidal graphite improved die filling depended upon the treatment given the billets prior to dipping in the graphite suspension. The best of these treatments consisted of etching in acetic acid or vapor blasting. These ratings were far superior to that obtained on untreated billets using the best of the commercial lubricants. Billets that were either vapor blasted or etched in acetic acid then dipped in colloidal graphite gave almost complete die filling when used with Lubricant 1 on the die.

Brightening treatments, by dipping in HNO_3, or in dichromate solution, after etching do not appear desirable if the billets are to be lubricated before heating. Probably brightening minimizes the surface roughness of the billet, thereby limiting the amount of colloidal graphite that the billet surface can hold. The data obtained in these tests indicate that a macroscopically rough surface is required to hold the colloidal graphite. The data do not show whether the surface coating produced on magnesium billets by etching in acetic acid is or is not beneficial. Because vapor-blasted billets were equally as good as those etched in acetic acid, it is believed that the coating or residue produced by etching was of no special benefit.

A series of tests was made to determine whether the improvements produced by etching billets then coating them with colloidal graphite would be effective when used with other lubricants. Tests were also made to determine whether a coating of molybdenum disulfide or boron nitride on the billets would be as effective as the coating of colloidal graphite. Table 27 lists the combinations of die lubricants and billet surface treatments used along with the corresponding forging-test rating. These data are shown graphically as bar charts in Figure 52.

The data show that etching the billets in acetic acid and then coating them with colloidal graphite improved die filling for all four die lubricants. There was considerably less difference in the performance of the various lubricants when such a billet treatment was used, than when untreated billets were used. The treated billets filled the die better than any untreated billet treated with the commercial lubricant. With pretreated billets, Lubricant 3 gave slightly poorer results than did the other three lubricants investigated.

Lubricant 6 gave the best results on untreated billets. When tested with this die lubricant, billets coated with boron nitride or molybdenum disulfide performed almost as well as billets coated with colloidal graphite. It is not known how effective the boron nitride coating would be with other die lubricants. However, billets coated with molybdenum disulfide did not fill the die as well as samples coated with colloidal graphite when forged with die Lubricants 1, 3, and 17.

TABLE 27. FORGING-TEST RATINGS FOR AZ80A MAGNESIUM ALLOY WHICH WAS WORKED USING VARIOUS COMBINATIONS OF DIE LUBRICANTS AND BILLET TREATMENTS

Lubricant	Billet Treatment: Treatment Number	Billet Treatment: Description	Penetration Into Die Cavity[a], in.
1 (flake graphite in oil)	--	None	1.11
	212	Acetic acid etch + dip in colloidal graphite	1.86
	213	Acetic acid etch, then surface rubbed with MoS_2 powder	1.33
3 (colloidal graphite in oil)	--	None	0.92
	212	Acetic acid etch + dip in colloidal graphite	1.72
	213	Acetic acid etch, then surface rubbed with MoS_2 powder	1.06
6 (graphite and MoS_2 in water)	--	None	1.62
	212	Acetic acid etch + dip in colloidal graphite	1.85
	213	Acetic acid etch, then surface rubbed with MoS_2 powder	1.86
	214	Acetic acid etch, then surface rubbed with BN powder	1.80
17 (MoS_2 in oil)	212	Acetic acid etch + dip in colloidal graphite	1.87
	213	Acetic acid etch, then surface rubbed with MoS_2 powder	1.13

(a) Forging tests were made using a billet temperature of 675 F, a die temperature of 500 F, and a punch pressure of 46,000 psi.

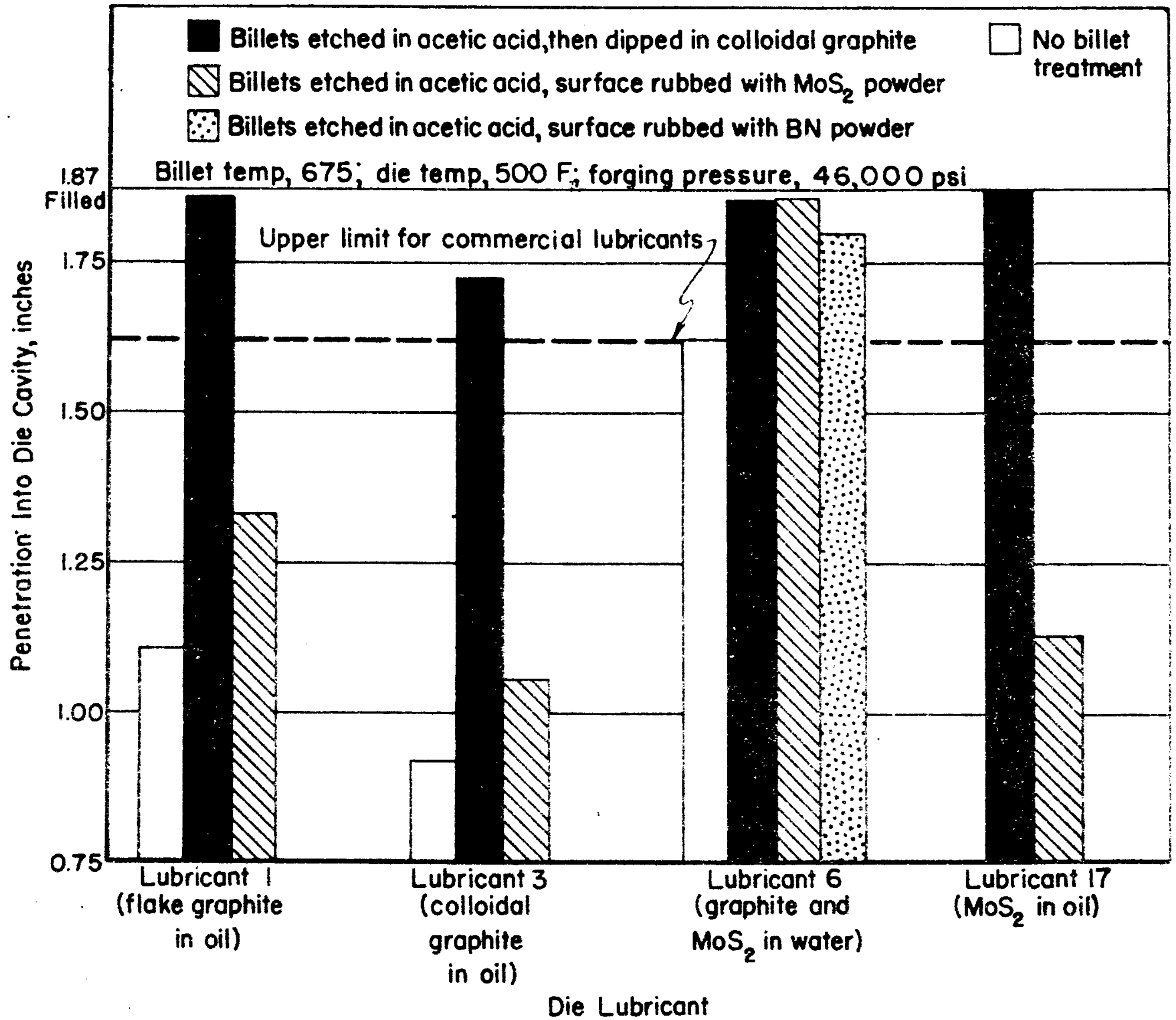


FIGURE 52. EFFECT OF VARIOUS SURFACE TREATMENTS WHEN USED WITH FOUR DIFFERENT DIE LUBRICANTS IN FORGING AZ80A MAGNESIUM ALLOY

A-16848

Extrusion Experiments on Magnesium

Magnesium is generally extruded without the use of lubricants. For most operations, flat dies having no entrance angle are used. Pressures for extruding magnesium commercially vary from 50, 000 to 100, 000 psi. Some types of extrusions require pressures up to 135, 000 psi to start the metal through the die.

It is believed that if friction between the billet and container and also between the billet and die could be lowered, the extrusion pressures could be materially reduced. By lowering the extrusion pressures, the production capacity of the extrusion presses would be increased; thus, larger or more complex shapes could be extruded with the same press.

Therefore, the extrusion tests on magnesium were designed to determine the effectiveness of various lubricants in reducing extrusion pressures. The number of lubricants tried in extruding magnesium was limited, because previous forging and pressing tests made on both aluminum and magnesium showed many materials to be unsatisfactory as lubricants.

The extrusion experiments were made on AZ80A magnesium alloy using a reduction in area of 10. 3 to 1. One-inch-diameter bar stock, 1-15/16 inches long, was extruded to a 5/16 inch rod using the experimental tooling arrangement described in Appendix C.

Two die shapes were used in the extruding experiments: one was a flat die having an included angle of 180 degrees, the other was a conical die having an included angle of 130 degrees.

The magnesium billets were heated in an electric muffle furnace for at least 20 minutes at 675 F before extruding. The die and container were heated to 600 F.

As with the experiments on aluminum, an instrument which automatically plotted the hydraulic line pressure against ram travel was used to record the loads during the extrusion cycle.

Data obtained in the extrusion experiments on AZ80A magnesium alloy using various lubricants and two different die shapes are summarized in Table 28. The original data obtained in the experiments are given in Table H-4 of Appendix H. Extrusion pressures for front, middle, and back positions were calculated from the line pressure versus ram-travel charts obtained for each extrusion. Most of the extrusion pressures listed in Table 28 are averages of the values obtained for each group with a clean container and a clean die.

The initial extrusion experiments made on AZ80A magnesium alloy were made using an exit extrusion speed of 22.3 feet per minute. This was the rate used in the extrusion experiments made on 2014 aluminum alloy. However, at this rate, all extrusions made in a flat die (180-degree entrance angle) were completely segmented. This type of cracking, sometimes called a "pine cone" or "rattlesnake" defect, is illustrated in Figure 53. No segmentation occurred if the conical die, having an entrance angle of 130 degrees, was used. Representative extrusions made at this speed using the two types of dies are shown in Figure 53. Because of the tendency for segmentation, the exit rate of extrusion was reduced to 8.5 feet per minute. At this speed, segmentation was almost eliminated when the flat die was used.

Data presented in Table 28 indicate that, even though an exit extrusion rate of 8.5 feet per minute was used, almost all of the extrusions made in the flat die showed some segmentation present at the extreme back end of the extrusion. However, no segmentation was shown when the conical die, which had an entrance angle of 130 degrees, was used. These data show that a conical die may be useful in eliminating or at least minimizing segmentation, which is one of the chief problems in extruding magnesium. The data suggest that higher extrusion rates may be used with conical dies. However, only one conical angle was used in this study, and it is not known what die angle would give optimum results in preventing segmentation. Apparently, the use of the conical die produced less heat than the flat die in working magnesium. Segmentation is generally believed to be caused by hot shortness which results from working the metal at too high a temperature.

The pressure necessary to extrude through each type of die using no lubricant was used as a basis for comparing the effectiveness of the various lubricants studied. With no lubricant, and using the flat die (180-degree entrance angle), a pressure of 66,100 psi was required to start extruding; this decreased to 42,700 psi at the back end of the extrusion. The pressures required for extruding through the conical die (130-degree included entrance angle) under the same conditions were roughly 10 per cent higher than those for the flat die.

With few exceptions, lubricants lowered the pressures required for extruding magnesium. This was true for both types of extruding dies used. The lubricants studied were not rated in precisely the same order by the two dies. Data plotted in Figure 54 indicate that, generally, the flat die required higher pressures to start extruding, while the conical die required higher pressures at the end of the extruding operation. With poor lubricants, the flat die required less pressure than the conical die. However, for the better lubricants which required relatively low pressures for extruding, the conical die required less pressure than the flat die.

TABLE 28. DATA OBTAINED IN LABORATORY EXTRUSION EXPERIMENTS ON AZ80A

Lubricant and Brief Description	Extrustion Sample		Flat Die (180-Degree			
			Extrusion Pressure, 1000 psi			Surface Rating[a]
	Flat	Conical	Front	Middle	Back	
None	1M-3M	4M-6M	66.1	49.0	42.7	G, G, G
None + Billet Treatment 212[c]	67M-69M	71M-73M	84.2	58.7	47.1	G, G, G
1 (flake graphite in oil)	13M-16M	16M-18M	54.4	43.6	35.5	G, G, G
1 + Billet Treatment 212[c]	31M-33M	34M-36M	55.1	40.9	35.9	P, F, F
3 (colloidal graphite in oil)	19M-21M	22M-24M	48.1	39.2	37.7	VG, G, G
5 (graphite + MoS_2 in oil)	55M-57M	58M-60M	56.9	43.5	39.0	F, F, F
5 + Billet Treatment 212[c]	37M-39M	40M-42M	56.1	41.7	39.0	G, G, G
6 (graphite + MoS_2 in water)	25M-27M, 81M-83M	28M-30M, 84M-86M	69.9	50.4	42.8	F, F, F, G, G, G
6 + Billet Treatment 212[c]	61M-63M	64M-66M	70.3	43.5	34.5	F, P, F
123 (extra-fine flake graphite in sodium Paraplex G60 grease)	43M-45M	46M-48M	50.9	39.6	32.8	G, G, G
124 (Boron nitride in sodium Paraplex G60 grease)	49M-51M	52M-54M	51.3	38.5	33.5	G, G, G
149 (tetrafluorethylene resin, primer for steel, applied to billets)	7M-9M	10M-12M	48.1	35.5	28.6	F, F, F
None	70M[e]	74M[e]	81.1	49.0	39.5	VP

(a) Surfaces were rated according to the following classifications:

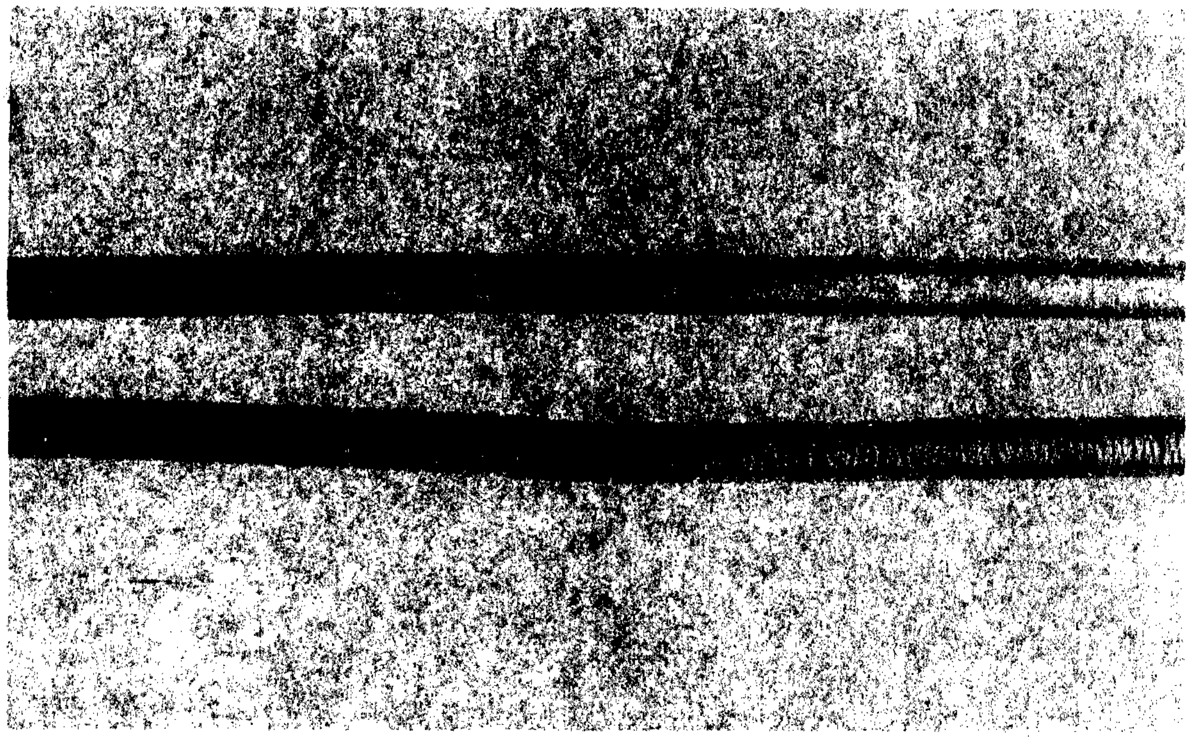
VG - very good, no scoring
G - good, negligible scoring
F - fair, light scoring
P - poor, heavy scoring
VP - very poor, rough, heavy scoring

(b) Segmentation took place at the back end of the extrusion. Values listed show length of segmentation.
(c) Billets etched in glacial acetic acid, then dipped in an aqueous suspension of colloidal graphite.
(d) Piping at back end of extrusion in skull.
(e) Extruded at an exit rate of 22.3 feet per minute.

Testing conditions: 1-inch-diameter billets were extruded to 5/16-inch-diameter rods using a billet temperature of 625 F and die and container temperatures of 600 F. An exit extrusion rate of 8.5 feet per minute was used unless otherwise indicated.

MAGNESIUM ALLOY USING VARIOUS LUBRICANTS AND TWO DIFFERENT DIE SHAPES

Included Angle)	Conical Die (130-Degree Included Angle)				
	Extrusion Pressure, 1000 psi			Surface	
Segmentation[b]	Front	Middle	Back	Rating[a]	Segmentation[b]
--[d]	74.3	56.9	45.9	G, G, G	--
--	73.3	51.2	41.7	VG, G, VG	--[d]
1-1/2 in. on Samples 14M and 15M[d]	43.5	42.2	39.2	F, F, G	--
1/2 to 1-1/2 in.[d]	41.7	39.2	34.5	G, G, G	--
1/2 to 1 in. on Samples 19M and 21M[d]	44.6	39.0	37.7	G, F, F	--
1/2 to 1 in.[d]	47.6	45.5	42.7	G, G, G	--
1 in. on Samples 37M and 39M[d]	44.0	45.2	41.7	G, G, G	--
1/2 to 1 in.[d]	72.5	58.4	48.1	F, G, G, G, G, G	--
1 in.[d]	66.8	58.8	47.2	F, G, G	--
1-1/2 in. on Sample 45M[d]	48.6	43.5	38.8	G, G, G	--
1/2 in. on Sample 51M[d]	42.6	40.8	35.3	G, G, G	--
1/2 to 1 in.[d]	38.5	32.3	25.3	F, F, F	--
Entire rod	88.9	59.8	46.3	VG	--



1X N25936

Top extrusion – Made using a conical die having an entrance angle of 130 degrees

Bottom extrusion – Made using a flat die having an entrance angle of 180 degrees

FIGURE 53. AZ80A MAGNESIUM ALLOY EXTRUSIONS MADE AT AN EXIT EXTRUSION RATE OF 22. 3 FEET PER MINUTE USING NO LUBRICANT

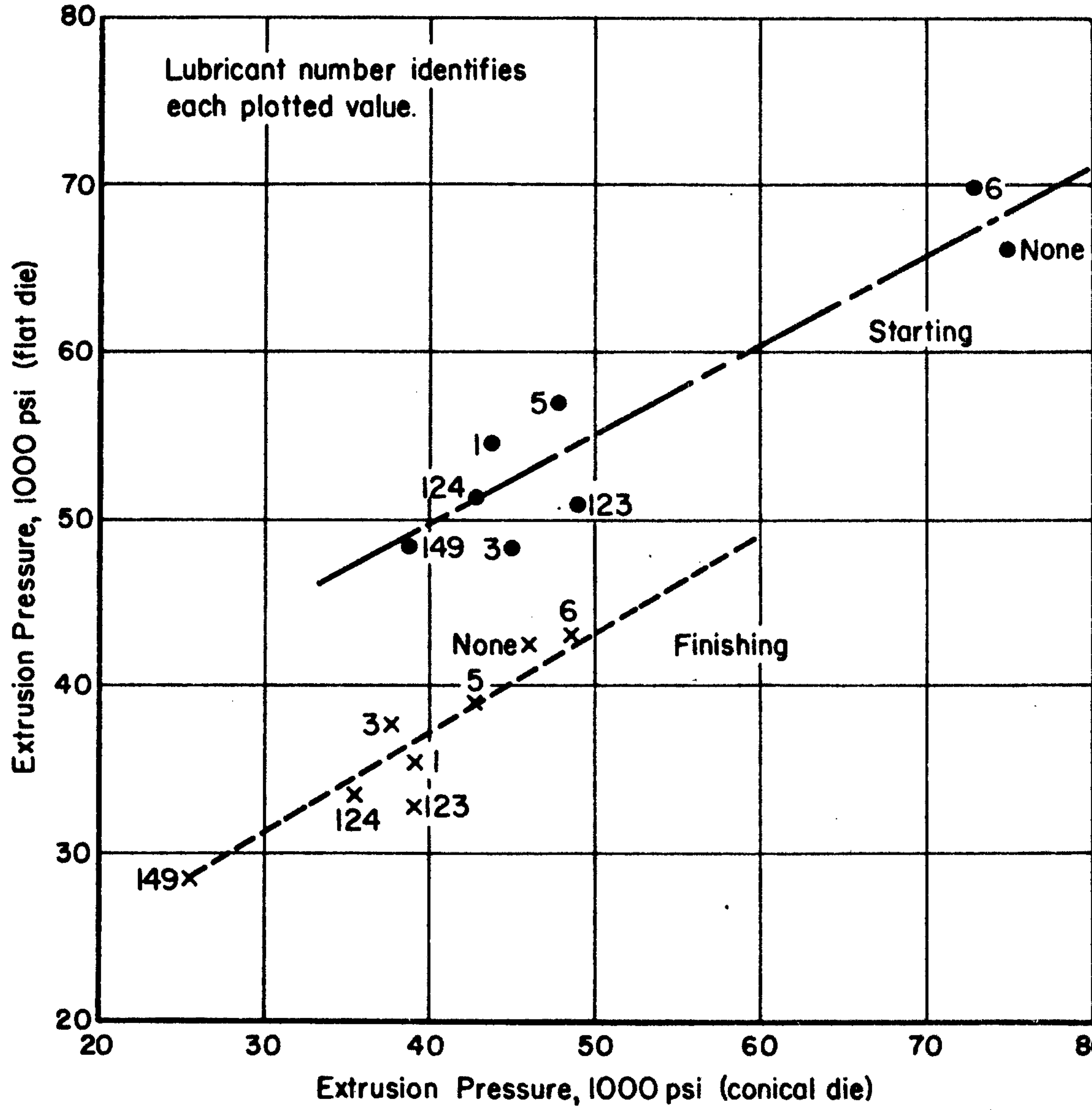


FIGURE 54. CORRELATION BETWEEN EXTRUSION PRESSURES OBTAINED USING FLAT AND CONICAL DIES IN EXTRUDING AZ80A MAGNESIUM ALLOY USING VARIOUS LUBRICANTS A-16854

The degree to which the starting extrusion pressure was lowered by the use of a lubricant was not always reflected in a similar reduction of pressure at the back end of the extrusion. Considering both factors, Lubricant 149 (tetrafluoroethylene resin primer for steel) when applied to the billets before extruding appeared the most promising material in reducing friction during extrusion.

When this material (Lubricant 149) was used as a lubricant, by painting it on the billets before heating, the pressure required for extruding through a flat die was lowered about 30 per cent from that required with no lubricant. When the conical die (130-degree included angle) was used, the pressures were lowered 45 to 50 per cent by lubrication. Although higher pressures were required to extrude unlubricated billets through the conical die than through the flat die, the pressures for the conical die were lowered from 12 to 20 per cent below those for the flat die when tetrafluoroethylene resin was used. In spite of the unusually low pressures required for extruding with the tetrafluoroethylene resin lubricant, light scoring occurred on the extrusions. The data obtained using this material as a lubricant were meager, and it is not known whether the scoring can be attributed to some characteristic of the lubricant. Additional work should be performed to determine the possibilities and the limitations of the use of the tetrafluoroethylene resins as lubricants for extruding magnesium.

Two other materials containing either extra-fine flake graphite or boron nitride in a sodium Paraplex G60 grease (Lubricants 123 and 124, respectively) showed promise as lubricants for magnesium extrusions. These materials, however, were not as effective in lowering extrusion pressures as the tetrafluoroethylene resin and were similar to the behavior of Lubricant 3, a commercial product containing colloidal graphite in oil.

Lubricant 6, a commercial product containing graphite and molybdenum disulfide in water, gave pressures similar to those for no lubricant. This was surprising, considering the exceptionally good results obtained in the laboratory forging test using this lubricant. It is difficult to make this water-carried lubricant stick to the vertical sides of the container, particularly when the spray strikes the container surface at a very oblique angle.

A billet-surface treatment, consisting of etching in glacial acetic acid then coating with colloidal graphite, did not significantly lower extrusion pressures. This was true in experiments made with and without a lubricant. Any improvements noted were small and they did not reflect the benefits associated with the coating in the laboratory forging tests.

Representative samples of extrusions were examined macroscopically to determine whether any significant differences existed in metal flow between lubricated and unlubricated extrusions and also between those made using flat and conical dies. Such a study was made on samples representing those produced with no lubricant, and with Lubricant 149 (tetrafluoroethylene resin). Representative macrostructures are shown in Figures 55 and 56. The macrographs in Figure 55 for magnesium extruded without a lubricant showed very little effect of die shape. The back portion of the extrusion made in the flat die (180-degree included angle) appeared to be less uniform than the same location in the extrusion made in the conical die (130-degree included angle). Except for the segmentation shown in Figure 56 for the back portion of the extrusion made using the flat die (180-degree included angle) and Lubricant 149, no significant difference in macrostructure seemed to be produced by the two die shapes.

STUDIES ON TITANIUM

Pressing and Forging Tests

Because of their high strength-to-weight ratios, titanium and its alloys are finding many new uses, particularly in high-performance aircraft. Since the working of titanium is relatively new, manufacturing procedures are still in the experimental stage. In forging titanium, much of the present commercial work is more or less exploratory. Information is needed on die design, precautions for heating and surface preparation, and on the proper forging lubricants for titanium alloys.

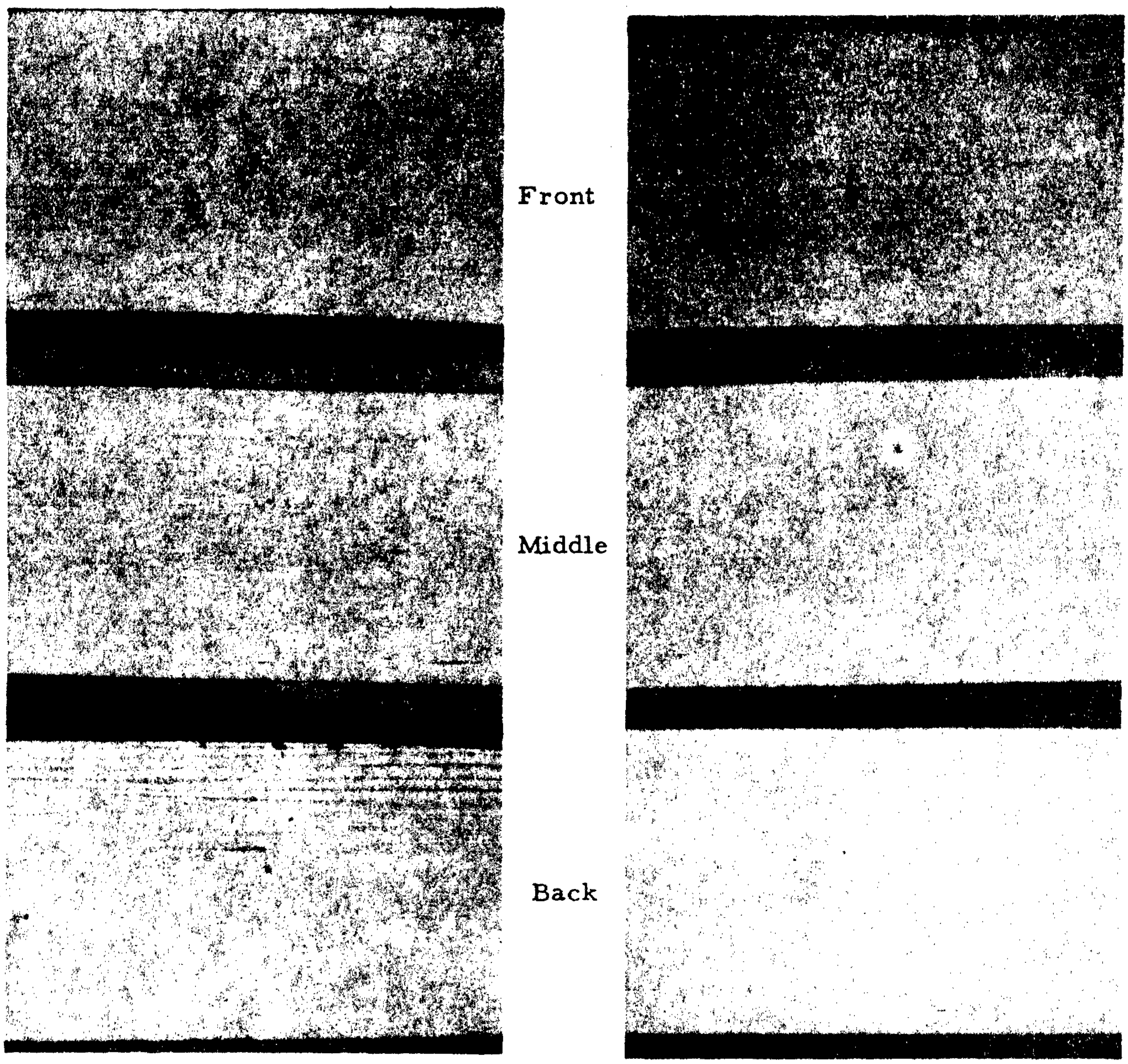
Because of its higher strength, titanium is usually press forged at higher die temperatures than those used for aluminum. Therefore, many of the forge shops are using conventional lubricating materials, such as graphite, in a more viscous carrier than what is used for forging aluminum. Since titanium is normally forged at temperatures near 1700 F, the working of this metal is similar to that for steel. However, heating of titanium for forging presents problems that are not ordinarily encountered in heating steel. Titanium can absorb oxygen, nitrogen, and carbon when heated in atmospheres which would be suitable for heating steel. Consequently, the greater reactivity of titanium presents special problems.

Unalloyed titanium was selected as working stock for the experimental work in the study of lubricants for working titanium. Forging and pressing test specimens were prepared from 1-inch-diameter extruded bar stock. The samples were machined to 0.950 inch in diameter, then machined to the proper length. The samples were machined to this diameter to eliminate surface imperfections present in the as-extruded bar stock.

The billets were heated to 1750 F in a stainless steel muffle which was placed in an electric muffle furnace for heating. Argon was fed into the rear of the muffle to keep it purged of air. A door was provided at

Included Die Angle, 180 degrees

Included Die Angle, 130 degrees



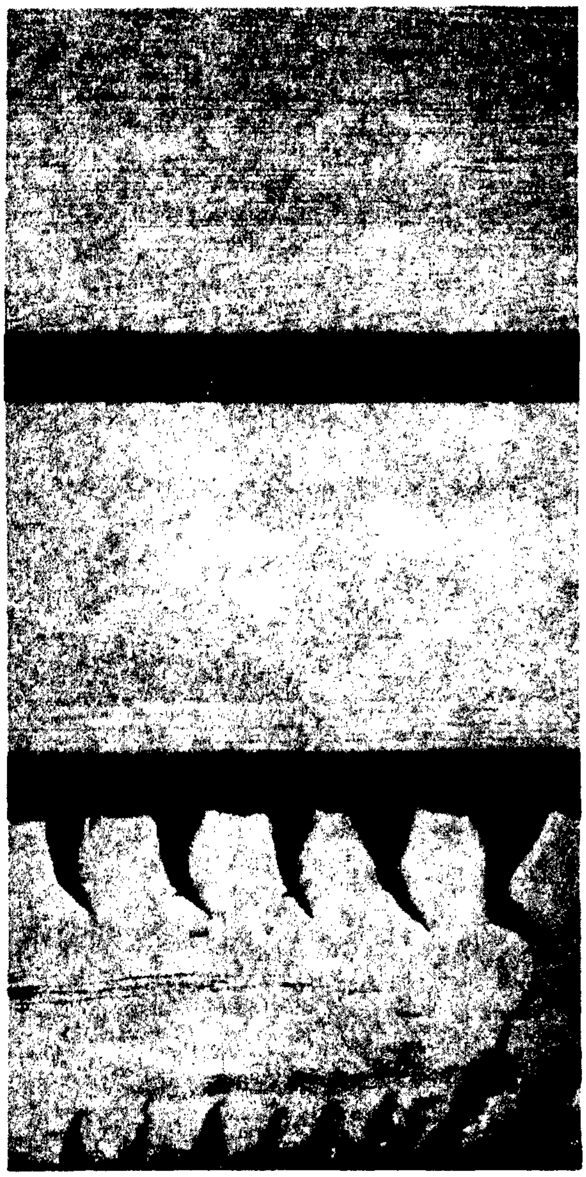
6X N26087

6X N26088

Etched in solution of 5 per cent HNO_3 and 1 per cent acetic acid in ethyl alcohol, followed by an etch in a solution of 25 per cent acetic acid in nital

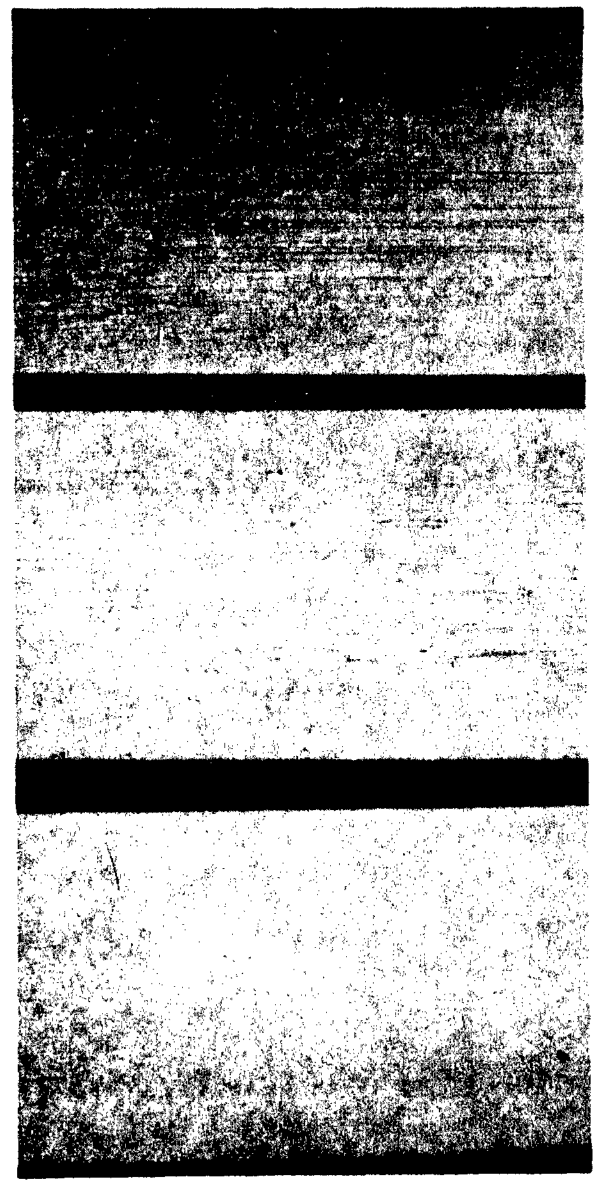
FIGURE 55. REPRESENTATIVE MACROSTRUCTURES OF AZ80A MAGNESIUM ALLOY EXTRUSIONS MADE USING NO LUBRICANT (LONGITUDINAL SECTION)

Included Die Angle, 180 degrees



6X N26089

Included Die Angle, 130 degrees



6X N26090

Front

Middle

Back

Etched in solution of 5 per cent HNO_3 and 1 per cent acetic acid in ethyl alcohol, followed by an etch in a solution of 25 per cent acetic acid in nital

FIGURE 56. REPRESENTATIVE MACROSTRUCTURES OF AZ80A MAGNESIUM ALLOY EXTRUSIONS MADE USING LUBRICANT 149; TETRAFLUORETHYLENE RESIN (LONGITUDINAL SECTION)

the front of the muffle for inserting and removing the billets from the muffle. Because of the relatively small size of the test billets, they cooled fairly rapidly when removed from the furnace. Therefore, forging- and pressing-test procedures were standardized, so that testing conditions would be uniform. A die temperature of 900 F was used for testing. Although the temperature differential between the die and billet was large, it is comparable to that used commercially.

Lubricants used in tests on titanium are listed in Table E-1 of Appendix E. This table lists all materials and billet treatments used in the entire investigation. Not all materials listed were used in tests on titanium.

Complete lists of all data obtained in the forging and pressing tests on unalloyed titanium are given in Tables J-1 and J-2, respectively, of Appendix J. Many of the materials screened in the pressing test were not further evaluated in the forging test because they performed poorly in the pressing test. As usual, the thickness of the disks produced in the standard pressing test was used as the parameter for screening the various lubricants.

Commercial and Experimental Lubricants

Forging- and pressing-test data obtained in the laboratory using a number of commercial and experimental lubricants in working unalloyed titanium are given in Table 29. A brief description of each lubricant is also included in the table. Titanium did not forge as easily as aluminum or magnesium in these laboratory tests. Much poorer die filling in the forging test and thicker pressings in the pressing test were characteristic of titanium.

Five commercial lubricants were used in the pressing and forging tests. These are listed as Lubricants 1, 5, 8, 107, and 177 in Table 29. The first three of these lubricants were tried in both undiluted and diluted conditions. The pressing test indicated that Lubricants 1 and 8, both containing flake graphite in an oil base, gave better performance when used in the undiluted condition. With Lubricant 5, however, dilution had no significant effect in the pressing test. This lubricant consisted of graphite and molybdenum disulfide in oil. The pressings made with this lubricant were better than those obtained with the other two lubricants in the undiluted condition. In fact, the pressing test ratings for Lubricant 5 were the best of all materials tried in working titanium.

A very poor correlation existed between the ratings obtained in the pressing test and those obtained in the forging test. In spite of this, Lubricant 5, containing graphite and molybdenum disulfide in oil, gave next to the best die filling of the commercial lubricants. Lubricant 177, a commercial product containing flake graphite and powdered aluminum in an

TABLE 29. FORGING- AND PRESSING-TEST DATA OBTAINED WITH COMMERCIAL AND EXPERIMENTAL LUBRICANTS IN WORKING UNALLOYED TITANIUM

Lubricant	Lubricant Description	Penetration Into Die Cavity in Forge Test[a], in.		Pressed Thickness After Pressing Test[b], in.
		Range	Average	
1	Diluted commercial product containing flake graphite in oil	0.58/0.97	0.69	0.152
1A	Same as above but undiluted	0.33/0.38	0.36	0.122
5	Diluted commercial product containing graphite and MoS_2 in oil	0.77/0.93	0.85	0.110
5A	Same as above but undiluted	0.64/0.85	0.75	0.112
8	Diluted commercial product containing flake graphite in oil	0.42/0.42	0.42	0.146
8A	Same as above but undiluted	0.63/0.66	0.64	0.118
107	Undiluted commercial product containing flake graphite in a heavy-consistency carrier containing aluminum soap	--	--	0.125
177	Diluted commercial product containing flake graphite and powdered aluminum in an oil carrier	0.59/1.10	0.88	--
49A[c]	Undiluted experimental product containing 35% flake graphite and 5% mica in a calcium-base grease	0.46/0.49	0.47	0.114
50A[c]	Undiluted experimental product containing 25% MoS_2 and 5% mica in a calcium-base grease	0.84/0.99	0.93	0.140
51A[c]	Undiluted experimental product containing 25% flake graphite, 15% MoS_2, 5% mica in a calcium-base grease	0.47/0.68	0.58	0.119
52A[c]	Undiluted experimental product containing 25% flake graphite, 15% MoS_2, 5% mica in a Bentone grease	0.50/0.55	0.53	0.117
65	Boron nitride in Paraplex G62	0.52/0.52	0.52	0.134

TABLE 29. (Continued)

Lubricant	Lubricant Description	Penetration Into Die Cavity in Forge Test[a], in.		Pressed Thickness After Pressing Test[b], in.
		Range	Average	
123	Extra-fine flake graphite in sodium Paraplex G60 grease	0.52/0.78	0.66	0.116
124	Boron nitride in sodium Paraplex G60 grease	0.38/0.42	0.41	0.114

(a) Forge tests were made using a billet temperature of 1750 F, a die temperature of 900 F, and a forging pressure of 46, 000 psi.

(b) Billets, 0.950 inch in diameter by 1/2 inch high, were pressed between flat, parallel dies using a billet temperature of 1750 F, a die temperature of 900 F, and a pressing load of 138, 000 pounds.

(c) These lubricants were compounded by a lubricant manufacturer and had been used in a previous study on the extrusion of titanium.

oil-type carrier gave a filling of 0.88 inch, the best of the commercial products studied. This product was found adequate for producing titanium extrusions on a commercial scale, according to previous work described by Sabroff and Frost(23).

Contrary to data obtained in the pressing test, diluted commercial lubricants appeared to produce better die penetration in the forging test than the same material in the undiluted condition. This was true for two of three lubricants studied in such a manner. This was attributed to the difficulty of coating the die cavity when swabbing a more viscous liquid.

Four lubricants containing combinations of graphite and/or molybdenum disulfide in calcium-base or bentone greases were studied by both test methods. These special materials were prepared by a manufacturer for use on a WADC project on the extrusion of titanium. These lubricants are listed in Table 29 as Lubricants 49A through 52A. Because the materials had a heavy consistency, they were brushed on the dies.

In the pressing test, Lubricant 50A, which contained molybdenum disulfide in a calcium-base grease gave the poorest results. The other three lubricants gave relatively good and fairly uniform thickness values in the pressing test. However, in the forging test, Lubricant 50A produced the best die filling of the four lubricants. The other three lubricants gave relatively poor but fairly uniform values for penetration into the forging die cavity. It is interesting to note that Lubricants 50A and 5, which showed relatively good die penetration, both contained molybdenum disulfide. Lubricant 50A contained molybdenum disulfide, while Lubricant 5 contained a combination of graphite and molybdenum disulfide.

Boron nitride added to Paraplex G62 (an ester-type plasticizer) did not appear promising as a lubricant. Extra-fine flake graphite, or boron nitride, added to a sodium Paraplex G60 grease prepared in the laboratory, gave fairly good pressing-test ratings. However, these two materials gave quite different results in forging. Boron nitride in the grease gave poor die penetration, while extra-fine flake graphite in the same grease base gave considerably better die filling, but not so good as Lubricants 50A, 177, or 5.

Effects of Heating Atmosphere

An inspection of the forgings listed in Table 29 disclosed an interesting and perhaps a very important clue which may have influenced the forging-test ratings and may be responsible for some of the discrepancies noted between the forging- and pressing-test ratings. Samples which showed good die penetration showed signs of being oxidized to a greater extent than those that showed poorer die filling.

Table 30 lists forging-test data obtained on titanium samples after heating in various manners before forging. This study was made to determine the effects of billet surface oxidation on die filling. Lubricant 1, a commercial product containing flake graphite in oil was used as the die lubricant in each case.

Samples 35T-38T were the first specimens made using Lubricant 1. Three samples were forged on one day, and the fourth sample was forged the next morning. The first three samples were charged into the stainless steel muffle at one time and, after heating for 1/2 hour, the samples were removed one at a time over a period of 3 hours. Each time a sample was removed, the muffle door was opened, thus allowing air to enter the muffle chamber. Therefore, the last sample forged would be exposed to a greater amount of air and would stand a greater chance of becoming oxidized. The data for the first three samples of this series showed increasing die penetration. The fourth sample was forged the following morning without cleaning the die. A freshly prepared sample was used; therefore, the heating conditions should have been the same as the first sample of the series. The die penetration for the fourth sample was similar to that for the first. Another series of six samples, 45T through 50T, which were heated in the stainless steel muffle also showed improved die filling on the fifth and sixth samples of the series. The samples which showed good die filling were also oxidized to a greater extent than those showing poorer die filling. These data suggested that billet oxidation influenced the forging-test rating.

Therefore, to determine whether or not oxidized billets produced improved die penetration, a series of three samples were heated in air instead of an argon atmosphere. These are identified as Samples 57T through 59T in Table 30. With the exception of the heating atmosphere, the tests were conducted in the same manner as those for Samples 35T-38T and 45T-50T. The forge test data for these samples showed much better die filling than the samples heated in an argon atmosphere.

Four other series of samples were tested to determine the effects of heating time in air, and the time lapse between billet removal from the furnace and the beginning of forging, on die filling. Two samples represented each series. Two series of samples were heated for 1/2 hour, and two additional series were heated for 3/4 hour. One series representing each heating time was given the normal time lapse of 7 seconds between removal from the furnace and forging. The other series representing each heating time was given a longer time lapse of 13 seconds. Data obtained for these tests are also given in Table 30. The data indicated that increasing the billet heating time in air from 1/2 to 3/4 hour resulted in improved die filling. The data also indicated, but not strongly, that increased transfer time from 7 to 13 seconds improved die filling, in spite of the lower billet temperatures that must have accompanied the longer transfer time. Apparently, improvement in die filling as a result of oxidation more than compensated for the loss of billet temperature. These data indicate that it was easier to produce flow in titanium billets with oxidized surfaces than

TABLE 30. LABORATORY FORGING-TEST RESULTS ON UNALLOYED TITANIUM HEATED AND COOLED IN VARIOUS MANNERS BEFORE FORGING

Forging Sample	Heating Atmosphere	Time in Furnace, hr	Time Out of Furnace Before Forging[a], sec	Penetration Into Die Cavity for Individual Samples, in.						Average Penetration Into Die Cavity, in.
				1	2	3	4	5	6	
35T-38T	Argon	1/2 to 3[b]	7 each	0.58	0.71	0.97	0.50[c]	--	--	0.69
45T-50T	Argon	1/2 to 5[d]	7 each	0.83	0.61	0.72	0.70	0.99	0.94	0.80
57T-59T	Air[e]	1/2 to 3[b]	7 each	1.06	0.96	1.10	--	--	--	1.03
66T-67T	Air[e]	1/2[f]	7 each	0.84	0.80	--	--	--	--	0.82
68T-69T	Air[e]	1/2[f]	13 each	1.08	0.80	--	--	--	--	0.94
70T-71T	Air[e]	3/4[f]	7 each	0.94	1.16	--	--	--	--	1.05
72T-73T	Air[e]	3/4[f]	13 each	1.11	1.08	--	--	--	--	1.10

Lubricant 1, a commercial preparation containing flake graphite in oil, was used as the die lubricant in each case. A clean die was used to start each series of samples. The forging tests were made using a billet temperature of 1750 F, a die temperature of 900 F, and a forging pressure of 46,000 psi.

(a) The normal time lapse between removal from furnace and beginning of forging was 7 seconds.
(b) Same as in Footnote (d), but only three samples were forged and 3 hours had elapsed by the time the third billet was forged.
(c) The first three samples were made consecutively one day. The fourth sample was made the following day.
(d) The billets were all charged into the furnace at the same time. Billets remained in the furnace 1/2 hour before forging. By the time the sixth billet was forged, 4-1/2 hours had elapsed.
(e) This is identified as Billet Treatment 218.
(f) Billets were charged into a hot furnace and remained for the indicated time before removal.

in machined billets in which oxidation was prevented by an inert atmosphere. The mechanism by which scale improves metal flow is not known. Titanium oxides or nitrides in the scale may act to reduce friction, or the scale may act as a vehicle for carrying the lubricant.

Effects of Billet Surface Treatments

The effect of coating unalloyed titanium billets with colloidal graphite before heating and forging was studied on two groups of samples. One group of samples was vapor blasted before applying the coating of colloidal graphite. The other group was coated in the as-machined condition after degreasing in acetone. The billets were heated in an argon atmosphere in the same manner as the previous billets were heated. Lubricant 1, a commercial preparation containing flake graphite in oil was used on the die.

Data obtained in the tests are given in Table 31. The individual test data showed that the third sample in each series gave improved die filling, similar to the behavior noted previously. The average values indicate that the colloidal graphite coatings on the billets were not beneficial when compared with the data for untreated billets used with Lubricant 1 (shown in Table 29).

A group of six unalloyed titanium billets was heated in a salt bath instead of the conventional argon atmosphere. They were tested to determine whether or not the salt adhering to the billet would have any lubricating properties. The salt bath was a commercial product that melted at 1550 F and consisted mainly of barium chloride and fluorides. The billets were heated to 1750 F for periods ranging from 4 to 15 minutes. The billets, with the molten salt adhering to them, were forged using Lubricant 1. Forging-test data obtained on these six samples are given in Table 32.

With the exception of two samples, these forgings showed unusually good die penetration. The first sample, 60T, almost filled the die, except for the corners. This forging is shown in Figure 57. Three other samples of the group also gave excellent die filling, but not as good as Sample 60T. Two forgings, Samples 61T and 65T, showed much poorer die filling than the others. However, these samples held more salt on their surfaces, indicating that they were colder than the others.

Although unusually good die filling was produced by the heating of the billets in a salt bath, then forging with Lubricant 1 on the die, the forgings had poor surfaces. Some of the defects appeared to be caused by salt solidifying in the corners of the die cavity, which produced underfilling in those locations. Solidification of the salt occurred because the temperature of the die was considerably below the melting point of the salt. Furthermore, the billets were attacked by the molten salt. This may have contributed to the poor surfaces noted for the samples. Since additional work

TABLE 31. FORGING-TEST RATINGS FOR UNALLOYED TITANIUM BILLETS COATED WITH COLLOIDAL GRAPHITE BEFORE FORGING

Lubricant[a]	Billet Treatment		Penetration Into Die Casting, in.			
			Individual Forgings			
	Treatment Number	Description	1	2	3	Average
1	181	Vapor blasted, then dipped in an aqueous suspension of colloidal graphite	0.565	0.595	0.765	0.64
1	182	Degreased billets dipped in an aqueous suspension of colloidal graphite	0.55	0.595	0.97	0.71

Forging tests were made using a billet temperature of 1750 F, a die temperature of 900 F, and a forging pressure of 46,000 psi.
(a) Lubricant 1 was a commercial preparation consisting of flake graphite in an oil carrier.

TABLE 32. FORGING-TEST DATA FOR UNALLOYED TITANIUM SAMPLES HEATED IN A SALT BATH BEFORE FORGING

Forging Sample	Time in Salt Bath, min		Penetration Into Die Cavity, in.
60T	5		1.78
61T	4		0.97[a]
62T	6		1.57
63T	10		1.60
64T	15		1.55
65T	5		0.72[a]
		Average	1.36

Lubricant 1, a commercial preparation containing flake graphite in oil, was used as the die lubricant for each sample. The forging tests were made using a billet temperature of 1750 F, a die temperature of 900 F, and a forging pressure of 46,000 psi. The salt bath used was a commercial product that melted at 1550 F, and consisted mainly of barium salts (chloride and fluoride).

(a) These samples were believed to be cooler than the other samples, due to uneven heating in the salt bath. More salt adhered to these samples than the others, indicating a lower temperature.

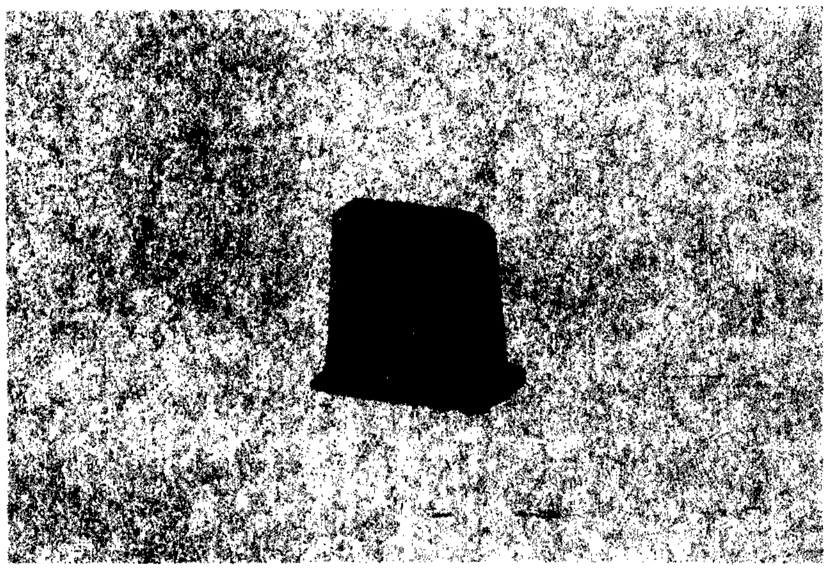


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FIGURE 57. EXPERIMENTAL UNALLOYED TITANIUM FORGING MADE BY HEATING THE BILLET IN A SALT BATH PRIOR TO FORGING WITH LUBRICANT 1 ON THE DIE

was not done using the salt bath as a heating medium, the reason for the unusually good die filling in several of the trials was not determined. Perhaps the improved die filling resulted from one or more of the following mechanisms:

(1) The salt acted as a lubricant.

(2) The salt, acting as an insulating material, prevented heat loss from the billet to the die, thus enabling the metal to be worked at an essentially higher temperature.

(3) Products of a chemical reaction between the molten salt and the titanium metal acted to reduce friction between the die and billet.

The latter point appears likely, and it is believed that additional work along these lines may be worth while and fruitful.

Studies on Glasses as Lubricants

Eighteen glasses of various compositions were prepared in the laboratory for trials as lubricants in working titanium. The glass compositions are listed in Table 33. Also listed in the table are pressing-test ratings obtained on all the glasses, and forging-test ratings obtained on the few which appeared the most promising. The glasses were all crushed to minus 65 mesh and were applied to the billets by rolling them in the powder.

Glasses 108 through 113 were first prepared to study the effects of various additions made to a silica-type glass. These glasses had about the same viscosity at 1700 F and were very fluid at this temperature. The pressing-test data on these six glasses showed that the best ratings were obtained with Glasses 111 and 113. Glass 111 contained 25 per cent lead oxide, and Glass 113 contained 10 per cent copper oxide along with 15 per cent titania. Glass 111 produced the thinnest pressings of all the glasses tested. This rating was about the same as the best of the commercial lubricants tested (Lubricant 5). A mixture consisting of 50 per cent by weight of each of 111 and 113, and identified as Glass 122, gave a pressing-test rating intermediate between those for Glasses 111 and 113.

Forging tests were made using Glasses 111, 113, and 122 as lubricants in working unalloyed titanium. These data which are also listed in Table 33 showed that these glasses, when used as lubricants, produced very poor die filling. This is illustrated in Figure 58, in which a forging lubricated with Glass 122 is compared with one lubricated with Lubricant 5. Lubricant 5 is a commercial product containing graphite and molybdenum disulfide in an oil base. The use of the glasses as lubricants resulted in underfilling, especially in the corners. During forging, the glass flowed

TABLE 33. FORGING- AND PRESSING-TEST RATINGS OBTAINED IN WORKING UNALLOYED TITANIUM USING VARIOUS TYPES OF GLASS AS LUBRICANTS

Glass[a]	Glass Composition, weight per cent							Average Penetration Into Die Cavity In Forge Test[b], in.	Pressed Thickness After Pressing Test[c], in.
	Na_2O	B_2O_3	SiO_2	TiO_2	BaO	ZrO_2	Other		
108	20	15	30	--	30	5	--	--	0.137
109	25	20	30	25	--	--	--	--	0.170
110	20	20	30	20	--	--	10PbO	--	0.140
111	25	20	30	--	--	--	25PbO	0.41	0.115
112	25	20	30	5	--	--	20SnO	--	0.149
113	25	20	30	15	--	--	10CuO	0.35	0.120
114	22	20	33	25	--	--	--	--	0.158
115	19	20	36	25	--	--	--	--	0.161
116	16	20	39	25	--	--	--	--	0.167
117	13	20	42	25	--	--	--	--	(d)
118	17	15	33	--	30	5	--	--	0.135
119	14	15	36	--	30	5	--	--	0.144
120	11	15	39	--	30	5	--	--	0.160
121	8	15	42	--	30	5	--	--	0.170
122	50% of Glass 111 and 50% of Glass 113 (by weight)							0.38	0.116
172	20	15	30	--	--	--	35PbO	--	0.130
173	25	20	30	--	--	--	25CuO	--	0.143
174	25	20	30	--	--	--	12.5PbO, 12.5CuO	--	0.149
175	20	15	30	--	--	--	35CuO	--	0.141

(a) Glasses 108-113 were made to have similar viscosities at 1700 F. These glasses were very fluid at this temperature. Glasses 114-117 and 118-121 were prepared to vary in viscosity at 1700 F. Viscosities ranged from very fluid for Glasses 114 and 118 to very viscous for Glasses 117 and 121.

(b) Forge tests were made using a billet temperature of 1750 F, a die temperature of 900 F, and a forging pressure of 46,000 psi.

(c) Billets, 0.950 inch in diameter by 1/2 inch high, were pressed between flat, parallel dies using a billet temperature of 1750 F, a die temperature of 900 F, and a pressing load of 138,000 pounds.

(d) Upon solidification, this material was not a glass, but crystalline; therefore, it was not tested.

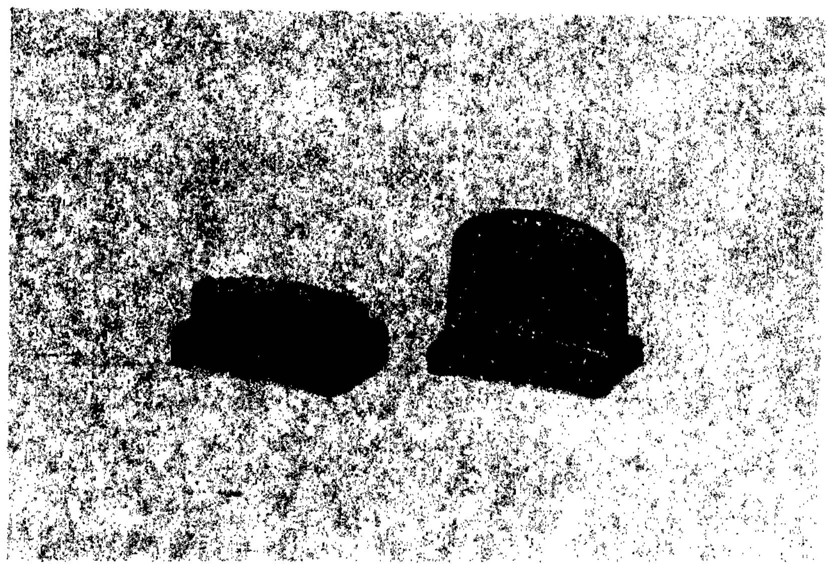

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FIGURE 58. COMPARISON OF DIE PENETRATION IN LABORATORY FORGING TESTS FOR UNALLOYED TITANIUM SAMPLES LUBRICATED IN DIFFERENT MANNERS

The sample on the left was lubricated with Glass 122, while the one on the right was lubricated with a commercial product containing graphite and molybdenum disulfide in oil (Lubricant 5).

to the corners and solidified, thus producing a buildup of glass in the corners of the die cavity. The glasses were also very difficult to remove from the die cavity.

Because of the good pressing-test ratings shown for Glasses 111 and 113, four additional glasses were prepared with higher percentages of lead oxide and copper oxide and combinations of the two oxides. These glasses are identified in Table 33 as Glasses 172 through 175. The viscosities at 1700 F were about the same as those for Glasses 108 through 113. These glasses gave poorer ratings in the pressing test than Glasses 111 and 113.

A series of glasses containing titania and varying in viscosity was prepared for testing. These glasses are identified as Glasses 114 through 117 in Table 33. The viscosity of Glass 114 was similar to those for Glasses 108-113. By increasing the silica and decreasing the soda contents, the viscosity of the glass was increased. The viscosity of Glass 117 was very high and upon solidification the material was crystalline and not glassy. Therefore it was not tested. The pressing-test data indicated that the pressed thickness increased with increasing viscosity.

Another series of glasses containing 30 per cent baria and 5 per cent zirconia and varying in viscosity was prepared for pressing tests. These glasses are identified in Table 33 as Glasses 118 through 121. As in the previous series of glasses, the soda and silica contents were varied to change the viscosity. Glass 118 was very fluid at 1700 F, similar in viscosity to Glasses 108 through 113. Glass 121 was very viscous at 1700 F. The pressing tests also indicated that the pressed thickness increased with increasing viscosity. Furthermore, the ratings obtained with the less viscous glasses were poorer than those obtained with Glasses 111 and 113.

Extrusion Studies on Titanium

The extrusion of titanium and its alloys is still in the development stage. However, recent experimental information has shown that the hot extrusion of titanium is technically feasible and economically sound[23, 41]. Sabroff, Parris, and Frost[23] found that on the basis of metal flow, surface finish, and extrusion pressure, the best die angle for extruding titanium was an included angle of 130 degrees. They also found that graphite and/or molybdenum disulfide with mica in greases gave acceptable surface finishes when used as lubricants. These materials compounded in a bentone grease gave the best surface finish and the least amount of die pickup. An NLGI No. 2 grease consistency was found to produce the best surface finish. Also, a mixture of graphite and powdered aluminum in a bentone grease gave equally good surface finishes.

With this background, extrusion experiments were conducted on unalloyed titanium billets using an extrusion ratio similar to that for aluminum and magnesium. Billets, 0.950 inch in diameter by 1-15/16 inches long, were extruded to a 5/16 inch-diameter rod through a conical die having an included entrance angle of 130 degrees. The billets were heated in an argon atmosphere to 1750 F for extruding. The die and container temperatures were maintained at 900 F during the experiments.

Extrusion experiments were made on two lubricants. In using the second lubricant, the extrusion pressure was so high that deformation of the ram occurred and the experiments were discontinued. Dies were designed and made to produce a 1/2-inch-diameter extruded rod, but time limitations prevented additional studies using the larger die opening. The larger die opening should result in lower extrusion pressures and, at the same time, should be sufficiently high for evaluating various lubricants.

Laboratory extrusion data obtained using the two lubricants are given in Table 34. Lubricant 49A contained 35 per cent flake graphite and 5 per cent mica in a calcium-base grease. Lubricant 50A contained 25 per cent molybdenum disulfide and 5 per cent mica in the same calcium-base grease.

Contrary to data obtained on aluminum and magnesium, the pressure for extruding titanium increased from beginning to end of the extrusion stroke. This probably indicates that the billet cooled considerably during the extrusion stroke because of its small mass and the relatively large temperature difference between billet and tools. Apparently, the pressure required for overcoming the increase in strength caused by the drop in temperature was greater than the reduction in friction force resulting from less contact area between billet and container as extrusion proceeded.

The breakthrough pressures measured in these experiments are of the order determined on larger billets in plant experiments[23]. The pressures developed during the course of extrusion in the laboratory, however, were much higher than those measured with commercial-scale equipment.

The extrusion data indicated that less pressure was required for extruding with the lubricant containing graphite than with the one containing molybdenum disulfide. In fact, on the third extrusion using the latter lubricant, the pressure near the end of the stroke was so high that the punch deformed. All of the extrusions were characterized by relatively poor surfaces.

This brief experience indicated that the experimental conditions should be changed before extruding titanium with other lubricants. The investigation was discontinued at this point.

TABLE 34. DATA OBTAINED IN EXTRUSION EXPERIMENTS ON UNALLOYED TITANIUM

Extrusion Sample	Die and Container Lubricant	Extrusion Pressure, psi			Surface Condition[a]
		Front	Middle	Back	
1T	49A[b]	87,600	131,500	147,500	P
2T	49A[b]	75,700	110,100	127,800	P
3T	49A[b]	59,800	120,900	131,500	P
	Average	74,400	120,800	135,600	
4T	50A[c]	75,700	107,300	112,900	VP
5T	50A[c]	75,700	120,900	134,500	P
6T	50A[c]	107,300	144,600	180,000[d]	P
	Average	86,200	124,300	142,500	

(a) The surfaces were rated according to the following classification:

VG = very good, no scoring
G = good, negligible scoring
F = fair, light scoring
P = poor, heavy scoring
VP = very poor, rough and heavily scored.

(b) Undiluted experimental product containing 35 per cent flake graphite and 5 per cent mica in a calcium-base grease.

(c) Undiluted experimental product containing 25 per cent molybdenum disulfide and 5 per cent mica in a calcium-base grease.

(d) Extrusion stopped near the back end of Sample 6T because the extrusion pressure caused the ram to deform.

Testing conditions: 0.950-inch-diameter by 1-15/16-inch-long billets extruded to 5/16-inch-diameter rods using a billet temperature of 1750 F and die and container temperatures of 900 F. Exit extrusion speed was 22.3 feet per minute.

STUDIES ON STEEL

Pressing and Forging Tests on Steel

Closed-die or impression-die steel forgings are generally produced by quick-acting forging hammers or mechanical presses. Lubricants used in these operations generally consist of some type of graphite in water or a heavy mineral oil. Sometimes an aqueous sodium chloride solution is used as a lubricant in working steel in hammer forging. Aqueous solutions or suspensions are used when the die temperature is sufficiently low to prevent a vapor barrier from forming.

Because of the high temperatures involved, forging of steel in slower acting hydraulic presses has not been too widely practiced. With the longer time of contact between the workpiece and the dies in hydraulic presses, the dies are apt to become overheated and soften. With the loss in hardness, die wear becomes excessive and die dimensions may be changed as a result of die deformation.

At steel forging temperatures, scaling of the billet surface becomes excessive especially if no protective atmosphere is used. Therefore, some method of scale control is generally practiced. This consists of either heating in a controlled atmosphere or heating in a salt bath. Even if heated in a controlled atmosphere furnace, scale forms on the billet surface during the transfer from the furnace to the forging press. This scale is generally considered to be abrasive and results in rapid die wear. On the other hand, the scale or oxide is believed to prevent seizing between the workpiece and the dies such as that encountered with the light metals where only a very thin oxide film is formed during heating.

In forging steel, generous draft angles are employed to facilitate the removal of the forging from the die. These angles usually range between 7 and 10 degrees. Smaller draft angles may create sticking of the forging in the die as a result of thermal contraction of the forged part. This, of course, would depend on the configuration of the die cavity. On steel, thermal contraction of the forging may be very great because of the large temperature differential between the die and workpiece.

In the original bulge tests made on steel, 4340 steel was used. However, for subsequent pressing and forging tests, Type 403 stainless steel was used as the working stock. This is a turbine-quality stainless steel containing a maximum of 0.15 per cent carbon and 12 per cent chromium. Both types of steel billets were heated in a controlled-atmosphere furnace to the forging temperature of 2150 F. Forging- and pressing-test samples were machined to the proper length from wrought 1-inch-diameter bar stock. Because of the relatively small size of the test billets, they cooled fairly rapidly when removed from the furnace. Therefore, test procedures were standardized, so that testing conditions would be uniform. For most of the tests, a die temperature of 900 F was used.

Lubricants used in tests on steel are listed in Table E-1 of Appendix E. This table lists all materials and billet treatments used in the entire investigation. Not all materials were used in tests on steel, because some were used specifically for working other metals. Each lubricant or material is identified by number.

Complete lists of all data obtained in forging, pressing, and bulge tests on steel are given in Tables K-1, K-2, and K-3, respectively, of Appendix K. Data obtained for various materials used as lubricants in working 4340 steel in the bulge test are not believed to be reliable. All samples exhibited an unusually large amount of bulging and the differences were not significant. In these tests the metal adjacent to the dies cooled very rapidly, leaving the center of the billet much hotter than the ends. Under these conditions no lateral metal movement occurred at the billet ends; all deformation occurred in the hotter center portion as bulging.

Data given in Tables K-1 and K-2 of Appendix K for forging and pressing tests, using various lubricants in working Type 403 stainless steel, are summarized in Table 35. In general, thicker pressings and poorer die filling were obtained on steel than for aluminum, magnesium, or titanium. This indicates that under the testing conditions used, higher pressures were required for working 403 stainless steel than for working aluminum, magnesium, or titanium. This is believed to have been caused by the relatively greater chilling effect produced by the dies on steel than on the other metals studied. The temperature differential between dies and workpiece was greater for the steel samples than for any of the other metals.

Variations in die filling in the forging test for the commercial lubricants (Lubricants 1, 5, and 8) were quite small. These values varied from 0.33 to 0.42 inch and none appeared to be outstanding. Lubricant 8, which is used in at least one forge plant for forging steel, showed the best die penetration of the three lubricants. Lubricant 1 in the undiluted condition produced a little better die filling than the same lubricant in the diluted condition. However, no significant difference in die filling was shown for Lubricants 5 and 8 in diluted and undiluted conditions.

The effects of variations in die temperature on die filling when using Lubricants 8 and 65 were studied. Lubricant 8 was used at die temperatures of 700, 900, and 1100 F. A die temperature of 900 F produced slightly better die filling than 700 F. However, heating the dies to 1100 F produced no additional improvement in die filling. Lubricant 65 showed a more marked improvement in die filling than Lubricant 8 when the die temperature was raised from 700 to 900 F. Although some improvement in die filling seemed to result from increasing the die temperature, the effect was not as marked as that produced in tests on aluminum. For steel,

TABLE 35. FORGING- AND PRESSING-TEST DATA OBTAINED IN WORKING TYPE 403 STAINLESS STEEL USING VARIOUS MATERIALS AS LUBRICANTS

Lubricant	Lubricant Description	Die Temperature, F	Average Penetration Into Die Cavity In Forge Test[a], in.	Pressed Thickness After Pressing Test[b], in.
1	Oil-diluted commercial product containing flake graphite in oil	900	0.33	--
1A	Same as Lubricant 1 but undiluted	900	0.39	0.166
5	Oil-diluted commercial product containing graphite and MoS_2 in oil	900	0.39	--
5A	Same as Lubricant 5 but undiluted	900	0.39	0.146
8	Oil-diluted commercial product containing flake graphite in oil	700	0.38	--
8	Ditto	900	0.42	--
8	"	1100	0.41	--
8A	Same as Lubricant 8 but undiluted	900	0.38	0.150
49	Diluted experimental product containing 35% flake graphite and 5% mica in a calcium-base grease	700	0.46	--
22	Phosphate-type glass	700	0.41	--
81	Commercial borax glass	700	0.27	--
111	Na_2O-B_2O_3-SiO_2 glass containing 25% PbO	900	0.35	0.169
113	Na_2O-B_2O_3-SiO_2-TiO_2 glass containing 10% CuO	--	--	0.187
122	50% Lubricant 111 and 50% Lubricant 113 by weight	--	--	0.198
172	Na_2O-B_2O_3-SiO_2 glass containing 35% PbO	--	--	0.202
173	Na_2O-B_2O_3-SiO_2 glass containing 25% CuO	--	--	0.203
174	Na_2O-B_2O_3-SiO_2 glass containing 12.5% PbO and 12.5% CuO	--	--	0.208
175	Na_2O-B_2O_3-SiO_2 glass containing 35% CuO	--	--	0.217

TABLE 35. (Continued)

Lubricant	Lubricant Description	Die Temperature, F	Average Penetration Into Die Cavity In Forge Test[a], in.	Pressed Thickness After Pressing Test[b], in.
143	Nylon powder	--	--	0.223
65	20% (wt) boron nitride in Paraplex G62	700	0.31	--
65	Ditto	900	0.39	--
123	25% (wt) extra fine flake graphite in sodium Paraplex G60 grease	900	0.50	--
124	25% (wt) boron nitride in sodium Paraplex G60 grease	900	0.38	--

(a) Forge tests were made using a billet temperature of 2150 F, a die temperature indicated in the table, and a forging pressure of 46,000 psi.

(b) Billets 1 inch in diameter by 1/2 inch high were pressed between flat parallel dies using a billet temperature of 2150 F, a die temperature indicated in the table, and a pressing load of 138,000 pounds.

the temperature differential between die and workpiece was much greater than for forging aluminum. In fact, die temperatures of 700 to 1100 F all cooled the steel billets quite rapidly. This chilling effect raised the strength of the steel adjacent to the die surface, thus making it more difficult to deform. This chilling effect would be less pronounced on larger or thicker samples and a greater amount of metal flow would be expected.

Eight glass compositions were studied using the pressing test. These materials were all quite fluid at 1700 F. The ratings were all poorer than those obtained with the commercial lubricants. Glass 111 gave the thinnest pressing. This confirmed the experience in pressing tests on unalloyed titanium. Glass 111 was also tried as a lubricant for Type 403 stainless steel in the laboratory forging test but resulted in poor die filling. Although the glass was fluid at high temperatures, the die temperature was sufficiently low that excess glass solidified in the corners of the die cavity. This produced underfilling at the outer sides of the horizontal section of the T.

The best die penetration of all materials studied as lubricants in forging Type 403 stainless steel was produced by Lubricant 123. This lubricant was prepared in the laboratory and consisted of a sodium Paraplex G60 grease containing 25 per cent by weight of extra-fine flake graphite. Boron nitride added to the same grease (Lubricant 124), and used as a lubricant, produced poorer die filling. Additional information, using larger samples, should be obtained to confirm the information obtained in these experiments.

Extrusion Experiments on Steel

Because of limitations in time and equipment, no studies on the extrusion of steel were made.

* * * * * * *

Data on which this report is based are recorded in Battelle Laboratory Record Books Numbers 8973, 9206, 9288, 9578, 9579, 9619, 9620, 9937, 9938, 10219, 10433, 10478, 10628, and 11074.

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HLS:FWB:CHL/ims:dp:bt

APPENDIX A

FORGING-DIE EQUIPMENT

APPENDIX A

FORGING-DIE EQUIPMENT

A drawing of the die equipment used in the forging test is shown in Figure A-1. The split die and the punch were made from Darwin-Milner "HWA" die steel having the following nominal composition:

	Per Cent
Carbon	0.35
Chromium	5.0
Molybdenum	1.0
Vanadium	1.0
Silicon	1.0

These parts were oil quenched from 1900 F, then tempered at a temperature of 1100 F to a hardness of 50 Rockwell C. The die container and the punch backup plate were made from Darwin-Milner brake die steel, heat treated to a hardness of about 30 Rockwell C.

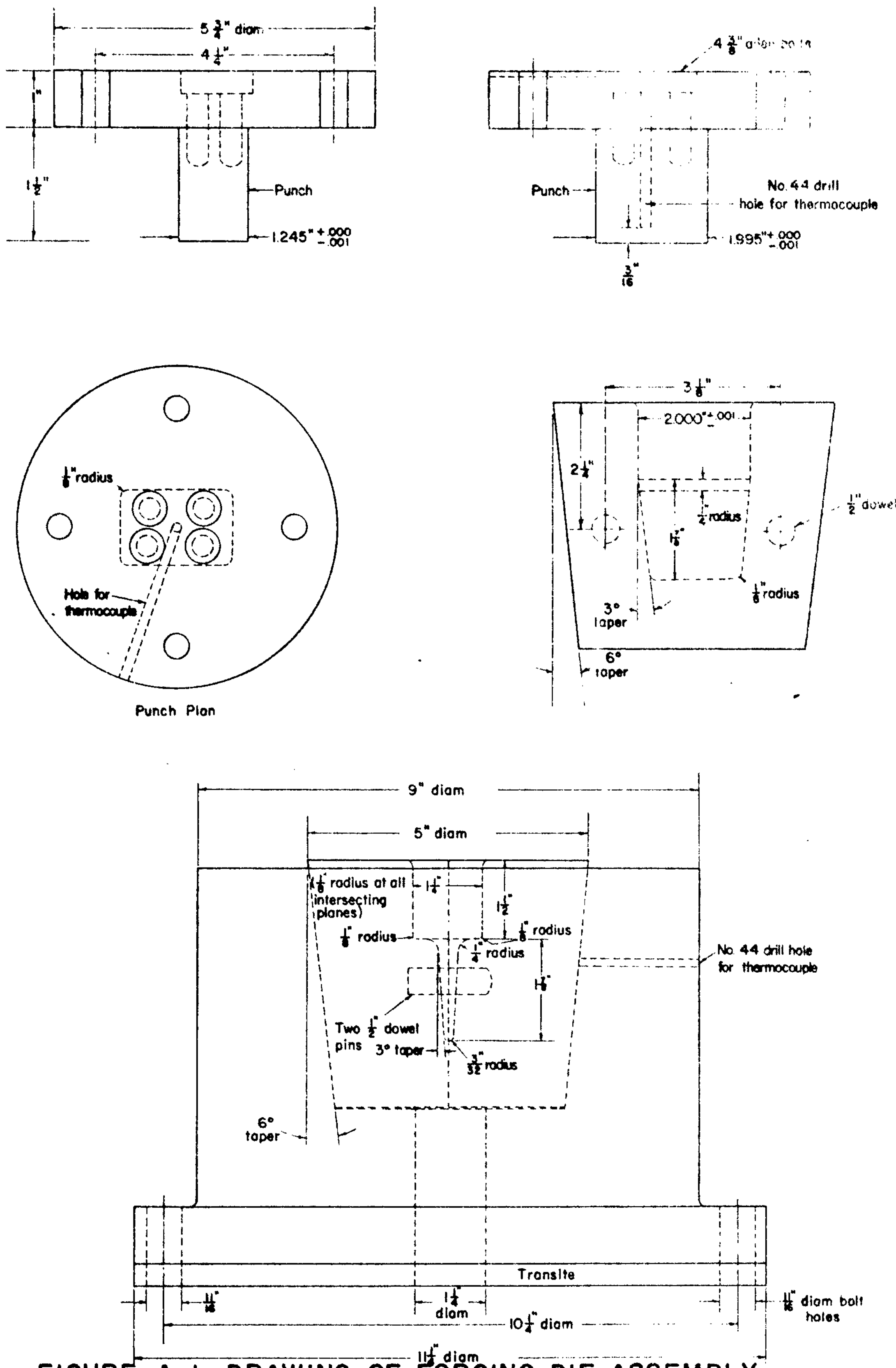

FIGURE A-1. DRAWING OF FORGING DIE ASSEMBLY

B-16183

APPENDIX B

PRELIMINARY BULGE-TEST EXPERIMENTS

APPENDIX B

PRELIMINARY BULGE-TEST EXPERIMENTS

It is well known that inadequately lubricated specimens will "barrel" in compression tests because friction retards the spread of the metal layers next to the tool(31, 42)*. That is, friction restrains deformation. It is less widely realized that friction increases the load required for producing a particular amount of deformation. Preliminary experiments were made to determine whether or not measurements of loads and bulging dimensions would be suitable for evaluating metal-working lubricants.

The first tests were made at room temperature on wrought 2017 aluminum-alloy cylinders. The specimens were machined to lengths of 1-1/2, 1, and 1/2 inch from 1-inch round bar stock. The billets were compressed between flat, hardened steel dies in an Amsler universal testing machine. The loads required for compressing the right cylinders, to reductions ranging from 8 to 45 per cent in height, were measured. Three conditions of lubrication were investigated. Data obtained in these experiments are given in Table B-1.

The term "bulge index" is used in Table B-1 to indicate the difference in inches between the maximum diameter of a barreled specimen and the average diameter of the ends. According to the theory, friction is the cause of bulging or barreling so higher bulge indexes indicate poorer lubrication.

Data from Table B-1 are shown graphically in Figures B-1 and B-2. These room-temperature data indicate that mineral oil was a better lubricant than dry molybdenum disulfide powder. Specimens compressed with either lubricant required lower pressures and bulged less than unlubricated samples. Varying the ratio of the height to the diameter of the specimen did not influence this conclusion. However, the bulge indexes were higher for the 1-1/2-inch-high cylinders. The larger slenderness ratio of the 1-1/2-inch-high specimens made them more sensitive to barreling. The pressure required for producing a particular reduction in height was not affected significantly by the original height-to-diameter ratios of the specimens. In these experiments, the forging pressures varied up to about 10 per cent, depending upon the lubricant employed.

The results of the room-temperature tests suggested that bulge indexes showed some promise of being reliable for rating lubricants. At the time, relatively thick specimens were considered desirable because they would retain a more uniform temperature during tests at forging temperature.

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* References are to the Bibliography at the end of the text to this report.

TABLE B-1. DATA OBTAINED IN PRESSING COLD ROUND BILLETS OF 2017 ALUMINUM BETWEEN COLD FLAT STEEL DIES WITH DIFFERENT TYPES OF LUBRICATION[a]

Sample	Reduction in Height		Pressed Dimensions						
	Inch	Per Cent	Diameter of Original End Surface, in.	End Diameter, in.	Barrel Diameter, in.	End Area, sq in.	Bulge Index[b], in.	Maximum Load, lb	Maximum Pressure[c], psi
(1-1/2-Inch Height, No Lubricant)									
5	0.125	8.3	1.015	1.026	1.059	0.83	0.023	36,000	43,400
4	0.250	16.6	1.045	1.052	1.124	0.87	0.072	42,000	48,300
1	0.372	24.7	1.054	1.077	1.196	0.91	0.119	50,000	55,000
3	0.499	33.2	1.050	1.124	1.278	0.99	0.154	57,000	57,700
16	0.622	41.3	1.048	1.185	1.371	1.10	0.186	68,000	62,000
2	0.668	44.4	1.058	1.218	1.407	1.165	0.189	~ 72,000	61,800
(1-1/2-Inch Height, Mineral Oil)									
11	0.125	8.3	1.030	1.040	1.050	0.85	0.010	36,000	42,400
12	0.250	16.6	1.068	1.076	1.109	0.91	0.033	42,000	46,200
13	0.372	24.7	1.088	1.114	1.177	0.975	0.063	50,000	51,300
14	0.499	33.2	1.105	1.160	1.258	1.055	0.098	57,000	54,000
15	0.621	41.3	1.118	1.225	1.351	1.18	0.126	68,000	57,600
(1-1/2-Inch Height, Molybdenum Disulfide Powder)									
23	0.124	8.2	1.030	1.031	1.056	0.835	0.025	38,000	45,500
24	0.250	16.6	1.048	1.054	1.118	0.87	0.064	43,000	49,500
25	0.372	24.7	1.060	1.090	1.191	0.935	0.101	51,000	54,500
26	0.499	33.2	1.079	1.143	1.273	1.025	0.130	58,000	56,600
27	0.622	41.3	1.105	1.213	1.358	1.155	0.145	69,000	59,800

TABLE B-1. (Continued)

	Reduction in Height		Pressed Dimensions						
Sample	Inch	Per Cent	Diameter of Original End Surface, in.	End Diameter, in.	Barrel Diameter, in.	End Area, sq in.	Bulge Index(b), in.	Maximum Load, lb	Maximum Pressure(c), psi
				(1-Inch Height, No Lubricant)					
6	0.123	12.3	1.036	1.040	1.085	0.85	0.045	41,000	48,300
7	0.249	24.8	1.058	1.100	1.185	0.95	0.085	52,000	54,800
8	0.367	36.5	1.074	1.174	1.295	1.08	0.121	68,000	63,000
				(1-Inch Height, Mineral Oil)					
17	0.123	12.3	1.060	1.065	1.075	0.89	0.010	41,000	46,100
18	0.247	24.6	1.106	1.127	1.165	0.995	0.038	52,000	52,300
19	0.369	36.8	1.145	1.213	1.290	1.155	0.077	68,000	59,000
				(1-Inch Height, Molybdenum Disulfide Powder)					
28	0.122	12.2	1.050	1.051	1.082	0.87	0.31	41,000	47,200
29	0.248	24.7	1.093	1.114	1.180	0.975	0.066	51,000	52,300
30	0.371	36.9	1.141	1.205	1.293	1.140	0.088	66,000	57,900
				(1/2-Inch Height, No Lubricant)					
22	0.088	17.5	1.085	1.090	1.115	0.935	0.025	47,000	50,300
10	0.108	21.4	1.094	1.107	1.147	0.960	0.040	54,000	56,300
9	0.124	24.6	1.081	1.121	1.181	0.985	0.060	63,000	64,000
				(1/2-Inch Height, Mineral Oil)					
20	0.059	11.7	1.060	1.062	1.071	0.885	0.009	39,000	44,100
21	0.123	24.4	1.130	1.137	1.161	1.015	0.024	53,000	52,200

TABLE B-1. (Continued)

Sample	Reduction in Height		Pressed Dimensions						
	Inch	Per Cent	Diameter of Original End Surface, in.	End Diameter, in.	Barrel Diameter, in.	End Area, sq in.	Bulge Index[b], in.	Maximum Load, lb	Maximum Pressure[c], psi
(1/2-Inch Height, Molybdenum Disulfide Powder)									
31	0.059	11.7	1.056	1.059	1.072	0.880	0.013	41,000	46,600
32	0.124	24.6	1.130	1.133	1.163	1.005	0.030	58,000	57,700

(a) The purified mineral oil used for the tests had a Seybolt viscosity of 310 to 320 seconds at 100 F. The dry molybdenum disulfide powder particles ranged in size from 1 to 70 microns.
(b) Bulge index = Barrel diameter minus end diameter.
(c) Area used for determining pressure was the average area of the ends of the pressed billet.

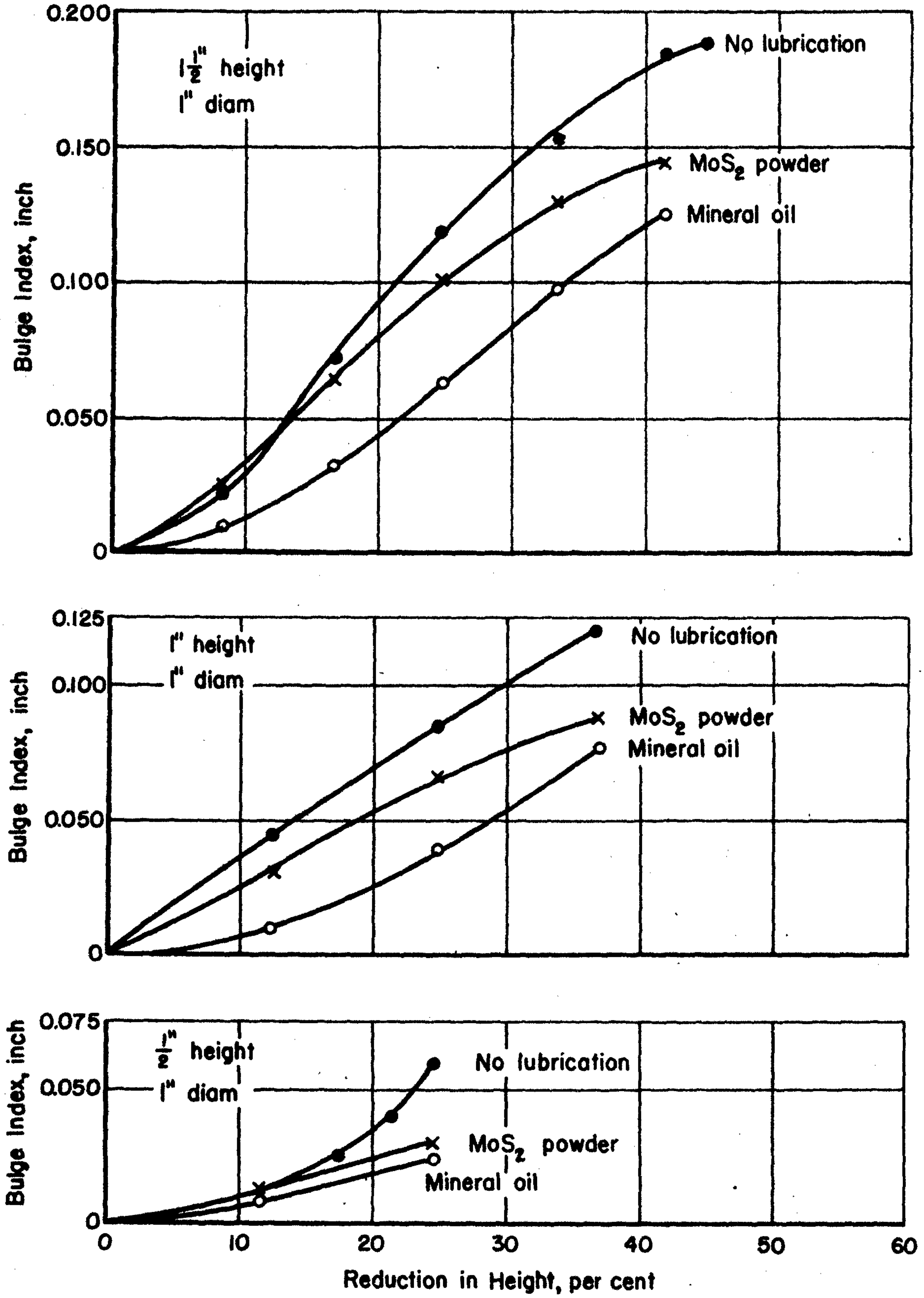


FIGURE B-1. RELATIONSHIP BETWEEN BULGE INDEX AND REDUCTION IN THE HEIGHT OF 2017 ALUMINUM ALLOY BILLETS OF DIFFERENT HEIGHT PRESSED COLD UNDER THREE CONDITIONS OF LUBRICATION A-16862

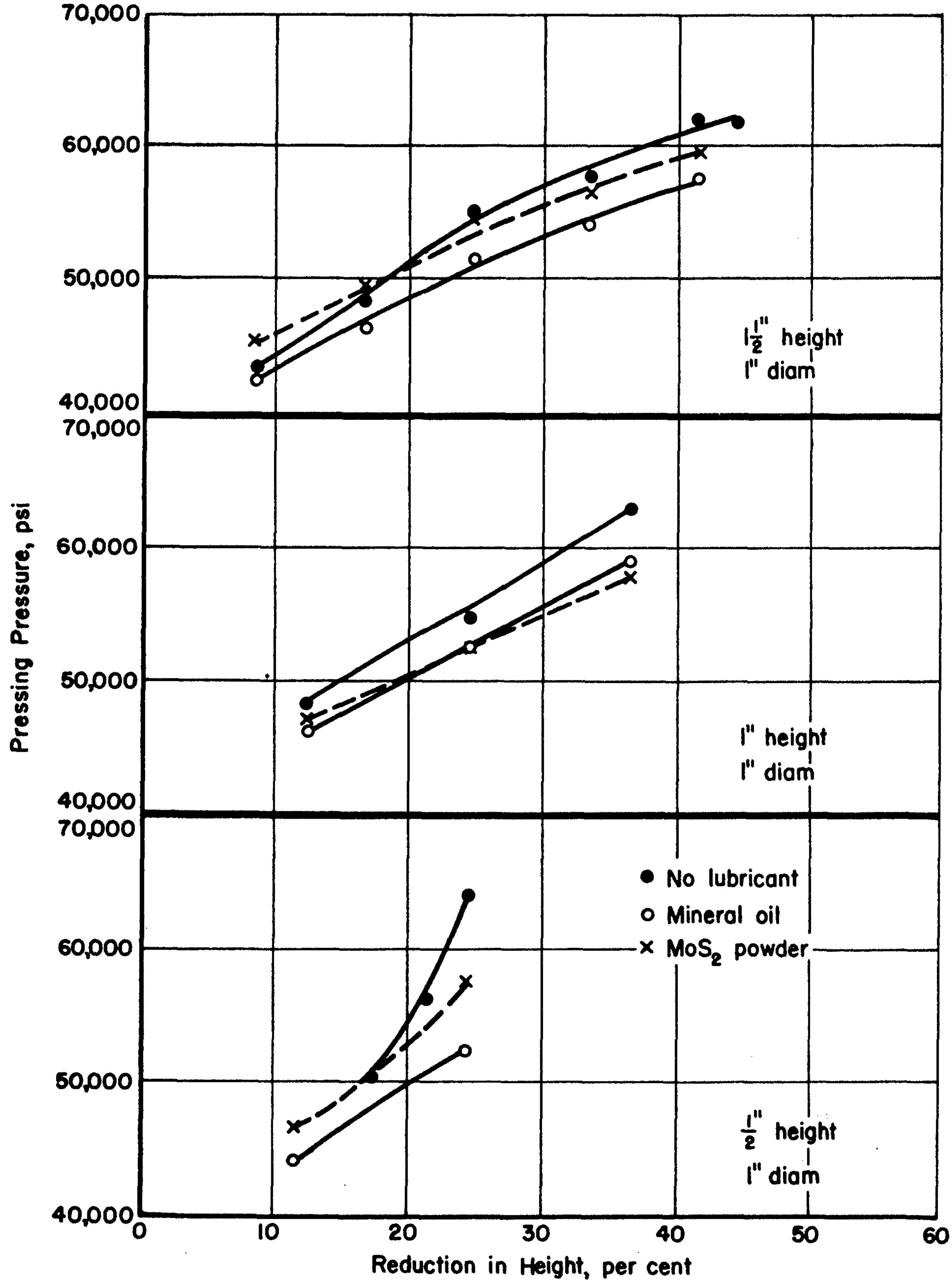


FIGURE B-2. PRESSURES REQUIRED TO PRESS 2017 ALUMINUM ALLOY CYLINDRICAL BILLETS OF VARIOUS HEIGHTS TO VARIOUS REDUCTIONS IN HEIGHT UNDER DIFFERENT CONDITIONS OF LUBRICATION AT ROOM TEMPERATURE

A-16864

A second series of bulge tests was made on 2017 aluminum alloy at elevated temperatures. The billet and die temperatures were 800 F and 700 F, respectively. The loads required for reducing the original heights of the cylinders by 25, 50, and 75 per cent were measured. The billets were tested dry and also with two types of lubricants.

Data obtained in these experiments are given in Table B-2 and plotted in Figure B-3. The least bulging occurred when the oil-graphite lubricant was used. This commercial lubricant also permitted the reductions to be accomplished with smaller pressures. On the average, the pressures were one-sixth lower than those for the unlubricated specimens. In general, the pressures for hot upsetting were only about one-fifth as high as those required for equal reductions at room temperature.

Billets lubricated with molybdenum disulfide did not bulge quite as much as unlubricated specimens. Since the difference was slight, it appears that the sulfide particles did not provide good lubrication in these tests.

The forging pressures increased with the amount of deformation largely because the specimens cooled during the time of testing. Despite the variations in bulge indexes, the maximum loads required for deformation did not vary appreciably with the lubricant until the deformation was 75 per cent in height. In the unlubricated condition, the shorter specimens required larger loads for heavy reductions than the longer samples.

Figure B-3 indicates that bulge indexes based on samples reduced 50 per cent in height were more sensitive than the other reductions to the variations in lubrication investigated. At this reduction, the bulge indexes for the taller specimens seemed to be more discriminating. Therefore, it was concluded from this preliminary study that compression tests on 1-inch-round cylinders, 1-1/2 inches high would distinguish between materials which might be used as lubricants in forging and extrusion. Therefore, this simple bulge test was adopted as the method for rapidly evaluating potential lubricants.

TABLE B-2. DATA OBTAINED IN PRESSING HOT ROUND BILLETS OF 2017 ALUMINUM BETWEEN HEATED FLAT DIES[(a)] WITH VARIOUS TYPES OF LUBRICATION

Sample	Original Height, in.	Lubricant	Reduction in Height		Pressed Dimensions		Bulge Index[(b)]	End Area, sq in.	Maximum Load, lb	Maximum Pressure, psi
			Inch	Per Cent	End Diameter, in.	Barrel Diameter, in.				
42	1.5	None	0.386	25.7	1.064	1.213	0.149	0.890	10,000	11,200
43	1.5	None	0.759	50.6	1.268	1.500	0.232	1.260	14,000	11,100
44	1.5	None	1.130	75.4	1.891	2.074	0.183	2.820	50,000	17,700
39	1.5	7[(c)]	0.388	25.8	1.148	1.175	0.027	1.035	9,000	8,700
40	1.5	7	0.758	50.5	1.371	1.449	0.078	1.480	16,000	10,800
41	1.5	7	1.130	75.4	1.942	2.055	0.113	2.960	35,000	11,800
45	1.5	151[(d)]	0.387	25.8	1.078	1.210	0.132	0.910	9,000	9,900
46	1.5	151	0.757	50.4	1.263	1.496	0.233	1.250	14,000	11,200
47	1.5	151	1.130	75.4	1.898	2.068	0.170	2.830	40,000	14,100
33	1.0	None	0.259	25.9	1.086	1.209	0.123	0.925	9,000	9,700
34	1.0	None	0.507	50.7	1.301	1.487	0.186	1.330	17,500	13,200
35	1.0	None	0.749	74.7	1.905	2.034	0.129	2.850	60,000	21,000
36	1.0	7[(c)]	0.258	25.8	1.150	1.185	0.035	1.040	11,500	11,100
37	1.0	7	0.504	50.4	1.385	1.452	0.067	1.520	16,000	10,500
38	1.0	7	0.755	75.5	1.973	2.050	0.077	3.060	40,000	13,100

(a) Diameter of billets was 1 inch
Billet temperature was 800 F
Die temperature was 700 F.
(b) Bulge index = bulge diameter minus end diameter.
(c) A commercial hot-forging lubricant (Lubricant 7) containing flake graphite. The as-received material was diluted with a 106 SUS/100 F soluble oil.
(d) Lubricant 151 was powdered molybdenum disulfide applied to the die surfaces.

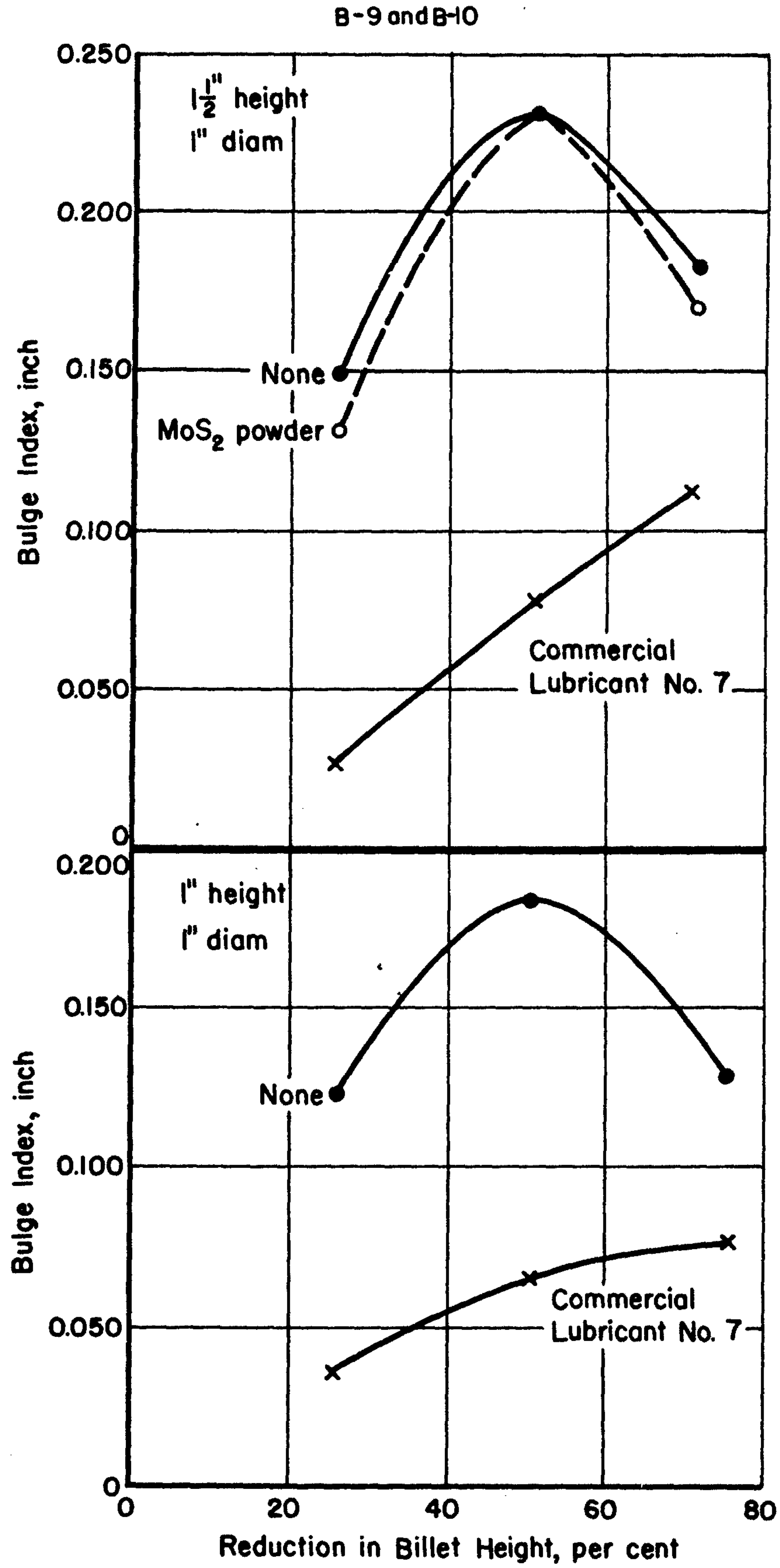


FIGURE B-3. RELATIONSHIP BETWEEN BULGE INDEX AND REDUCTION IN HEIGHT OF 2017 ALUMINUM ALLOY BILLETS OF DIFFERENT HEIGHT PRESSED UNDER VARIOUS CONDITIONS OF LUBRICATION

A-16863

APPENDIX C

EXTRUSION EQUIPMENT

APPENDIX C

EXTRUSION EQUIPMENT

The extrusion equipment was designed to fit an 80-ton experimental press which was available. The design of the equipment is shown in Figure C-1. All die equipment was made from Darwin No. 93 die steel. The nominal composition of this steel was as follows:

	Per Cent
Carbon	0.30
Manganese	0.85
Chromium	3.0
Vanadium	0.45
Tungsten	9.0

The punch, die, and container were oil quenched from 2100 F, then tempered at 1100 F to produce a hardness of 50 to 53 Rockwell C.

After extrusion, the container was lifted from the die, and the skull was cut from the extrusion with bolt cutters.

The two die designs available for use in the extrusion equipment are shown in Figure C-2.

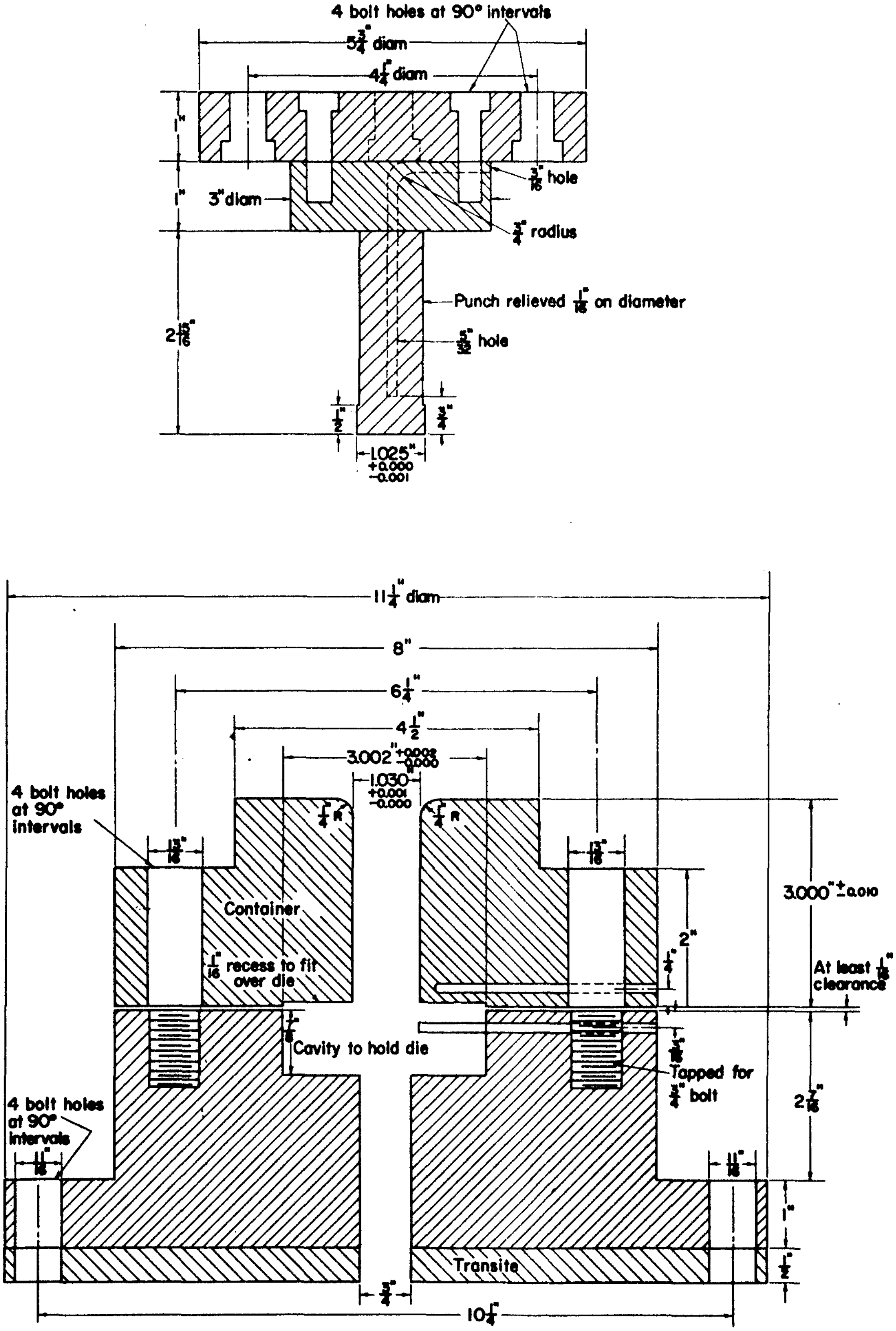
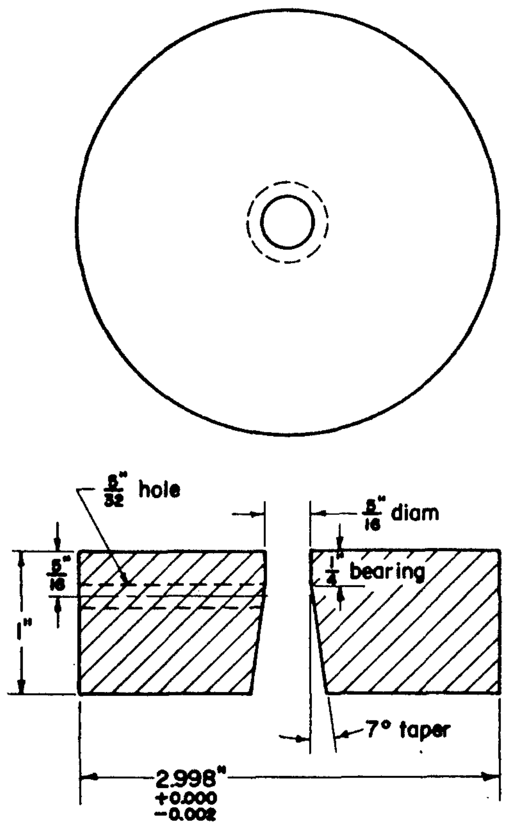


FIGURE C-1. DESIGN OF EXPERIMENTAL EXTRUSION EQUIPMENT

C-16186

C-3 and C-4



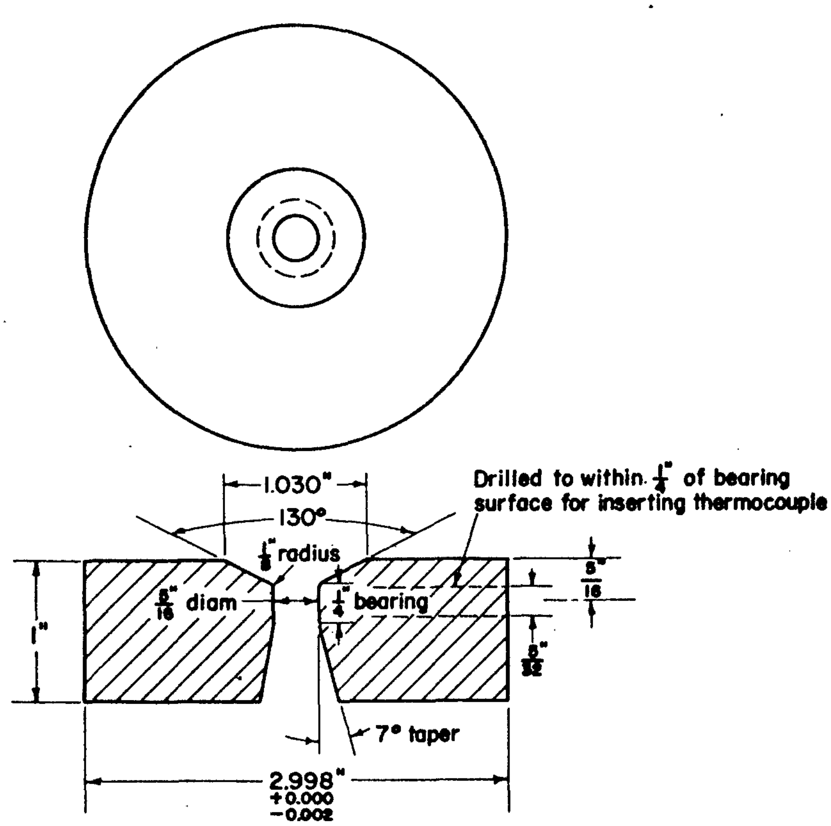


FIGURE C-2. DIE DESIGN USED IN LABORATORY EXTRUSION EXPERIMENTS

B-16187

APPENDIX D

SUPPLEMENTAL DATA ON PRESSING TEST

APPENDIX D

SUPPLEMENTAL DATA ON PRESSING TEST

In plastic working, the resistance to metal flow in a direction normal to the applied stress increases with:

(1) Distance from a free surface

(2) Decreasing height or thickness

(3) Increasing surface friction.

This is true for forging and upsetting operations. Although various investigators[9, 16, 24, 28, 31]* agree on the relative importance of these factors, Stone[36] seems to be responsible for the simplest equations expressing the relationships. Stone's equation for forging circular disks is:

$$\text{Forging pressure} = s \left[\frac{e^{\frac{\mu D}{t}} - \frac{\mu D}{t} - 1}{1/2 \left(\frac{\mu D}{t} \right)^2} \right]$$

where s = flow stress of metal appropriate speed and temperature

μ = coefficient of friction between dies and workpiece

D = diameter of disk being forged

t = thickness of disk

e = base of natural logarithms.

The forging pressure exceeds the flow strength by a multiplication factor that varies with the instantaneous dimension of the forging and the friction coefficient. Figure 6 in the text of this report is a chart representing the solution of the equation for a variety of disk dimensions and friction coefficients.

The data obtained from pressing tests could be used with Figure 6 to obtain apparent friction coefficients. Many results of such computations are given in this report.

A decrease in the effective friction coefficient permits a particular press to produce forgings with either larger areas or with thinner webs.

* References are to the Bibliography at the end of the text of this report.

Stone's formula indicates that the decrease in the limiting web thickness is approximately proportional to the reduction in friction coefficient. For example, a load of 20,000 tons on a circular blank of metal having an average flow stress of 8000 psi could produce a forging 35.7 inches in diameter and 0.79 inch thick if $\mu = 0.08$. If the friction coefficient were decreased to 0.04 by better lubrication, a thinner blank, 35.7 inches in diameter x 0.395 inch thick, could be produced.

If the maximum load available was used for forging the blanks to 0.59-inch gage, the limiting final diameters would be 30.7 and 43.4 inches for friction coefficients of 0.08 and 0.04, respectively.

These calculations indicate that it is possible to halve the final thickness or to double the final area of the forging by cutting friction in half. In effect, better lubricants increase press capacities.

Some experiments were made to check the effect of variations in blank dimensions and lubrication practices predicted by the equation given above. Billets of 2014 aluminum, of various sizes, were heated to 825 F and upset between flat dies with loads ranging from 33-1/2 to 600 tons. The dies on the smaller press were heated to 700 F; the dies on the larger press were heated to 300 F. Data obtained from these experiments are given in Table D-1. The data obtained from the ten sets of 1-inch-diameter billets are plotted in Figure D-1.

Pretreating the 1-inch billets with a lubricant before they were heated lowered the friction coefficient from about 0.16 to about 0.10. The final forging pressures ranged from 17,800 to 42,400 psi, depending on the friction coefficient and the final diameter and thickness of the disks. Thicker disks and lower friction coefficients resulted in lower forging pressures.

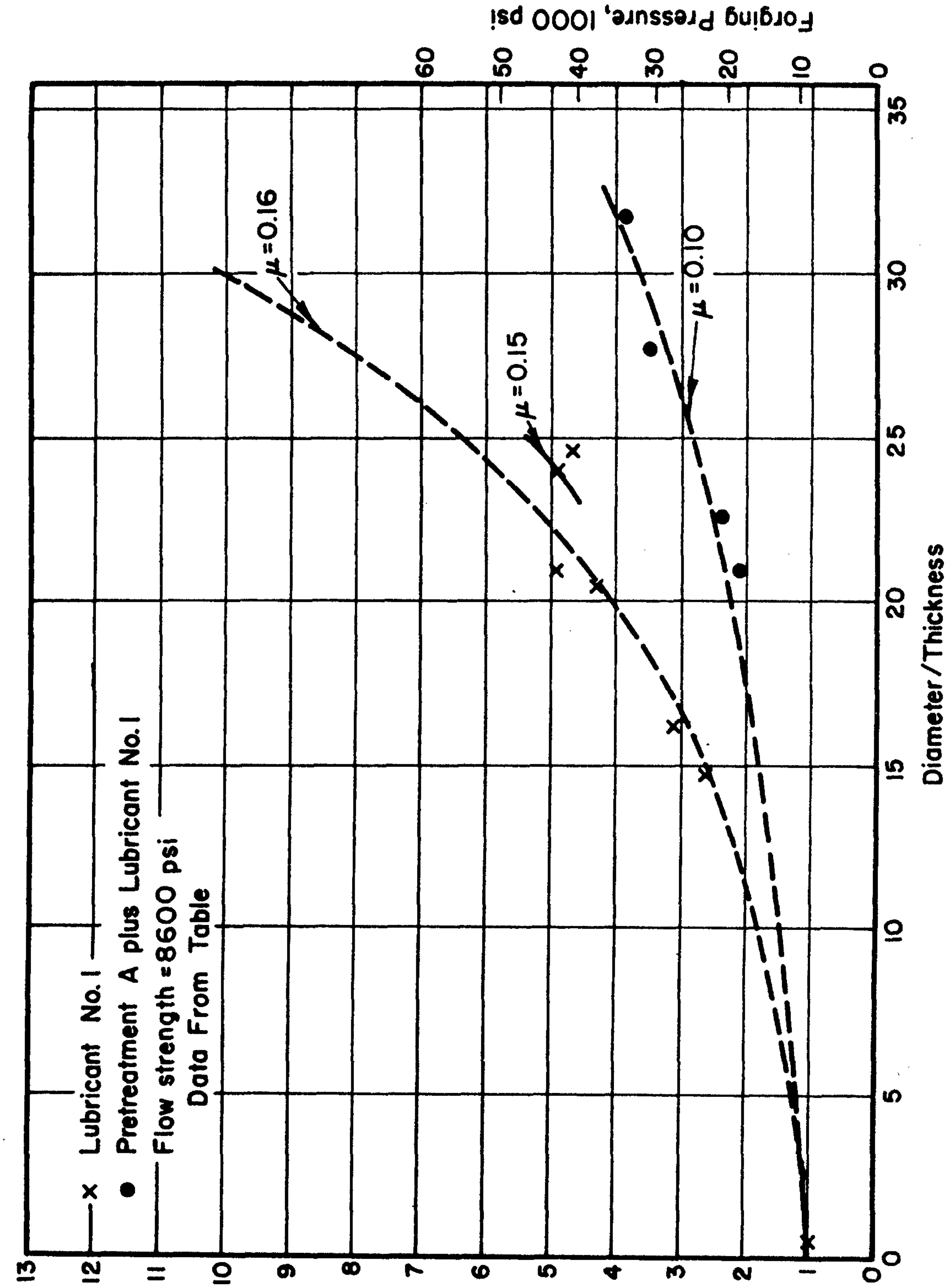
The larger billets had higher flow strengths than the 1-inch rounds because they were chilled by contact with dies heated to only 300 F. Based on bulging tests, an appropriate flow stress was chosen for calculating friction coefficients. The friction coefficients were higher in the tests with the big press because the dies were rough and worn. Nevertheless, the tests showed that the lubricating pretreatment lowered the friction coefficients about one-third. The changes in forging pressures and friction coefficients were comparable to those shown by the smaller specimens.

These and other tests described in this report show that the pressing test is useful for rating lubricants, especially for forging with flat dies. The data correlated fairly well with the laboratory forging tests, so the pressing test was used regularly for screening potential lubricants.

TABLE D-1. FRICTION COEFFICIENTS AND PRESSURE-MULTIPLICATION FACTORS IN FORGING FLAT DISKS OF 2014 ALUMINUM ALLOY WITH LUBRICANT 1[(a)]

Sample	Billet Treatment	Volume of Specimen[(b)], cu in.	Final Dimensions Diameter, in.	Final Dimensions Thickness, in.	Applied Load, 1000 lb	Average Pressure, 1000 lb	D/t	Friction Coefficient[(c)] (μ)	Pressure Multiplication Factor[(d)]
4-6	None	0.383	2.19	0.104	160	42.4	21.0	0.17	4.9
420-425	None	0.383	2.17	0.106	138	37.2	20.5	0.165	4.3
435-437	None	0.383	1.94	0.132	67	22.6	14.7	0.16	2.6
15	None	0.294	2.09	0.086	144	42.2	24.0	0.15	4.9
426-428	None	0.294	2.10	0.085	138	39.9	24.6	0.14	4.6
432-434	None	0.294	1.83	0.113	67	26.4	16.2	0.16	3.1
L2-L4	None	10.6	5.92	0.387	1200	43.5	15.3	0.22	4.1
L8-L9	None	7.1	5.38	0.306	1200	51.9	17.6	0.20	4.9
408-410	Caustic etch plus colloidal graphite	0.383	2.40	0.087	138	30.4	27.7	0.11	3.5
411-413		0.383	2.19	0.105	67	17.8	21.0	0.09	2.1
417-419		0.294	2.29	0.072	138	33.6	31.9	0.10	3.9
414-16		0.294	2.03	0.090	67	20.4	22.6	0.10	2.4
L5-L7		10.6	6.7	0.313	1200	35.4	21.4	0.13	3.4
L10-L11		7.1	5.9	0.258	1200	43.9	22.6	0.15	4.2

(a) Lubricant 1 contained flake graphite in an oil base. Data are averages for three or more specimens.
(b) Cylinders were 1 inch in diameter x 1/2 inch high, 1 inch in diameter x 3/8 inch high, 3 inches in diameter x 1/2 inch high, 3 inches in diameter x 1 inch high, respectively.
(c) Friction coefficients were calculated by the formula on page D-1.
(d) The pressure multiplication factor is equal to the average forging pressure divided by 8600 psi for the small specimens and 10,500 psi for the large specimens, the apparent flow strength under the testing conditions employed. In the tests on the larger specimens, the dies were rougher than they were in tests on the small billets. All billets were heated to 825 F; the dies were heated to 700 F and 300 F for small and large specimens, respectively.



A-16861

FIGURE D-1. EXPERIMENTAL DATA CONFIRMING THE RELATIONSHIP BETWEEN FORGING PRESSURES, FRICTION COEFFICIENTS, AND DIAMETER-TO-THICKNESS RATIOS EXPRESSED BY THE FORMULA ON PAGE D-1

APPENDIX E

MATERIALS AND BILLET TREATMENTS USED AS LUBRICANTS

TABLE E-1. LIST OF MATERIALS AND VARIOUS BILLET TREATMENTS USED IN THE STUDY ON LUBRICANTS FOR FORGING AND EXTRUDING FERROUS AND NONFERROUS MATERIALS

Lubricant	Description[a]
1	Commercial hot-forging die lubricant containing flake graphite in an oil carrier. This material is being used currently by a large forge shop as a die lubricant in forging aluminum.
	Dilution: 1 to 1 by volume with Oil A[b].
1A	Same as above, but undiluted.
2	Commercial hot-forging die lubricant containing flake graphite in an oil carrier.
	Dilution: 1 to 1 by volume with Oil A[b].
3	Commercial hot-forging die lubricant containing colloidal graphite in an oil carrier.
	Dilution: 1 part to 30 parts by volume of Oil A[b].
4	Commercial hot-forging die lubricant containing colloidal graphite in a water carrier.
	Dilution: 1 part to 30 parts by volume of distilled water.
4A	Same as Lubricant 4, except diluted 1 part to 5 parts by volume of distilled water.
4B	Same as Lubricant 4, except diluted 1 part to 20 parts by volume of distilled water.
4C	Same as Lubricant 4, except diluted 1 part to 10 parts by volume of distilled water.
5	Experimental commercial lubricant containing graphite and powdered molybdenum disulfide in an oil carrier.
	Dilution: 1 part to 10 parts by volume of Oil A[b].
6	Experimental commercial lubricant containing a dispersion of graphite and powdered molybdenum disulfide in a water carrier. The solid portions of this lubricant are the same as in Lubricant 5.
	Dilution: 1 part to 20 parts by volume of distilled water.
7	Commercial hot-forging die lubricant containing flake graphite in an oil carrier (same as Lubricant 2).
	Dilution: 1 to 1 by volume with 100-SUS soluble oil.
8	Commercial hot-forging die lubricant containing flake graphite in an oil carrier.
	Dilution: 1 to 1 by volume with Oil A[b].

TABLE E-1. (Continued)

Lubricant	Description[a]
9	Commercial hot-forging die lubricant containing flake graphite in an oil carrier. Dilution: 1 to 1 by volume with Oil A[b].
10	Commercial water-soluble hot-forging die lubricant containing graphite. Dilution: 1 part to 2 parts by volume of distilled water.
11	Five per cent by weight of boron nitride (98 per cent purity) in an ester-type synthetic high-temperature lubricant as a carrier.
12	Commercial hot-forging die lubricant containing colloidal graphite suspended in an oil carrier. Dilution: 1 part to 100 parts by volume of kerosene.
13	Commercial hot-forging die lubricant containing flake graphite in an oil carrier. The mixture contained a small percentage of aluminum soap. Dilution: 1 part to 2 parts by volume of Oil A[b].
14	Commercial hot-forging die lubricant containing a medium percentage of molybdenum disulfide in an oil-type carrier. The mixture contained lithium soap. Dilution: 1 part to 4 parts by volume of kerosene.
15	Same as Lubricant 14, but diluted 1 part to 4 parts by volume of Oil A[b].
16	Commercial hot-forging die lubricant containing a high percentage of molybdenum disulfide in an oil carrier. The mixture contained calcium soap. Dilution: 1 part to 4 parts by volume of kerosene.
17	Same as Lubricant 16, but diluted 1 part to 4 parts by volume of Oil A[b].
18	A commercial lubricant of the grease type containing extreme pressure characteristics but no solid lubricant. This is ordinarily used for cold operation. Dilution: 1 part to 3 parts by volume of Oil A[b].
19	A commercial soapless-type grease containing no solid lubricant. As in Lubricant 18, this is ordinarily used for cold operations. Dilution: 1 part to 3 parts by volume of Oil A[b].
20	Commercial lead-free glass wool.
21	Sodium silicate (water glass).
22	Phosphate-type glass containing 27.8% Na_2O, 63.6% P_2O_5, and 8.5% ZnO. This composition was produced in the laboratory and was ground to -65 + 80 mesh for use (see Appendix G for Development of Low-Melting Glasses).

TABLE E-1. (Continued)

Lubricant	Description[a]
23	Monoplex S-71 (ester-type plasticizer; flash point, 395 F).
24	Paraplex G62 (ester-type plasticizer; flash point, 590 F).
25	Dow Corning 550 Fluid (silicone fluid; viscosity 300-400 SUS at 100 F, flash point, 600 F).
26	Acryloid B-72 (acrylic resin in a toluene solvent).
27	Rhoplex AC-33 (water emulsion of an acrylic polymer having a solids content of 46 to 47 per cent).
28	Aluminum billet treatment consisting of a phosphatizing coating. The billets were prepared as follows: (1) Degreased in acetone (2) Alkaline cleaning bath at 180 F for 5 minutes (2-1/2% washing soda, 3/4% sodium silicate, in water) (3) Water rinse (cold) (4) Acid dip, 15 seconds at room temperature (40% HNO_3, 1% HF) (5) Water rinse (cold) (6) Phosphatizing bath, 7 minutes at room temperature (100 grams of 75% phosphoric acid in 900 cc water) (7) Water rinse (cold) (8) Acetone dip.
29	Aluminum billet treatment consisting of a zincate coating. The billets were prepared as follows: (1) Degreased in acetone (2) Alkaline cleaner (same as in 28) (3) Water rinse (cold) (4) 5% sodium hydroxide, 30 seconds at 170 F (5) Water rinse (cold) (6) Nitric acid (concentrated) dip; 1 minute at room temperature (7) Water rinse (cold) (8) Zincate bath; 2 minutes at room temperature (1050 grams NaOH, 200 grams ZnO in 2 liters water) (9) Water rinse (cold) (10) Acetone dip.
30	Aluminum billet treatment consisting of an etched surface. The billets were prepared as follows: (1) Degreased in acetone (2) Alkaline cleaner (same as in Lubricant 28) (3) Water rinse (4) Acid dip; 20 seconds at room temperature (40% HNO_3, 1% HF in water) (5) Water rinse (6) 5% sodium hydroxide; 150 F for 5 minutes (7) Water rinse (8) Acid dip, same as Step (4) (9) Water rinse.

TABLE E-1. (Continued)

Lubricant	Description[a]
31	Aluminum billet treatment consisting of a phosphate coating (alcohol). The billets were prepared as follows: (1) Degreased in acetone (2) Alkaline cleaner; 2 minutes at 180 F (washing soda and trisodium phosphate in water) (3) Water rinse (4) Acid dip; 20 seconds at room temperature (40% HNO_3, 1% HF in water) (5) Water rinse (6) Phosphoric acid (alcohol) dip for 60 minutes at room temperature (400 cc butyl alcohol, 300 cc isopropyl alcohol, 100 cc H_3PO_4, and 200 cc water) (7) Water rinse (8) Acetone dip.
32	Aluminum billet treatment consisting of a sealed Alrok coating. The billets were prepared as follows: (1) Degreased in acetone (2) Alkaline cleaner (same as in Lubricant 28) (3) Water rinse (4) 5% sodium hydroxide, 10 seconds at 120 F (5) Water rinse (6) Nitric acid (concentrated) dip; 10 seconds at room temperature (7) Water rinse (8) Acid dip; 20 seconds at room temperature (40% HNO_3, 1% HF in water) (9) Water rinse (10) Alrok solution; 20 minutes at 180 F (40 grams sodium carbonate, 2 grams potassium dichromate in 1958 cc water) (11) Water rinse (12) Sealer (5% potassium dichromate), 10 minutes at 180 F (13) Water rinse (14) Acetone dip.
33	Aluminum billet treatment consisting of an unsealed Alrok coating. The billets were prepared as in the first 11 steps of Lubricant 32 treatment plus a dip in acetone.
34	10% by weight of minus 100-mesh aluminum sulfate in Oil A[b].
35	10% by weight of minus 100-mesh ammonium sulfate in Oil A[b].
36	10% by weight of powdered molybdenum disulfide (Molykote Type Z) in Oil A[b].
37	10% by weight of medium flake graphite[c] in Oil A[b].
38	10% by weight of minus 100-mesh tungsten disulfide in Oil A[b].
39	20% by weight of aluminum powder in Oil A[b].
40	10% by weight of minus 48-mesh indium powder in Oil A[b].
41	20% by weight of medium flake graphite[c] in Monoplex S-71 as a carrier.

TABLE E-1. (Continued)

Lubricant	Description[a]
42	20% powdered molybdenum disulfide (Molykote Type Z) in Monoplex S-71 as a carrier. This carrier is the same as Lubricant 23.
43	10% by weight of minus 100-mesh tungsten disulfide in Oil B[b].
44	10% by weight of medium flake graphite[c] in Oil B[b].
45	10% by weight of molybdenum disulfide (Molykote Type Z) in Oil B[b].
46	10% by weight of finely powdered talc in Oil B[b].
47	10% by weight of water-ground powdered mica in Oil B[b].
48	Commercial Lubricant 3 consisting of colloidal graphite in an oil base diluted 1 part to 5 parts of Oil B[b].

The following four lubricants were compounded by a lubricants manufacturer for experimental work on the extrusion of titanium [WADC Technical Report 54-555, December 1954, for USAF Contract No. AF 33(038)-3736]. [Reference (23) in Bibliography.]

Lubricant	Description
49	Experimental lubricant containing 35% flake graphite and 5% mica in a calcium-base grease.
	Dilution: 1 part to 3 parts by volume of Oil A[b].
49A	Same as Lubricant 49, but undiluted.
50	Experimental lubricant containing 25% molybdenum disulfide and 5% mica in a calcium-base grease.
	Dilution: 1 part to 3 parts by volume of Oil A[b].
50A	Same as Lubricant 50, but undiluted.
51	Experimental lubricant containing 25% flake graphite, 15% molybdenum disulfide, and 5% mica in a calcium-base grease.
	Dilution: 1 part to 3 parts by volume of Oil A[b].
51A	Same as Lubricant 51, but undiluted.
52	Experimental lubricant containing 25% flake graphite, 15% molybdenum disulfide, and 5% mica in bentone grease.
	Dilution: 1 part to 3 parts by volume of Oil A[b].
52A	Same as Lubricant 52, but undiluted.
53	Silicone grease (Dow Corning No. 41). This grease is designed to operate at temperatures from -20 to 400 F.
	Dilution: 1 part to 8 parts by volume of Oil A[b].
54	Polyamide Resin No. 90 (General Mills).
55	5% by weight of powdered boron nitride (98% purity) in Oil B[b].
56	Di-ester synthetic turbo oil.

TABLE E-1. (Continued)

Lubricant	Description[a]
57	20% by weight of powdered molybdenum disulfide (Molykote Type Z) in Paraplex G62 as a carrier. This carrier is Lubricant 24.
58	20% by weight of medium flake graphite[c] in Paraplex G62 as a carrier. This carrier is Lubricant 24.
59	Oil B[b].
60	20% solution of potassium fluoborate in water.
61	20% solution of sodium fluoborate in water.
62	20% solution of ammonium fluoborate in water.
63	20% solution of stannous fluoborate in water.
64	20% solution of lead fluoborate in water.
65	20% by weight of powdered boron nitride (98% purity) in Paraplex G62 as a carrier. This carrier is the same as Lubricant 24.
66	Epoxy resin (Epon 828).
67	Epoxy resin (Epon RN34). This resin was much more viscous than Lubricant 66.
68	20% by weight of powdered molybdenum disulfide (Molykote Type Z) in Epon 828.
69	20% by weight of medium flake graphite[c] in Epon 828.
70	20% by weight of aluminum powder in Oil B[b].
71	20% by weight of minus 100-mesh tungsten disulfide in Paraplex G62 as a carrier. This carrier was the same as Lubricant 24.
72	20% by weight of minus 100-mesh tungsten disulfide in Epon 828, an epoxy resin, as a carrier.
73	Aluminum billet dip containing 2 parts of A and 1 part of B. A – 1 part of aqueous colloidal graphite concentrate (22% graphite) to 3.5 parts of distilled water. B – 15% sodium silicate in water. This coating has been used as a self-lubricating coating for aluminum articles subject to wear or friction. (U. S. Patent 2,157,155).
74	10% by weight of powdered boron nitride (98% purity) and 10% powdered molybdenum disulfide (Molykote Type Z) in Paraplex G62 as a carrier. This carrier was the same as Lubricant 24.
75	10% by weight of powdered boron nitride (98% purity) in Oil B[b].
76	10% by weight of aluminum powder in Oil B[b]
77	20% by weight of large flake graphite[c] in Oil B[b].

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TABLE E-1. (Continued)

Lubricant	Description[a]
78	20% by weight of medium flake graphite[c] in Oil B[b].
79	20% by weight of fine flake graphite[c] in Oil B[b].
80	20% by weight of extra-fine flake graphite[c] in Oil B[b].
81	Commercial borax glass (30 mesh).
82	Commercial potash feldspar (140 to 200 mesh).
83	20% by weight of extra-fine flake graphite[c] in Oil C[b].
84	20% by weight of extra-fine flake graphite[c] in Oil A[b].
85	20% by weight of extra-fine flake graphite[c] in Paraplex G62 as a carrier. This carrier was the same as Lubricant 24.
86	20% by weight of powdered boron nitride (98% purity) in Oil B[b].
87	13% by weight of powdered boron nitride (98% purity) in a mixture containing 1 part of Dow Corning Silicone Grease 41 to 2-1/2 parts of Oil B[b].
88	20% by weight of extra-fine flake graphite[c] in a 1-to-1 by volume mixture of Dow Corning Silicone Grease 41 and Oil B[b].
89	10% extra-fine flake graphite[c] and 10% boron nitride (98% purity) by weight in Paraplex G62 as a carrier. This carrier was the same as Lubricant 24.
90	10% large flake graphite[c] and 10% powdered boron nitride (98% purity) by weight in Paraplex G62 as a carrier.
91	Temperature-critical material; melting point, 650 F.
92	Temperature-critical material; melting point, 475 F.
93	Fused sodium hydroxide (cp grade).
94	Fused potassium hydroxide (cp grade).
95	Aluminum foil; 0.0015 inch thick; melting point, 1215 F.
96	Copper foil, 0.008 inch thick; melting point, 1980 F.
97	Tetrafluorethylene tape, 0.010 inch thick.
98	Zinc foil, 0.0005 inch thick; melting point, 787 F.
99	Lead foil, 0.004 inch thick; melting point, 620 F.
100	Tin foil, 0.002 inch thick; melting point, 450 F.
101	Paraplex G50, an ester-type plasticizer.
102	Paraplex G60, an ester-type plasticizer.
103	20% by weight of powdered boron nitride (98% purity) in Paraplex G60 as a carrier. This carrier was the same as Lubricant 102.

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TABLE E-1. (Continued)

Lubricant	Description[a]
104	20% by weight of powdered boron nitride (98% purity) in Paraplex G50 as a carrier. This carrier was the same as Lubricant 101.
105	20% extra-fine flake graphite[c] in Paraplex G50 as a carrier. This carrier was the same as Lubricant 101.
106	20% extra-fine flake graphite[c] in Paraplex G60 as a carrier. This carrier was the same as Lubricant 102.
107	Commercial hot-forging die lubricant containing flake graphite in an oil carrier. The mixture contained a small percentage of aluminum soap. The lubricant is the same as Lubricant 13 but of a heavier consistency.

Lubricants 108-122 are glasses of various compositions ground to minus 100-mesh powder. These materials were made in the laboratory.

	Composition, weight per cent							Relative Viscosity at 1700 F
	Na_2O	B_2O_3	SiO_2	TiO_2	BaO	ZrO_2	Others	
108	20	15	30	--	30	5	--	Very fluid
109	25	20	30	25	--	--	--	Ditto
110	20	20	30	20	--	--	10 PbO	"
111	25	20	30	--	--	--	25 PbO	"
112	25	20	30	5	--	--	20 SnO	"
113	25	20	30	15	--	--	10 CuO	"
114	22	20	33	25	--	--	--	Very fluid
115	19	20	36	25	--	--	--	More viscous than Lubricant 114
116	16	20	39	25	--	--	--	More viscous than Lubricant 115
117	13	20	42	25	--	--	--	Very viscous, would not pour
118	17	15	33	--	30	5	--	Very fluid
119	14	15	36	--	30	5	--	More viscous than Lubricant 118
120	11	15	39	--	30	5	--	More viscous than Lubricant 119
121	8	15	42	--	30	5	--	Very viscous, but would pour

122	50% No. 111 and 50% No. 113 by weight.
123	25% by weight of extra-fine flake graphite[c] in sodium Paraplex G60 grease.

The sodium Paraplex G60 grease was prepared by heating to about 300 F, 300 grams of Paraplex G60 and 70 grams of sodium stearate. Upon cooling, a heavy grease resulted. This grease was water soluble, that is, it could be removed from an object by cold or hot water without resorting to a solvent. This grease was prepared because other work had indicated that a grease-base carrier seemed to hold the solid portion of a lubricant in place on the tools for extruding.

124	25% by weight of powdered boron nitride (98% purity) in sodium Paraplex G60 grease (see Lubricant 123).
125	Temperature-critical material; melting point, 338 F.
126	Temperature-critical material; melting point, 363 F.
127	Temperature-critical material; melting point, 375 F.
128	Temperature-critical material; melting point, 388 F.
129	Temperature-critical material; melting point, 400 F.

TABLE E-1. (Continued)

Lubricant	Description[a]
130	Temperature-critical material; melting point, 413 F.
131	Temperature-critical material; melting point, 425 F.
132	Temperature-critical material; melting point, 438 F.
133	Temperature-critical material; melting point, 450 F.
134	Temperature-critical material; melting point, 463 F.
135	Temperature-critical material; melting point, 488 F.
136	Temperature-critical material; melting point, 500 F.
137	Temperature-critical material; melting point, 550 F.
138	Temperature-critical material; melting point, 600 F.
139	Temperature-critical material; melting point, 1150 F.
140	Temperature-critical material; melting point, 1250 F.
141	Temperature-critical material; melting point, 1350 F.
142	Temperature-critical material; melting point, 1450 F.
143	Nylon powder.
144	Tetra-n-butyl ammonium hexafluorophosphate; melting point, 482 F.
145	Mono-n-butyl ammonium hexafluorophosphate; melting point, 332 F.
146	Mono-tertiarybutyl ammonium hexafluorophosphate.
147	Potassium hexafluorophosphate.
148	Commercial hot-extrusion lubricant containing natural graphite in an oil carrier. Used as received.
149	Tetrafluorethylene resin finish, primer for steel (low-viscosity dispersion in essentially a water medium).
150	Tetrafluorethylene resin finish, primer for aluminum (as in Lubricant 149, this is a low-viscosity dispersion in essentially a water medium).
151	Molybdenum disulfide powder (Molykote Type Z).
152	5% by weight of coagulated tetrafluorethylene resin (primer for aluminum) in Paraplex G62. The material was coagulated by freezing and separated by levigation.
153	20% by weight of molybdenum disulfide (Molykote Type Z) in Paraplex G50.
154	Commercial hot-forging die lubricant containing colloidal graphite in an oil base (same as Lubricant 3).
	Dilution: 1 part to 5 parts by volume of Paraplex G50.

TABLE E-1. (Continued)

Lubricant	Description[a]
155	30% by weight of medium flake graphite[c] in Oil B[b].
156	10% by weight of extra-fine flake graphite[c] in Oil B[b].
157	30% by weight of extra-fine flake graphite[c] in Oil B[b].
158	1.25% by weight of colloidal graphite and an equal weight of powdered molybdenum disulfide (Molykote Type Z) in distilled water.
159	Same as Lubricant 158, but containing extra-fine flake graphite[c] in place of the colloidal graphite. A wetting agent was also added.
160	Trimethylammonium hexafluorophosphate; melting point, 338 F.
161	Tetramethylammonium fluoborate; melting point, 788 F. This material was prepared in the laboratory.
162	Tetraethylammonium fluoborate; melting point, 689 F. This material was prepared in the laboratory.
163	Tetra-n-tetraethylammonium hexafluorophosphate; melting point, 617 F. This material was prepared in the laboratory.
164	Tetra-n-tetramethylammonium hexafluorophosphate; melting point, >752 F. This material was prepared in the laboratory.
165	Isopropyl tri-n-propylammonium hexafluorophosphate; melting point, 365-374 F. This material was prepared in the laboratory.
166	n-Amyl triethylammonium hexafluorophosphate; melting point, 320-329 F. This material was prepared in the laboratory.
167	Methyl tri-n-butylammonium hexafluorophosphate; melting point, 257 F. This material was prepared in the laboratory.
168	n-Butyl-tri-n-triethylammonium hexafluorophosphate; melting point, 320 F. This material was prepared in the laboratory.
169	n-Soya trimethylammonium hexafluorophosphate; melting point, 329-365 F. This material was prepared in the laboratory.
170	n-Benzyl tri-n-trimethylammonium hexafluorophosphate; melting point, 248 F.
171	n-Dodecylbenzyl tri-n-trimethylammonium hexafluorophosphate; melting point, 354 F.

The four following materials are glasses having the indicated compositions. The glasses were prepared in the laboratory.

	Composition, weight per cent					Relative Viscosity at 1700 F
	Na_2O	B_2O_3	SiO_2	PbO	CuO	
172	20	15	30	35	--	Very fluid
173	25	20	30	--	25	Very fluid
174	25	20	30	12.5	12.5	Very fluid
175	20	15	30	--	35	Very fluid

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TABLE E-1. (Continued)

Lubricant	Description[a]
176	Commercial hot-forging die lubricant containing no solid lubricating material. Dilution: 1 part to 1 part by volume of Oil A[b].
177	Commercial hot-working die lubricant containing flake graphite and powdered aluminum in an oil base. Dilution: 1 part to 1 part by volume of Oil A[b].
178	11% by weight of the black residue resulting from etching 2014 aluminum alloy in sodium hydroxide in Oil B[b].
179	Billet given an unsealed Alrok coating (Lubricant 33) then dipped in an aqueous suspension of colloidal graphite[d] (10% by weight) at 150 F.
180	Billets vapor blasted.
181	Billets vapor blasted then dipped in an aqueous suspension of colloidal graphite[d] (10% by weight) at 150 F.
182	Billets untreated (degreased only) and dipped in an aqueous suspension of colloidal graphite[d] (10% by weight) at 150 F.

(The following surface preparations, Lubricants 183 through 208, were given aluminum billets.)

	Etching Conditions							
	Etchant	Concentration, per cent	Bath Temperature, F	Time in Bath	Rinse[e]	Acid Clean	Rinse[e]	Further Treatment
183	NaOH	10	150	30 sec	HW	--	--	Dip in suspension of colloidal graphite[f]
184	NaOH	10	150	2 min	HW	--	--	Ditto
185	NaOH	10	150	5 min	HW	--	--	None
186	NaOH	10	150	5 min	HW	--	--	Dip in suspension of colloidal graphite[f]
187	NaOH	10	150	5 min	HW	10% HNO_3	HW	None
188	NaOH	10	150	5 min	HW	10% HNO_3	HW	Dip in suspension of colloidal graphite[f]
189	NaOH	10	150	5 min	HW	--	--	Boron nitride powder rubbed on surface
190	NaOH	10	150	5 min	HW	--	--	Lubricant 73
191	NaOH	10	150	5 min	HW	--	--	Molybdenum disulfide powder rubber on surface[g]
192	NaOH	10	180	10 sec	HW	--	--	None

TABLE E-1. (Continued)

Lubricant	Description[a]							
	Etching Conditions							
	Etchant	Concentration, per cent	Temperature, F	Time in Bath	Rinse[e]	Acid Clean	Rinse[e]	Further Treatment
193	NaOH	10	180	30 sec	HW	--	--	None
194	NaOH	10	180	2 min	HW	--	--	None
195	NaOH	10	180	4 min	HW	--	--	None
196	NaOH	10	180	5 min	HW	--	--	None
197	NaOH	10	180	10 sec	HW	--	--	Dip in suspension of colloidal graphite[f]
198	NaOH	10	180	30 sec	HW	--	--	Ditto
199	NaOH	10	180	2 min	HW	--	--	"
200	NaOH	10	180	4 min	HW	--	--	"
201	Commercial caustic[h], Producer A	2.5 oz/gal[i]	180	2 min	HW	--	--	"
202	Ditto	Ditto	180	4 min	HW	--	--	"
203	"	6 oz/gal[j]	180	2 min	HW	--	--	"
204	"	Ditto	180	4 min	HW	--	--	"
205	Commercial caustic[h], Producer B	2.5 oz/gal[i]	180	2 min	HW	--	--	"
206	Ditto	Ditto	180	4 min	HW	--	--	"
207	"	6 oz/gal[j]	180	2 min	HW	--	--	"
208	"	Ditto	180	4 min	HW	--	--	"
209	Magnesium billets etched in 20% by volume of glacial acetic acid at room temperature for 2 minutes, then rinsed. This produced a light-gray hydroxide coating on the surface.							
210	Same as Lubricant 209 but further etched in 10% by volume of nitric acid.							
211	Same as Lubricant 210 but further dipped in an aqueous suspension of colloidal graphite[f].							
212	Magnesium billets etched in 20% by volume of glacial acetic acid at room temperature for 2 minutes, rinsed in water, then dipped in an aqueous suspension of colloidal graphite[f].							
213	Magnesium billets etched for 2 minutes in 20% by volume of glacial acetic acid, rinsed in water, then the surfaces were rubbed with powdered molybdenum disulfide[g].							

TABLE E-1. (Continued)

Lubricant	Description[a]
214	Same as Lubricant 213, but the surfaces were rubbed with powdered boron nitride (98% purity).
215	Magnesium billets etched in 15% by volume of hydrofluoric acid at room temperature, rinsed in water, then heated for 30 minutes in boiling sodium dichromate solution (50 g/500 ml of water) saturated with calcium fluoride.
216	Same as Lubricant 215, but further dipped in an aqueous suspension of colloidal graphite[f].
217	Titanium billets heated in a commercial salt bath consisting of barium chloride and fluoride and salts of sodium, calcium, and aluminum. Melting point, 1550 F.
218	No protective atmosphere used in furnace for heating titanium.
219	20% by weight of powdered molybdenum disulfide[g] in oil B[b].
220	20% by weight of powdered molybdenum disulfide[g] in Paraplex G60 as a carrier.
221	20% by weight of powdered boron nitride (98% purity) in Epon 828, an epoxy resin, as a carrier.

(a) Where possible, trade names are omitted.
(b) Oils used for compounding and diluting lubricants consist of the following:

Oil A – Napthene-base oil having a flash point of 320 F and a viscosity of 106 SUS at 100 F.

Oil B – One-to-one mixture by volume of Oils A and C.

Oil C – 600 W cylinder oil having a flash point of 540 F and a viscosity of 1970 SUS at 100 F.

(c) Flake graphites used in compounding various lubricants consisted of four different grades all produced by the same manufacturer. The sizes were graded according to the following classifications:

(1) Large flakes
(2) Medium powdered flakes
(3) Finely powdered flakes
(4) Extra-finely powdered flakes.

(d) The aqueous colloidal graphite used was a commercial preparation which contained 22 per cent graphite.
(e) Hot-water rinse.
(f) 10% by weight of an aqueous colloidal graphite commercial preparation, containing 22% graphite, was suspended in distilled water. This bath was maintained at 150 F in order to heat the billets. Upon removal from the bath, the billets dried quickly, leaving a uniform coating of colloidal graphite on the billet surface.
(g) Molykote Type Z.
(h) These are proprietary caustic etching preparations. They are specially formulated to prevent frothing of the bath and to prevent the buildup of sludge in the bottom of the etching tanks.
(i) 2.5 ounces per gallon is a minimum concentration that is sometimes used prior to replenishing the bath.
(j) 6 ounces per gallon is the recommended concentration for use.

APPENDIX F

DATA OBTAINED IN WORKING 2014 ALUMINUM ALLOY

TABLE F-1. FORGING-TEST DATA OBTAINED ON 2014 ALUMINUM ALLOY USING VARIOUS METHODS OF LUBRICATION

Lubricant[(a)]	Billet Treatment	Forging Pressure[(b)], psi	Die Temperature, F	Forging Sample	Penetration Into Die Cavity[(c)], in. 1	2	3	4	5	6	Average Penetration, in.	Surface Rating[(d)] Face	Radius	Ends	Remarks
1 (S)	None	36,000	500	1-2	0.55	0.56	-	-	-	-	0.56	A	B	A	-
1 (S)	None	46,000	500	3	0.78	-	-	-	-	-	0.78	A	B	A	-
1 (S)	None	55,000	500	4	0.89	-	-	-	-	-	0.89	A	B	A	-
1 (S)	None	65,000	500	5	1.06	-	-	-	-	-	1.06	A	B	B	-
1 (S)	None	36,000	700	6	1.16	-	-	-	-	-	1.16	B	A	A	-
1 (S)	None	46,000	700	7	1.39	-	-	-	-	-	1.39	B	B	B	-
1 (S)	None	55,000	700	8	1.50	-	-	-	-	-	1.50	B	A	A	-
1 (S)	None	65,000	700	9	1.80	-	-	-	-	-	1.80	A	A	B	-
1 (S)	None	46,000	700	152-154	1.55	1.48	1.37	-	-	-	1.47	A	A	A	Sprayed 10 sec
1 (S)	None	46,000	700	155-157	1.25	1.42	1.28	-	-	-	1.31	A	A	B	-
1 (S)	None	46,000	700	308-313	1.20	1.39	1.37	1.47	1.53	1.47	1.40	B	A	A	-
2 (S)	None	46,000	700	14	1.37	-	-	-	-	-	1.37	C	B	A	-
2 (S)	None	46,000	700	205-207	1.19	1.26	1.34	-	-	-	1.26	C	C	C	-
3 (S)	None	46,000	700	19-21	1.44	1.55	1.48	-	-	-	1.48	A	A	B	-
4 (S)	None	46,000	700	69-71	0.95	0.90	1.06	-	-	-	0.97	B	B	D	Sprayed from one side
4 (S)	None	46,000	700	137-139	1.00	1.23	1.39	-	-	-	1.20	C	B	B	Sprayed 10 sec
4 (S)	None	46,000	700	140-142	1.11	1.22	1.25	-	-	-	1.19	C	A	B	Sprayed 5 sec from two sides
4A (S)	None	46,000	700	166-168	1.19	1.66	1.73	-	-	-	1.53	B	A	B	Sprayed 10 sec
4A (S)	None	46,000	700	169-171	1.20	1.33	1.47	-	-	-	1.33	C	A	B	-
5 (S)	None	46,000	700	12	1.48	-	-	-	-	-	1.48	B	A	B	-
5 (S)	None	46,000	700	208-210	1.34	1.37	1.31	-	-	-	1.34	B	A	A	-
5 (S)	None	46,000	700	549-554	1.45	1.55	1.66	1.53	1.58	1.58	1.56	C	B	B	-
6 (S)	None	46,000	700	72-74	1.19	1.34	1.11	-	-	-	1.22	B	A	A	-
6 (S)	None	46,000	700	555-560	1.05	1.14	1.11	1.14	1.12	1.16	1.12	C	B	C	-
7 (S)	None	46,000	700	13	1.33	-	-	-	-	-	1.33	B	A	B	-
7 (S)	None	46,000	700	211-213	1.03	1.23	1.31	-	-	-	1.19	B	A	B	Sprayed 10 sec
8 (S)	None	46,000	300	58-59	0.53	0.44	-	-	-	-	0.48	A	A	A	-
8 (S)	None	46,000	500	10, 57	0.78	0.76	-	-	-	-	0.77	B	B	A	-
8 (S)	None	46,000	700	11, 22-23	1.42	1.37	1.40	-	-	-	1.40	B	B	B	-
8 (S)	None	46,000	700	158-160	1.12	1.53	1.69	-	-	-	1.45	C	A	C	Sprayed 10 sec
8 (S)	None	46,000	700	163-165	1.30	1.44	1.66	-	-	-	1.47	C	A	C	-
8 (S)	None	46,000	900	55-56	1.62	1.73	-	-	-	-	1.69	A	A	A	-
10 (S)	None	46,000	700	78-80	0.98	1.06	1.14	-	-	-	1.06	B	A	B	5 sec, sprayed one direction
10 (S)	None	46,000	700	134-136	1.23	1.31	1.31	-	-	-	1.28	C	A	A	10 sec, sprayed two directions
10 (S)	None	46,000	700	143-145	1.08	1.28	1.37	-	-	-	1.25	C	B	B	5 sec, sprayed two directions
13 (S)	None	46,000	700	81-83	1.12	1.31	1.51	-	-	-	1.31	C	B	B	-
15 (S)	None	46,000	700	84-86	1.11	1.22	1.14	-	-	-	1.16	A	A	A	-
17 (S)	None	46,000	700	24-26	1.39	1.53	1.40	-	-	-	1.44	B	A	A	-
18 (S)	None	46,000	700	87-89	0.97	0.95	1.01	-	-	-	0.98	A	A	B	-
19 (S)	None	46,000	700	90-92	0.97	0.94	0.90	-	-	-	0.94	A	A	B	-
22 (BR)	None	46,000	700	223-225	1.12	1.19	1.03	-	-	-	1.11	A	C	C	Billet rolled in powdered glass
23 (B)	None	46,000	700	93-95	1.03	1.05	1.00	-	-	-	1.03	A	A	B	-
24 (B)	None	46,000	700	102-104	1.08	0.98	1.06	-	-	-	1.05	A	A	B	-
43 (S)	None	46,000	700	105-107	0.90	1.05	1.08	-	-	-	1.01	A	A	A	-
44 (S)	None	46,000	700	108-110	1.08	1.48	1.34	-	-	-	1.30	B	A	B	-
44 (S)	None	46,000	700	391-394	1.31	1.44	1.59	1.55	-	-	1.47	B	B	A	-
45 (S)	None	46,000	700	111-113	0.98	1.22	1.08	-	-	-	1.09	A	A	A	-
45 (S)	None	46,000	700	149-151	1.05	1.08	1.05	-	-	-	1.06	A	A	B	-
45 (S)	None	46,000	700	146-148	1.44	1.25	1.17	-	-	-	1.28	B	B	B	10-sec spray
46 (S)	None	46,000	700	114-116	1.11	1.20	1.05	-	-	-	1.12	A	A	A	-
47 (S)	None	46,000	700	117-119	0.89	0.90	0.94	-	-	-	0.90	B	A	B	-
48 (S)	None	46,000	700	120-122	1.09	1.26	1.11	-	-	-	1.16	B	A	B	-

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TABLE F-1 (Continued)

Lubricant[a]	Billet Treatment	Forging Pressure[b], psi	Die Temperature, F	Forging Sample	Penetration Into Die Cavity[c], in. 1	2	3	4	5	6	Average Penetration, in.	Surface Rating[d] Face	Radius	Ends	Remarks
49 (S)	None	46,000	500	99-101	0.67	0.75	0.83	–	–	–	0.75	B	A	A	–
49 (S)	None	46,000	700	29-31	1.56	1.64	1.70	–	–	–	1.64	C	A	C	–
49 (S)	None	46,000	900	96-98	1.80	1.75	1.64	–	–	–	1.73	C	B	C	–
50 (S)	None	46,000	700	32-34	1.67	1.48	1.39	–	–	–	1.51	B	A	B	–
51 (S)	None	46,000	700	38-40	1.69	1.56	1.62	–	–	–	1.62	B	A	B	–
52 (S)	None	46,000	700	41-43	1.31	1.39	1.45	–	–	–	1.39	A	A	A	–
53 (S)	None	46,000	700	27-28, 226-227	1.20	1.12	1.00	0.98	–	–	1.10	B	A	C	–
54 (DR)	None	46,000	700	123-125	1.01	0.95	0.97	–	–	–	0.98	A	A	A	–
57 (B)	None	46,000	700	126-128	1.06	1.16	1.12	–	–	–	1.11	A	A	B	–
58 (B)	None	46,000	700	129-131, 80	1.05	1.03	1.25	1.25	–	–	1.15	B	A	B	–
59 (S)	None	46,000	700	199-201	0.90	1.06	1.16	–	–	–	1.05	A	A	A	–
65 (B)	None	46,000	700	15-16	1.26	1.17	–	–	–	–	–	A	A	B	–
65 (B)	None	46,000	700	228-229	1.12	1.45	–	–	–	–	–	A	C	C	(e)
65 (B)	None	46,000	700	230-242	1.20 1.39 1.40	1.42 1.72	1.78 1.23	1.36 1.53	1.34 1.45	1.33 1.81	– 1.50 (Flamed) 1.20 (Didn't flame)	A	A	B	(e)
66 (B)	None	46,000	700	190-192	0.94	0.90	1.00	–	–	–	0.95	A	A	A	–
68 (B)	None	46,000	700	193-195	1.05	1.06	1.08	–	–	–	1.06	A	A	A	–
69 (B)	None	46,000	700	196-198	1.09	1.11	1.23	–	–	–	1.14	B	B	B	–
70 (S)	None	46,000	700	202-204	0.94	1.09	1.01	–	–	–	1.01	A	A	B	–
71 (B)	None	46,000	700	220-222, 18	1.08	1.31	1.26	1.30	–	–	1.24	A	A	B	–
72 (B)	None	46,000	700	603-605	1.19	1.19	1.42	–	–	–	1.26	B	B	B	–
74 (B)	None	46,000	700	172-174	1.14	1.23	1.36	–	–	–	1.25	A	B	B	–
75 (S)	None	46,000	700	630-632	1.12	1.08	1.19	–	–	–	1.12	B	B	C	–
76 (S)	None	46,000	700	633-635	1.08	1.11	1.14	–	–	–	1.11	A	A	A	–
77 (S)	None	46,000	700	175-177	1.11	1.23	1.19	–	–	–	1.17	A	A	B	Graphite flakes clogged spray gun
78 (S)	None	46,000	700	187-189	1.11	1.33	1.36	–	–	–	1.26	A	A	C	–
78 (S)	None	46,000	700	178-180	1.12	1.61	1.47	–	–	–	1.55	A	A	B	–
78 (S)	None	46,000	700	395-398	1.09	1.55	1.47	1.62	–	–	1.44	B	B	A	–
79 (S)	None	46,000	700	181-183	1.14	1.50	1.45	–	–	–	1.36	A	C	C	–
80 (S)	None	46,000	700	184-186	1.14	1.50	1.59	–	–	–	1.40	B	B	B	–
80 (S)	None	46,000	700	407-412	1.48	1.51	1.78	1.64	1.75	1.55	1.64	B	A	B	–
83 (S)	None	46,000	700.	214-216	1.09	1.44	1.59	–	–	–	1.37	B	B	B	–
83 (S)	None	46,000	700	246-251	1.01	1.84	1.76	1.67	1.37	1.70	1.56	A	A	B	–
84 (S)	None	46,000	700	217-219	1.16	1.17	1.25	–	–	–	1.19	C	B	C	–
85 (S)	None	46,000	700	279-282	1.08	1.12	1.23	1.08	–	–	1.12	B	B	B	–
86 (S)	None	46,000	700	243-245	1.17	1.34	1.37	–	–	–	1.30	B	B	B	–
87 (B)	None	46,000	700.	606-608	1.36	1.34	1.36	–	–	–	1.36	C	B	C	
88 (B)	None	46,000	700	609-611	1.36	1.39	1.33	–	–	–	1.36	C	B	C	–
89 (B)	None	46,000	700	612-614	1.58	1.42	1.36	–	–	–	1.45	C	B	B	–
90 (B)	None	46,000	700	615-615	1.28	1.25	1.48	–	–	–	1.34	C	B	B	–
92 (BR)	Brushed on billet before heating	46,000	700	258-260	1.06	0.87	1.09	–	–	–	1.00	B	A	A	–
97[f]	None	46,000	700	275	1.01	–	–	–	–	–	1.01	Stuck, had to be chisled out			Tape inserted into die cavity

TABLE F-1. (Continued)

Lubricant[a]	Billet Treatment	Forging Pressure[b], psi	Die Temperature, F	Forging Sample	Penetration Into Die Cavity[c], in. 1	2	3	4	5	6	Average Penetration, in.	Surface Rating[d] Face	Radius	Ends	Remarks
104 (S)	None	46,000	700	297-299	1.17	1.17	1.23	–	–	–	1.19	B	B	B	–
105 (S)	None	46,000	700	291-293	1.51	1.40	1.42	–	–	–	1.45	C	A	A	–
106 (S)	None	46,000	700	294-296	1.14	0.90	0.97	–	–	–	1.00	C	B	A	–
143 (BR)	None	46,000	700	288-290	0.94	0.89	0.78	–	–	–	0.86	A	A	A	–
144 (BR)	None	46,000	700	261-263	0.95	0.89	0.94	–	–	–	0.92	A	A	A	Applied to billet
149 (B)	None	46,000	700	264-266	1.84	1.83	1.78	–	–	–	1.84	A	A	A	One application to dies
149 (B)	None	46,000	700	267-268	1.83	1.78	–	–	–	–	1.83	B	A	A	One application to dies
149 (B)	None	46,000	700	269-271	1.83	1.80	1.55	–	–	–	1.83	C	B	B	One application to dies
149 (B)	None	46,000	700	483-488	1.87	1.87	1.87	1.62	1.51	1.64	1.87	B	A	A	One application to dies, reapplied by spraying the die for Samples 487 and 488
152 (S)	None	46,000	700	276-278	1.06	1.08	1.22	–	–	–	1.12	A	A	A	–
153 (S)	None	46,000	700	300, 305-307	0.97	1.03	0.90	0.84	–	–	0.94	C	B	B	–
154 (S)	None	46,000	700	301-304	1.25	1.36	1.17	1.37	–	–	1.28	C	C	C	–
155 (S)	None	46,000	700	399-402	1.17	1.56	1.61	1.75	–	–	1.51	C	C	B	–
156 (S)	None	46,000	700	403-406	1.53	1.34	1.47	1.37	–	–	1.43	C	B	B	–
157 (S)	None	46,000	700	413-418	1.33	1.73	1.58	1.66	1.59	1.61	1.58	C	A	B	–
176 (S)	None	46,000	700	567-572	1.75	1.61	1.59	1.72	1.58	1.67	1.66	C	B	C	–
178 (S)	None	46,000	700	573-578	1.30	1.26	1.40	1.12	1.23	1.25	1.26	A	A	B	–
1 (S)	29	46,000	700	60-62	1.26	1.26	1.26	–	–	–	1.26	A	B	B	–
1 (S)	33	46,000	700	63-65	1.51	1.31	1.37	–	–	–	1.40	B	A	A	–
None	149	46,000	700	272	1.28	–	–	–	–	–	1.28	C	A	B	Billet temperature 750 F
None	149	46,000	700	489-494	1.51	1.48	1.56	1.39	1.42	1.40	1.47	B	C	B	–
None	150	46,000	700	273-274	1.87	1.33	–	–	–	–	1.59	C	B	A	Applied to billets before heating
None	150	56,000	700	495-500	1.56	1.34	1.33	1.36	1.22	1.12	1.31	C	B	C	Applied to billets before heating
1 (S)	179	46,000	700	66-68	1.73	1.42	1.55	–	–	–	1.56	A	A	A	–
1 (S)	180	46,000	700	344-349	1.30	1.34	1.44	1.42	1.36	1.30	1.36	C	B	A	–
1 (S)	181	46,000	700	350-355	1.53	1.67	1.59	1.45	1.53	1.55	1.55	B	A	A	–
1 (S)	182	46,000	700	320-325	1.40	1.53	1.66	1.72	1.47	1.40	1.53	B	A	A	
1 (S)	183	46,000	700	579-584	1.51	1.72	1.72	1.81	1.76	1.55	1.69	B	A	A	–
1 (S)	184	46,000	700	585-590	–	1.78	1.80	1.83	1.83	1.80	1.80	B	A	B	–
3 (S)	185	46,000	700	48-49	1.64	1.61	–	–	–	–	1.62	A	A	A	–
1 (S)	185	46,000	700	326-331	1.70	1.75	1.66	1.69	1.76	1.76	1.72	C	B	B	–
3 (S)	186	46,000	700	35-37	1.75	1.80	1.72	–	–	–	1.75	A	A	A	–
1 (S)	186	46,000	700	314-319	1.84	1.81	1.81	1.83	1.83	1.86	1.83	B	A	A	
17 (S)	186	46,000	700	368-373	1.83	1.81	1.83	1.83	1.80	1.81	1.81	A	A	B	–
105 (B)	186	46,000	700	386-391	1.69	1.51	1.53	1.81	1.84	1.81	1.70	B	A	A	–
3 (S)	187	46,000	700	44-45	1.55	1.81	–	–	–	–	1.69	A	A	A	–
1 (S)	187	46,000	700	332-337	1.26	1.51	1.44	1.56	1.47	1.44	1.44	B	B	B	–
3 (S)	188	46,000	700	46-47	1.36	1.66	–	–	–	–	1.51	A	A	B	
1 (S)	188	46,000	700	338-343	1.39	1.42	1.62	1.47	1.66	1.72	1.55	C	B	B	–
3 (S)	189	46,000	700	283-285	1.48	1.30	1.33	–	–	–	1.37	A	A	B	–
None	190	46,000	700	50-51	1.26	1.14	–	–	–	–	1.20	B	A	B	–
3 (S)	190	46,000	700	52-54	1.47	1.53	1.56	–	–	–	1.51	A	A	B	–
1 (S)	191	46,000	700	356-361	1.66	1.72	1.72	1.80	1.78	1.84	1.75	B	A	A	–
3 (S)	191	46,000	700	374-379	1.81	1.64	1.58	1.56	1.56	1.53	1.61	A	A	A	–
17 (S)	191	46,000	700	380-385	1.66	1.67	1.66	1.69	1.83	1.78	1.72	B	A	A	–
1 (S)	192	46,000	700	419-424	1.44	1.40	1.62	1.70	1.61	1.56	1.56	C	A	B	–
1 (S)	193	46,000	700	425-430	1.51	1.72	1.73	1.69	1.67	1.72	1.67	B	A	A	–

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TABLE F-1. (Continued)

Lubricant[a]	Billet Treatment	Forging Pressure[b], psi	Die Temperature, F	Forging Sample	Penetration Into Die Cavity[c], in. 1	2	3	4	5	6	Average Penetration, in.	Surface Rating[d] Face	Radius	Ends	Remarks
1 (S)	194	46,000	700	459-464	1.83	1.83	1.81	1.50	1.53	1.53	1.67	B	A	A	-
1 (S)	195	46,000	700	465-470	1.58	1.58	1.64	1.64	1.78	1.80	1.67	B	A	A	-
1 (S)	196	46,000	700	431-434	1.64	1.70	1.81	1.84	-	-	1.75	C	B	B	-
1 (S)	197	46,000	700	435-440	1.64	1.73	1.72	1.76	1.76	1.70	1.72	B	B	B	-
1 (S)	198	46,000	700	441-446	1.81	1.76	1.78	-	1.80	1.83	1.80	A	A	A	-
1 (S)	198	46,000	700	591-596	1.67	1.81	1.81	1.83	1.78	1.86	1.80	B	A	B	-
1 (S)	199	46,000	700	447-452	1.80	1.83	1.84	1.81	1.83	1.86	1.83	A	A	B	-
1 (S)	199	46,000	700	597-602	1.83	1.81	1.84	1.86	1.87	1.86	1.84	A	A	B	-
1 (S)	200	46,000	700	453-458	1.84	1.87	1.84	1.86	1.86	1.84	1.84	B	A	A	-
1 (S)	200	46,000	700	471-476	1.84	1.84	1.80	1.83	1.78	1.81	1.81	B	A	B	Billets preheated 6 hr
1 (S)	200	46,000	700	477-482	1.80	1.84	1.87	1.81	1.83	1.86	1.84	B	A	B	Billets preheated 10 hr
176 (S)	200	46,000	700	561-566	1.87	1.87	1.87	1.87	1.87	1.87	1.87	B	A	A	-
1 (S)	201	46,000	700	501-506	1.75	1.75	1.87	1.87	1.87	1.87	1.83	A	A	A	-
1 (S)	202	46,000	700	507-512	1.73	1.76	-	1.86	1.84	1.80	1.80	B	A	B	-
1 (S)	203	46,000	700	525-530	1.87	1.87	1.87	1.87	1.87	1.87	1.87	A	A	B	-
1 (S)	204	46,000	700	531-536	1.87	1.87	1.87	1.87	1.87	1.87	1.87	A	A	B	-
1 (S)	205	46,000	700	513-518	1.75	1.86	1.80	1.75	1.87	1.86	1.81	C	B	B	-
1 (S)	206	46,000	700	519-524	1.87	1.87	1.87	1.87	1.87	1.87	1.87	B	A	B	-
1 (S)	207	46,000	700	537-542	1.87	1.87	1.87	1.87	1.87	1.87	1.87	A	A	B	-
1 (S)	208	46,000	700	543-548	1.87	1.87	1.87	1.87	1.87	1.87	1.87	A	A	A	-

Note: Billet temperature used was 825 F unless otherwise noted under "Remarks".
Dies were hardened steel having a surface roughness of about 10 microinches. The dies were cleaned between the use of each lubricant with 320-grit paper, which produced a surface roughness of 10 microinches.

(a) Letters in parentheses indicate the method of application. S = sprayed; BR = billets rolled in powder; B = brushed on dies; DR = dies rubbed with lubricant.
(b) Pressure based on a load of 115,000 pounds on an area of 2.5 sq in.
(c) Average penetration into the die measured from the shoulder. The value given is an average of measurements obtained at both ends and at the center.
(d) The surface ratings listed summarize the surface conditions at the various locations on the forgings for the series of samples. The ratings were made visually and correspond to the following classification: A = no scoring; B = slight scoring or drag; C = severe scoring or tearing.
(e) Values underscored indicate that the lubricant caught fire.
(f) Teflon sheet layed in die cavity.

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TABLE F-2. PRESSING-TEST DATA OBTAINED ON 2014 ALUMINUM ALLOY USING VARIOUS METHODS OF LUBRICATION

Lubricant[(a)]	Billet Treatment	Pressing Sample	Applied Load, lb	Die Temperature, F	Average Pressed Thickness for Individual Pressings, inch						Average Values for Test Series				Coefficient of Friction (μ)	Remarks
					1	2	3	4	5	6	Thickness, in.	Diameter, in.	Area, sq in.	Maximum Pressure, psi		
1 (S)	None	1	91,000	700	0.126	–	–	–	–	–	0.126	1.99	3.12	29,200	0.18	–
1 (S)	None	2	115,000	700	0.108	–	–	–	–	–	0.108	2.15	3.64	31,600	0.16	–
1 (S)	None	3	138,000	700	0.101	–	–	–	–	–	0.101	2.22	3.88	35,600	0.15	–
1 (S)	None	4-6	138,000	700	0.101	0.103	0.105	–	–	–	0.104	2.19	3.77	36,400	0.16	–
1 (S)	None	15	138,000	700	0.086	–	–	–	–	–	0.086	2.09	3.42	40,300	0.13	0.375-in. billet height
1 (S)	200	408-410	138,000	700	0.094	0.087	0.079	–	–	–	0.087	2.40	4.57	30,400	0.11	–
1 (S)	200	411-413	67,000	700	0.104	0.105	0.104	–	–	–	0.105	2.19	3.76	17,800	0.09	–
1 (S)	200	414-416	67,000	700	0.095	0.090	0.085	–	–	–	0.090	2.03	3.29	20,400	0.085	0.375-in. billet height
1 (S)	200	417-419	138,000	700	0.078	0.070	0.068	–	–	–	0.072	2.29	4.12	33,600	0.09	0.375-in. billet height
1 (S)	None	420-425	138,000	700	0.100	0.106	0.112	0.104	0.110	0.103	0.106	2.17	3.72	37,200	0.16	–
1 (S)	None	426-428	138,000	700	0.085	0.086	0.085	–	–	–	0.085	2.10	3.46	39,900	0.12	0.375-in. billet height
1 (S)	None	429-431	138,000	700	0.103	0.104	0.099	–	–	–	0.102	2.24	3.95	34,900	0.15	–
1 (S)	None	432-434	67,000	700	0.113	0.112	0.113	–	–	–	0.113	1.83	2.62	26,400	0.14	0.375-in. billet height
1 (S)	None	435-437	67,000	700	0.127	0.133	0.135	–	–	–	0.132	1.94	2.99	22,600	0.16	–
1 (S)	None	438-443	138,000	700	0.108	0.105	0.107	0.104	0.108	0.102	0.106	2.18	3.70	37,300	0.16	Ductile iron dies
1 (S)	None	444-449	138,000	500	0.146	0.135	0.142	0.131	0.128	0.152	0.139	0.190	2.67	51,700	0.26	Beryllium-copper dies
1 (S)	None	450-455	138,000	700	0.114	0.101	0.108	0.104	0.112	0.111	0.108	2.15	3.64	37,900	0.17	Beryllium-copper dies
1 (S)	None	456-461	138,000	700	0.105	0.104	0.107	0.105	0.107	0.103	0.105	2.18	3.74	36,900	0.16	27-μin. surface roughness
1 (S)	None	462-467	138,000	700	0.107	0.108	0.105	0.105	0.106	0.105	0.106	2.18	3.70	37,300	0.16	55-μin. surface roughness
1 (S)	None	468-473	138,000	700	0.102	0.105	0.102	0.109	0.108	0.107	0.106	2.18	3.70	37,300	0.16	8-μin. surface roughness
1 (S)	None	474-479	138,000	700	0.104	0.105	0.099	0.107	0.105	0.088	0.101	2.22	3.88	35,600	0.16	9-μin. surface roughness
1 (S)	None	480-485	138,000	700	0.107	0.107	0.108	0.113	0.111	0.109	0.109	2.14	3.60	38,400	0.19	13-μin. surface roughness
2 (S)	None	16-18	138,000	700	0.083	0.079	0.075	–	–	–	0.079	2.51	4.97	27,800	0.09	–
3 (S)	None	19-21	138,000	700	0.096	0.084	0.094	–	–	–	0.091	2.33	4.32	31,800	0.12	–
3 (S)	185	139-141	138,000	700	0.098	0.094	0.095	–	–	–	0.096	2.28	4.10	33,700	0.13	–
3 (S)	None	396-398	138,000	700	0.078	0.083	0.084	–	–	–	0.082	2.47	4.79	28,800	0.095	–
3 (S)	None	399-401	67,000	700	0.097	0.085	0.089	–	–	–	0.091	2.04	3.33	20,500	0.085	0.375-in. billet height
3 (S)	None	402-404	67,000	700	0.122	0.113	0.115	–	–	–	0.117	2.07	3.38	19,800	0.11	–
3 (S)	None	405-407	138,000	700	0.058	0.065	0.068	–	–	–	0.064	2.34	4.17	33,100	0.07	0.375-in. billet height
4 (S)	None	85-87	138,000	700	0.087	0.088	0.083	–	–	–	0.086	2.41	4.57	30,200	0.11	–
4A (S)	None	160-162	138,000	700	0.088	0.077	0.070	–	–	–	0.078	2.53	5.06	27,300	0.085	–
5 (S)	None	22-24	138,000	700	0.081	0.081	0.078	–	–	–	0.080	2.50	4.91	28,100	0.09	–
6 (S)	None	91-93	138,000	700	0.106	0.094	0.087	–	–	–	0.096	2.29	4.21	32,800	0.135	–
7 (S)	None	37-39	138,000	700	0.092	0.085	0.084	–	–	–	0.087	2.40	4.52	30,600	0.11	–
8 (S)	None	25-27	138,000	900	0.090	0.086	0.088	–	–	–	0.088	2.38	4.46	31,000	0.12	–
8 (S)	None	28-30	138,000	300	0.131	0.138	0.134	–	–	–	0.134	1.93	2.92	47,300	0.25	–
8 (S)	None	31-33	138,000	500	0.102	0.098	0.111	–	–	–	0.104	2.20	3.79	36,400	0.14	–
8 (S)	None	34-36	138,000	700	0.087	0.078	0.075	–	–	–	0.080	2.50	4.92	28,000	0.09	–
8 (S)	None	201-203	138,000	700	0.097	0.093	0.078	–	–	–	0.089	2.37	4.41	31,300	0.11	10-μin. surface roughness
8 (S)	None	204-206	138,000	700	0.103	0.097	0.086	–	–	–	0.095	2.29	4.13	33,400	0.13	55-μin. surface roughness
8 (S)	None	210-212	138,000	700	0.093	0.087	0.086	–	–	–	0.089	2.37	4.41	31,300	0.11	9-μin. surface roughness
8 (S)	None	213-215	138,000	700	0.089	0.077	0.082	–	–	–	0.083	2.45	4.73	29,200	1.10	9-μin. surface roughness
8 (S)	None	246-248	138,000	700	0.089	0.074	0.066	–	–	–	0.076	2.57	5.16	26,800	0.08	5.5-μin. surface roughness

TABLE F-2. (Continued)

Lubricant[a]	Billet Treatment	Pressing Sample	Applied Load, lb	Die Temperature, F	Average Pressed Thickness for Individual Pressings, inch: 1	2	3	4	5	6	Average Values for Test Series: Thickness, in.	Diameter, in.	Area, sq in.	Maximum Pressure, psi	Coefficient of Friction (μ)	Remarks
9 (S)	None	94-96	138,000	700	0.098	0.095	0.095	–	–	–	0.096	2.28	4.09	33,700	0.14	–
10 (S)	None	97-99	138,000	700	0.079	0.073	0.072	–	–	–	0.075	2.58	5.26	26,200	0.08	–
13 (S)	None	100-102	138,000	700	0.094	0.084	0.093	–	–	–	0.090	2.35	4.35	31,700	0.12	–
15 (S)	None	103-105	138,000	700	0.103	0.106	0.100	–	–	–	0.103	2.20	3.81	36,200	0.16	–
17 (S)	None	88-90	138,000	700	0.099	0.094	0.101	–	–	–	0.098	2.26	4.00	34,500	0.14	–
17 (S)	None	163-165	138,000	700	0.087	0.083	0.089	–	–	–	0.086	2.41	4.54	30,400	0.11	–
18 (S)	None	106-108	138,000	700	0.107	0.107	0.109	–	–	–	0.108	2.15	3.65	37,800	0.17	–
19 (S)	None	109-111	138,000	700	0.107	0.109	0.111	–	–	–	0.109	2.14	3.60	38,300	0.17	–
23 (B)	None	79-81	138,000	700	0.111	–	0.108	–	–	–	0.110	2.14	3.59	38,400	0.17	–
24 (B)	None	82-84	138,000	700	0.087	0.084	0.088	–	–	–	0.087	2.41	4.55	30,400	0.11	–
43 (S)	None	61-63	138,000	700	0.091	0.091	0.089	–	–	–	0.090	2.35	4.34	31,800	0.12	–
44 (S)	None	64-66	138,000	700	0.093	0.100	0.100	–	–	–	0.098	2.27	4.03	34,200	0.14	–
45 (S)	None	58-60	138,000	700	0.085	0.082	0.085	–	–	–	0.084	2.44	4.67	29,600	0.10	–
46 (S)	None	112-114	138,000	700	0.102	0.088	0.088	–	–	–	0.093	2.32	4.26	32,400	0.12	–
47 (S)	None	115-117	138,000	700	0.101	0.100	0.090	–	–	–	0.097	2.27	4.06	34,000	0.14	–
48 (S)	None	55-57	138,000	700	0.089	0.085	0.085	–	–	–	0.086	2.40	4.54	30,400	0.11	–
49 (S)	None	7-9	138,000	700	0.074	0.064	0.063	–	–	–	0.067	2.74	5.89	23,500	0.06	–
49 (S)	None	14	138,000	700	0.062	–	–	–	–	–	0.062	2.46	4.74	29,200	0.11	0.375-in. billet height
49 (S)	None	70-72	138,000	500	0.109	0.114	0.088	–	–	–	0.104	2.20	3.83	36,100	0.14	–
49 (S)	None	73-75	138,000	900	0.086	0.086	0.085	–	–	–	0.086	2.41	4.58	30,200	0.11	–
50 (S)	None	40-42	138,000	700	0.075	0.080	0.083	–	–	–	0.079	2.51	4.95	27,900	0.09	–
51 (S)	None	43-45	138,000	700	0.077	0.069	0.069	–	–	–	0.072	2.63	5.48	25,200	0.085	–
52 (S)	None	46-48	138,000	700	0.093	0.095	0.097	–	–	–	0.095	2.29	4.13	33,400	0.13	–
53 (S)	None	49-51	138,000	700	0.104	0.104	0.101	–	–	–	0.103	2.20	3.81	36,200	0.16	–
54 (DR)	None	67-69	138,000	700	0.077	0.079	0.081	–	–	–	0.079	2.52	4.97	27,800	0.09	–
57 (B)	None	118-120	138,000	700	0.089	0.084	0.074	–	–	–	0.082	2.47	4.89	28,200	0.095	–
58 (B)	None	121-123	138,000	700	0.083	0.067	0.063	–	–	–	0.071	2.67	5.60	24,600	0.075	–
59 (S)	None	124-126	138,000	700	0.104	0.098	0.092	–	–	–	0.098	2.27	4.01	34,400	0.14	–
63A	Billet dipped before heating	196-198	138,000	700	0.102	0.105	0.107	–	–	–	0.105	2.18	3.75	36,800	0.16	Lube etched aluminum slightly

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TABLE F-2. (Continued)

Lubricant(a)	Billet Treatment	Pressing Sample	Applied Load, lb	Die Temperature, F	Average Pressed Thickness for Individual Pressings, inch 1	2	3	4	5	6	Average Values for Test Series: Thickness, in.	Diameter, in.	Area, sq in.	Maximum Pressure, psi	Coefficient of Friction (μ)	Remarks
65 (B)	None	13	138,000	700	0.036	–	–	–	–	–	0.036	3.23	8.17	16,900	0.02	0.375-in. billet height
65 (B)	None	10-12	138,000	700	0.098	0.077	0.095	–	–	–	0.090	2.37	4.41	31,400	0.12	–
66 (B)	None	52-54	138,000	700	0.106	0.109	0.109	–	–	–	0.108	2.15	3.63	38,000	0.16	–
68 (B)	None	127-129	138,000	700	0.101	0.097	0.096	–	–	–	0.098	2.26	4.01	34,500	0.14	–
69 (B)	None	130-132	138,000	700	0.087	0.083	0.079	–	–	–	0.083	2.45	4.73	29,200	0.095	–
70 (S)	None	133-135	138,000	700	0.098	0.090	0.090	–	–	–	0.093	2.33	4.24	32,600	0.13	–
71 (B)	None	136-138	138,000	700	0.069	0.078	0.079	–	–	–	0.075	2.58	5.23	26,400	0.08	–
74 (B)	None	76-78	138,000	700	0.078	0.077	0.084	–	–	–	0.079	2.51	4.93	28,000	0.09	–
77 (S)	None	142-144	138,000	700	0.091	0.076	0.058	–	–	–	0.075	2.62	5.41	25,500	0.075	Large flakes clogged spray gun
78 (S)	None	145-147	138,000	700	0.093	0.088	0.100	–	–	–	0.094	2.31	4.20	31,900	0.13	–
79 (S)	None	148-150	138,000	700	0.087	0.082	0.084	–	–	–	0.084	2.44	4.66	29,600	0.10	–
80 (S)	None	151-153	138,000	700	0.083	0.072	0.062	–	–	–	0.072	2.65	5.51	25,100	0.07	–
84 (S)	None	166-168	138,000	700	0.100	0.106	0.106	–	–	–	0.104	2.19	3.78	36,500	0.16	–
85 (B)	None	157-159	138,000	700	0.055	0.060	0.058	–	–	–	0.058	2.95	6.82	20,300	0.04	–
86 (S)	None	154-156	138,000	700	0.084	0.086	0.086	–	–	–	0.085	2.42	4.60	30,000	0.10	–
87 (B)	None	169-171	138,000	700	0.081	0.079	0.067	–	–	–	0.076	2.58	5.21	26,500	0.08	Aluminum pickup on dies
88 (B)	None	172-174	138,000	700	0.072	0.068	0.070	–	–	–	0.070	2.67	5.61	24,600	0.065	Little smoke
89 (B)	None	175-177	138,000	700	0.065	0.061	0.070	–	–	–	0.065	2.77	6.03	22,900	0.055	–
90 (E,	None	178-180	138,000	700	0.073	0.067	0.072	–	–	–	0.071	2.66	5.56	24,800	0.07	–
91	Brushed on before heating	181-183	138,000	700	0.090	0.082	0.081	–	–	–	0.084	2.44	4.67	29,600	0.010	–
92	Brushed on before heating	184-186	138,000	700	0.066	0.056	0.050	–	–	–	0.057	2.37	6.96	19,800	0.04	–
92	Brushed on before heating	187-189	138,000	700	0.068	0.057	0.045	–	–	–	0.057	3.00	7.13	19,400	0.04	–
92	Brushed on before heating	221-223	138,000	700	0.082	0.099	0.098	–	–	–	0.093	2.33	4.25	32,500	0.12	Billets heated 20-25 min
92	Brushed on before heating	224-226	138,000	700	0.086	0.073	0.071	–	–	–	0.077	2.56	5.15	26,800	0.085	Billets heated 10-12 min
92 (d)	None	227-229	138,000	700	0.094	0.064	0.068	–	–	–	0.075	2.60	5.36	25,800	0.08	–
92	Brushed on before heating	230-232	138,000	700	0.117	0.101	0.096	–	–	–	0.105	2.19	3.77	36,600	0.16	–
92 (d)	None	233-235	138,000	700	0.081	0.085	0.081	–	–	–	0.082	2.47	4.77	29,000	0.095	Samples 230-235 run without cleaning dies
93	Billet dipped	190-192	138,000	700	0.104	0.099	0.102	–	–	–	0.102	2.21	3.86	35,800	0.16	Etched die surface slightly
94	Billet dipped	193-195	138,000	700	0.087	0.102	0.102	–	–	–	0.097	2.27	4.06	34,000	0.14	Billets attacked
95	Billets wrapped in sheet	19[illegible] 200	138,000	700	0.095	0.097	–	–	–	–	0.096	2.28	4.09	33,800	0.14	–
95	–	219-220	138,000	700	0.091	0.098	–	–	–	–	0.095	2.30	4.16	33,200	0.13	Sheets between billet and dies
96	–	207-209	138,000	700	0.102	0.106	0.114	–	–	–	0.107	2.16	3.67	37,600	0.17	Sheets between billet and dies

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TABLE F-2. (Continued)

Lubricant(a)	Billet Treatment	Pressing Sample	Applied Load, lb	Die Temperature, F	Average Pressed Thickness for Individual Pressings, inch: 1	2	3	4	5	6	Average Values for Test Series: Thickness, in.	Diameter, in.	Area, sq in.	Maximum Pressure, psi	Coefficient of Friction (μ)	Remarks
96	Billets wrapped in sheets	216-218	138,000	700	0.106	0.108	0.108	–	–	–	0.107	2.16	3.67	37,600	0.17	–
97	–	236-238	138,000	700	–	0.050	0.043	–	–	–	0.047	3.29	8.49	16,300	0.025	Sheets between billet and dies; gave wrinkled surface
98	–	239-241	138,000	700	0.101	0.090	0.072	–	–	–	0.088	2.40	4.56	30,300	0.11	Sheets between billet and dies
99	–	242	138,000	700	0.103	–	–	–	–	–	0.103	2.29	3.81	36,200	0.16	Sheets between billet and dies
100	–	243-245	138,000	700	0.103	0.106	0.111	–	–	–	0.107	2.16	3.68	37,500	0.17	Sheets between billet and dies
101 (B)	–	249-251	138,000	700	0.095	0.088	0.094	–	–	–	0.092	2.32	4.25	32,500	0.12	–
102 (B)	–	252-254	138,000	700	0.094	0.080	0.094	–	–	–	0.089	2.37	4.41	31,300	0.12	–
103 (B)	–	255-257	138,000	700	0.078	0.079	0.082	–	–	–	0.080	2.05	4.93	28,100	0.09	–
104 (B)	–	258-260	138,000	700	0.087	0.080	0.081	–	–	–	0.083	2.46	4.75	29,100	0.095	–
105 (B)	–	261-263	138,000	700	0.076	0.072	0.058	–	–	–	0.069	2.71	5.79	23,900	0.065	–
106 (B)	–	264-266	138,000	700	0.077	0.064	0.060	–	–	–	0.067	2.75	5.95	23,200	0.06	–
125 (B)	(B)	267-269	138,000	700	0.098	0.096	0.100	–	–	–	0.098	2.26	4.02	34,400	0.14	–
126 (B)	(B)	270-272	138,000	700	0.115	0.096	0.100	–	–	–	0.104	2.20	3.81	36,200	0.16	–
127 (B)	(B)	273-275	138,000	700	0.095	0.101	0.104	–	–	–	0.100	2.23	3.94	35,000	0.15	–
128 (B)	(B)	276-278	138,000	700	0.097	0.102	0.105	–	–	–	0.101	2.12	3.55	38,800	0.16	–
129 (B)	(B)	279-281	138,000	700	0.104	0.105	0.106	–	–	–	0.105	2.18	3.74	36,900	0.17	–
130 (B)	(B)	282-284	138,000	700	0.100	0.102	0.102	–	–	–	0.101	2.22	3.87	35,600	0.15	–
131 (B)	(B)	285-287	138,000	700	0.100	0.102	0.103	–	–	–	0.101	2.21	3.86	35,700	0.15	–
132 (B)	(B)	288-290	138,000	700	0.098	0.099	0.087	–	–	–	0.093	2.30	4.16	33,200	0.13	–
133 (B)	(B)	291-293	138,000	700	0.101	0.101	0.102	–	–	–	0.101	2.22	3.88	35,600	0.15	–
134 (B)	(B)	294-296	138,000	700	0.105	0.101	0.106	–	–	–	0.104	2.19	3.78	36,600	0.16	–
135 (B)	(B)	297-299	138,000	700	0.099	0.102	0.101	–	–	–	0.100	2.22	3.90	35,400	0.15	–
136 (B)	(B)	300-302	138,000	700	0.103	0.099	0.099	–	–	–	0.100	2.23	3.92	35,300	0.15	–
137 (B)	(B)	303-305	138,000	700	0.101	0.101	0.102	–	–	–	0.101	2.22	3.88	35,600	0.15	–
138 (B)	(B)	306-308	138,000	700	0.096	0.099	0.102	–	–	–	0.099	2.14	3.64	37,900	0.15	–
139 (C)	(B)	324-326	138,000	700	0.097	0.101	0.106	–	–	–	0.101	2.23	3.88	35,600	0.15	Pressings had to be knocked off with hammer
140 (B)	(B)	327-329	138,000	700	0.103	0.102	0.105	–	–	–	0.103	2.20	3.86	35,700	0.15	Pressings had to be chiseled off dies
141 (B)	(B)	330-332	138,000	700	0.095	0.103	0.104	–	–	–	0.101	2.23	3.91	35,300	0.15	–
142 (B)	(B)	333-335	138,000	700	0.098	0.101	0.103	–	–	–	0.101	2.23	3.90	35,400	0.15	–

TABLE F-2. (Continued)

Lubricant[a]	Billet Treatment	Pressing Sample	Applied Load, lb	Die Temperature, F	Average Pressed Thickness for Individual Pressings, inch: 1	2	3	4	5	6	Average Values for Test Series: Thickness, in.	Diameter, in.	Area, sq in.	Maximum Pressure, psi	Coefficient of Friction (μ)	Remarks
143 (BR)	–	336-338	138,000	700	–	0.074	0.070	–	–	–	0.072	2.64	5.46	25,200	0.07	Dies difficult to clean
144 (BR)	–	339-341	138,000	700	0.099	.(b)	–	–	–	–	0.099	2.22	3.97	34,800	0.14	Sample 340 damaged in removing pressing from die
144 (BR)[c]	–	321-323	138,000	700	0.104	0.102	0.102	–	–	–	0.102	2.20	3.83	36,000	0.15	–
144 (BR)	–	309-311	138,000	700	0.101	0.103	0.104	–	–	–	0.102	2.20	3.83	36,000	0.15	–
145 (BR)	–	312-314	138,000	700	0.094	0.096	0.095	–	–	–	0.095	2.29	4.14	33,400	0.13	Produced obnoxious fumes
146 (BR)	–	315-317	138,000	700	0.097	0.098	0.101	–	–	–	0.098	2.25	3.98	34,700	0.14	–
147 (BR)	–	318-320	138,000	700	0.102	0.097	0.098	–	–	–	0.099	2.25	3.97	34,800	0.14	–
148 (B)	–	342-344	138,000	700	0.083	0.066	0.061	–	–	–	0.070	2.66	5.71	24,200	0.065	–
149 (B)	–	345-347	138,000	700	0.035	0.074[d]	0.081[d]	–	–	–	0.035	3.78	11.2	19,300	0.01	Applied to cold dies, then heated to 700 F
–	149 (B)[e]	357-359	138,000	700	0.070	0.059	0.057	–	–	–	0.062	2.85	6.37	21,600	0.05	Billet temperature, 750 F
–	150 (B)[e]	348-350	138,000	700	0.062	0.055	0.052	–	–	–	0.056	2.95	7.01	19,700	0.04	–
–	150 (B)[e]	351-353	138,000	700	0.075	0.066	0.062	–	–	–	0.067	2.72	5.84	23,600	0.06	Billet temperature, 750 F
–	150 (B)[e]	354-356	138,000	700	0.076	0.063	0.057	–	–	–	0.065	2.78	6.14	22,500	0.055	Billet temperature, 750 F
160 (BR)	–	360-362	138,000	700	0.097	0.100	0.103	–	–	–	0.100	2.23	3.92	35,200	0.15	–
161 (BR)	–	363-365	138,000	700	0.089	0.084	–	–	–	–	0.087	2.41	4.54	30,400	0.11	–
162 (BR)	–	366-368	138,000	700	0.098	0.091	0.091	–	–	–	0.094	2.30	4.18	33,000	0.13	–
163 (BR)	–	369-371	138,000	700	0.095	0.091	0.071	–	–	–	0.085	2.43	4.68	29,500	0.10	–
164 (BR)	–	372-374	138,000	700	0.100	0.098	0.103	–	–	–	0.101	2.23	3.91	35,300	0.15	–
165 (BR)	–	375-377	138,000	700	0.111	0.095	0.111	–	–	–	0.106	2.18	3.75	37,800	0.17	–
166 (BR)	–	378-380	138,000	700	0.104	0.102	0.098	–	–	–	0.101	2.22	3.87	35,700	0.15	–
167 (BR)	–	381-383	138,000	700	0.108	0.114	0.117	–	–	–	0.113	2.11	3.49	39,600	0.19	–
168 (BR)	–	384-386	138,000	700	0.119	0.107	0.121	–	–	–	0.116	2.08	3.41	40,500	0.20	–
169 (BR)	None	387-389	138,000	700	0.109	0.104	0.103	–	–	–	0.105	2.18	3.74	36,900	0.16	–
170 (BR)	None	390-392	138,000	700	0.107	0.094	0.105	–	–	–	0.102	2.22	3.87	35,700	0.15	–
171 (BR)	None	393-395	138,000	700	0.099	0.100	0.104	–	–	–	0.101	2.23	3.91	35,300	0.15	–

Note: All samples were 1 inch in diameter by 1/2 inch in thickness unless otherwise indicated under "Remarks".
Billet temperature was 825 F.
Dies were hardened steel unless otherwise indicated under "Remarks." Dies were cleaned and polished between use of different lubricants with 320-grit paper which produced a die roughness of about 10 microinches.

(a) Letters in parentheses indicate method of application, S=sprayed; BR=billets rolled in powder; B=brushed on dies; DR=dies rubbed with lubricant.
(b) Sample could not be measured because it was damaged.
(c) Hot billet rolled in powder then reheated 10 minutes before forging.
(d) No additional lubricant added to dies.
(e) Thin layer brushed on billets, then allowed to dry before heating for forging.

TABLE F-3. BULGE-TEST DATA OBTAINED ON 2014 ALUMINUM ALLOY USING VARIOUS TYPES OF LUBRICANTS

Lubricant[a]	Billet Treatment	Bulge Sample	Die Temperature, F	Bulge Index for Individual Pressings, in.[b] 1	2	3	4	5	6	7	Average Bulge Index, in.	Average Maximum Load, lb	Average Maximum Pressure, psi[c]
None	None	19-25	500	0.254	0.264	0.281	0.241	0.256	0.267	0.281	0.261	18,400	15,700
None	None	71-73	500	0.253	0.262	0.273	–	–	–	–	0.263	18,500	15,100
None	None	175-178	500	0.287	0.282	0.299	0.300	–	–	–	0.292	14,700	12,900
None	None	180-182	700	0.197	0.202	0.198	–	–	–	–	0.199	15,550	12,200
None	None	238-239	800	0.202	0.220	–	–	–	–	–	0.211	11,900	9,500
1 (S)	None	145-147	500	0.230	0.199	0.209	–	–	–	–	0.216	17,200	13,500
1 (S)	None	92-94	500	0.190	0.188	0.205	–	–	–	–	0.194	18,400	14,400
1 (S)	None	183-186	700	0.185	0.011	0.013	0.069	–	–	–	0.069	14,700	10,200
2 (S)	None	148-150	500	0.208	0.238	0.224	–	–	–	–	0.223	16,600	13,100
2 (S)	None	193-195	700	0.066	0.033	0.063	–	–	–	–	0.054	13,500	9,100
3 (S)	None	151-153	500	0.199	0.216	0.223	–	–	–	–	0.213	17,100	13,100
3 (S)	None	199-201	700	0.133	0.165	0.169	–	–	–	–	0.156	13,100	9,700
4 (S)	None	163-165	500	0.270	0.284	0.286	–	–	–	–	0.280	14,800	12,700
4 (S)	None	202-204	700	0.226	0.214	0.203	–	–	–	–	0.214	13,400	10,700
5 (S)	None	154-156	500	0.129	0.154	0.154	–	–	–	–	0.146	17,500	12,900
5 (S)	None	190-192	700	0.127	0.136	0.115	–	–	–	–	0.126	13,700	10,100
6 (S)	None	166-168	500	0.235	0.266	0.253	–	–	–	–	0.251	15,500	12,800
6 (S)	None	205-207	700	0.188	0.181	0.166	–	–	–	–	0.178	12,900	9,800
7 (S)	None	157-159	500	0.206	0.205	0.218	–	–	–	–	0.209	15,300	12,100
7 (S)	None	137-139[d]	500	0.249	0.269	–	–	–	–	–	0.259	15,300	12,900
7 (S)	None	196-198	700	0.052	0.034	0.036	–	–	–	–	0.041	14,100	9,400
7 (S)	None	140-141[d]	700	0.152	0.141	–	–	–	–	–	0.147	13,900	10,100
8 (S)	None	218-220	300	0.277	0.269	0.266	–	–	–	–	0.270	18,300	15,400
8 (S)	None	142-144	500	0.205	0.218	0.216	–	–	–	–	0.213	15,900	13,700
8 (S)	None	187-189	700	−0.021	−0.012	+0.017	–	–	–	–	−0.016	14,700	9,600
8 (S)	None	211-213	800	+0.110	−0.019	−0.069	–	–	–	–	0.007	15,400	9,800
8 (S)	None	418-420	900	0.167	0.183	0.192	–	–	–	–	0.181	11,700	9,100
9 (S)	None	160-162	500	0.229	0.235	0.209	–	–	–	–	0.224	15,900	12,800
10 (S)	None	169-171	500	0.198	0.213	0.204	–	–	–	–	0.205	16,400	13,600
11 (S)	None	172-174	500	0.205	0.198	0.194	–	–	–	–	0.198	14,900	12,300
13 (S)	None	221-223	500	0.173	0.180	0.213	–	–	–	–	0.188	17,800	13,600
15 (S)	None	224-226	500	0.186	0.239	0.231	–	–	–	–	0.218	17,000	13,400
17 (S)	None	227-229	500	0.223	0.234	0.226	–	–	–	–	0.227	15,900	12,800
18 (S)	None	230-232	500	0.261	0.256	0.257	–	–	–	–	0.258	14,800	12,500
19 (S)	None	235-236	500	0.216	0.222	–	–	–	–	–	0.219	16,600	13,200
22 (BR)	None	131-132	700	0.151	0.065	–	–	–	–	–	0.108	16,500	11,500
22 (BR)	None	133-136	800	0.081	0.096	0.085	0.120	–	–	–	0.096	15,300	10,800
23 (B)	None	114-118	500	0.182	0.129	0.182	0.217	0.228	–	–	0.188	17,800	13,800
23 (B)	None	384-386	700	0.183	0.113	0.164	–	–	–	–	0.153	17,300	13,000
24 (B)	None	119-121	500	0.219	0.225	0.228	–	–	–	–	0.224	15,900	12,800
24 (B)	None	387-389	700	0.031	0.095	0.092	–	–	–	–	0.073	15,500	10,700
25 (B)	None	122-124	500	0.273	0.282	0.277	–	–	–	–	0.277	14,800	12,700
25 (B)	None	390-392	700	0.106	0.117	0.169	–	–	–	–	0.131	19,300	14,200
26 (B)	None	125-127	500	0.206	0.216	0.218	–	–	–	–	0.213	16,000	12,700
26 (B)	None	393-395	700	0.173	0.155	0.149	–	–	–	–	0.162	15,900	12,000
27 (B)	None	128-130	500	0.186	0.195	0.199	–	–	–	–	0.193	14,800	11,600
27 (B)	None	396-398	700	0.144	0.131	0.149	–	–	–	–	0.141	16,600	12,400
34 (S)	None	240-242	500	0.263	0.277	0.284	–	–	–	–	0.275	18,100	15,500

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TABLE F-3. (Continued)

Lubricant[a]	Billet Treatment	Pressing Sample	Die Temperature, F	Bulge Index for Individual Pressings, in.[b] 1	2	3	4	5	6	7	Average Bulge, Index, in.	Average Maximum Load, lb	Average Maximum Pressure, psi[c]
35 (S)	None	243-245	500	0.286	0.276	0.274	–	–	–	–	0.279	17,600	15,100
36 (S)	None	246-248	500	0.264	0.270	0.277	–	–	–	–	0.270	15,900	13,600
36 (S)	None	270-272	700	0.235	0.249	0.249	–	–	–	–	0.244	17,900	14,700
37 (S)	None	249-251	500	0.261	0.268	0.252	–	–	–	–	0.260	17,800	15,100
37 (S)	None	267-269	700	0.210	0.218	0.225	–	–	–	–	0.218	16,200	12,900
38 (S)	None	252-254	500	0.191	0.196	0.220	–	–	–	–	0.202	18,000	14,200
38 (S)	None	273-275	700	0.209	0.223	0.229	–	–	–	–	0.220	15,200	12,300
39 (S)	None	255-257	500	0.271	0.281	0.287	–	–	–	–	0.280	15,800	13,600
40 (S)	None	258-260	500	0.259	0.255	0.259	–	–	–	–	0.258	16,500	13,700
41 (S)	None	261-263	500	0.237	0.218	0.216	–	–	–	–	0.224	15,000	11,800
41 (S)	None	276-278	700	0.147	0.098	0.075	–	–	–	–	0.107	13,800	9,900
42 (S)	None	264-266	500	0.228	0.222	0.221	–	–	–	–	0.224	14,800	11,800
42 (S)	None	279-281	700	0.174	0.146	0.147	–	–	–	–	0.156	12,100	9,000
43 (S)	None	318-320	300	0.250	0.271	0.285	–	–	–	–	0.269	22,300	18,900
43 (S)	None	285-287	500	0.250	0.255	0.236	–	–	–	–	0.247	15,300	12,800
43 (S)	None	306-308	700	0.019	0.026	0.050	–	–	–	–	0.032	15,500	10,400
44 (S)	None	321-323	300	0.304	0.323	0.321	–	–	–	–	0.316	19,800	17,800
44 (S)	None	288-290	500	0.246	0.255	0.255	–	–	–	–	0.252	15,500	13,000
44 (S)	None	309-311	700	0.146	0.090	0.094	–	–	–	–	0.110	13,300	9,600
45 (S)	None	324-326	300	0.275	0.271	0.289	–	–	–	–	0.278	20,900	18,100
45 (S)	None	291-293	500	0.253	0.260	0.248	–	–	–	–	0.254	14,400	12,000
45 (S)	None	312-314	700	0.115	0.063	0.072	–	–	–	–	0.083	14,000	9,900
46 (S)	None	327-329	300	0.331	0.321	0.341	–	–	–	–	0.331	19,300	17,800
46 (S)	None	294-296	500	0.200	0.211	0.258	–	–	–	–	0.220	16,900	13,700
46 (S)	None	315-317	700	0.127	0.093	0.090	–	–	–	–	0.103	13,300	9,400
47 (S)	None	330-332	300	0.333	0.314	0.315	–	–	–	–	0.321	19,300	17,600
47 (S)	None	297-299	500	0.252	0.269	0.273	–	–	–	–	0.265	15,100	12,800
47 (S)	None	300-302	700	0.078	0.084	0.104	–	–	–	–	0.089	13,900	9,700
48 (S)	None	333-335	300	0.305	0.311	0.315	–	–	–	–	0.310	18,200	16,300
48 (S)	None	282-284	500	0.162	0.182	0.226	–	–	–	–	0.190	17,300	13,400
48 (S)	None	303-305	700	0.095	0.093	0.124	–	–	–	–	0.104	13,400	9,500
49 (S)	None	348-350	500	0.103	0.143	0.197	–	–	–	–	0.148	20,700	15,700
49 (S)	None	336-338	700	0.124	0.104	0.084	–	–	–	–	0.104	14,600	10,400
50 (S)	None	351-353	500	0.182	0.207	0.233	–	–	–	–	0.207	16,300	13,100
50 (S)	None	339-341	700	0.066	0.106	0.090	–	–	–	–	0.087	12,900	9,000
51 (S)	None	354-356	500	0.185	0.193	0.207	–	–	–	–	0.195	17,200	13,500
51 (S)	None	342-344	700	0.128	0.136	0.146	–	–	–	–	0.137	12,500	9,300
52 (S)	None	357-359	500	0.236	0.244	0.249	–	–	–	–	0.243	15,300	12,700
52 (S)	None	345-347	700	0.212	0.215	0.219	–	–	–	–	0.215	11,900	9,500
53 (S)	None	360-362	500	0.202	0.215	0.213	–	–	–	–	0.210	20,500	16,400
53 (S)	None	366-368	700	0.131	0.141	0.158	–	–	–	–	0.143	16,200	12,100
54 (DR)	None	363-365	500	0.209	0.208	0.216	–	–	–	–	0.211	19,300	15,500
54 (DR)	None	369-371	700	0.105	0.102	0.102	–	–	–	–	0.103	16,000	11,400
55 (S)	None	372-374	500	0.177	0.198	0.214	–	–	–	–	0.196	19,100	15,100
55 (S)	None	381-383	700	0.117	0.062	0.071	–	–	–	–	0.083	16,000	11,200
55 (S)	None	484-486	900	0.140	0.094	0.158	–	–	–	–	0.131	13,400	9,900
56 (S)	None	375-377	500	0.207	0.220	0.218	–	–	–	–	0.215	18,700	15,000
56 (S)	None	378-380	700	0.194	0.189	0.126	–	–	–	–	0.170	20,100	15,400
57 (B)	None	399-401	500	0.184	0.191	0.202	–	–	–	–	0.192	20,500	15,700
57 (B)	None	414-416	700	0.057	0.043	0.065	–	–	–	–	0.055	14,800	9,900

TABLE F-3. (Continued)

Lubricant[a]	Billet Treatment	Pressing Sample	Die Temperature, F	Bulge Index for Individual Pressings, in.[b] 1	2	3	4	5	6	7	Average Bulge Index, in.	Average Maximum Load, lb	Average Maximum Pressure, psi[c]
58 (B)	None	402-404	500	0.142	0.152	0.159	–	–	–	–	0.151	19,000	14,000
58 (B)	None	411-413	700	–0.028	–0.007	+0.018	–	–	–	–	–0.008	16,300	10,500
58 (B)	None	490-492	900	–0.021	–0.015	–0.066	–	–	–	–	–0.034	10,700	6,800
59 (S)	None	405-407	500	0.180	0.195	0.228	–	–	–	–	0.201	17,800	13,900
59 (S)	None	408-410	700	0.167	0.090	0.082	–	–	–	–	0.113	13,800	9,800
60 (S)	None	421-423	500	0.271	0.289	0.295	–	–	–	–	0.285	18,900	16,100
61 (S)	None	424-426	500	0.204	0.222	0.250	–	–	–	–	0.225	18,400	14,800
62 (S)	None	427-429	500	0.299	0.286	0.293	–	–	–	–	0.293	17,300	15,100
63 (S)	None	430-432	500	0.302	0.301	0.312	–	–	–	–	0.305	17,400	15,600
64 (S)	None	433-435	500	0.301	0.306	0.303	–	–	–	–	0.305	16,600	14,900
65 (B)	None	436-438	500	0.071	0.145	0.150	–	–	–	–	0.122	22,100	15,900
65 (B)	None	460-462	700	–0.106	–0.058	–0.035	–	–	–	–	–0.066	17,000	10,600
65 (B)	None	487-489	900	–0.131	–0.129	–0.114	–	–	–	–	–0.125	12,200	7,200
66 (B)	None	439-441	500	0.243	0.267	0.251	–	–	–	–	0.254	20,000	16,700
66 (B)	None	463-465	700	0.167	0.148	0.152	–	–	–	–	0.156	15,800	12,000
67 (B)	None	442-444	500	0.218	0.231	0.248	–	–	–	–	0.232	20,400	16,800
67 (B)	None	466-468	700	0.157	0.138	0.155	–	–	–	–	0.150	16,100	12,100
68 (B)	None	445-447	500	0.245	0.231	0.220	–	–	–	–	0.232	18,100	14,800
68 (B)	None	469-471	700	0.148	0.079	0.077	–	–	–	–	0.101	13,900	9,900
68 (B)	None	493-495	900	0.140	0.115	0.091	–	–	–	–	0.115	13,400	10,000
69 (B)	None	448-450	500	0.217	0.187	0.195	–	–	–	–	0.200	19,200	15,100
69 (B)	None	472-474	700	0.076	0.032	0.058	–	–	–	–	0.055	14,800	10,100
69 (B)	None	496-498	900	0.147	0.062	0.014	–	–	–	–	0.074	11,200	8,000
70 (S)	None	451-453	500	0.232	0.243	0.241	–	–	–	–	0.239	17,500	14,300
70 (S)	None	475-477	700	0.110	0.088	0.064	–	–	–	–	0.087	13,900	9,800
71 (B)	None	454-456	500	0.184	0.180	0.187	–	–	–	–	0.184	16,000	13,000
71 (B)	None	478-480	700	–0.028	–0.034	0.001	–	–	–	–	–0.020	15,600	9,800
71 (B)	None	499-502	900	0.019	–0.090	0.042	–0.080	–	–	–	–0.027	11,700	6,900
72 (B)	None	457-459	500	0.254	0.247	0.252	–	–	–	–	0.251	15,900	13,100
72 (B)	None	481-483	700	0.181	0.132	0.138	–	–	–	–	0.150	14,500	10,600
72 (B)	None	503-506	900	0.092	0.093	0.166	0.093	–	–	–	0.111	12,600	9,100
None	28	74-76	500	0.288	0.290	0.287	–	–	–	–	0.288	15,400	13,700
1 (S)	28	95-97	500	0.226	0.221	0.240	–	–	–	–	0.229	16,100	13,000
None	29	77-79	500	0.264	0.278	0.281	–	–	–	–	0.274	16,100	13,700
1 (S)	29	98-100	500	0.211	0.239	0.237	–	–	–	–	0.229	15,900	12,600
None	30	80-82	500	0.286	0.287	0.294	–	–	–	–	0.289	14,500	12,700
1 (S)	30	101-103	500	0.241	0.260	0.242	–	–	–	–	0.248	14,800	12,200
None	31	83-85	500	0.282	0.293	0.291	–	–	–	–	0.289	15,000	13,000
1 (S)	31	104-106	500	0.242	0.246	0.220	–	–	–	–	0.236	15,300	12,400
None	32	86-88	500	0.304	0.305	0.303	–	–	–	–	0.304	13,800	12,100
1 (S)	32	107-109	500	0.258	0.242	0.254	–	–	–	–	0.251	15,400	12,700
None	33	89-91	500	0.303	0.309	0.310	–	–	–	–	0.307	14,100	12,400
1 (S)	33	110-112	500	0.246	0.248	0.244	–	–	–	–	0.246	14,800	12,200

(a) Letter in parenthesis indicates method of application: S = sprayed; BR = billets rolled in powder; B = brushed on dies; DR = dies rubbed with lubricant.
(b) Bulge index = maximum concavity or convexity minus the end diameter of the samples after pressing 1-inch-diameter x 1-1/2-inch-high billets to a height of 0.75 inch.
(c) Maximum pressure is based on the average contact area between billet and die. Billet temperature was 875 F.
(d) 17 S aluminum.

TABLE F-4. DATA OBTAINED IN EXTRUSION EXPERIMENTS ON 2014 ALUMINUM ALLOY

Extrusion Sample	Die[a]	Die and Container Lubricant	Method of Application[b]	Billet Treatment or Billet Lubricant	Extrusion Pressure, psi Front	Middle	Back	Surface Rating[c]	Extruded Diameter, in. Front	Back
1	Flat	None	–	–	78,200	47,500	37,300	F	0.311	0.311
2	Flat	None	–	–	71,500	49,000	38,400	F	0.311	0.311
3	Flat	None	–	–	66,700	47,500	38,400	F	0.311	0.311
					Average 72,100	48,000	38,000			
7	Conical	None	–	–	82,500	56,800	43,400	VG	0.311	0.311
8	Conical	None	–	–	82,500	56,800	40,800	VG	0.311	0.311
9	Conical	None	–	–	81,100	56,800	43,400	VG	0.311	0.311
					Average 82,000	56,800	42,500			
19	Flat	1	S	–	67,800	54,000	40,800	VG	0.311	0.311
20	Flat	1	S	–	59,800	51,800	33,900	VG	0.311	0.311
21	Flat	1	S	–	66,700	53,100	39,500	VG	0.311	0.311
					Average 64,800	53,000	38,100			
16	Conical	1	S	–	81,100	53,100	39,500	G	0.311	0.311
17	Conical	1	S	–	76,800	53,100	39,500	G	0.311	0.311
18	Conical	1	S	–	79,500	53,100	40,800	G	0.311	0.311
					Average 79,100	53,100	39,900			
13	Flat	1	S	200	54,200	51,800	38,400	VG	0.311	0.311
14	Flat	1	S	200	47,500	45,200	38,400	G	0.311	0.311
15	Flat	1	S	200	50,500	43,400	33,900	G	0.311	0.311
					Average 50,700	46,800	36,900			
22	Conical	1	S	200	40,800	39,500	38,400	G	0.311	0.311
23	Conical	1	S	200	43,400	46,300	38,400	G	0.311	0.311
24	Conical	1	S	200	43,400	42,000	39,500	G	0.311	0.311
					Average 42,500	42,600	38,800			
4	Flat	3	S	–	67,800	49,000	38,400	VG	0.311	0.311
5	Flat	3	S	–	53,100	49,000	38,400	VG	0.311	0.311
6	Flat	3	S	–	67,800	51,800	40,800	VG	0.311	0.311
					Average 62,900	49,900	39,200			
10	Conical	3	S	–	68,900	56,800	42,000	F	0.311	0.311
11	Conical	3	S	–	62,400	54,200	42,000	F	0.311	0.311
12	Conical	3	S	–	70,200	59,800	42,000	G	0.311	0.311
					Average 67,200	56,900	42,000			
69	Flat	–	R	22	49,000	40,800	32,800	P	0.311	0.311
70	Flat	–	R	22	75,700	51,800	40,800	F	0.311	0.311
					Average 62,300	46,300	36,800			
39	Conical	–	R	22	–	49,000	42,000	VP	0.311	0.311
40	Conical	–	R	22	54,200	49,000	40,800	VP	0.311	0.311
41	Conical	–	R	22	56,800	53,100	43,400	VP	0.311	0.311
					Average 55,500	50,400	42,100			
54	Flat	49A	B	–	54,200	45,200	35,300	F	0.311	0.311
55	Flat	49A	B	–	63,800	54,200	42,000	G	0.311	0.311
56	Flat	49A	B	–	59,800	47,500	39,500	F	0.311	0.311
					Average 59,300	49,000	38,900			
51	Conical	49A	B	–	51,800	49,000	35,300	G	0.311	0.311
52	Conical	49A	B	–	49,000	43,400	40,800	F	0.311	0.311
53	Conical	49A	B	–	40,800	38,400	29,800	G	0.311	0.311
					Average 47,200	43,600	35,300			
48	Flat	65	B	–	42,000	38,400	31,400	F	0.311	0.311
49	Flat	65	B	–	42,000	38,400	31,400	F	0.311	0.311
50	Flat	65	B	–	43,400	40,800	32,800	F	0.311	0.311
					Average 42,500	39,200	31,900			
42	Conical	65	B	–	54,200	40,800	35,300	VG	0.311	0.311
43	Conical	65	B	–	54,200	40,800	35,300	G	0.311	0.311
44	Conical	65	B	–	47,500	40,800	38,400	G	0.311	0.311
					Average 52,000	40,800	36,300			
66	Flat	123	B	–	40,800	38,400	31,400	G	0.311	0.311
67	Flat	123	B	–	–	–	–	F	0.311	0.311
68	Flat	123	B	–	40,800	38,400	31,400	G	0.311	0.311
					Average 40,800	38,400	31,400			

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TABLE F-4. (Continued)

Extrusion Sample	Die(a)	Die and Container Lubricant	Method of Application(b)	Billet Treatment or Billet Lubricant	Extrusion Pressure, psi Front	Middle	Back	Surface Rating(c)	Extruded Diameter, in. Front	Back
45	Conical	123	B	–	38,400	42,000	38,400	F	0.311	0.311
46	Conical	123	B	–	43,400	40,800	38,400	F	0.311	0.311
47	Conical	123	B	–	37,300	40,800	35,300	F	0.311	0.311
					Average 39,700	41,200	37,400			
72	Flat	124	B	–	38,400	35,300	29,800	VP	0.311	0.311
73	Flat	124	B	–	40,800	38,400	33,900	F	0.311	0.311
74	Flat	124	B	–	39,500	35,300	32,800	P	0.311	0.311
					Average 39,600	36,300	32,200			
75	Conical	124	B	–	75,700	51,800	51,800	VP	0.311	0.311
76	Conical	124	B	–	59,800	46,300	46,300	VP	0.311	0.311
77	Conical	124	B	–	46,300	38,400	38,400	P	0.311	0.311
					Average 60,600	45,500	45,500			
31	Flat	–	B	149	45,200	40,800	29,800	F	0.311	0.311
32	Flat	–	B	149	40,800	35,300	28,200	F	0.311	0.311
33	Flat	–	B	149	43,400	39,500	31,400	F	0.311	0.311
					Average 43,100	38,500	29,800			
34	Conical	–	B	149	32,800	29,800	29,800	F	0.311	0.311
35	Conical	–	B	149	37,300	38,400	38,400	F	0.311	0.311
36	Conical	–	B	149	35,300	38,400	35,300	F	0.311	0.311
					Average 35,100	35,500	34,500			
63	Flat	149	B	–	75,700	53,100	40,800	G	0.311	0.311
64	Flat	149	B	–	81,100	53,100	42,000	G	0.311	0.311
65	Flat	149	B	–	84,900	54,200	43,400	G	0.311	0.311
37	Conical	149	B	–	38,400	32,800	40,800	F	0.311	0.311
38	Conical	149	B	–	83,600	54,200	40,800	VG	0.311	0.311
38A	Conical	149	B	–	83,600	56,800	43,400	VG	0.311	0.311
25	Flat	–	B	150	42,000	38,400	32,800	VG	0.311	0.311
26	Flat	–	B	150	43,400	38,500	29,800	F	0.311	0.311
27	Flat	–	B	150	39,500	32,800	27,100	F	0.311	0.311
					Average 41,200	36,900	29,900			
28	Conical	–	B	150	38,400	29,800	27,100	F	0.311	0.311
29	Conical	–	B	150	37,300	38,400	29,800	F	0.311	0.311
30	Conical	–	B	150	33,900	33,900	31,400	F	0.311	0.311
					Average 36,500	34,000	29,400			

(a) Flat die – 180-degree entrance angle; conical die – 130-degree entrance angle.
(b) S = sprayed; B = brushed; R = rolled in powder.
(c) The surfaces were rated according to the following classifications: VG = very good, no scoring, G = good, negligible scoring, F = fair, light scoring, P = poor, heavy scoring, VP = very poor, rough and heavily scored.

Testing Conditions: One-inch-diameter billets extruded to 5/16-inch-diameter rods using a billet temperature of 825 F and die and container temperatures of 800 F. Exit extrusion speed was 22.3 feet per minute.

APPENDIX G

PREPARATION OF GLASSES HAVING LOW SOFTENING TEMPERATURES

APPENDIX G

PREPARATION OF GLASSES HAVING LOW SOFTENING TEMPERATURES

Table G-1 lists the compositions of fourteen glasses which were prepared in the laboratory. These glasses were prepared in an attempt to produce a glass that had a sufficiently low softening temperature that would permit it to be used in working 2014 aluminum alloy. Also, if possible, it was desired to produce a glass that might permit its use in working magnesium and its alloys. For working aluminum, the glass should at least soften at the die temperature used and become considerably less viscous at the temperature of the billet.

It was believed that the phosphate-type glass offered the greatest promise of obtaining a glass having the desired softening range. These glasses are also water soluble, to a certain extent, which would be a desirable feature in cleaning the dies and/or the worked stock.

Glasses 1 through 5 listed in Table G-1 were prepared to determine the effects of various additions on the properties of glasses with a Na_2O-P_2O_5 base. Fusion tests were made on 1/2-inch-diameter by 1/2-inch-long compacts produced by pressing minus 100-mesh powder having the proper composition. Heating the compacts for 10 minutes at temperatures between 600 F and 1200 F showed that Glass 2 had the lowest softening temperature. The compacts made from this glass, containing 8.5 per cent zinc oxide, became vitreous at 600 F and flowed at 900 F. Glass 1 became vitreous at about 700 F and flowed at 1000 F. Glasses 3, 4, and 5 had much higher softening ranges, from about 1000 to 1200 F. Broken pieces of Glasses 1 and 2 were heated at 700 and 800 F to determine the degree of softening that took place at these temperatures. Glass 2 showed slight rounding of the sharp corners when heated at 700 F. This indicated that the glass was beginning to soften slightly. At a temperature of 800 F, the degree of softening was more pronounced. For the same temperatures, Glass 1 showed less rounding of corners, confirming the fusion experiments.

Based on these data, eight additional glasses were made to determine whether or not a glass having a lower softening temperature than Glass 2 could be made. Glass 12-1 had about the same nominal composition as Glass 2. Subsequent tests, in which a broken piece of each batch was heated at 800 F to note the softening tendencies, showed that the additional batches had higher softening temperatures than Glass 2. Glass 12-1, however, was similar to Glass 2. One additional glass (Glass 23-1) having lead oxide as a base and containing silica and B_2O_3 as additives, had a softening range higher than 800 F.

TABLE G-1. COMPOSITIONS AND CHARACTERISTICS OF LOW MELTING GLASSES PREPARED IN THE LABORATORY

Glass	Constituents, weight per cent										Description of Glass(a)	Fusion Test(b)	Rounding of Corners in Softening Test at Indicated Temperature(c)	
	Na_2O	P_2O_5	B_2O_3	Al_2O_3	CuO	ZnO	K_2O	PbO	F	SiO_2			700 F	800 F
1	27.8	63.6	-	-	-	-	-	8.5	-	-	A	Vitreous at 700 F, flowed at 1000 F	Very slight	Slight
2	27.8	63.6	-	-	-	8.5	-	-	-	-	A	Vitreous at 600 F, flowed at 900 F	Slight	Rounded
3	22.4	37.7	6.88	20.4	7.62	-	-	-	4.92	-	B	Semivitreous at 1000 F, near fusion at 1050 F	None	None
4	23.3	42.0	5.18	23.9	-	4.15	-	-	-	-	C	Vitreous at 1000 F, near fusion at 1100 F	None	None
5	14.11	41.6	5.18	23.9	-	4.15	10.7	-	-	-	C	Semivitreous at 1000 F, near fusion at 1200 F	None	None
12-1	30	60	-	-	-	10	-	-	-	-	A	-	Slight	Rounded
12-2	30	50	-	-	-	20	-	-	-	-	D	-	None	None
12-3	30	70	-	-	-	-	-	-	-	-	A	-	None	None
12-4	40	60	-	-	-	-	-	-	-	-	D	-	None	None
12-5	30	60	10	-	-	-	-	-	-	-	A	-	None	None
12-6	30	50	10	-	-	10	-	-	-	-	E	-	None	None
12-7	30	40	20	-	-	10	-	-	-	-	E	-	None	None
12-8	30	50	20	-	-	-	-	-	-	-	E	-	None	None
23-1	-	-	6.1	-	-	-	-	77.6	-	16.3	Clear yellow	-	None	None

(a) A - colorless and clear
B - clouded, then dark green when cold
C - contained unreacted oxides
D - immiscible fraction, white and opaque
E - immiscible fraction, milky and opaque.

(b) Minus 100-mesh powder compacts 1/2 inch in diameter by 1/2 inch in height heated for 10 minutes at temperatures from 600 to 1200 F.

(c) Piece of broken glass heated at the indicated temperatures to note the degree of rounding of sharp corners.

Based on these results, Glass 2 was selected for testing as a possible lubricating material. This glass is listed as Lubricant 22 in the list of lubricants given in Table E-1 of Appendix E.

APPENDIX H

DATA OBTAINED IN WORKING AZ80A MAGNESIUM ALLOY

TABLE H-1. FORGING-TEST DATA OBTAINED ON AZ80A MAGNESIUM ALLOY

Lubricant[a]	Billet Treatment	Forging Pressure[b], psi	Die Temperature, F	Forging Sample	Penetration Into Die Cavity[c], in.						Average Penetration, in.	Surface Rating[d]			Remarks
					1	2	3	4	5	6		Face	Radius	Ends	
1 (S)	None	46,000	500	4M-6M	0.94	1.125	1.11	–	–	–	1.06	A	A	A	–
1 (S)	None	46,000	500	80M-83M	1.03	1.22	1.28	1.08	–	–	1.16	B	A	A	–
1 (S)	None	46,000	500	172M-177M	0.76	1.01	1.12	1.20	1.28	1.37	1.12	A	A	A	–
2 (S)	None	46,000	500	7M-9M	0.87	0.98	1.00	–	–	–	0.95	A	A	A	–
3 (S)	None	46,000	500	10M-12M	0.94	0.92	0.90	–	–	–	0.92	A	A	A	–
4 (S)	None	46,000	500	238M-243M	1.16	1.26	1.53	1.55	1.55	1.53	1.44	B	B	A	–
4A (S)	None	46,000	500	232M-237M	1.19	1.26	1.47	1.66	1.16	1.73	1.48	B	B	A	–
4B (S)	None	46,000	500	214M-219M	1.16	1.59	1.80	1.81	1.80	1.81	1.66	B	B	A	–
4 C (S)	None	46,000	500	244M-249M	1.45	1.66	1.62	1.67	1.69	1.56	1.61	B	A	A	–
5 (S)	None	46,000	500	16M-18M	0.94	1.00	1.09	–	–	–	1.01	B	B	A	–
6 (S)	None	46,000	500	19M-21M	1.33	1.40	1.66	–	–	–	1.47	B	A	A	–
6 (S)	None	46,000	500	166M-171M	1.42	1.87	1.86	1.86	1.86	1.87	1.78	A	A	A	–
8 (S)	None	46,000	500	1M-3M	1.03	1.22	1.17	–	–	–	1.14	B	B	A	–
12 (S)	None	46,000	500	22M-24M	0.89	0.92	0.89	–	–	–	0.90	B	B	A	–
14 (S)	None	46,000	500	25M-27M	0.80	0.83	0.72	–	–	–	0.78	A	A	A	–
16 (S)	None	46,000	500	28M-30M	0.80	0.80	0.80	–	–	–	0.80	A	A	A	–
27 (B)	None	46,000	500	44M-46M	0.83	0.80	0.80	–	–	–	0.81	A	A	A	–
53 (S)	None	46,000	500	47M-49M	0.86	0.83	0.80	–	–	–	0.83	B	A	A	–
54 (DR)	None	46,000	500	32M-34M	0.86	0.87	0.95	–	–	–	0.89	A	A	A	–
55 (S)	None	46,000	500	35M-37M	0.80	1.00	0.89	–	–	–	0.89	B	B	A	–
56 (S)	None	46,000	500	38M-40M	0.73	0.78	0.73	–	–	–	0.75	A	B	A	–
58 (B)	None	46,000	500	41M-43M	0.95	1.06	1.06	–	–	–	1.03	C	B	A	–
65 (B)	None	46,000	500	31M	0.78	–	–	–	–	–	0.78	A	A	A	–
97[e]	None	46,000	500	71M-73M	1.00	1.14	1.16	–	–	–	1.09	B	B	C	–
105 (S)	None	46,000	500	74M-76M	0.87	0.97	0.92	–	–	–	0.92	A	A	A	–
106 (S)	None	46,000	500	77M-79M	0.98	1.00	0.95	–	–	–	0.98	B	B	A	–
143 (BR)	Billets rolled in powder before forging	46,000	500	65M-67M	0.64	0.59	0.92	–	–	–	0.72	A	A	A	–
144 (BR)	Applied to billets before heating	46,000	500	68M-70M	0.62	0.73	0.76	–	–	–	0.70	A	A	A	–
149 (B)	None	46,000	500	50M-52M	1.51	1.12	0.89	–	–	–	1.51	B	A	A	Applied to die before heating; no further application
149 (B)	None	46,000	500	56M-58M	1.87	1.53	1.05	–	–	–	1.87	B	B	A	Applied to dies cold, heated to 700 F, then cooled to 500 F for forging; no further application
149 (B)	None	46,000	600	59M-61M	1.87	1.64	1.42	–	–	–	1.87	B	A	A	Applied to dies cold, heated to 600 F for forging; no further application
149 (B)	None	46,000	600	62M-64M	1.83	1.53	1.39	–	–	–	1.83	B	A	A	Applied to dies cold, heated to 600 F before forging; lubricant reapplied on hot dies for Samples 63M and 64M

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TABLE H-1. (Continued)

Lubricant(a)	Billet Treatment	Forging Pressure(b), psi	Die Temperature, F	Forging Sample	Penetration Into Die Cavity(c), in. 1	2	3	4	5	6	Average Penetration, in.	Surface Rating(d) Face	Radius	Ends	Remarks
None	149	46,000	500	53M-55M	1.39	1.37	1.48	–	–	–	1.40	B	B	B	Applied before heating; some spalling after heating
None	149	46,000	500	178M-183M	1.87	1.87	1.87	1.84	1.87	1.76	1.84	A	A	A	Applied before heating; no spalling
None	150	46,000	500	184M-189M	1.83	1.87	1.69	1.80	1.69	1.66	1.75	A	A	A	Applied before heating
158 (S)	None	46,000	500	222M-225M	0.97	1.47	1.69	1.73	1.81	1.81	1.58	A	A	A	–
159 (S)	None	46,000	500	226M-231M	0.95	0.90	0.90	0.89	0.86	0.98	0.92	A	A	A	–
1 (S)	180	46,000	500	118M-123M	0.98	1.16	1.30	1.36	1.31	1.45	1.26	B	B	A	–
1 (S)	181	46,000	500	124M-129M	1.845	1.845	1.875	1.875	1.875	1.875	1.860	B	A	A	–
1 (S)	182	46,000	500	112M-117M	1.485	1.705	1.830	1.860	1.860	1.860	1.765	C	B	A	–
1 (S)	209	46,000	500	88M-93M	1.405	1.53	1.300	1.220	1.160	1.190	1.300	B	B	A	–
1 (S)	210	46,000	500	100M-105M	1.015	1.205	1.205	1.390	1.595	1.300	1.280	B	A	A	–
1 (S)	211	46,000	500	106M-111M	1.220	1.500	1.66	1.765	1.815	1.830	1.625	C	A	A	–
1 (S)	212	46,000	500	94M-99M	1.875	1.875	1.875	1.860	1.845	1.860	1.860	A	A	B	–
1 (S)	213	46,000	500	130M-135M	1.095	1.375	1.265	1.390	1.420	1.455	1.330	B	A	A	–
1 (S)	215	46,000	500	190M-195M	1.015	1.125	1.160	1.190	1.235	1.390	1.190	A	A	A	–
1 (S)	216	46,000	500	160M-165M	1.080	1.300	1.390	1.455	1.390	1.360	1.330	B	A	A	–
3 (S)	212	46,000	500	154M-159M	1.485	1.640	1.815	1.750	1.750	1.845	1.720	A	A	A	–
3 (S)	213	46,000	500	148M-153M	1.000	1.060	1.095	1.125	1.050	1.030	1.060	A	B	A	–
6 (S)	212	46,000	500	196M-201M	1.800	1.830	1.845	1.860	1.860	1.875	1.845	A	A	A	–
6 (S)	213	46,000	500	202M-207M	1.815	1.875	1.875	1.875	1.875	1.875	1.860	A	A	A	–
6 (S)	214	46,000	500	208M-213M	1.500	1.830	1.875	1.875	1.860	1.875	1.800	A	A	A	–
17 (S)	212	46,000	500	136M-141M	1.860	1.875	1.875	1.875	1.875	1.875	1.875	A	A	A	–
17 (S)	213	46,000	500	142M-147M	1.125	1.160	1.170	1.095	1.160	1.080	1.125	B	A	A	–

(a) Letters in parentheses indicate method of application. S = sprayed; BR = billets rolled in powder; B = brushed on dies; DR = dies rubbed with lubricant.
(b) Pressure based on a load of 115,000 pounds on an area of 2.5 square inches.
(c) Average penetration into the die measured from the shoulder. The value given is an average of measurements obtained at both ends and at the center.
(d) Surface ratings: A = no scoring; B = slight scoring or drag; C = severe scoring or tearing.
(e) Tetrafluoroethylene resin sheet laid in die cavity.

TABLE H-2. PRESSING-TEST DATA OBTAINED ON AZ80A MAGNESIUM ALLOY USING VARIOUS METHODS OF LUBRICATION

Lubricant[a]	Billet Treatment	Pressing Sample	Applied Load, lb	Die Temperature, F	Average Pressed Thickness for Individual Pressings, inch				Average Value for Test Series			
					1	2	3	4	Thickness, in.	Diameter, in.	Area, sq in.	Maximum Pressure, psi
1 (S)	None	1-3	138,000	500	0.093	0.092	0.083	–	0.089	2.370	4.400	31,400
1 (S)	None	82-84	138,000	500	0.085	0.084	0.079	–	0.082	2.460	4.700	29,400
1 (S)	None	85-87	67,000	500	0.115	0.103	0.102	–	0.106	2.170	3.700	18,100
1 (S)	212	92-94	138,000	500	0.059	0.059	0.054	–	0.058	2.950	6.870	20,100
1 (S)	212	88-91	67,000	500	0.071	0.067	0.076	0.076	0.072	2.620	5.440	12,300
2 (S)	None	4-6	138,000	500	0.075	0.052	0.067	–	0.065	2.800	6.210	22,200
3 (S)	None	7-9	138,000	500	0.104	0.104	0.107	–	0.105	2.180	3.740	36,900
3 (S)	None	95-97	138,000	500	0.102	0.093	0.097	–	0.097	2.270	4.050	34,000
3 (S)	None	98-100	67,000	500	0.139	0.132	0.122	–	0.131	1.960	3.010	22,200
4 (S)	None	7-9	138,000	500	0.086	0.086	0.085	–	0.086	2.410	4.580	30,100
5 (S)	None	13-15	138,000	500	0.091	0.086	0.079	–	0.085	2.420	4.610	29,900
6 (S)	None	16-18	138,000	500	0.076	0.078	0.079	–	0.078	2.540	5.050	27,400
8 (S)	None	19-21	138,000	500	0.049	0.063	0.053	–	0.055	3.030	7.210	19,100
12 (S)	None	22-24	138,000	500	0.106	0.107	0.108	–	0.107	2.160	3.670	37,600
14 (S)	None	25-27	138,000	500	0.095	0.098	0.101	–	0.098	2.260	4.000	34,500
16 (S)	None	28-30	138,000	500	0.088	0.109	0.096	–	0.098	2.270	4.050	34,000
23 (B)	None	40-42	138,000	500	0.103	0.101	0.110	–	0.105	2.180	3.750	36,800
24 (B)	None	43-45	138,000	500	0.109	0.109	0.111	–	0.110	2.130	3.580	38,600
25 (B)	None	46-48	138,000	500	0.086	0.099	0.108	–	0.098	2.270	3.870	35,700
26 (B)	None	49-51	138,000	500	0.083	0.089	0.098	–	0.090	2.370	4.380	31,600
27 (B)	None	52-54	138,000	500	0.085	0.096	0.096	–	0.092	2.330	4.280	32,200
53 (S)	None	64-66	138,000	500	0.108	0.110	0.117	–	0.112	2.120	3.520	39,300
54 (DR)	None	37-39	138,000	500	0.086	0.078	0.075	–	0.080	2.520	4.940	28,000
55 (S)	None	61-63	138,000	500	0.082	0.082	0.090	–	0.085	2.400	4.500	30,700
56 (S)	None	58-60	138,000	500	0.111	0.113	0.114	–	0.113	2.100	3.480	39,700
58 (B)	None	55-57	138,000	500	0.076	0.068	0.066	–	0.070	2.680	5.630	24,500
60 (S)	None	67-69	138,000	500	0.111	0.115	0.118	–	0.115	2.090	3.430	40,250
61 (S)	None	70-72	138,000	500	0.087	0.092	0.101	–	0.093	2.320	4.200	32,900
62 (S)	None	73-75	138,000	500	0.101	0.099	0.098	–	0.099	2.240	3.950	35,000
63 (S)	None	76-78	138,000	500	0.109	0.118	0.118	–	0.115	2.090	3.420	40,300
64 (S)	None	79-81	138,000	500	0.109	0.115	0.115	–	0.113	2.100	3.470	39,800
65 (B)	None	31-33	138,000	500	0.082	0.085	0.081	–	0.083	2.460	4.760	29,000
74 (B)	None	34-36	138,000	500	0.090	0.094	0.096	–	0.093	2.310	4.200	32,800

(a) Letters in parentheses indicate the method of application. S = sprayed; B = brushed; DR = dies rubbed with lubricant.

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TABLE H-3. BULGE-TEST DATA OBTAINED ON AZ80A MAGNESIUM ALLOY USING VARIOUS TYPES OF LUBRICANTS

Lubricant[a]	Billet Treatment	Bulge Sample	Die Temperature, F	Bulge Index for Individual Pressing[b] 1	2	3	4	5	6	Average Bulge Index, in.	Average Maximum Load, lb	Average Maximum Pressure, psi[c]
None	None	1M-6M	300	0.563	0.534	0.494	0.500	0.561	0.538	0.527	25,320	28,560
None	None	7M-12M	500	0.295	0.330	0.344	0.356	0.356	0.408	0.351	20,200	18,405
1 (S)	None	28M-30M	300	0.533	0.503	0.528	–	–	–	0.521	19,530	21,860
1 (S)	None	25M-27M	500	0.148	0.159	0.306	–	–	–	0.204	19,330	14,910
2 (S)	None	16M-18M	300	0.484	0.462	0.436	–	–	–	0.461	18,670	19,480
2 (S)	None	13M-15M	500	0.021	–0.143	0.094	–	–	–	0.009	21,500	13,890
3 (S)	None	19M-21M	300	0.517	0.485	0.524	–	–	–	0.509	22,800	22,490
3 (S)	None	22M-24M	500	0.350	0.305	0.327	–	–	–	0.327	16,200	14,480
4 (S)	None	67M-69M	300	0.548	0.513	0.540	–	–	–	0.537	25,600	28,970
4 (S)	None	91M-93M	500	0.298	0.363	0.352	–	–	–	0.337	30,370	27,100
5 (S)	None	64M-66M	300	0.520	0.537	0.494	–	–	–	0.517	21,630	23,970
5 (S)	None	31M-33M	500	–0.188	–0.088	0.135	–	–	–	–0.037	25,930	16,330
6 (S)	None	61M-63M	300	0.525	0.523	0.516	–	–	–	0.521	22,300	24,920
6 (S)	None	34M-36M	500	0.348	0.330	0.360	–	–	–	0.346	24,470	21,530
8 (S)	None	58M-60M	300	0.483	0.511	0.482	–	–	–	0.492	22,130	23,710
8 (S)	None	37M-39M	500	–0.122	0.055	0.143	–	–	–	0.025	22,970	15,020
12 (S)	None	55M-57M	300	0.503	0.535	0.507	–	–	–	0.515	26,130	28,700
12 (S)	None	40M-42M	500	0.336	0.354	0.375	–	–	–	0.355	18,800	17,230
14 (S)	None	52M-54M	300	0.503	0.497	0.482	–	–	–	0.494	26,300	28,150
14 (S)	None	43M-45M	500	0.085	0.256	0.361	–	–	–	0.234	20,970	16,880
16 (S)	None	49M-51M	300	0.497	0.519	0.463	–	–	–	0.493	29,800	31,870
16 (S)	None	46M-48M	500	0.159	0.199	0.288	–	–	–	0.215	18,330	14,700
23 (B)	None	76M-78M	300	0.492	0.501	0.549	–	–	–	0.514	28,770	31,400
23 (B)	None	100M-102M	500	0.253	0.268	0.150	–	–	–	0.224	24,300	19,370
24 (B)	None	79M-81M	300	0.497	0.501	0.513	–	–	–	0.504	27,130	29,820
24 (B)	None	103M-105M	500	0.183	0.101	0.167	–	–	–	0.150	25,300	17,510
25 (B)	None	82M-84M	300	0.506	0.491	0.500	–	–	–	0.499	22,800	24,720
25 (B)	None	106M-108M	500	0.122	0.281	0.200	–	–	–	0.201	20,830	16,020
26 (B)	None	85M-87M	300	0.454	0.451	0.476	–	–	–	0.460	24,300	25,720
26 (B)	None	109M-111M	500	–0.018	0.104	0.151	–	–	–	0.079	21,630	14,680
27 (B)	None	88M-90M	300	0.476	0.458	0.485	–	–	–	0.473	22,300	24,480
27 (B)	None	112M-114M	500	0.109	0.285	0.141	–	–	–	0.178	17,700	13,200
53 (S)	None	70M-72M	300	0.506	0.512	0.539	–	–	–	0.519	27,130	30,070
53 (S)	None	94M-96M	500	0.209	0.256	0.200	–	–	–	0.222	23,630	18,630
54 (DR)	None	73M-75M	300	0.475	0.517	0.482	–	–	–	0.491	20,370	22,030
54 (DR)	None	97M-99M	500	–0.099	0.005	0.003	–	–	–	0.030	25,970	16,400
55 (S)	None	142M-144M	300	0.490	0.543	0.551	–	–	–	0.528	24,200	26,900
55 (S)	None	115M-117M	300	0.465	0.432	0.500	–	–	–	0.466	34,700	36,400
55 (S)	None	124M-126M	500	0.222	0.264	0.263	–	–	–	0.250	21,800	17,800
55 (S)	None	151M-153M	500	0.172	0.300	0.269	–	–	–	0.247	21,200	17,100
56 (S)	None	118M-120M	300	0.480	0.494	0.503	–	–	–	0.492	25,400	27,700
56 (S)	None	121M-123M	500	0.216	0.171	0.185	–	–	–	0.191	24,200	18,300
58 (B)	None	145M-147M	300	0.523	0.520	0.499	–	–	–	0.514	24,200	26,400
58 (B)	None	154M-156M	500	0.067	0.065	0.166	–	–	–	0.099	24,500	17,200
60 (S)	None	127M-129M	500	0.319	0.386	0.410	–	–	–	0.372	22,400	21,100
61 (S)	None	130M-132M	500	0.223	0.312	0.373	–	–	–	0.303	24,400	21,500
62 (S)	None	133M-135M	500	0.349	0.386	0.399	–	–	–	0.378	18,500	17,800
63 (S)	None	136M-138M	500	0.337	0.450	0.428	–	–	–	0.403	21,000	20,800

TABLE H-3. (Continued)

Lubricant(a)	Billet Treatment	Bulge Sample	Die Temperature, F	Bulge Index for Individual Pressing(b) 1	2	3	4	5	6	Average Bulge Index, in.	Average Maximum Load, lb	Average Maximum Pressure, psi(c)
64 (S)	None	139M-141M	500	0.364	0.436	0.455	–	–	–	0.418	19,200	19,400
65 (B)	None	157M-159M	300	0.461	0.462	0.466	–	–	–	0.463	25,200	26,000
65 (B)	None	148M-150M	500	0.125	0.215	0.125	–	–	–	0.155	20,100	15,000

(a) Letter in parenthesis indicates method of application: S = sprayed; B = brushed on dies; BR = billets rolled in powder; DR = dies rubbed with lubricant.
(b) Bulge index = maximum concavity or convexity minus the end diameter of the samples after pressing 1-inch-diameter x 1-1/2-inch-high billets to a height of 0.75 inch. Values underscored are for samples that showed diagonal slip or shear.
(c) Maximum pressure is based on the average contact area between billet and die.

TABLE H-4. DATA OBTAINED IN EXTRUSION EXPERIMENTS ON AZ80A MAGNESIUM ALLOY

Extrusion Sample	Die[a]	Die and Container Lubricant	Method of Lubrication[b]	Billet Treatment or Billet Lubricant		Extrusion Pressure, psi Front	Middle	Back	Surface Rating[c]	Extruded Diameter, in. Front	Back	Remarks
1M	Flat	None	–	–		65,300	46,300	40,800	G	0.311	0.311	Small pipe
2M	Flat	None	–	–		67,800	51,800	43,400	G	0.311	0.311	Small pipe
3M	Flat	None	–	–		65,300	49,000	42,000	G	0.311	0.311	Small pipe
					Average	66,100	49,000	42,000				
4M	Conical	None	–	–		70,200	54,200	45,200	G	0.311	0.311	–
5M	Conical	None	–	–		72,900	56,800	56,300	G	0.311	0.311	–
6M	Conical	None	–	–		81,100	59,800	46,300	G	0.311	0.311	–
					Average	74,700	56,900	45,900				
13M	Flat	1	S	–		62,400	45,200	38,400	G	0.311	0.311	Small pipe
14M	Flat	1	S	–		49,000	46,300	32,800	G	0.311	0.311	1-1/2-in. segmented, pipe
15M	Flat	1	S	–		51,800	38,400	35,300	G	0.311	0.311	1-1/2-in. segmented, pipe
					Average	54,400	43,600	35,500				
16M	Conical	1	S	–		40,800	42,000	38,400	F	0.311	0.311	–
17M	Conical	1	S	–		40,800	38,400	38,400	F	0.311	0.311	–
18M	Conical	1	S	–		49,000	46,300	40,800	G	0.311	0.311	–
					Average	43,500	42,200	39,200				
19M	Flat	3	S	–		43,400	37,300	35,300	VG	0.311	0.311	1-in. segmented, pipe
20M	Flat	3	S	–		49,000	39,500	38,400	G	0.311	0.311	Pipe
21M	Flat	3	S	–		51,800	40,800	38,400	G	0.311	0.311	1/2-in. segmented, pipe
					Average	48,100	39,200	37,700				
22M	Conical	3	S	–		38,400	32,800	32,800	G	0.311	0.311	–
23M	Conical	3	S	–		49,000	43,400	38,400	F	0.311	0.311	–
24M	Conical	3	S	–		46,300	40,800	42,000	F	0.311	0.311	–
					Average	44,600	39,000	37,700				
55M	Flat	5	S	–		54,200	40,800	35,300	F	0.311	0.311	1/2-in. segmented, pipe
56M	Flat	5	S	–		62,400	49,000	43,400	F	0.311	0.311	1-in. segmented, pipe
57M	Flat	5	S	–		54,200	40,800	38,400	F	0.311	0.311	1-in. segmented, pipe
					Average	56,900	43,500	39,000				
58M	Conical	5	S	–		49,000	38,400	38,400	G	0.311	0.311	–
59M	Conical	5	S	–		46,300	49,000	46,300	G	0.311	0.311	–
60M	Conical	5	S	–		47,500	49,000	43,400	G	0.311	0.311	–
					Average	47,600	45,500	42,700				
25M	Flat	6	S	–		70,200	51,800	46,300	F	0.311	0.311	Pipe
26M	Flat	6	S	–		65,300	47,500	40,800	G	0.311	0.311	1-in. segmented, pipe
27M	Flat	6	S	–		75,700	51,800	43,400	G	0.311	0.311	1-in. segmented, pipe
					Average	70,400	50,400	43,500				
28M	Conical	6	S	–		59,800	56,800	49,000	F	0.311	0.311	–
29M	Conical	6	S	–		72,900	59,800	49,000	F	0.311	0.311	–
30M	Conical	6	S	–		67,800	59,800	51,800	F	0.311	0.311	–
					Average	66,900	58,800	49,900				
81M	Flat	6	S	–		70,200	50,500	42,000	G	0.311	0.311	1-in. segmented, pipe
82M	Flat	6	S	–		70,200	51,800	43,400	G	0.311	0.311	1/2-in. segmented, pipe
83M	Flat	6	S	–		67,800	49,000	40,800	G	0.311	0.311	1/2-in. segmented, pipe
					Average	69,400	50,400	42,100				
84M	Conical	6	S	–		65,300	58,400	49,000	G	0.311	0.311	–
85M	Conical	6	S	–		65,300	62,400	49,000	G	0.311	0.311	–
86M	Conical	6	S	–		66,700	62,400	53,100	G	0.311	0.311	–
					Average	65,800	61,100	50,400				
43M	Flat	123	B	–		51,800	38,400	32,800	G	0.311	0.311	Pipe
44M	Flat	123	B	–		49,000	39,500	32,800	G	0.311	0.311	Pipe
45M	Flat	123	B	–		51,800	40,800	32,800	G	0.311	0.311	1-1/2-in. segmented, pipe
					Average	50,900	39,600	32,800				
46M	Conical	123	B	–		54,200	43,400	38,400	G	0.311	0.311	–
47M	Conical	123	B	–		46,300	40,800	38,400	G	0.311	0.311	–
48M	Conical	123	B	–		45,200	46,300	39,500	G	0.311	0.311	–
					Average	48,600	43,500	38,800				
49M	Flat	124	B	–		49,000	35,300	31,400	G	0.311	0.311	Pipe
50M	Flat	124	B	–		53,100	40,800	35,300	G	0.311	0.311	Pipe
51M	Flat	124	B	–		51,800	39,500	33,900	G	0.311	0.311	1/2-in. segmented, pipe
					Average	51,300	38,500	33,500				
52M	Conical	124	B	–		40,800	40,800	35,300	G	0.311	0.311	–
53M	Conical	124	B	–		40,800	40,800	35,300	G	0.311	0.311	–
54M	Conical	124	B	–		46,300	40,800	35,300	G	0.311	0.311	–
					Average	42,600	40,800	35,300				

TABLE H-4. (Continued)

Extrusion Sample	Die(a)	Die and Container Lubricant	Method of Lubrication(b)	Billet Treatment or Billet Lubricant		Extrusion Pressure, psi Front	Middle	Back	Surface Rating(c)	Extruded Diameter, in. Front	Back	Remarks
7M	Flat	–	B	149		49,000	37,300	32,800	F	0.311	0.311	1/2-in. segmented, pipe
8M	Flat	–	B	149		49,000	35,300	27,100	F	0.311	0.311	1-in. segmented, pipe
9M	Flat	–	B	149		46,300	33,900	26,000	F	0.311	0.311	1-in. segmented, pipe
					Average	48,100	35,500	28,600				
10M	Conical	–	B	149		39,500	31,400	24,400	F	0.311	0.311	–
11M	Conical	–	B	149		35,300	32,800	24,400	F	0.311	0.311	–
12M	Conical	–	B	149		40,800	32,800	27,100	F	0.311	0.311	–
					Average	38,500	32,300	25,300				
67M	Conical	None	–	212		88,900	55,400	43,400	G	0.311	0.311	–
68M	Conical	None	–	212		81,100	59,800	49,000	G	0.311	0.311	–
69M	Conical	None	–	212		82,500	61,000	49,000	G	0.311	0.311	–
					Average	84,200	58,700	47,100				
71M	Flat	None	–	212		68,900	46,300	38,400	VG	0.311	0.311	Pipe
72M	Flat	None	–	212		78,200	53,100	43,400	G	0.311	0.311	Pipe
73M	Flat	None	–	212		72,900	54,200	43,400	VG	0.311	0.311	Pipe
					Average	73,300	51,200	41,700				
31M	Flat	1	S	212		51,800	38,400	33,900	P	0.311	0.311	1-1/2-in. segmented, pipe
32M	Flat	1	S	212		58,400	43,400	38,400	F	0.311	0.311	1-in. segmented, pipe
33M	Flat	1	S	212		55,400	40,800	35,300	F	0.311	0.311	1/2-in. segmented, pipe
					Average	55,100	40,900	35,900				
34M	Conical	1	S	212		40,800	40,800	35,300	G	0.311	0.311	–
35M	Conical	1	S	212		43,400	38,400	32,800	G	0.311	0.311	–
36M	Conical	1	S	212		40,800	38,400	35,300	G	0.311	0.311	–
					Average	41,700	39,200	34,500				
37M	Flat	5	S	212		54,200	43,400	35,300	G	0.311	0.311	1-in. segmented, pipe
38M	Flat	5	S	212		59,800	40,800	40,800	G	0.311	0.311	Pipe
39M	Flat	5	S	212		54,200	40,800	40,800	G	0.311	0.311	1-in. segmented, pipe
					Average	56,100	41,700	39,000				
40M	Conical	5	S	212		43,400	45,200	43,400	G	0.311	0.311	–
41M	Conical	5	S	212		43,400	45,200	40,800	G	0.311	0.311	–
42M	Conical	5	S	212		45,200	45,200	40,800	G	0.311	0.311	–
					Average	44,000	45,200	41,700				
61M	Flat	6	S	212		70,200	46,300	35,300	F	0.311	0.311	1-in. segmented, pipe
62M	Flat	6	S	212		72,900	43,400	32,800	P	0.311	0.311	1-in. segmented, pipe
63M	Flat	6	S	212		67,800	40,800	35,300	F	0.311	0.311	1-in. segmented, pipe
					Average	70,300	43,500	34,500				
64M	Conical	6	S	212		67,800	59,800	46,300	F	0.311	0.311	–
65M	Conical	6	S	212		70,200	62,400	49,000	G	0.311	0.311	–
66M	Conical	6	S	212		62,400	54,200	46,300	G	0.311	0.311	–
					Average	66,800	58,800	47,200				
70M	Flat	None	–	–		81,100	49,000	39,500	VP(d)	0.311	0.311	Entire rod segmented
74M	Conical	None	–	–		88,900	59,800	46,300	VG(d)	0.311	0.311	–

(a) Flat die, 180-degree entrance angle; conical die, 130-degree entrance angle.

(b) S = sprayed; B = brushed.

(c) The surfaces were rated according to the following classifications: VG = very good, no scoring; G = good, negligible scoring; F = fair, light scoring; P = poor, heavy scoring; VP = very poor, rough, scored.

Testing conditions: One-inch-diameter billets extruded to 5/16-inch-diameter rods using a billet temperature of 675 F and die and container temperatures of 600 F.

(d) Extruded at an exit rate of 22.3 feet per minute instead of normal 8.5 feet per minute.

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APPENDIX J

DATA OBTAINED IN WORKING UNALLOYED TITANIUM

TABLE J-1. DATA OBTAINED IN FORGING TESTS USING VARIOUS TYPES OF LUBRICANTS ON UNALLOYED TITANIUM

Lubricant[a]	Billet Treatment	Forging Pressure[b], psi	Die Temperature, F	Forging Sample	Penetration Into Die Cavity[c], in. 1	2	3	4	5	6	Average Penetration, in.	Surface Rating[d] Face	Radius	Ends	Remarks
1 (S)	None	46,000	900	35-38	0.580	0.705	0.970	0.500	–	–	0.690	A	A	A	–
1 (S)	None	46,000	900	45-50	0.830	0.610	0.720	0.705	0.985	0.940	0.800	B	A	A	–
1 (S)	218	46,000	900	57-59	1.06	0.955	1.095	–	–	–	1.030	B	A	A	–
1 (S)	218[e]	46,000	900	66-67	0.845	0.800	–	–	–	–	0.82	A	A	A	Out of furnace 7 sec before forging
1 (S)	218[f]	46,000	900	68-69	1.080	0.800	–	–	–	–	0.940	A	A	A	Out of furnace 13 sec before forging
1 (S)	218[e]	46,000	900	70-71	0.940	1.160	–	–	–	–	1.050	A	A	A	Out of furnace 13 sec before forging
1 (S)	218[f]	46,000	900	72-73	1.110	1.080	–	–	–	–	1.095	A	A	A	Out of furnace 7 sec before forging
1 (S)	181	46,000	900	42-44	0.565	0.595	0.765	–	–	–	0.640	A	A	A	–
1 (S)	.82	46,000	900	39-41	0.550	0.595	0.970	–	–	–	0.705	B	A	A	–
1 (S)	217	46,000	900	60-65	1.780[g]	0.970[h]	1.565[i]	1.595[j]	1.550[k]	0.720[l]	1.360	C	C	C	–
1A (B)	None	46,000	900	23-24	0.375	0.330	–	–	–	–	0.360	A	A	A	–
5 (S)	None	46,000	900	9-11	0.765	0.830	0.925	–	–	–	0.845	A	A	A	–
5A (B)	None	46,000	900	12-13	0.640	0.845	–	–	–	–	0.750	A	A	A	–
5 (S)	181	46,000	900	14-16	1.170	1.220	1.140	–	–	–	1.170	A	A	A	–
8 (S)	None	46,000	900	5-6	0.420	0.420	–	–	–	–	0.420	A	A	A	–
8A (B)	None	46,000	900	7-8	0.625	0.660	–	–	–	–	0.640	A	A	A	–
49A (B)	None	46,000	900	3-4	0.485	0.455	–	–	–	–	0.470	A	A	A	–
50A (B)	None	46,000	900	17-18	0.845	0.985	–	–	–	–	0.925	B	B	A	–
51A (B)	None	46,000	900	19-20	0.470	0.675	–	–	–	–	0.580	A	A	A	–
52A (B)	None	46,000	900	21-22	0.550	0.500	–	–	–	–	0.525	A	A	A	–
65 (B)	None	46,000	900	25-26	0.515	0.515	–	–	–	–	0.515	A	A	A	–
111 (BR)	None	46,000	900	31-32	0.470	0.360	–	–	–	–	0.405	A	A	A	–
113 (BR)	None	46,000	900	33-34	0.360	0.330	–	–	–	–	0.345	A	A	A	–
122 (BR)	None	46,000	900	1-2	0.405	0.345	–	–	–	–	0.375	A	A	A	–
123 (B)	None	46,000	900	27-28	0.780	0.515	–	–	–	–	0.660	A	A	A	–
124 (B)	None	46,000	900	29-30	0.375	0.420	–	–	–	–	0.405	A	A	A	–
177 (S)	None	46,000	900	51-56	0.750	0.595	0.985	0.940	0.890	1.095	0.875	B	A	A	–

Note: Billet temperature used was 1750 F.
Dies were hardened steel. The dies were cleaned between use of each lubricant with 320-grit paper which produced a surface roughness of 10 microinches.

(a) Letters in parentheses indicate the method of application: S = sprayed; BR = billets rolled in powder; B = brushed on dies.
(b) Pressure based on a load of 115,000 pounds on an area of 2.5 square inches.
(c) Average penetration into the die measured from the shoulder. The value given is an average of measurements obtained at both ends and at the center.
(d) The surface ratings listed summarize the surface conditions at the various locations on the forgings for the series of samples. The ratings were made visually and correspond to the following classification: A = no scoring; B = slight scoring or drag; C = severe scoring or tearing.
(e) Time in furnace, 30 minutes.
(f) Time in furnace, 45 minutes.
(g) Time in salt bath, 5 minutes.
(h) Time in salt bath, 4 minutes.
(i) Time in salt bath, 6 minutes.
(j) Time in salt bath, 10 minutes.
(k) Time in salt bath, 15 minutes.
(l) Time in salt bath, 5 minutes.

TABLE J-2. DATA OBTAINED IN PRESSING TESTS USING VARIOUS LUBRICANTS IN WORKING UNALLOYED TITANIUM

Lubricant[a]	Billet Treatment	Pressing Sample	Applied Load, lb	Die Temperature, F	Average Pressed Thickness for Individual Pressings, in. 1	2	3	4	Average Value of Test Series: Thickness, in.	Diameter, in.	Area, sq in.	Maximum Pressure, psi
1 (S)	None	21-22	138,000	900	0.148	0.155	–	–	0.152	1.73	2.33	59,200
1A (B)	None	19-20	138,000	900	0.120	0.124	–	–	0.122	1.92	2.90	47,600
5 (S)	None	59-60	138,000	900	0.108	0.111	–	–	0.110	2.03	3.24	42,600
5A (B)	None	57-58	138,000	900	0.107	0.117	–	–	0.112	2.01	3.17	43,600
8 (S)	None	53-54	138,000	900	0.149	0.142	–	–	0.146	1.76	2.43	56,800
8A (B)	None	23-24	138,000	900	0.113	0.122	–	–	0.118	1.96	3.02	45,800
49A (B)	None	1-2	138,000	700	0.124	0.128	–	–	0.126	1.91	2.84	48,400
49A (B)	None	9-10	138,000	900	0.115	0.112	–	–	0.114	2.00	3.12	44,200
50A (B)	None	3-4	138,000	700	0.134	0.132	–	–	0.133	1.85	2.68	51,500
50A (B)	None	11-12	138,000	900	0.152	0.127	–	–	0.140	1.80	2.56	54,000
51A (B)	None	5-6	138,000	700	0.126	0.124	–	–	0.125	1.91	2.85	48,400
51A (B)	None	13-14	138,000	1000	0.122	0.116	–	–	0.119	1.95	2.98	46,300
52A (B)	None	7-8	138,000	700	0.126	0.127	–	–	0.126	1.91	2.83	48,800
52A (B)	None	15-16	138,000	900	0.127	0.107	–	–	0.117	1.98	3.05	45,300
65 (B)	None	55-56	138,000	900	0.140	0.128	–	–	0.134	1.83	2.65	52,200
107 (B)	None	17-18	138,000	900	0.123	0.127	–	–	0.125	1.91	2.84	48.600
108 (BR)	None	25-26	138,000	900	0.135	0.139	–	–	0.137	1.81	2.58	55,700
109 (BR)	None	27-28	138,000	900	0.167	0.172	–	–	0.170	1.63	2.09	66,000
110 (BR)	None	29-30	138,000	900	0.147	0.133	–	–	0.140	1.80	2.53	54,600
111 (BR)	None	31-32	138,000	900	0.112	0.118	–	–	0.115	1.98	3.08	44,800
112 (BR)	None	33-34	138,000	900	0.153	0.144	–	–	0.149	1.74	2.39	57,800
113 (BR)	None	35-36	138,000	900	0.117	0.123	–	–	0.120	1.98	3.10	44,500
114 (BR)	None	37-38	138,000	900	0.154	0.161	–	–	0.158	1.69	2.25	61,400
115 (BR)	None	39-40	138,000	900	0.167	0.155	–	–	0.161	1.67	2.20	62,800
116 (BR)	None	41-42	138,000	900	0.170	0.164	–	–	0.167	1.64	2.12	65,100
118 (BR)	None	43-44	138,000	900	0.137	0.133	–	–	0.135	1.82	2.62	52,900
119 (BR)	None	45-46	138,000	900	0.138	0.150	–	–	0.144	1.77	2.46	56,100
120 (BR)	None	47-48	138,000	900	0.161	0.158	–	–	0.160	1.68	2.22	62,200
121 (BR)	None	49-50	138,000	900	0.171	0.169	–	–	0.170	1.62	2.08	66,400
122 (BR)	None	51-52	138,000	900	0.112	0.119	–	–	0.116	1.98	3.07	45,000
123 (B)	None	61-62	138,000	900	0.110	0.121	–	–	0.116	1.98	3.08	44,800
124 (B)	None	63-64	138,000	900	0.110	0.118	–	–	0.114	1.98	3.11	44,400
172 (R)	None	65-66	138,000	900	0.128	0.131	–	–	0.130	1.86	2.72	50,800
173 (R)	None	67-68	138,000	900	0.140	0.145	–	–	0.143	1.77	2.48	55,700
174 (R)	None	69-70/73-74	138,000	900	0.141	0.150	0.147	0.157	0.149	1.86	2.65	52,100
175 (R)	None	71-72	138,000	900	0.138	0.143	–	–	0.141	1.89	2.81	49,200

Note: All samples were 0.950 inch in diameter by 0.500 inch in thickness.
Billet temperature was 1750 F.
Dies were hardened steel and were cleaned and polished between use of different lubricants with 320-grit paper which produced a die roughness of about 10 microinches.

(a) Letters in parentheses indicate method of application: S = sprayed; B = brushed on dies; BR = billets rolled in powder.

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APPENDIX K

DATA OBTAINED IN WORKING STEEL

TABLE K-1. DATA OBTAINED IN FORGING TESTS USING VARIOUS TYPES OF LUBRICANTS IN WORKING TYPE 403 STAINLESS STEEL

Lubricant[a]	Billet Treatment	Forging Pressure, psi	Die Temperature, F	Forging Sample	Penetration Into Die Cavity[c], inch 1	2	3	Average Penetration, in.	Surface Rating[d] Face	Radius	Ends
1 (S)	None	46,000	900	44-46	0.310	0.345	0.345	0.330	A	A	A
1A (B)	None	46,000	900	32-34	0.405	0.405	0.345	0.390	A	B	A
5 (S)	None	46,000	900	22-24	0.345	0.405	0.440	0.390	A	A	A
5A (B)	None	46,000	900	25-27	0.390	0.330	0.470	0.390	A	B	B
8 (S)	None	46,000	700	5-7	0.405	0.375	0.375	0.375	A	A	A
8 (S)	None	46,000	900	8-10	0.420	0.420	0.405	0.420	A	A	A
8 (S)	None	46,000	1100	11-12	0.390	0.420	–	0.405	A	A	A
8A (B)	None	46,000	900	29-31	0.360	0.405	0.360	0.375	A	A	A
22 (BR)	None	46,000	700	13-15	0.390	0.420	–	0.405	B	C	C
49 (S)	None	46,000	700	1-4	0.455	0.440	0.485	0.455	A	A	A
65 (B)	None	46,000	700	16-18	0.330	0.330	0.300	0.310	A	A	A
65 (B)	None	46,000	900	35-37	0.390	0.390	0.390	0.390	A	A	A
81 (BR)	None	46,000	700	19-21	0.280	0.265	0.265	0.265	B	B	B
111 (BR)	None	46,000	900	47-49	0.345	0.345	0.330	0.345	C	C	B
123 (B)	None	46,000	900	38-40	0.500	0.500	0.500	0.500	B	B	A
124 (B)	None	46,000	900	41-43	0.360	0.420	0.330	0.375	A	A	A

Note: Billet temperature used was 2150 F.

(a) Letters in parentheses indicate the method of application; S = sprayed; B = brushed on dies; BR = billets rolled in powder.

(b) Pressure based on a load of 115,000 pounds on an area of 2.5 square inches.

(c) Average penetration into the die measured from the shoulder. The value given is an average of measurements obtained at both ends and at the center.

(d) The surface ratings listed summarize the surface conditions at the various locations on the forgings for the series of samples. The ratings were made visually and correspond to the following classification: A = no scoring; B = slight scoring or drag; C = severe scoring or tearing.

TABLE K-2. DATA OBTAINED IN PRESSING TESTS ON TYPE 403 STAINLESS STEEL USING VARIOUS MATERIALS AS LUBRICANTS

Lubricant(a)	Billet Treatment	Pressing Sample	Applied Load, lb	Die Temperature, F	Average Pressed Thickness for Individual Pressings, in.						Average Value for Test Series			
					1	2	3	4	5	6	Thickness, in.	Diameter, in.	Area, sq in.	Maximum Pressure, psi
1A (B)	None	10-12	138,000	900	0.175	0.153	0.157	–	–	–	0.166	1.76	2.44	56,600
5A (B)	None	13-15	138,000	900	0.143	0.142	0.154	–	–	–	0.146	1.86	2.69	51,400
8A (B)	None	16-18	138,000	900	0.145	0.147	0.158	–	–	–	0.150	1.83	2.62	52,700
111 (BR)	None	1-3	138,000	900	0.159	0.176	0.174	–	–	–	0.169	1.72	2.32	59,500
113 (BR)	None	4-6	138,000	900	0.180	0.209	0.172	–	–	–	0.187	1.64	2.12	65,100
122 (BR)	None	7-9	138,000	900	0.191	0.200	0.203	–	–	–	0.198	1.59	1.99	69,300
143 (BR)	None	19-21	138,000	900	0.219	0.223	0.227	–	–	–	0.223	1.49	1.76	78,400
172 (BR)	None	22-24	138,000	900	0.216	0.188	–	–	–	–	0.202	1.58	1.96	70,500
173 (BR)	None	25-27	138,000	900	0.196	0.206	0.207	–	–	–	0.203	1.58	1.94	71,000
174 (BR)	None	31-33	138,000	900	0.218	0.197	0.211	–	–	–	0.208	1.55	1.89	73,000
175 (BR)	None	34-36	138,000	900	0.209	0.218	0.224	–	–	–	0.217	1.52	1.81	76,300

Note: All samples were 1 inch in diameter by 0.500 inch thick.
Billet temperature used was 2150 F.
Dies were hardened steel and were cleaned and polished between use of different lubricants with 320-grit paper which produced a die roughness of about 10 microinches.

(a) Letters in parentheses indicate method of application; B = brushed on billets; BR = billets rolled in powder.

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TABLE K-3. BULGE-TEST DATA OBTAINED ON 4340 STEEL USING VARIOUS MATERIALS AS LUBRICANTS

Lubricant[a]	Billet Treatment	Bulge Sample	Die Temperature, F	Bulge Index for Individual Pressings[b], in. 1	2	3	4	5	Average Bulge Index, in.	Average Maximum Load, lb	Average Maximum Pressure[c], psi
None	None	1-2, 4-5	700	1.059	0.829	0.889	0.920	–	0.919	12,950	13,900
5 (S)	None	14-16	700	0.877	0.899	0.884	–	–	0.887	13,533	15,266
8 (S)	None	6-10	700	0.902	0.891	0.909	0.920	0.906	0.906	12,640	13,700
20 (BR)	None	11-13	700	0.877	0.942	1.013	–	–	0.944	14,467	15,400
21 (B)	None	23-25	700	0.924	0.856	0.933	–	–	0.904	12,866	14,100
22 (BR)	None	26-28	700	0.892	0.902	0.902	–	–	0.899	13,333	14,833
23 (B)	None	17-19	700	0.894	0.902	0.906	–	–	0.901	11,467	12,733
27 (B)	None	20-22	700	0.899	0.883	0.894	–	–	0.892	12,801	14,400

Note: Billet temperature was 2150 F.

(a) Letters in parentheses indicates method of application: S = sprayed; B = brushed on dies; BR = billets rolled in powder.
(b) Bulge index = maximum concavity or convexity minus the end diameter of the samples after pressing 1-inch-diameter by 1.5-inch-high billets to a height of 0.75 inch.
(c) Maximum pressure is based on the average contact area between billet and die.