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**PROCESS DEVELOPMENT FOR DEFORMED METASTABLE
AUSTENITIC ULTRAHIGH-STRENGTH STEEL**

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BATTELLE MEMORIAL INSTITUTE

Preliminary trials have been conducted to establish suitable hot-cold forging procedures for D6AC, 300 M, H-11, 4340, HP 9-4, and AM 355 steels. Closed step dies are employed to produce a part having reduction levels of approximately 20, 40, and 60 per cent. After suitable heating and forging procedures are established, screening studies will be conducted to determine the response of the six steels to hot-cold working.

Minor difficulties have been encountered in maintaining die temperatures above 600 F and in removing the forgings from the die. In addition, filling of the die was incomplete, even though the maximum forging pressure of 700 tons was employed. This resulted in reduction levels slightly lower than desired. Attempts are being made to alleviate these difficulties by improving the die heating arrangement, modifying the die design, and improving lubrication.

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ASD Project 7-891

Interim Technical Documentary Progress Report No. 2
10 January 1963 - 30 April 1963

Preliminary trials have been conducted to establish suitable hot-cold forging procedures for D6AC, 300 M, H-11, 4340, HP 9-4, and AM 355 steels. Closed step dies are employed to produce a part having reduction levels of approximately 20, 40, and 60 per cent. After suitable heating and forging procedures are established, screening studies will be conducted to determine the response of the six steels to hot-cold working.

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FOREWORD

This Interim Technical Report covers the work performed under Contract No. AF 33(657)-9139 from 10 January, 1963 to 30 April, 1963. It is published for information only and does not necessarily represent the recommendations, conclusions, or approval of the Air Force.

This contract with Battelle Memorial Institute of Columbus, Ohio, was initiated under ASD Manufacturing Technology Laboratory Project 7-891 "Process Development for Deformed, Metastable, Austenitic Ultrahigh-Strength Steel". It is administered under the direction of Mr. G. W. Trickett of the Basic Industry Branch (ASRCT), Manufacturing Technology Laboratory, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio.

This program is being carried out by Battelle's Metalworking Division under the supervision of Dr. C. W. Marschall, Senior Metallurgist, Mr. J. H. Gehrke, Research Metallurgist; Mr. A. M. Sabroff, Research Associate, and Mr. F. W. Boulger, Division Chief.

The primary objective of the Air Force Manufacturing Methods Program is to increase producibility, and improve the quality and efficiency of fabrication of aircraft, missiles, and components thereof. This report is being disseminated in order that methods and/or equipment developed may be used throughout the industry thereby reducing costs and giving "MORE AIR FORCE PER DOLLAR".

Your comments are solicited on the potential utilization of the information contained herein as applied to your present or future programs.

PUBLICATION REVIEW

Approved by: 

F. W. Boulger, Chief
Metalworking Research Division

Approved by: 

S. L. Fawcett
Manager, Department of Metallurgy

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PROCESS DEVELOPMENT FOR DEFORMED METASTABLE AUSTENITIC ULTRAHIGH-STRENGTH STEEL

by

C. W. Marschall, J. H. Gehrke, A. M. Sabroff, and F. W. Boulger

INTRODUCTION

Many investigators have established the increased strengthening produced by hot-cold working as compared to conventional heat treatment. The ultimate objective of the present program is to develop suitable methods for producing actual hardware items by hot-cold forging techniques. The program has been divided into three phases:

Phase I. State-of-the-Art Survey

Phase II. Hot-Cold Forging Process Development Studies

**Phase III. Experimental Production of a Typical Part by
Hot-Cold Forging.**

The findings of Phase I were summarized in the First Interim Technical Documentary Progress Report, dated November, 1962.

In the development of hot-cold forging practices for commercial production of parts, several major problems in producibility that must be overcome are:

- (1) The extremely high forging pressures required to deform austenite below its recrystallization temperature
- (2) The nonhomogeneous deformation usually found in forgings, leading to nonuniform strengthening by hot-cold working
- (3) The directionality of properties frequently observed after hot-cold working.

Accordingly, the recommendations as to steel selection and experimental work for Phase II were directed toward overcoming these problems. To reduce the forging-pressure requirements, hot-cold forging would be performed at temperatures near or above the pearlite nose on steels having isothermal-transformation diagrams which exhibit a suppressed pearlite nose. Results would be compared with those obtained at hot-cold forging temperatures near 1000 F. Preparation of the forging blanks by blocking at hot-cold working temperatures would be investigated as a means of reducing the degree of nonuniform deformation that is typical of closed-die forging. Finally, the steels used in this program would be consumable-electrode vacuum-arc melted and be as free from inclusions as possible to minimize directionality of properties.

Approval to proceed with Phase II was received from the Manufacturing Technology Laboratory, ASD, on January 10, 1963. This report presents details of progress made in Phase II from January 10 to April 30, 1963. The primary objectives of Phase II are:

- (1) To determine, by screening studies, the response of the candidate steels to hot-cold forging and their general suitability for processing by this technique
- (2) To choose, on the basis of the screening studies, the three most promising steels for studies of mechanical properties
- (3) To establish realistic hot-cold forging cycles that lead to consistent mechanical-property response
- (4) To obtain information on forging pressures, forgeability, and related die-forging characteristics
- (5) To select an appropriate production-type forging design that can be produced produced successfully by hot-cold forging techniques in Phase III.

Six steels were selected for study on the basis of potential strength level and pearlite-transformation characteristics. These steels are D6AC, 300M, HP 9-4, AM355, H-11, and 4340. The H-11 and 4340 steels were included because they are currently used in forgings for aerospace applications. The major portion of the time and effort expended during this period has been on procurement of materials and preparation of equipment for the hot-cold forging trials. Preliminary trials were made on several steels to check out the tooling and forging procedures.

PHASE II. HOT-COLD FORGING DEVELOPMENT STUDIES

The over-all objective of Phase II is to develop the most promising process for economical production of simple and complex forged components from high-strength steels by hot-cold working. Variables such as the forging temperature, forging reduction, and deformation rate are being studied for their effects on microstructure, flow pattern, longitudinal and transverse properties, etc., of a number of the most promising steels amenable to strengthening by hot-cold working.

Materials

The six steels chosen for preliminary investigation and their nominal compositions are:

Steel	Nominal Composition, per cent								
	C	Mn	Si	Cr	Mo	V	Ni	Co	N
D6AC	0.47	0.7	0.3	1.0	--	0.08	0.5	--	--
300 M	0.4	0.75	1.6	0.85	0.4	0.08	1.85	--	--
H-11	0.4	0.3	0.9	5.0	1.2	0.5	--	--	--
4340	0.4	0.7	0.25	0.8	0.3	--	1.9	--	--
HP 9-4	0.4	0.2	0.1	0.3	0.3	0.1	9.0	4.0	--
AM355	0.13	0.95	0.25	15.5	2.75	--	4.3	--	0.1

These steels were ordered from suppliers who indicated they could (1) provide consumable-electrode vacuum-arc-melted stock of aircraft quality, (2) provide chemical analysis of heat, and (3) offer the shortest delivery from receipt of order. The steels were obtained in the form of forged billet stock from the following companies:

Alloy	Supplier	Billet Size, in.	Delivery Date
D6AC	Midvale-Heppenstall	4 pc. - 8 x 8 x 3-1/4	April 3, 1963
300M	"	4 pc. - 8 x 7-3/4 x 3	"
H-11	"	2 pc. - 8-1/4 x 5-1/4 x 5-1/4	"
4340	"	1 pc. - 9-1/2 x 8-1/2 x 3	April 30, 1963
		1 pc. - 9 x 3 x 1-3/4	April 30, 1963
HP 9-4	Republic Steel	2 pc. - 8 x 8 x 3	April 29, 1963
AM355	Allegheny-Ludlum	2 pc. - 68 x 1-1/2 x 1-1/2	March 15, 1963

All of the alloys were supplied in the as-forged (cogged) condition with the exception of AM355 which was annealed.

Chemical analyses of the heats of each alloy are being supplied by each of the suppliers. Analyses of four of the alloys have been received and are as follows:

Steel	Composition, weight per cent										
	C	Mn	P	S	Si	Cr	Ni	Mo	V	N	Al
H-11	0.43	0.25	0.008	0.010	0.95	5.24	0.15	1.30	0.47	--	--
300 M	0.43	0.71	0.005	0.005	1.67	0.78	1.80	0.34	0.07	--	0.10
D6AC	0.47	0.68	0.008	0.006	0.30	0.98	0.60	1.01	--	--	0.031
AM 355	0.120	0.93	0.018	0.008	0.16	15.14	4.27	2.65	--	0.082	--

With the exception of AM 355, typical isothermal-transformation diagrams for these steels were presented in Figures 1 and 2 of the First Interim Technical Documentary Progress Report. AM 355, as reported by Allegheny-Ludlum, does not exhibit a pearlite reaction in any reasonable times. However, there is a chromium-carbide precipitation from the austenite that requires the following times for initiation:*

Temperature, F	Time, seconds
1490	90
1400	120
1300	300
1200	1800

To prepare forging preforms from the as-received material, sections were sawed from the cogged billets as shown in Figure 1. These sections were then hammer forged to 1-5/8 inch-square bars, softened by overtempering, and cut in half to supply two preforms roughly 4-1/4 inches long. Each preform was then machined to 1-1/2 inches square. In the case of AM 355, no intermediate processing was required. Blanks were cut 4-1/4 inches long and machined to 1-1/2-inch-square preforms.

Design and Preparation of Dies for Hot-Cold Forging

Previous experience indicated that closed-die systems would be more suitable for hot-cold forging than would an open-die system. The forging design chosen for Phase II studies is shown in Figure 2. This design, when hot-cold forged from a 1-1/2- x 1-1/2- x 4-1/4-inch preform, will provide various deformation levels in a single part.

The dies necessary to produce this part have been prepared from H-11 steel to the dimensions shown in Figure 3, heat treated, and triple tempered to Rockwell C 48 to 52. One-half of the machined die is shown in Figure 4 prior to heat treatment. The other half of the die is identical.

Hot-Cold Forging Trials to Establish Procedures

Preliminary hot-cold forging experiments have been conducted on AM 355, H-11, D6AC, and 300 M steels to establish suitable procedures and to test the tooling. HP 9-4 and 4340 were not included because of their late delivery date.

*George Arten, Allegheny-Ludlum Steel Corporation, private communication.

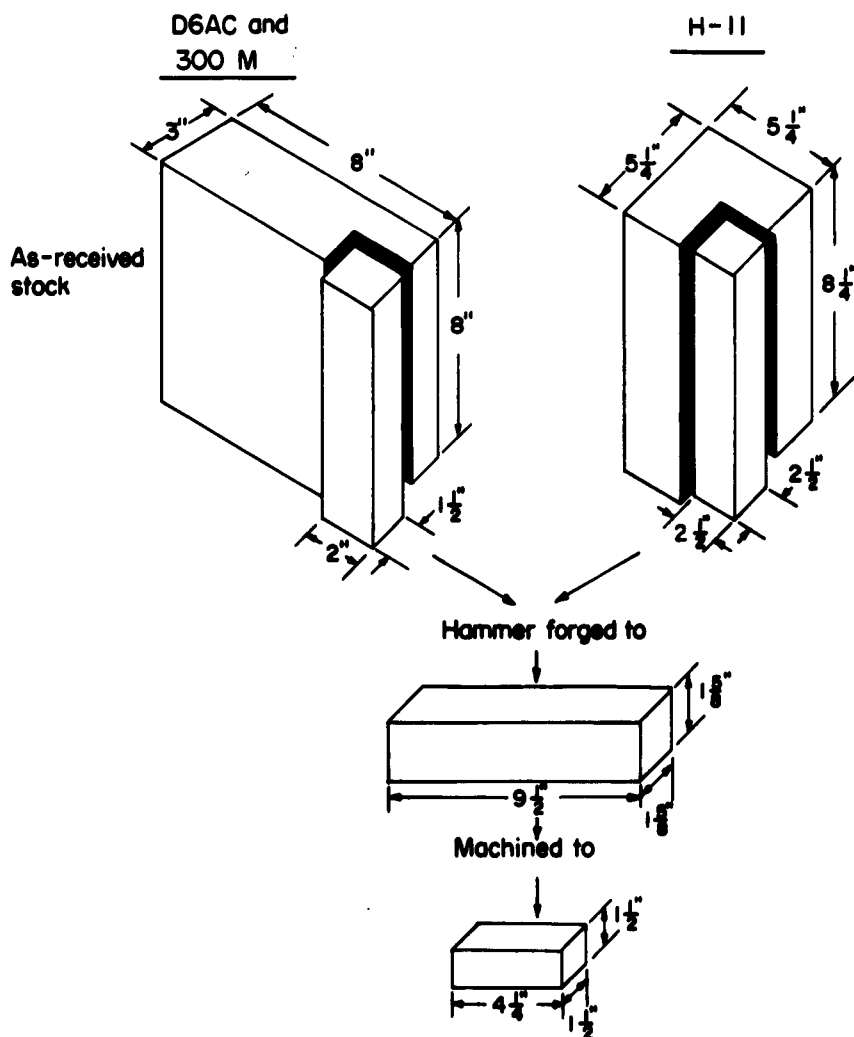
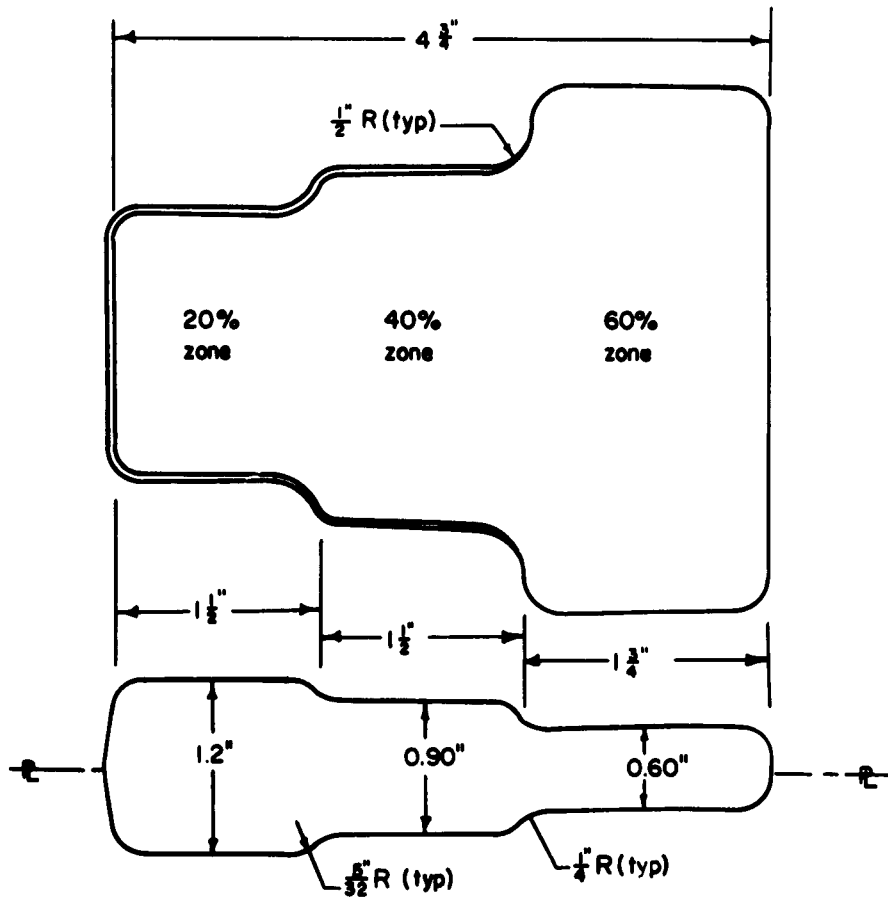


FIGURE 1. PREPARATION OF FORGING PREFORMS FROM AS-RECEIVED STOCK



Plan Area 13.5 sq in. (approx)
 Stock Size $1\frac{1}{2} \times 1\frac{1}{2} \times 4\frac{3}{4}$ in.

Print Notes:
 Draft 5°
 Fillet Radii $\frac{1}{4}$ in.
 Corner Radii $\frac{5}{32}$ in.
 Approximate Linear
 Reduction, %: 20, 40, 60

FIGURE 2. STEP-BAR FORGING REPRESENTING THREE LEVELS OF REDUCTION

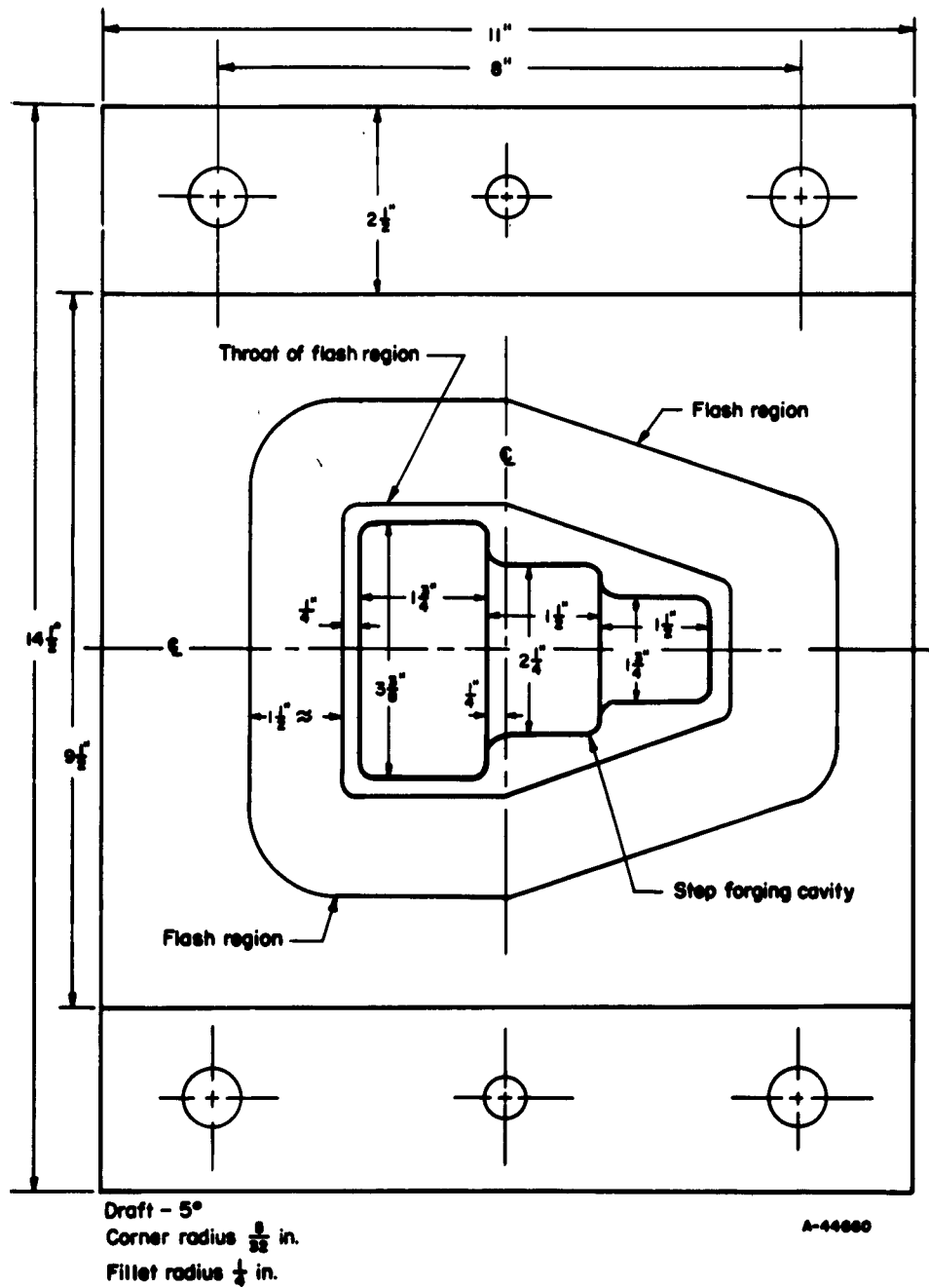


FIGURE 3. DESIGN OF CAVITY IN MATCHED IMPRESSION DIES FOR STEP FORGING

Flash region around cavity is shown by light outline.

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FIGURE 4. VIEW OF LOWER HALF OF MATCHED IMPRESSION DIES FOR STEP FORGING

Die material: H-11 tool steel, 48-52 Rc.

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Preforms 1-1/2 x 1-1/2 x 4-1/4 inches were austenitized at appropriate temperatures in an electric air furnace. They were then cooled rapidly to the deformation temperature, held several minutes to establish temperature uniformity, and quickly transferred to the heated dies of a 700-ton forging press, operating at a ram speed of 80 inches per minute. The time required to deform the metal was of the order of 1 second. The step-bar forging was then removed from the die and allowed to cool in air. Measurements were taken to determine the actual percentage reduction in each section of the forging.

To cool the preform from the austenitizing temperature to the deformation temperature, two different methods were employed. For cooling to temperatures in the "deep-bay" region (near 1000 F), a 500-cubic-inch bath of molten salt (Houghton No. 810) was employed. For cooling to temperatures near the pearlite nose, a circulating-air furnace was used, inasmuch as quench time is not critical.

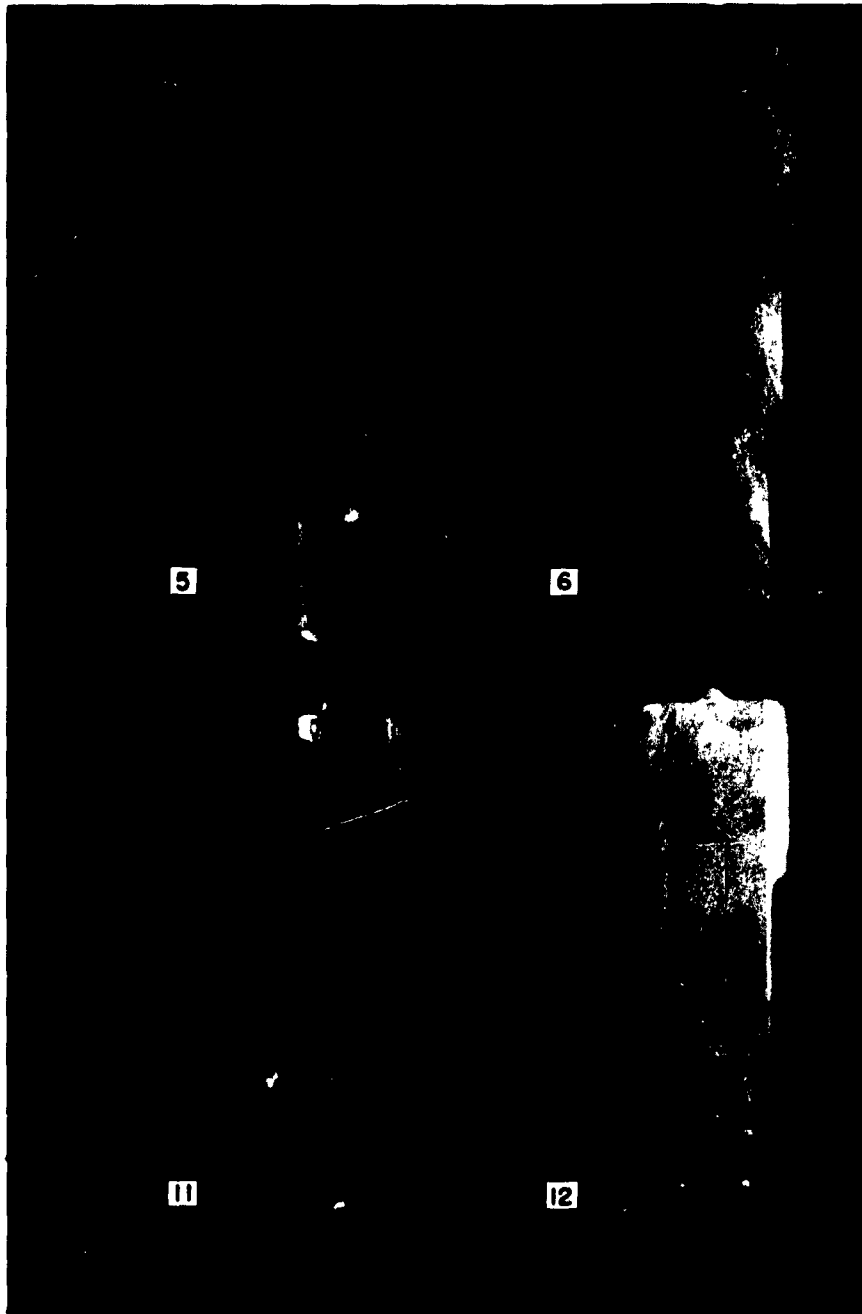
The lubricant for all trials was a mixture of kerosene and graphite on the die surface. Combustion of the kerosene in contact with the hot dies left a residue on the die surface that served as a parting agent. Molten salt remaining on the preforms cooled in the salt bath also acted as a lubricant.

The dies were preheated to 700 F in an air furnace, and then transferred to the forging press. A gas flame was employed to maintain the temperature at 600 F, which is above the M_s temperature for most of the steels being investigated. In conjunction with the gas flame encircling the die, asbestos foil separators were used between the die block and the press platens to reduce the heat-sink effect of the forging-press mass. Asbestos-foil shielding was also employed to minimize convection heat losses.

Results of Preliminary Forging Trials

Photographs of several step-bar forgings prepared from AM 355 are shown in Figure 5. It is apparent that the total amount of reduction is greatest at the higher forging temperature, Samples 5 and 6. In every case, fill was incomplete in the zone of highest reduction because the metal flow occurred predominantly in the long direction of the preform as forging proceeded. This reduced the volume of metal available for lateral movement in the zone of highest reduction. Furthermore, the early formation of flash at the ends and at the sides of the thick sections of the step forging acted to retard die filling in the thin section. As a result, the actual reductions in all of the trials conducted to date were slightly less than the desired reductions of 20, 40, and 60 per cent, even though the full 700-ton press capacity was used in each trial. The forging conditions and measured percentage reductions are presented in Table 1 for each forging trial.

Another factor in these preliminary trials which probably had an effect on the reductions and die fill obtained was die temperature. The gas heating method employed did not supply sufficient heat to maintain the dies at the desired temperature of 600 F. In future trials, it is planned to replace the gas heater with electrical-resistance heaters, as well as to increase the thermal shielding. The problem of incomplete filling of the die cavity also appears to be associated with lubrication. Several other lubricants of the grease-type are being obtained for use in future trials.



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FIGURE 5. STEP FORGINGS OF AM 355 SHOWING TYPICAL EFFECT OF HOT-COLD FORGING TEMPERATURE

AM bars annealed at 1800 F, Bars 5 and 6 forged at 1840-1825 F, Bars 11 and 12 forged at 1800 F.

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TABLE 1. MEASURED REDUCTIONS OBTAINED IN HOT-COLD FORGING TRIALS

Steel	Trial Number	Deformation Temperature, F	Die Temperature, F	Transfer Time to Dies, seconds	Per Cent Reduction		
					Maximum	Intermediate	Minimum
H-11	1	945	310	9	50.2	30.2	10.2
H-11	2	985	270	8	53.0	33.0	13.0
H-11	3	1205	500	4	58.1	37.3	16.8
H-11	4	1410	470	6	58.1	37.3	16.8
H-11	21(a)	1070	530	7	55.0	34.4	14.6
H-11	22(a)	1090	490	6	55.8	35.6	15.1
AM 355	5	1425	470	6	57.0	36.3	15.7
AM 355	6	1340	470	6	57.1	36.4	15.7
AM 355	11	1000	510	8	53.2	32.7	12.1
AM 355	12	1005	510	9	54.7	34.3	13.4
AM 355	17(a)	1400	580	6	55.5	35.2	14.3
AM 355	18(a)	1400	580	6	56.2	35.7	15.3
AM 355	19(a)	1090	580	8	53.5	33.1	12.3
AM 355	20(a)	1090	580	9	53.5	33.0	12.3
D6AC	9	1465	500	6	59.1	38.3	18.0
D6AC	10	1425	500	6	59.3	39.0	18.6
D6AC	13	1030	510	11	56.8	36.4	15.5
D6AC	14	1035	510	8	55.1	34.6	13.9
300 M	7	1355	500	6	59.2	38.2	17.7
300 M	8	1410	500	6	59.1	38.2	17.8
300 M	15	1040	520	7	57.1	36.7	15.8
300 M	16	1045	520	9	55.8	35.0	14.4

(a) Trials conducted after increasing draft angle from 3 to 5 degrees to alleviate difficulty in removing forged part from dies.

Difficulty was also experienced in removing the forged part from the die. The die-draft angle was increased from 3 to 5 degrees to alleviate this difficulty, as indicated in Table 1. Although this made it somewhat easier to remove the part from the dies, it did not completely eliminate the problem and further modifications in die design may be necessary.

FUTURE WORK

After establishing suitable procedures, the six steels will be studied to determine their response to hot-cold forging and their general suitability for processing by this technique. Preforms will be hot-cold forged to the step-bar configuration shown in Figure 3 to achieve reductions in thickness of approximately 20, 40, and 60 per cent, accompanied by lateral flow. Two deformation temperatures will be chosen for each steel, one at about 200 F above the pearlite nose and the other in the deep-bay region of the I-T diagram. The approximate austenitizing temperatures, forging temperatures, quenching media, and tempering temperatures for each steel are:

Steel	Austenitizing Temperature, F	Forging Temperature, F		Quench	Tempering Range, F
		High	Low		
D6AC	1550	1475	1000	Oil	500-900
300 M	1600	1400	1000	Oil	500-900
H-11	1850	1550	1000	Air	600-1100
4340	1550	1400	1000	Oil	400-800
HP9-4	1550	1250	1000	Oil	400-800(a)
AM 35	1710	1400	1000	Air	850-1100(a)

(a) After subzero cooling.

The preforms will be austenitized, cooled rapidly to the forging temperature, held to establish temperature uniformity, forged to the step-bar configuration in dies preheated to at least 600 F (above M_s for all six steels), and immediately quenched. Duplicate forgings will be prepared for each steel and each deformation temperature - a total of 24 forgings.

The step-bar forgings will be cut longitudinally into sections, and examined in the as-quenched condition as well as after tempering at various temperatures. The evaluation will include both microscopic examination and hardness determinations to establish the response of the steels to the varying amounts of deformation, the different deformation temperatures, and the tempering conditions. The results will be compared with results obtained from conventionally treated specimens of the same steels. Based upon these results, the steels will be rated according to their general suitability for achieving increased strength through hot-cold forging. Factors favoring one steel over another will include:

- (1) Little tendency to recrystallize or to transform to nonmartensitic products before, during, or after hot-cold forging
- (2) Large increase in hardness after tempering when compared with conventionally hardened and tempered material
- (3) Ease of forging (i. e., low pressures, little tendency toward cracking).

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After rating the six steels, the three most promising steels will be subjected to further study to establish realistic hot-cold forging cycles that lead to consistent mechanical-property response.

* * * *

Data upon which this report is based are recorded in Battelle Laboratory Record Books Nos. 19371 and 20164.

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