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PRELIMINARY STUDIES OF SPECIAL ALUMINUM ARMOR FORGINGS

13th PARTIAL REPORT ON LIGHT ARMOR

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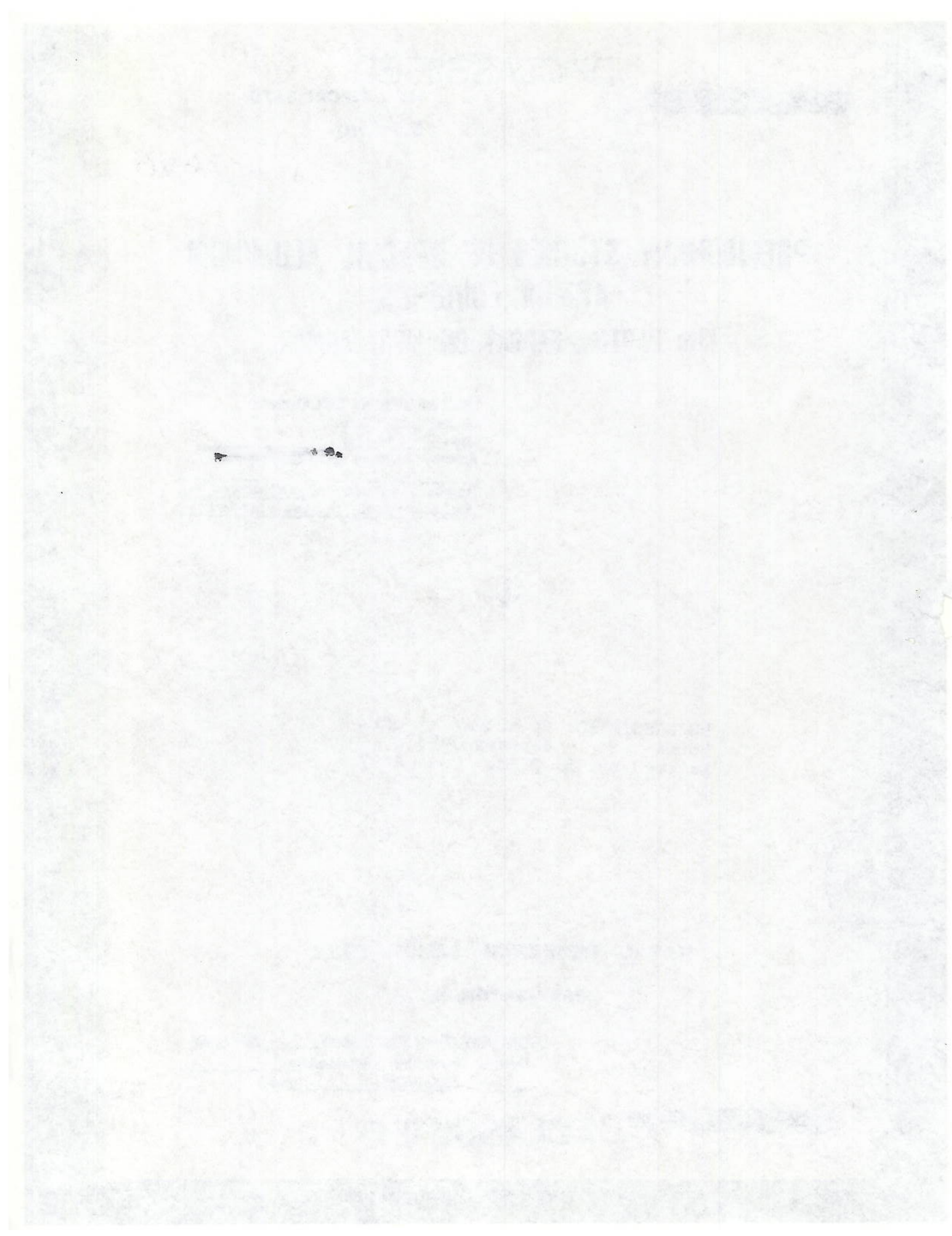
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PRELIMINARY STUDIES OF SPECIAL ALUMINUM ARMOR FORGINGS

13th PARTIAL REPORT ON LIGHT ARMOR

Harold Bernstein, Naval Gun Factory
and
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April 1, 1950

Approved by:

Dr. G. R. Irwin, Superintendent, Mechanics Division



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CONTENTS

Abstract	vi
Problem Status	vi
Authorization	vi
I. INTRODUCTION	1
Aluminum as Armor	1
Spalling Characteristics	1
Fracture Characteristics	1
Forged Armor	2
II. FABRICATION AND HEAT TREATMENT	3
Directionality of Mechanical Properties	3
Source of Material	3
Heat Treatment	4
Forging Process	4
Forging Reductions and Fractures	5
Anomalous Effects	7
Hardness Distribution	7
Macrostructures and Microstructures	7
Shingling and Spalling	9
III. BALLISTIC STUDIES	12
Choice of Projectile	12
Form Factor	13
Ballistic Data	13
Limit Velocity vs. Plate Thickness	16
"p" Coefficient	16
Summary of Ballistic Data	18
Limitations to Present Work	18
IV. CONCLUSIONS	19
V. RECOMMENDATIONS	19
VI. ACKNOWLEDGMENTS	19

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ABSTRACT

The report describes some preliminary unsuccessful attempts to reduce the spalling of samples of a three-inch R-301 aluminum alloy armor plate (essentially 14S composition) by hot and "cool" forging the samples to a range of smaller thicknesses. Cal. 50 sphere ballistic studies of the materials showed a progressive increase in the limit velocities of the "cool" forged plate over the limits for equivalent thickness of commercially rolled 24S-T4 plate for thicknesses greater than about 3/4-inch. The sphere performance of the "cool" forged material showed 13 percent higher limit velocities than the 24S-T4 commercial rolled plate at the 1-1/2-inch thickness.

PROBLEM STATUS

This is an interim report on a problem sponsored by the Bureau of Ordnance. It represents the 13th partial report issued by NRL on light armor. Work is continuing.

AUTHORIZATION

NRL work authorized by NRL Problem No. F04-04R. The Naval Gun Factory work was authorized by Bureau of Ordnance letter to NGF dated 14 April 1947, file S13-1 (Re3a-117). NO 413-129

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PRELIMINARY STUDIES OF SPECIAL ALUMINUM ARMOR
FORGINGS 13TH PARTIAL REPORT ON LIGHT ARMOR

I. INTRODUCTION

Aluminum as Armor

When judged on the basis of equal armor weight, the ballistic performance of the higher strength commercial aluminum alloys for certain selected types of missile attack has been shown clearly to be superior to that of more common armor types. In spite of this superiority of performance, a wide adoption of aluminum alloy armors in applicable fields has not occurred. Only in the case of aircraft armor can the use of aluminum alloys be considered as extensive. Perhaps the principal reason for the limited adoption by the military services of these materials is connected with their tendency to spall under missile attack. This may occur even under conditions where the primary missile is rejected by the armor. The usual measures of penetration resistance do not always reflect in a sensitive manner the tendency of armors to spall.

Spalling Characteristics

Practical realization of service performance commensurate with the present high measurements of penetration resistance of aluminum alloys is limited to those types of armor applications where either the effects of the secondary spall missiles can be safely regarded as negligible, or the type of attack is such that spall formation is quite unlikely.

When comparisons are restricted to a single armor material type it is evident that a reduction of spalling usually results in increased penetration resistance. Thus, the incentive to reduce spalling of aluminum armors comes both from a desire to eliminate the objectionable secondary missile character of the spall, and the desire for higher penetration resistance which is to be expected to accompany such a reduction. It appears, then, that the development of techniques which minimize, if not completely eliminate, spalling characteristics in these materials will result in a direct stimulus to the adoption of aluminum alloy armors in applicable fields.

This report discusses certain early, unsuccessful, attempts to reduce this spall formation in the case of one particular alloy, R301, which is essentially 14S. The work was performed in cooperation with the Naval Gun Factory.

Fracture Characteristics

A careful microscopic study by this Laboratory¹ and Aluminum Research Laboratory² of the spall fractures resulting from fragment penetration of commercial sheet

¹Unpublished NRL Work, Ballistics Branch

²Giesler, A. H., Aluminum Research Laboratory Report to NRL, 1943

products has shown that these fractures are mixed in character, the fracture being randomly composed of approximately equal portions, trans- and inter-granular fractures. A similar study^{3,1} of the distribution and arrangement of visible undissolved microconstituents, always present in commercial sheet alloys, failed to suggest any weakening mechanism based on these factors which would separate materials with vastly different spall tendencies. On the other hand, from studies of thick rolled plate, Pellini and others working at Dahlgren⁴ attempted, with more success, to trace the tendency to spall excessively in certain aluminum alloys to alignments of undissolved constituents in planes parallel to the plate surfaces and the appearance of "Chinese script"--shaped constituents formed during ingot solidification and retained in the microstructure in the central regions of the thick rolled plate. The latter are characteristics of ingot microstructures and their presence often indicates a poor mechanically worked structure. The Dahlgren group also attempted to show that plates which exhibited poorer shock properties in contact detonations of 20 mm H.E. projectiles also had lower normal tensile impact properties. Sachs *et al.*⁵ working at the Case Institute of Technology on aluminum alloy "ductility," have been able to show for certain alloys studied that these normal tensile impact properties can be improved somewhat by very long solution heat treatments, together with certain noncommercial mechanical working schedules.⁶ A direct evaluation of the spall tendency of the materials prepared in this fashion to give maximum normal tensile impact properties remains to be made at the date of this writing.

Forged Armor

At the beginning of the NGF-NRL work, it appeared that improvement in the spall resistance of aluminum alloys demanded an approach and viewpoint considerably different from those cited above. One possible point of view which appeared promising was to regard the mechanical strength of the aluminum alloys of interest to be primarily controlled by factors not visible in the microstructure. This viewpoint is not original with the authors; it was originally suggested to one of the authors (W.G.) by Messrs. Dix and Fink of Alcoa some years ago. Considerable work has been done by Guinier, Preston, Gaylor, and Fink, among others, designed to show that many of the mechanical properties of the higher strength aluminum alloy systems are very considerably affected by the state and arrangement of submicroscopic phases precipitated from the solid solution during the precipitation heat treatment of these alloys. Further, it is clearly recognized that the amounts, types, and sequences of mechanical and thermal treatment of these alloys play an important role in the determination of mechanical strength. In connection with mechanical working, some interesting X-ray studies due to Wood in England suggest that the mechanism of deformation at nominal forging temperatures changes with the speed of deformation. It was decided to initiate a program of experimental study designed to explore the range of change in ballistic properties possible when one subjects certain of the high-strength alloys to reasonable changes in mechanical and thermal treatments. Since in the past almost all of

³Unpublished NRL Work, Ballistics Branch

⁴"First Partial Report on Aluminum Alloy Armor, Part I and II" Naval Proving Ground Report No. 14-45, December 1945

⁵Sachs, G., Baldwin, W. M., et al., Reports on Contract W33-019-ORD-6061 Cleveland Ordnance District, Final Report issued July 1949 (Restricted)

⁶The schedules are not those currently used in producing commercial rolled plate, but facilities currently available in industry are thought to be adequate to accomplish them.

the materials which have been studied ballistically have been fabricated by commercial rolling processes, it appeared interesting to attempt to prepare on a laboratory scale samples worked by forging.⁷ Consequently, a study was initiated on the ballistic properties of samples of an easy-forging alloy which were worked at various temperatures, at as widely different speeds as practicable, and subjected to a reasonable range of precipitation treatments. The ballistic studies to be used were to be such as to make very considerable demands on the spall resistance of the plate.

This report will describe (in Part II) the fabrication of approximately the first hundred plates and their hardness properties together with the principal features of their microstructures and macrostructures. Part III is devoted to a discussion of the ballistic tests and certain practical limitations to a study of this type. Conclusions are formulated in Part IV, and recommendations in Part V.

II. FABRICATION AND HEAT TREATMENT

Directionality of Mechanical Properties

The conventional mechanical properties of rolled plate are sensitive to the direction of working. They are generally higher in the longitudinal direction than in the transverse direction or in the normal direction, i.e., through the thickness. Considerable significance has been ascribed to the role normal properties of rolled aluminum plate play in determining ballistic performance.⁸ It is considered, possible, therefore, that press working rolled aluminum plate in the normal direction might result in improved ballistic performance.

Source of Material

The material used in this investigation was one of a series of special experimental 3-inch clad aluminum alloy plates produced by the Reynolds Alloys Company⁹ for the Bureau of Ships during World War II. Certain large scale ballistic tests on the plates, not the subject of this report, were made by the Naval Proving Ground, Dahlgren. These tests, together with other pertinent information, have been reported elsewhere.¹⁰ The composition of the plate, together with certain commercial analyses included for comparison, is listed in Table 1.

The original ingot, No. 161X-768, nominal size 27-1/2 x 45 x 100 inches, weighing approximately 11,000 lbs, was cast at the Reynolds Alloys Company, Sheffield, Alabama. At the Lukens Steel Company, Coatesville, Pennsylvania, the ingot was hot rolled (800° - 825° F) to 18 x 52 x 120 inches. After suitable surface preparations, it was again hot rolled between two plates of cladding each measuring 0.455 inch thick. The 3-inch plate thus fabricated was roll leveled and sheared to 84 x 288 inches.

⁷Certain special materials have been prepared by R. L. Templin of Alcoa over the past few years for study at NRL. The results of these studies are not yet complete.

⁸See footnotes 4 and 5

⁹Formerly the Reynolds Metals Company

¹⁰NPG ltr. to BuOrd, S13-1(3) (BPO 97475), dated 17 April 1946; Ibid., S13-1(3) (BXO 98008), dated 9 July 1946

The plate was heat treated as follows:

1. Solution treated at 940° F for 3 hours (at Lukens).
2. Quenched horizontally in water spray (at Lukens).
3. Re-solution treated at 940° F for 5 hours (at Lukens).
4. Quenched horizontally in water spray (at Lukens).
5. Precipitation treated at 340° F for 8 hours (at Reynolds).
6. Air cooled (at Reynolds).

The plate was shot at the Naval Proving Ground, Dahlgren, Virginia, and subsequently sections of it were shipped to the Naval Research Laboratory, Washington, D. C., late in 1945.

TABLE 1
Chemical Composition of Aluminum Alloys

Material		Cu	Si	Mn	Mg	Fe	Cr	Zn
Specimen Plate	Core	4.40	0.96	0.80	0.39	0.56	0.03	0.05
	Cladding	0.03	0.70	0.55	0.95	0.50	0.03	
	14S	4.4	0.8	0.8	0.4			
	24S	4.5		0.6	1.5			
R-301	Core	4.5	1.0	0.8	0.4			
	Cladding		0.7	0.5	1.0			

Heat Treatment

Specimens for mechanical working in the shape of 3-inch cubes were cut from the original plate well away from the areas affected by the previous penetration tests at NPG. Prior to working, they were heat treated to the W or T temper. For the W temper, the cubes were solution treated at 950° F for about 2 hours, quenched into boiling water, and allowed to age five days at room temperature. For the T temper, the cubes were aged one hour at 300° F following solution treatment.

Forging Process

The facilities of the Naval Gun Factory were used for working the cubes. They consisted of a 2000-ton nominal capacity Mesta steam press and a 6000-ton nominal capacity Lake Erie hydraulic press. There was no weighing system on the steam press which was utilized to approximately full capacity in working the alloy. The hydraulic press was used up to about 2000 tons. The cubes were compressed between flat, smooth, dry steel dies, initially at room temperature. During forging, both die and specimen temperatures rose an undetermined extent. In the steam press, the reductions were made in up to ten increments, with total time per reduction step about ten seconds. Reductions were continuous in the hydraulic press and lasted about thirty seconds. Four initial working temperatures were used, varying from room temperature to 400° F. A limited number of specimens were forged quasi-conventionally in a 6000-lb steam hammer at an initial temperature of about 900° F for comparison with the cool forging process. Photographs of the first ten specimens appear in Figures 1 and 2.

Following the reductions, the test specimens were again heat treated to the W or T temper. Brinell hardness measurements using a 10-mm steel ball under a 500-kilogram load, applied for 30 seconds¹¹ were made on the core material after each operation.

¹¹ASTM Standard Procedure for Nonferrous Metals

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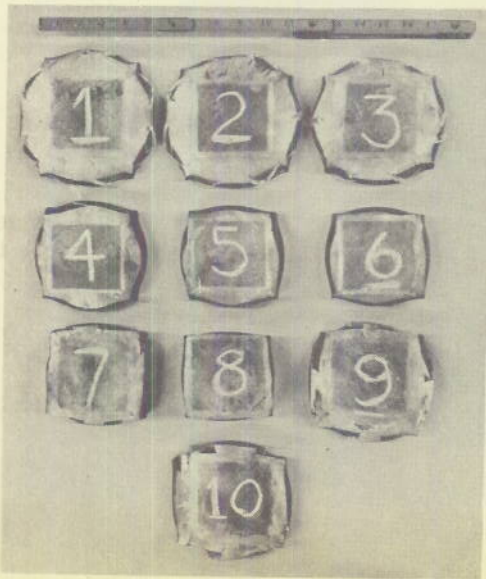


Figure 1 - Top configuration effect of forging aluminum plate

formed easily. The difference between deformation at 380° F and deformation at room temperature (approximately 80° F) may be seen in Figures 1 and 2. Specimens 1 through 6 were worked at 380° F, and 7 through 10 were worked at room temperature. Some edge

Hardness and working data may be found in Table 4.* After processing, the specimens were delivered to Naval Research Laboratory for ballistic tests.

Forging Reductions and Fractures

The preliminary temper designations assigned to the specimen cubes must be qualified in the light of the precipitation hardening characteristics of this aluminum alloy. It must be assumed that the effect of the heating (prior to the mechanical working) was to tend to further age the W temper cubes (and overage the T temper cubes). Further, the W temper material is probably susceptible to straining when worked.

The original aim was to reduce the cubes about 80 percent in thickness. However, this figure was lowered to between 30 percent and 70 percent because of excessive fracture casualties. Below initial forging temperatures to 300° F, larger reductions were obtained with T temper material than with W temper. Above this temperature, the material was fairly plastic and de-

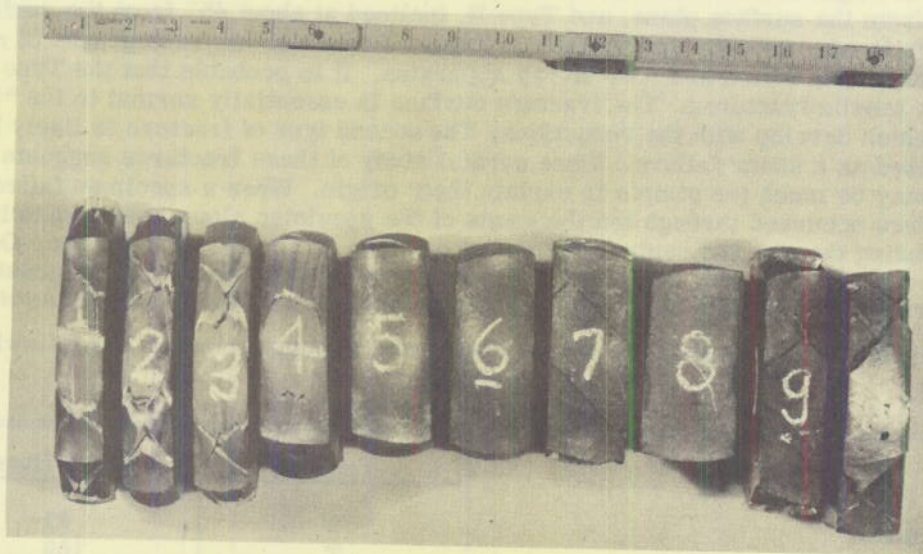


Figure 2 - Edge configuration effect of forging aluminum plate

*Table 4 appears at the end of the report.

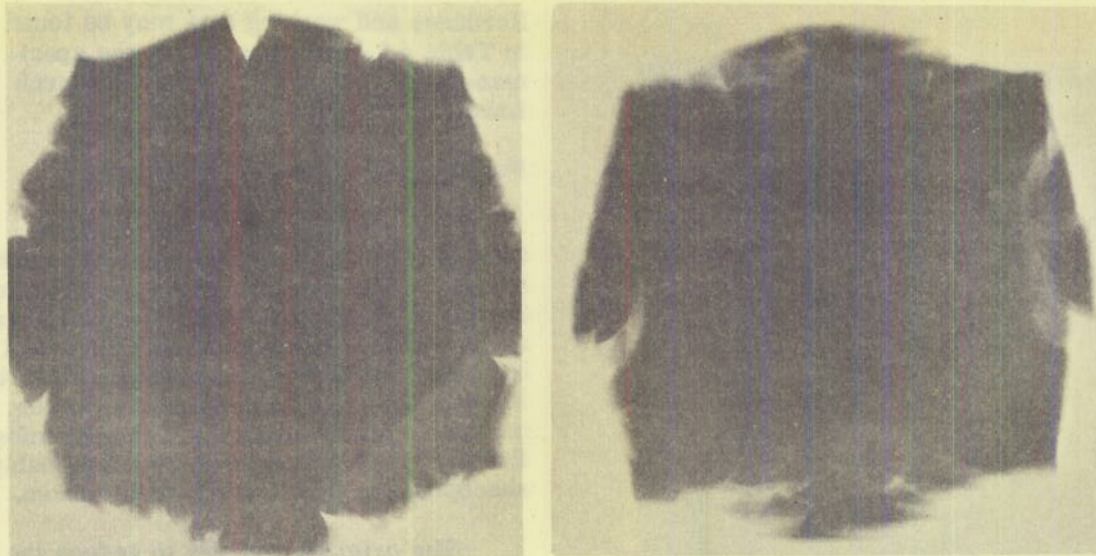


Figure 3a and 3b - Radiographs of forged aluminum plates

cracking is apparent in specimens 1, 2, and 3 which received severe reductions of approximately 65 percent. Note that the deformation is symmetrical and apparently ductile. Specimens 9 and 10 exhibit an entirely different type of deformation. Here a prism of metal, in the shape of a parallelogram with included angle of about 45° , has pushed out beyond the main edge of the specimen. Figure 2 shows the top edge of the same specimens. Two types of edge failure are demonstrated: Type I, in which the fractures are inclined at about 90° from the surface plane, and Type II, inclined at about 45° from the surface. Characteristic edge cracks may be seen in Figure 3 which shows radiographs of specimens 2 and 9 taken with a 250 KVP X-ray apparatus. It is probable that the Type I cracks are simple tensile fractures. The fracture surface is essentially normal to the "hoop" stresses which develop with the reductions. The second type of fracture is likely better characterized as a shear failure. More careful study of these fractures suggests that this view may be much too simple to explain their origin. When a specimen failed in the press, failure occurred through the thickness of the specimen along approximately a 45° plane extending through the central regions at one face to an edge of the other. Occasionally, a specimen failed with explosive violence, throwing out fragments with great speed. These latter types of failures were most common for the lower initial temperatures of working.

The typical hardness data for all the specimens is summarized in the following table:

TABLE 2
Typical Hardness Data

	Temper	Brinnell Hardness
Before working	W	83
	T	109
After working at 300° F and below and reheat treatment	W	107
	T	132
After working at 300° F and above and reheat treatment	W	94

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Anomalous Effects

A certain anomaly was observed in the response of specimens 5 and 6, and 7 through 10 to precipitation heat treatment. As expected, most specimens made in this study by forging at 380°F and 400°F exhibited normal precipitation hardening effects. Specimens 5 and 6 were worked from 380°F initially to about 45 percent over-all reduction. This was (in general) a somewhat lower reduction than that obtained when working from 380° or 400°F initially. Specimens 5 and 6 failed to show the normal age hardening effects following a quench in boiling H₂O and room temperature aging, but rather softened measurably during the five days of aging at room temperature. (These specimens were thought initially to have been stabilized in the "W" temper prior to heating to 380°F for forging.)

Specimens 7 through 10 were worked from room temperature initially to between about 33 and 56 percent over-all reduction. These specimens likewise were supposedly stabilized in the "W" temper prior to working. As did specimens 5 and 6, these (7 through 10) also showed a considerable softening following quenching after forging. (In general, specimens exhibiting normal aging after forging from room temperature received reductions between 30 and 40 percent.)

The explanation of this softening phenomenon is not yet apparent, but is possibly related to a reversion¹² phenomenon. This point will be discussed in subsequent reports.

Hardness Distribution

A 2-inch thick specimen of 24S-T4 aluminum plate and a similar thickness cool forged aluminum plate specimen (No. 8), both attacked by cal. 50 spheres at approximately the same velocity (3300 fps), were sectioned parallel to the trajectory through the center of penetration, polished and indented several hundred times using a Vickers Hardness Machine with a diamond point and 1 kg load. All indents were measured and plots were made showing contours of equal hardness.

A comparison between the micro hardness contours for rolled and forged plate (Figures 4a and 4b respectively) suggests that a greater volume of plate material is work hardened in the case of the "cool" forged material than the commercially rolled stock when both are penetrated under similar initial conditions. The noticeable difference in penetration depth is probably due to the different initial hardness level existing between the two plates, the rolled plate having a lower hardness value.

Macrostructures and Microstructures

The effect of cool forging¹³ upon the macrostructure of rolled plate is illustrated in Figure 5 at approximately 1.3X. The upper specimen is a 3-inch cube, with transverse section exposed. The lower specimen was reduced approximately 55 percent from initially the W temper at 380°F. Both specimens were polished and etched to reveal flow lines. Three zones are visible in the "as rolled" cube—a somewhat narrow heavily worked zone adjacent to the cladding at top and bottom, and a lightly worked zone in the middle. Three zones can be seen also in the press worked specimen, but here the middle

¹²Guinier, A., "Age Hardening of Light Alloys," Research, 2:6-11, January 1949

¹³i.e., forging below the recrystallization temperature (ca 1200°F for 14S)

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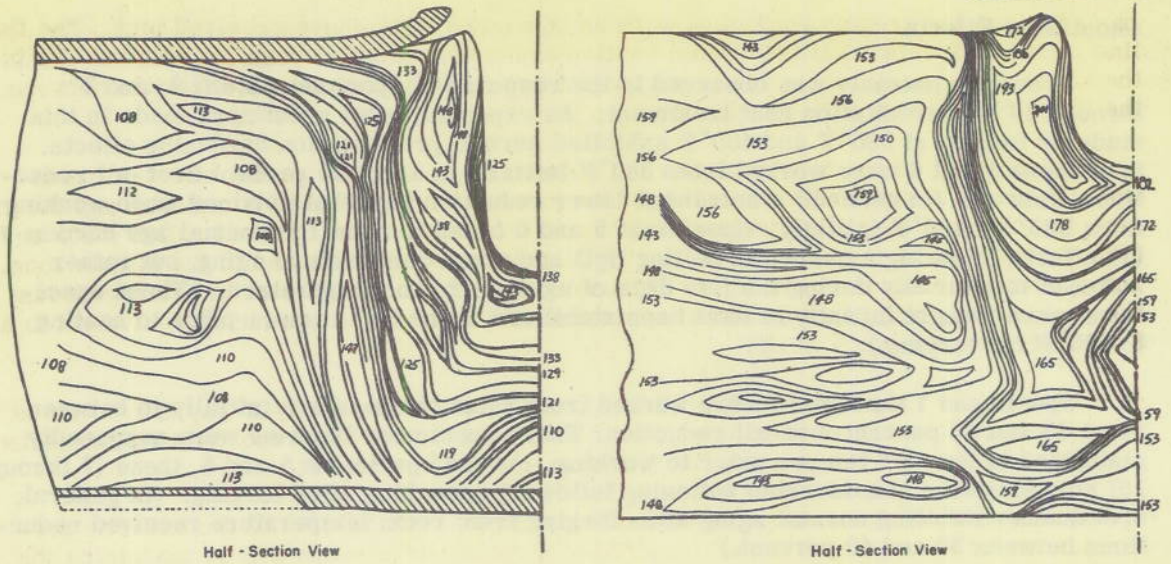


Figure 4a and 4b - Microhardness distribution in rolled and forged aluminum plate

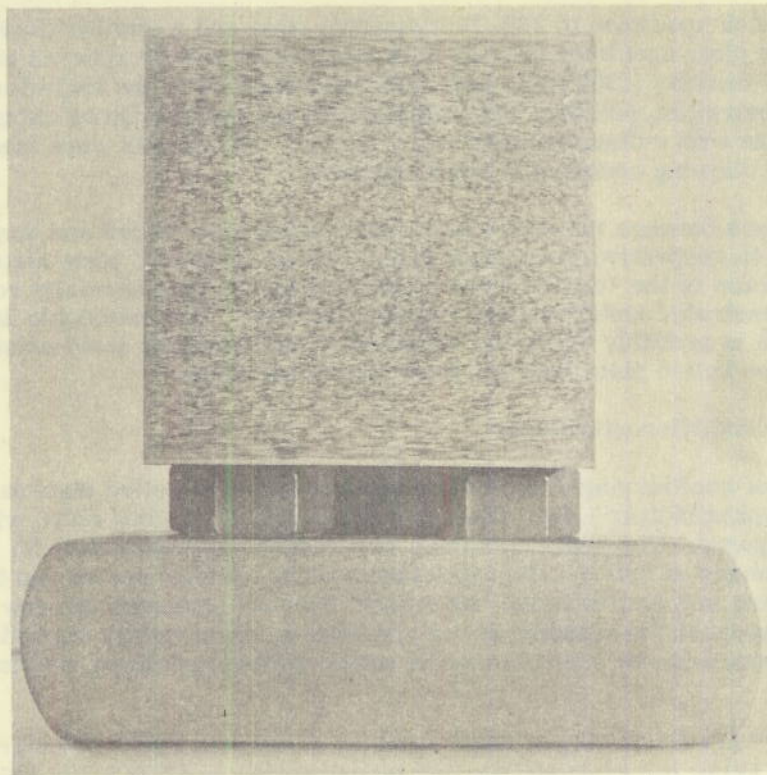


Figure 5 - Macrostructure of R-301 aluminum forging

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has received the greater amount of working; the outer zones have received less. The flow line pattern indicates that the middle section has squeezed out beyond the original limits of the cube. This, no doubt, is due in part to the presence of considerable friction between the die and specimen during reduction.

Examination of the microstructures (Figures 6a and 6b) shows the effect of press-working upon the size and distribution of the insoluble intermetallic complexes and the grain size and shape of the rolled material. Photomicrographs of the original rolled plate at 75X (Figure 6b) show in the upper zone, heavy, aligned intermetallics and in the middle zone, some intermetallics in the form of "Chinese scripts." The grain size is heterogeneous; the photomicrographs shown contain approximately four grains per inch² (equivalent to about 8×10^5 grains per inch² at 1X).

Four of the specimens, Nos. 31, 34, 43, and 56 were analyzed by X-ray diffraction at the Aluminum Research Laboratory, New Kensington, Pa. It was reported that complete recrystallization had occurred in the four specimens.¹⁴

Workers at the Naval Proving Ground have made a comparison of the ballistic performances of 3/4-inch and 1-1/2-inch rolled plate of composition 24S by machining the thicker plate to a thickness equal to that of the thinner.¹⁵ The performances of these two plates were then compared. It was found that the thinner plate, which probably had received more mechanical working had a greater penetration resistance than an equally thick section cut from a thicker plate. Thus, the 1-1/2-inch plates appeared to be 8 percent less efficient in resisting penetration on an energy per unit weight basis. This was attributed to the greater reduction in rolling of the thin plate, which perhaps resulted in a more complete breakdown of the original cast structure of the ingot.

Shingling and Spalling

Rolled aluminum alloy plate, even when well worked through the thickness, almost always shows ballistic, as well as mechanical, anisotropy in some form. Thick rolled plate is, in general, so poorly worked in the central regions that ballistic anisotropy due to the rolling itself is unimportant. Figure 7 shows sections through the penetration paths of two specimens penetrated by cal. 50 spheres, SKF grade 1. The upper specimen was cool forged from a 3-inch cube of the original material. The lower specimen is rolled 24S-T4. Although the thicknesses are equal, the limit velocity of the cool forged specimen is approximately 13 percent greater than that of the rolled plate. The shingle pattern on the surface of the penetration path may be associated with the mechanical anisotropy¹⁶ of the rolled aluminum alloy plate. The surface of the penetration path of the cool forged specimen is comparatively smooth through the midsection. Some shingling has occurred near

¹⁴ Fink, W., Private communication to author (W. G.)

¹⁵ Naval Proving Ground Report No. 14-45, op. cit.

¹⁶ One striking feature of mechanical anisotropy is the elongation of the grain structure in the direction of rolling.

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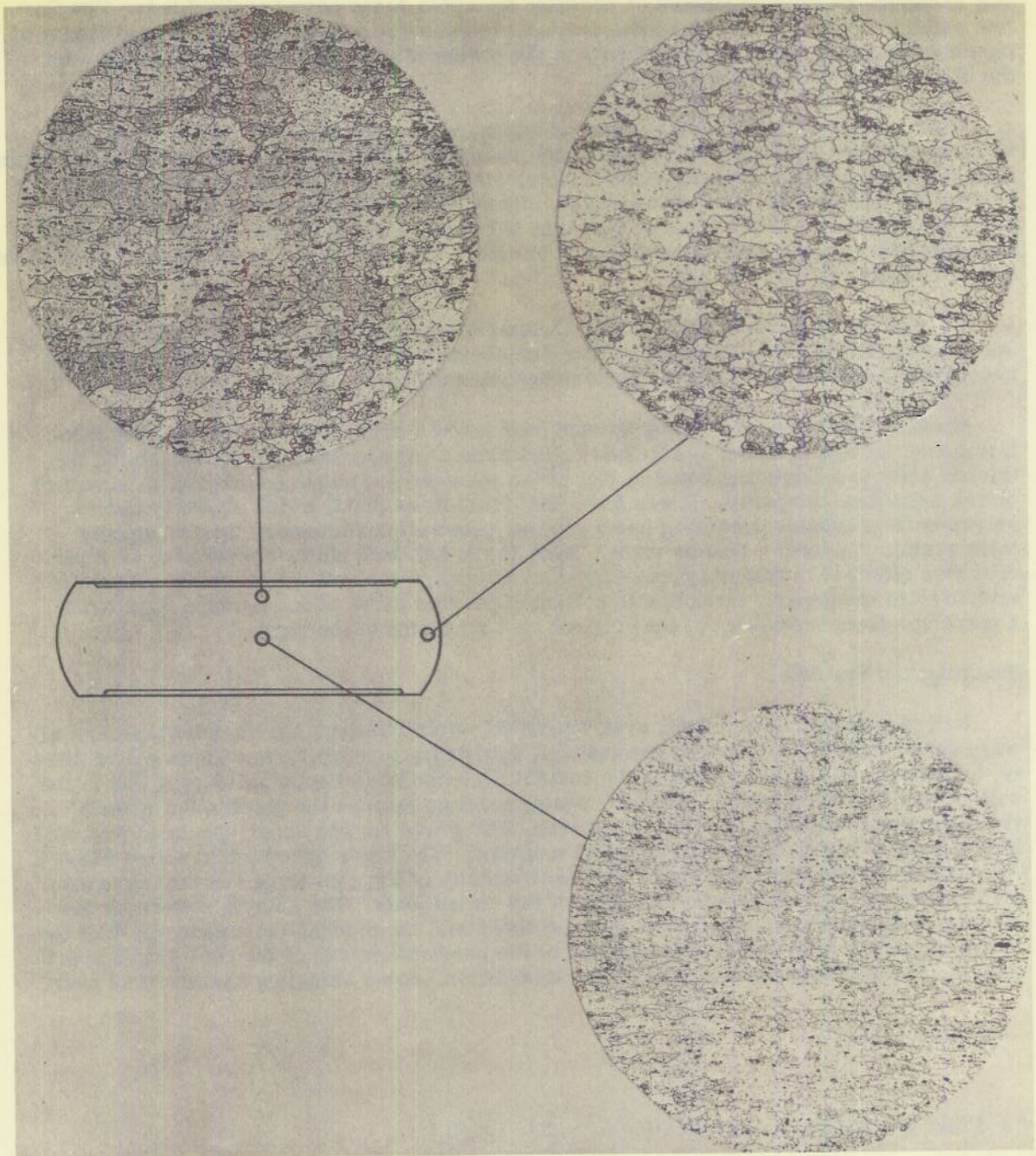


Figure 6a - Microstructure of R-301 aluminum forging - Magnified 75X

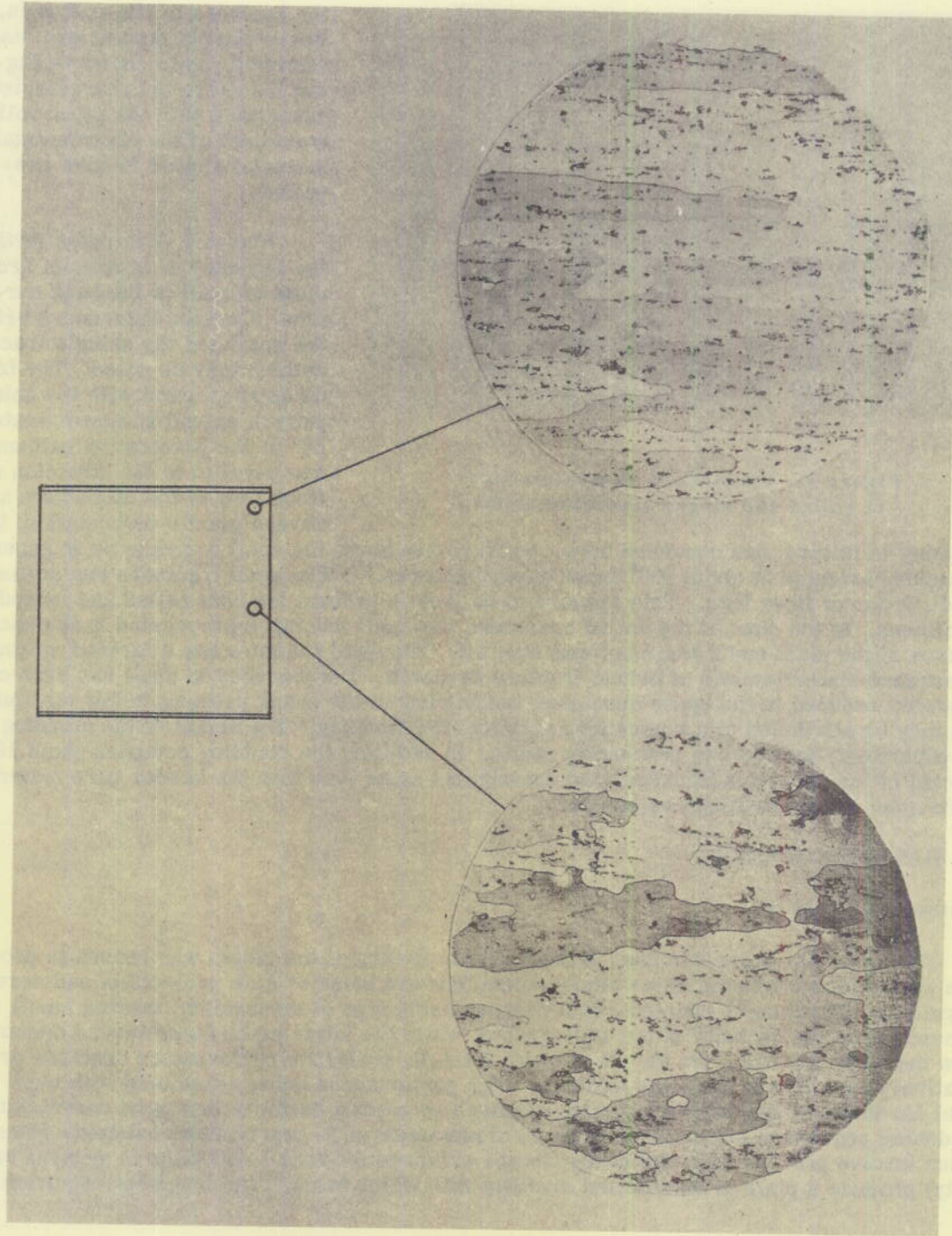


Figure 6b - Microstructure of R-301 aluminum forging — Magnified 75X

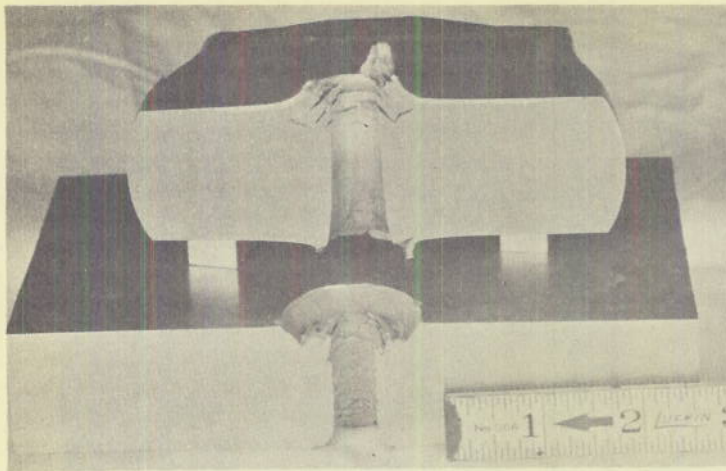


Figure 7 - Penetration characteristics of rolled and forged aluminum plate

the surfaces of the specimen, where the presswork was least effective, as is shown in Figure 6a where the characteristics associated with the prior rolling treatment of the experimental material appear to have prevailed.

Figure 7 illustrates further the tendency of aluminum armor plate to spall at the back surface. Certain differences between the spall and the shingle fracture pattern may be noted. The fractures associated with the shingle pattern extend at approximately 55° to the penetration path and are parallel to the direction of fiber flow in the immediate area. Severe plastic deformation, ter-

minating in failure, has occurred here. On the other hand, the spall boundary is in general a fracture oriented at about 100° from these fractures.¹⁷ The spall fractures run across the direction of fiber flow. This appears to be true in general for both rolled and forged specimens. In the case of the rolled specimen, the spall fractures propagated to the back surface of the plate and a fragment was cast off. The spall fracture has a faceted, grainy appearance characteristic of brittle fracture in steels. The tendency to spall has been considerably reduced in the upper specimen, but in view of the crack patterns below the cladding, this may be attributed to a restraining action of the cladding. The action of the cladding is not consistent, however, in preventing spalls. In addition, the cladding occupies about 10 percent of the specimen thickness and contributes much less than the harder core material to the over-all penetration resistance.

III. BALLISTIC STUDIES

Choice of Projectile

The spherical projectile used in the ballistic testing of the plates was chosen to provide penetration characteristics intermediate between those of A.P. projectiles and service fragments. The former penetrate by a pushing-aside type of mechanism, making small demands upon the ductility of the armor plate, while the latter make more severe demands upon the plate ductility. On the other hand, the A.P. projectile performance demands are relatively sensitive to the plate hardness, high performance being associated with high-level hardness. The service fragment requires so great a ductility that most conventional hardening processes for armors which yield maximum A.P. penetration resistance (those which involve precipitation and phase change accompanied with a reduction in general ductility) produce a plate of insufficient ductility with which to meet the fragment requirement.

¹⁷ These measurements were made relative to a line coincident with the trajectory but pointing in the direction of the origin of the attack.

Hence, fragment armor of high-performance quality is relatively softer than projectile armor of similar composition.

Form Factor

The demands on ductility referred to above can be simulated in terms of the "relative sharpness" of a penetrator. As noted above, sharp concentrated loading of the armor results, usually, in the pushing-aside type of deformation mechanism. A measure of this relative sharpness is conveniently obtained in terms of the mass of attacking penetrator per unit area of contact. Since this area varies during penetration, it is convenient to measure penetrator sharpness in terms of the maximum area at penetration. It is often more convenient to express the relative sharpness in terms of a form factor having the units of a density; the higher the form factor or penetrator density, the more sharp the penetration. Conversely, distributed loadings demanding more ductility in the armor result in low form factors. For projectiles it has been the practice for many years to express the relative projectile density as the form factor, f , where

$$f(\text{projectile}) = M/d^3$$

where M is the projectile (core) mass and d the caliber. Fragments possess no caliber, thus, in general it is convenient to replace d by the square root of the average area, \bar{A} , which the fragment presents to the plate. The form factor then becomes

$$f(\text{fragment}) = m/(\bar{A})^{3/2}$$

where m is the fragment mass and \bar{A} is the average presented area of the fragment. A list of values is given in Table 3.

It is at once seen from the above discussion and Table 3 that spherical missiles have form factors nearer those for fragments than projectiles, and thus that they make correspondingly greater demands upon the armor ductility. Yawed darts have form factors even nearer those for actual fragments, but the time and material available for the work of this report made it inadvisable to extend the investigations to include their use.

Ballistic Data

By varying the amount of propellant, it is possible to obtain a pair of attack velocities differing by an arbitrary amount (in the experiments reported herein never greater than 200 ft/sec), such that the lower fails and the other succeeds in accomplishing penetration of the test plate. These two velocities are the basis of the experimental determination of a limit velocity. Limit velocities are arbitrarily assigned as the mean of the two rounds described above. The limit velocity defined in the operational manner indicated above is in general a function of such missile parameters as its hardness relative to the armor hardness, fracture characteristics, form factor, yaw, etc.

For spherical (ball bearing) penetrators, fracture of the missile presents the most important complication to the physical interpretation of limit velocities. Fortunately, fracture enters in an essentially similar manner for the cases of both the rolled and forged plates (similar hardness), making the relative comparisons insensitive to this effect. The sphere fracture begins at limit velocities of approximately 3500 ft/sec for aluminum alloy and becomes progressively more severe with increasing limit velocity. Actually, the difference between rolled and forged plates is a little greater at intermediate limit velocities (ca. 3000-3500 ft/sec) since the forged plates were, on the average,

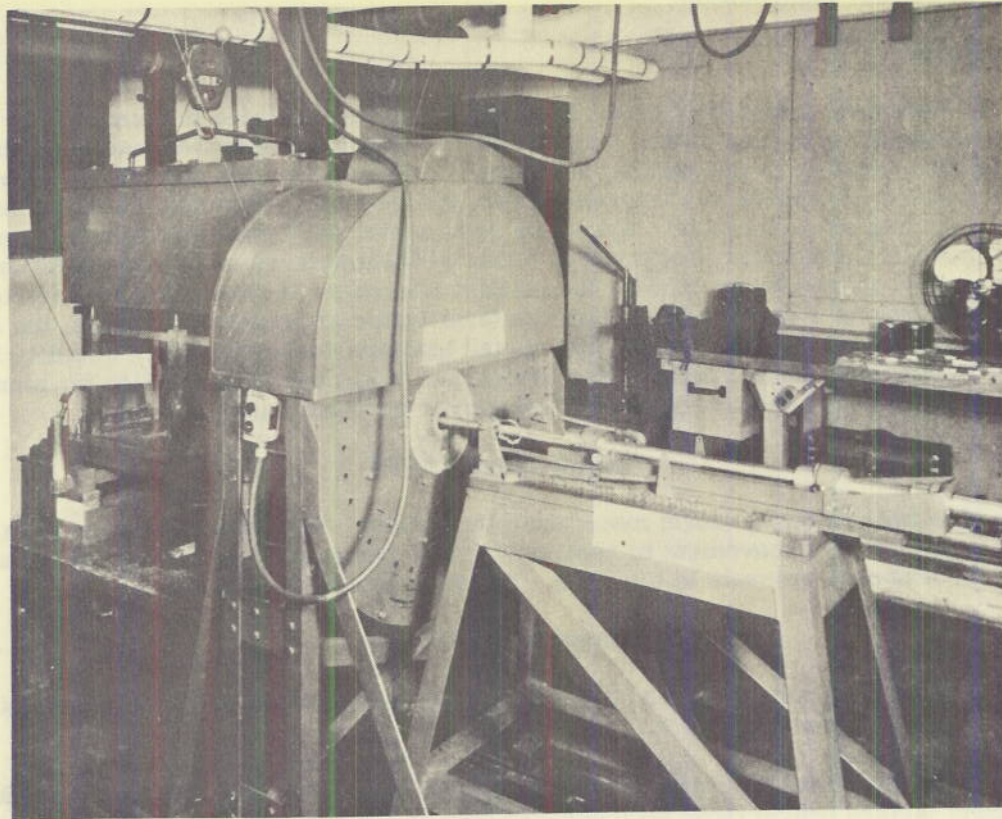


Figure 8 - Ballistic pendulum and gun arrangement

a little softer than the rolled plate used as a comparison. The short range facility used for obtaining the ballistic data on the forged plates described in Section II of this report is shown in Figure 8. Regular cal. 50 machine gun barrels were mounted in the gun mount. The blast deflector, silencer, and pendulum in which the plates were mounted are shown. The plates were mounted in the pendulum so that the impact occurred within about one inch of the center of gravity of the pendulum.

The pendulum weighs about 500 lbs and is supported by a five-wire suspension designed to possess high torsional rigidity, making it difficult to excite modes of vibration other than the simple one in which the displacement is, for small displacements, essentially parallel to the trajectory. The attack velocity, V , of a missile of mass m , using a pendulum with mass M , is obtained from the law of conservation of momentum to be

$$V = K \frac{M}{m} d$$

where d is the maximum deflection after impact and constant K has a value determined by dimensions of d , M and m , and the magnitude of the period of vibration in the mode parallel to the trajectory. Drag effects can be demonstrated to be negligible in this type of pendulum.

TABLE 3
Missile Form Factors

Missile	Yaw	Mass (M) (oz.)	Caliber (d) (inches)	Area (A) or (\bar{A}) (inches ²)	M/d ³ (oz./in ³)	M/A ^{3/2} (oz./in ³)
Cal. 50* AP M-2 (core)	0°	0.8959	0.4271	-	11.50	16.20
Cal. 30* AP M-2 (core)	0°	0.1926	0.2444	-	8.93	12.83
Cal. 30 AP M-2 (core)	30°	0.1926	-	0.0972	-	6.37
Cal. 50 Sphere (steel)**	0°	0.2857	0.500	-	2.285	3.28
Cal. 22 Yawed Dart***	90°	0.071	-	0.0993	-	2.34
1/2 oz. 3" H.E. Fragment †	average	0.566	-	0.53	-	1.49
Cal. 22 "G-2" ††	0°	0.0398	0.217	-	3.90	5.59
Cal. 30 "G-2" ††	0°	0.100	0.270	-	5.09	7.31

* M and d values as reported in NPG Report 14-45 (averages of a selected group of armor testing projectiles)

** SKF Grade 1 Ball Bearings

*** Standard NRL Fragment Simulating Armor Material Test Missile (30 grain Single Ended Yawed Dart)

† Typical of values reported from fragments recovered in sand pit fragmentation experiments. Value of A used is average of all possible presented areas.

†† Measurements from an arbitrary missile—not necessarily accurately representative of the average "G-2" missile type. It is believed, however, that the M/d³ and M/A^{3/2} values listed indicate accurately the values of the form factors of this missile type relative to the other types listed, i.e., intermediate between projectiles at 0° obliquity and spheres.

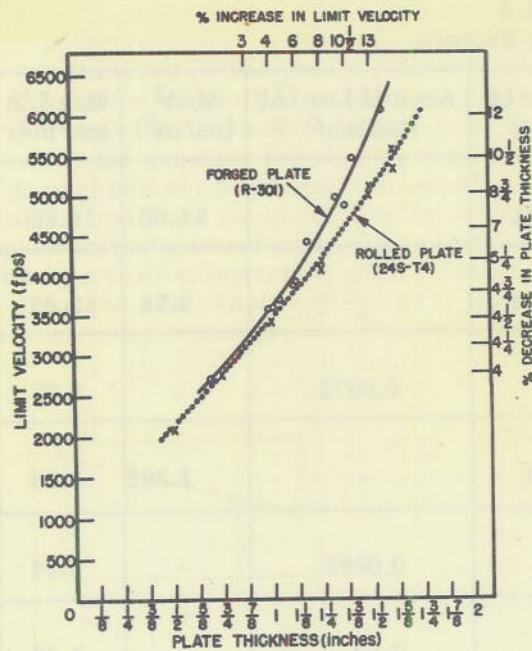


Figure 9 - Limit velocity vs. plate thickness (V vs. e) curve

otherwise noted, are the average of the velocities at which the spheres just penetrated but did not quite penetrate the targets.

Limit Velocity vs. Plate Thickness

The results of the ballistic tests listed in Table 4 were plotted with limit velocity versus plate thickness for the cool forged aluminum plates and compared with similar data obtained previously with 24S-T4 rolled aluminum plates.¹⁸ As shown in Figure 9, the limit velocities for forged plate were significantly greater than those for rolled plate as the thickness of the plates increased. Below 3/4-inch thickness the improvement in performance is negligible, it is within experimental error. But at the 1-1/2-inch level, the experimentally forged aluminum plates appear to have a limit velocity approximately 13 percent greater than the rolled plate. Although some scatter is evident in the results obtained, the trend toward improved performance over that of commercial 24S-T4 plate is clearly indicated.

"P" Coefficient

Another means of illustrating armor performance is provided by a plot of the "P" coefficient versus the Brinell hardness numbers for each test plate. The "P" value is the energy absorbed by the plate per unit of ideal volume of plate material pushed aside during penetration and may be termed the "ballistic efficiency." If A is the maximum area presented during penetration and e the plate thickness, this coefficient is given by

¹⁸Roberson, R. E., Irwin, G. R., and George, W., NRL Report 3507, 22 July 1949

$$P = \frac{mV_1^2}{2Aeg}$$

where g is the acceleration due to gravity, m the projectile mass, and V_1 the limit velocity. The units of P are pounds per square inch. The ballistic efficiency is useful in showing the effects of plate hardness on penetration resistance. For brittle types of armor performance, a plot of Bhn vs. P does not indicate a functional relation, but rather a wide scatter range. In general, it is possible to define an "envelope" for this type of data which represents the highest performance in terms of P for given hardness levels. This envelope represents an approximation to a functional relation between performance in terms of P and hardness. In general, the more ductile the performance over a given range of hardness, the higher this envelope will fall in the P -Bhn plane. The hardness values associated with these highest P values along the envelope represent optimum hardness ranges for the given penetrator class.

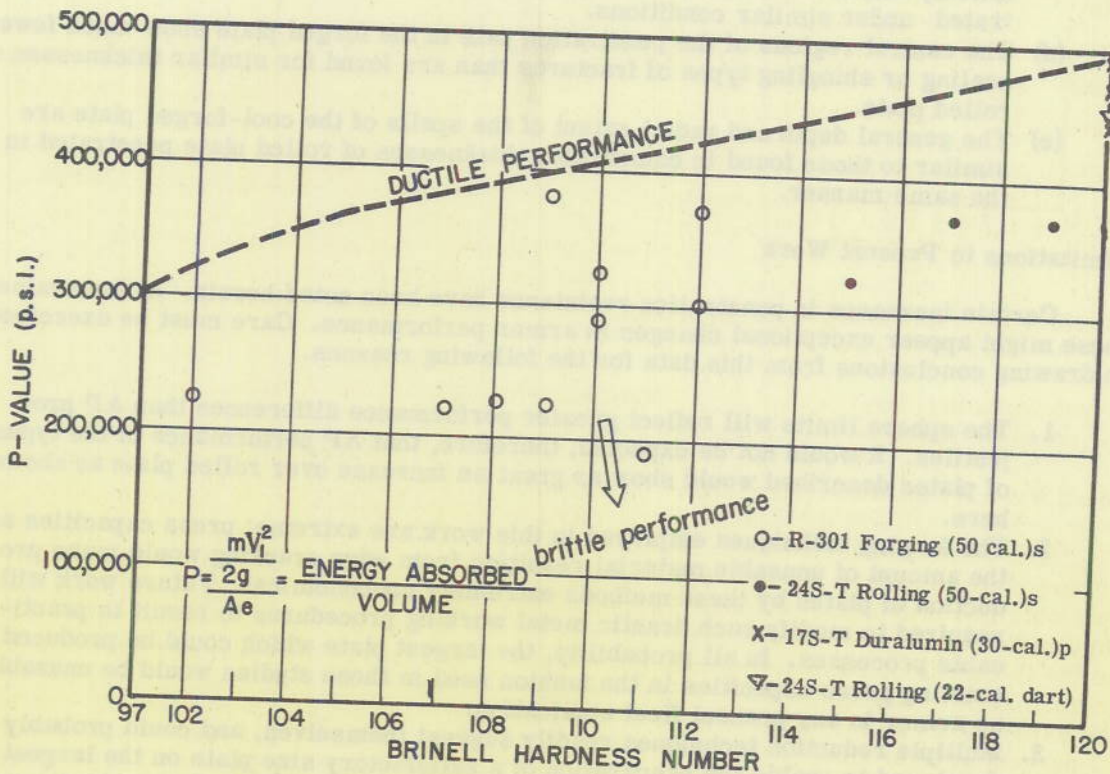


Figure 10 - Energy absorbed vs. Bhn (P_e coefficient)

Figure 10 shows a plot of P vs. Bhn. The data are from the cool forged plates described previously. Typical values obtained on similar alloys worked by conventional methods and tested using other projectile types are included for comparison purposes. It is to be noted that the general level of the P vs. Bhn points from the sphere data is comparable with points obtained from cal. 30 A.P. projectiles as well as NRL cal. 22 yawed dart fragment simulator. The scatter in the data is to be expected in view of the lack of correction for differences in projectile form factor between spheres, darts and A.P. projectiles.

Summary of Ballistic Data

For convenience and emphasis the essential ballistic data and other pertinent observations presented in this and the preceding section are summarized:

- (a) For thickness of plate between about 3/4 inch to 2 inches, the cool forged material, essentially 14S, possesses cal. 50 sphere limit velocities equal to or greater than similar thickness of rolled 24S-T4 plate.
- (b) The improvement¹⁹ of the cool-forged plate over the rolled plate increases with increasing thickness (up to 13 percent higher limits at 2-inch thicknesses).
- (c) Examination of the entrance and exit regions of the cool-forged plate, regardless of thickness, shows somewhat less complicated fractures than are expected from similar thickness of rolled plate. However, the spall regions are qualitatively similar to those found in other high strength aluminum alloy plates penetrated under similar conditions.
- (d) The central regions of the penetration path in the forged plate show much fewer scaling or shingling types of fractures than are found for similar thicknesses of rolled plate.
- (e) The general depth and radial extent of the spalls of the cool-forged plate are similar to those found in comparable thicknesses of rolled plate penetrated in the same manner.

Limitations to Present Work

Certain increases in penetration resistance have been noted herein. At face value these might appear exceptional changes in armor performance. Care must be exercised in drawing conclusions from this data for the following reasons.

1. The sphere limits will reflect greater performance differences than AP projectiles. It would not be expected, therefore, that AP performance of the types of plates described would show as great an increase over rolled plate as shown here.
2. The forging techniques employed in this work are extreme; press capacities and the amount of unusable material resulting from edge cracking would make production of plates by these methods extremely uneconomical. Future work will be required to modify such drastic metal working procedures to result in practicable processes. In all probability, the largest plate which could be produced by existing press capacities in the fashion used in these studies would be unusable as armor in any present fleet application.
3. Multiple reduction techniques readily suggest themselves, and could probably be developed to enable the preparation of a satisfactory size plate on the largest forging equipment now available. The plates made in this study required approximately 200 tons/square inch peak forging pressures.

¹⁹Improvement is indicated if one can assume that blast effects in the data from "cool" forged R301 alloy and 24S-T4 rolled plate will not effect this comparison. The equipment used in this study does not readily allow for a full correction of this effect.

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IV. CONCLUSIONS

Forging experiments have been made using samples cut from a 3-inch rolled plate of essentially 14S aluminum alloy principally worked at temperatures below the recrystallization temperature.

The original purpose for preparing the material described in the paragraph above was to determine if such material would possess significantly different spalling characteristics from those generally found in the stronger commercial aluminum alloys used for such rolled plate. The fabricating treatments used did not materially affect the spalling characteristics obtained with cal. 50 sphere penetrations. The spall areas were qualitatively similar to those found in rolled 24S-T4 plate subjected to similar ballistic attack.

Direct ballistic evaluation of the penetration resistance, using cal. 50 spheres and the NRL short range firing facilities, indicates that the cool-forged plates have a penetration resistance which is equal (in thinner gauges) to that of rolled 24S-T4 plate and significantly superior for thicker gauges (2-inch) to that of the rolled 24S-T4 plate (as much as 13 percent increase in limit velocity for cal. 50 sphere at 1-1/2-inch thickness).

V. RECOMMENDATIONS

It is recommended that future research include:

- (a) Work involving reductions from ingot stock be made in an effort to evaluate the degree of improvement traceable to cold working and yet ill-defined associated effects.
- (b) Work designed to demonstrate in a definite way those characteristics of the sphere penetration event which are altered by the mechanical working.
- (c) Work designed to reveal the role played by precipitates in determining dynamic hardness.
- (d) Attempts to ascertain whether or not ballistic strain rate effects in highly cold-worked aluminum alloys may be sensitive to the degree of such work, especially if performed below the recrystallization temperature.

VI. ACKNOWLEDGMENTS

The Naval Research Laboratory has no high-capacity facilities for the hot and cold forging of aluminum alloys under controlled conditions in sizes required for ballistic study. The cooperation of personnel of the Materials Laboratory of the Naval Gun Factory was therefore a necessity. This group under Commander J. P. Phillips, Jr., USN, and formerly under Commander H. G. Bowen, Jr., USN, has provided for, and actively participated in, the fabrication and the metallurgical examination of the materials (Part IV). Mr. Joseph Maltz, NGF, prepared the microsections and performed many of the heat treatments. The authors wish to acknowledge the cooperation of Master Mechanics Norman S. Blankenship and R. A. Tucker of the Naval Gun Factory, without whose aid the actual forging would have been impossible.

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Mr. W. K. Hampton, NRL Shop, assisted in the preparation of the original samples. Mr. H. G. Whitman, NRL Shop, and his group prepared certain sections for macrohardness and microhardness studies. Mr. John B. Clark performed most of the ballistics tests reported here. Mr. Bruce Johnston, Applied Physics Laboratory, a guest worker in the Ballistics Section, NRL, and Mr. David McGogney, NRL, assisted in obtaining some of the early ballistics results. Last, but not least, we acknowledge stimulating and helpful discussion with Messrs. E. L. Dix, R. L. Templin, and Dr. William Fink of the Aluminum Research Laboratories; with Drs. G. R. Irwin and W. H. Sanders, NRL; and with Mr. L. H. Fawcett, NGF.

V. RECOMMENDATIONS

- (a) Work involving selection of test specimens should be made in an effort to evaluate the effect of grain size on the mechanical properties of the material.
- (b) Work designed to determine the effect of grain size on the mechanical properties of the material should be carried out in a systematic way.
- (c) Work designed to evaluate the effect of grain size on the mechanical properties of the material should be carried out in a systematic way.
- (d) Work designed to evaluate the effect of grain size on the mechanical properties of the material should be carried out in a systematic way.

VI. ACKNOWLEDGMENTS

The Naval Research Laboratory has an obligation to the many individuals and groups who have assisted in the work reported here. The cooperation of personnel in the Ballistics Laboratory of the Naval Ordnance Laboratory, especially the group under Commander J. B. Clark, is gratefully acknowledged. The assistance of Mr. G. R. Irwin, Mr. W. H. Sanders, and Mr. L. H. Fawcett is also gratefully acknowledged. The assistance of Mr. J. B. Clark, Mr. Bruce Johnston, and Mr. David McGogney is also gratefully acknowledged. The assistance of Mr. E. L. Dix, Mr. R. L. Templin, and Dr. William Fink is also gratefully acknowledged. The assistance of Mr. G. R. Irwin and Mr. W. H. Sanders is also gratefully acknowledged. The assistance of Mr. L. H. Fawcett is also gratefully acknowledged.

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TABLE 4
Aluminum Forging and Ballistic Data
R-301 - 3-Inch Cube

Plate No.	Temper†		Work Temp. ° F	Final Thickness (Inches)	Percent Red.	Final Bhn	Group	Limit Velocity (ft/sec)
	S	F						
1	W	T	380	0.91	69.7	86	A-6	3300
2	W	T	380	1.02	66.0	86	A-6	0
3	W	T	380	1.19	60.3	86	A-7	3800
4	W	T	380	1.35	55.0	86	A-7	0
5	W	T	380	1.21	59.7	89	A-7	0
6	W	T	380	1.65	45.0	61	A-8	5000
7	W	T	80	1.60	46.7	50	A-2	5400
8	W	T	80	2.00	33.3	57	A-3	0
9	W	T	80	1.58	48.0	50	A-2	5200
10	W	T	80	1.30	56.6	61	A-1	4100
11	W							
12	W							
13	W							
14	W	T	80	2.05	31.6	130	A-3	0
15	W	T	80	2.00	33.3	130	A-3	*
16	W							
17	W	T	80	2.00	33.3	131	A-3	0
18	W	W	80	2.00	33.3	109	B-1	*
19	W	W	80	2.10	30.0	109	B-1	0
20	W	W	80	2.00	33.3	105	B-1	0
21	T	W	80	2.00	33.3	97	C-1	0
22	T	W	80	1.85	38.2	99	C-1	0
23	T	W	80	1.85	38.2	100	C-1	0
24	T	W	80	1.85	38.2	100	C-1	*
25	T	W	80	1.80	40.0	109	C-1	0
26	T	W	80	1.85	38.2	109	C-1	0
27	T	W	80	1.80	40.0	103	C-1	0
28	T	W	80	1.80	40.0	109	C-1	0
29	T							
30	T	T	200	1.40	53.3	134	D-2	4700
31	T	T	200	1.00	66.6	131	D-1	3600
32	T	T	200	1.40	53.3	130	D-2	0
33	T	W	200	1.00	66.6	103	C-2	3600
34	T	W	200	1.10	63.3	105	C-2	0
35	W	W	400	1.32	56.0	93	B-5	0
36	W	W	400	1.22	59.3	93	B-5	3900
37	W	W	400	1.21	59.7	93	B-5	0
38	W	W	400	1.15	61.6	92	B-5	0
39	W	W	400	1.15	61.6	93	B-5	3840
40	W	W	400	1.10	63.3	92	B-5	0
41	W	W	400	0.81	73.0	85	B-4	0
42	W	W	400	0.68	77.3	89	B-4	0
43	W	W	400	0.70	76.7	93	B-4	2715
44	W	W	400	0.70	76.7	97	B-4	0
45	W	W	400	0.80	80.0	93	B-4	0
46	W	W	400	0.68	77.3	96	B-4	0
47	W	W	900	1.04	65.3	93	B-6	0
48	W	W	900	1.05	65.0	91	B-6	3500
49	W	W	900	1.18	60.7	95	B-7	0
50	W	W	900	1.04	65.3	98	B-7	3650
50A	T	W	200	1.10	63.3	106	C-2	0
51	T							
52	W							
53	W							
54	W							
55	W	T	200	1.95	35.0	130	A-4	*
56	W	W	200	1.70	43.3	103	B-2	6050
57	W							
58	W							
59	W							
60	T	T	300	1.80	40.0	130	D-4	*
61	T	T	300	1.55	48.3	131	D-3	5575
62	T	W	300	1.55	48.3	109	C-3	4900
63	T	W	300	1.40	53.3	103	C-3	0
64	W	T	300	1.45	51.7	130	A-5	5000
65	W	T	300	1.40	53.3	132	A-5	0
66	W	W	300	1.40	53.3	114	B-3	0
67	W	W	300	1.35	55.0	103	B-3	4450

† S: Temper prior to heating for forging (initial).
F: Temper after last thermal treatment (final).

Forging Machines

Plates 1-34 -- 2000 ton steam press; plates 35-46 -- 6000 ton hydraulic press; plates 47-50 -- (hot forged) 6000 ton steam hammer; plates 50A-67 -- 2000 ton steam press.

Note: 0 - not tested for limit velocity.

* - fractured in press.

