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ESTABLISHMENT OF A PROCESS FOR CREEP FORGING ALUMINUM ALLOY WEAPON COMPONENTS

APRIL 1978

Prepared by

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TECHNICAL REPORT

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6. Fabrication of Weapon Components

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This program was aimed at a novel manufacturing method for the reduction of the fabrication costs of aluminum weapon components. Its technical goal was to combine the ability of powder metallurgy processing to produce a well-proportioned preform and of creep forging to make a precision part. The work was done in two phases. The first phase was devoted to characterizing elemental 7075 blended aluminum powder, establishing requisite process criteria, and formulating a preliminary process specification. Five variables were investigated under a statistical designed experimental program. They were

(Cont.)

20. ABSTRACT (cont.)

(1) particle size, (2) preform density, (3) sintering temperature, (4) forging temperature, and (5) percent forging deformation. Using the requisite process criteria set up from these variables, a preliminary process specification was formulated and further refined by isostatic pressing of trapezoidal preforms and their forging into "T" shapes. The resultant forgings had elements of forward extrusion, backward extrusion, and lateral flow and helped define the optimized parameters necessary for creep forging.

The second phase involved further optimization of the processing variables by use of proper preform and tooling design. Effectiveness of the process was demonstrated by a prototype production of a cam component, P/N 8433752, for the 105mm howitzer. Excellent cam forgings, free of any cracking and with complete die filling, were made in a single forging operation. The forging had many net surfaces and a smooth finish. Mechanical properties of the cam in longitudinal and transverse directions were practically the same and were UTS 72 ksi, 0.2% Y.S. 63 ksi, and elongation of 8.5% for longitudinal and 7% for transverse specimens. These properties exceeded those of specification QQ-A-367H for wrought materials in the transverse direction and approached those in the longitudinal direction. A finalized process specification was recommended defining powder size, preform density, and sintering and forging conditions. Preliminary cost analysis shows projected cost saving of 30% when the cam is made from a P/M forging as compared to making it from a conventional forging.

FOREWORD

This report covers the work performed under Contract No. DAAA09-75-C-2056 by Dr. K. M. Kulkarni, Dr. N. C. Birla, Mr. W. Berner, and Dr. S. Bhattacharyya of IIT Research Institute. The work was conducted under the direction of the Engineering Directorate, Rock Island Arsenal, Rock Island, Illinois. The report is designated internally as IITRI-B6137-6.

The contributions of the following people are gratefully acknowledged: Mr. Y. Lee, Mr. J. Dorcic, Mr. A. Means, and Mr. A. Hudson for the experimental work; Mr. S. Rajagopal for the tooling design, and Mr. J. Anderson for the isostatic pressing of preforms. This work was authorized as part of the Manufacturing Methods and Technology Program of the U.S. Army Materiel Development and Readiness Command, and was administered by the U.S. Army Industrial Base Engineering Activity.

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1. INTRODUCTION

Forging of aluminum bar stock in a series of open-die and closed-die forging operations is the traditional method used for fabricating high quality ordnance components. The conventional forgings do not have a high degree of precision, and the unit cost of the finished part increases tremendously because of further processing costs such as for numerically controlled (N/C) machining. A means of reducing these costs is of vital importance to the U.S. Army. To reduce these costs, powder metallurgy (P/M), with its potential for producing net or near-net shapes, and creep forging[(1)] with its ability to fabricate precision forgings at a substantially reduced forging load, are logical alternatives.

The approach used in this program was to take advantage of powder metallurgy processing to produce a well-proportioned preform and then to isothermally creep forge the resultant preform to produce a precision part (Fig. 1). The part selected, a cam for the 105 mm howitzer, is shown in Fig. 2 based on P/N 8433752. This 7075 aluminum alloy component has complex detail and nearly 10 in. length. When made from a conventional forging, it requires a significant amount of finish machining and a reduction of that cost along with material savings is highly desirable.

This program was divided into two phases, I and II, and is summarized in Fig. 3. The objectives of Phase I were to characterize the work material, establish the requisite process criteria, and formulate a process specification for prototype production. Phase I was divided into two tasks. Task A involved powder characterization, isostatic pressing, sintering, forging, and evaluation of round pancakes so as to select preliminary process specifications for Task B. Task B concerned forging of "T" shapes from wedge-shaped preforms to determine forward and backward extrusion and lateral flow properties of the preform. From Phase I, process specifications for Phase II were prepared.

Phase II started with the design and construction of the tooling for both isostatic pressing of the preform and precision forging of the final part. After the tooling was fabricated, the subsequent work concerned optimization of processing parameters for the cam using the process specification developed in Phase I as a guideline. Several variations in preform design, processing parameters, and die modification were required prior to a prototype production run of the component. Phase II also

(1) T. Watmough, K. M. Kulkarni, and N. M. Parikh, "Isothermal Forging of Titanium Alloys Using Large Precision-Cast Dies," Air Force Materials Laboratory, Technical Report AFML-TR-70-161, July 1970, prepared by IIT Research Institute, Chicago.

Conventional P/M Processing

Powder
|
Compact
|
Sinter

<u>Advantages</u>

Reduction in Machining

Uniform Properties

Better Part Precision

Creep Forging of P/M Preform

(Proposed Work)

Powder
|
Compact
|
Sinter
|
Reheat
|
Creep Forge

<u>Advantages</u>

Low Load

Less Machining

Uniform Properties (Much better than Conventional P/M)

Lower Production Cost

Creep Forging of Billet

Preform Preparation
|
Hot Die and Slow Press System Forging

<u>Advantages</u>

Reduction in Machining

Reduction in Forging Load

Fewer Processing Steps

Wrought Properties

Figure 1

Philosophy of the Proposed Effort

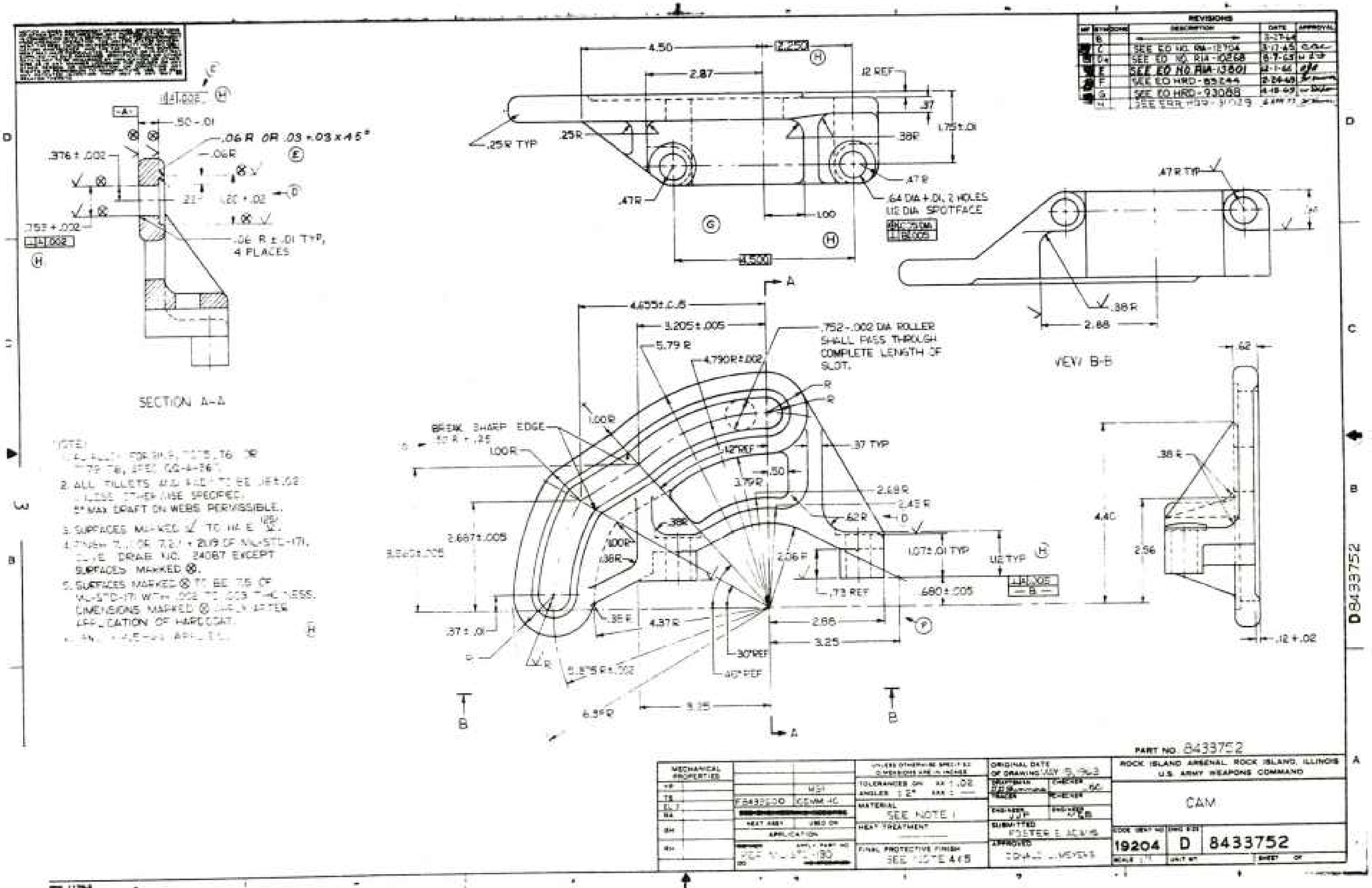
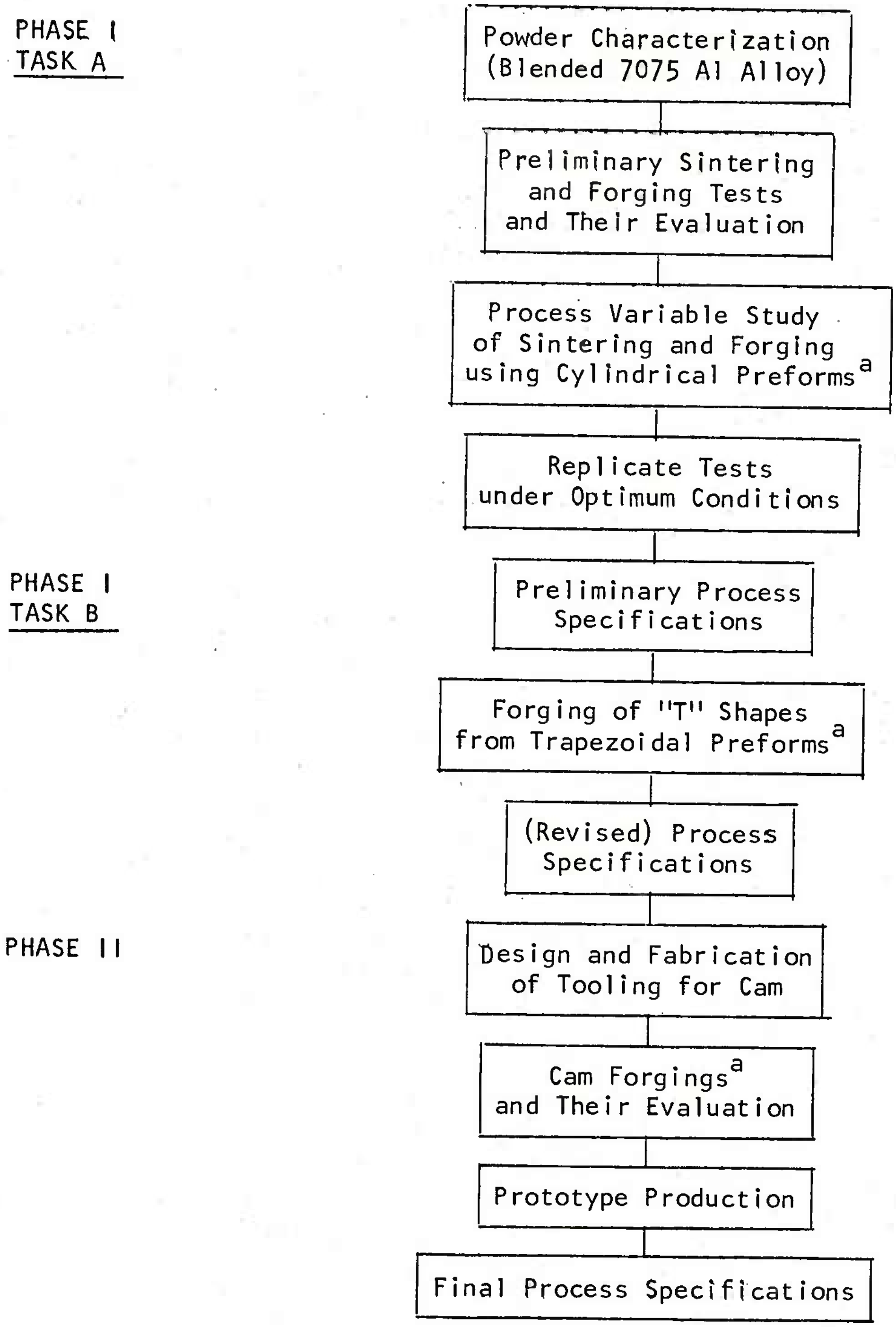


Figure 2

Finish-Machined Drawing for the Cam



[a]All preforms for forging were made by cold isostatic pressing.

Figure 3

Summary of Program Plan

involved the use of powder obtained from two sources, i.e., Aluminum Company of America (Alcoa), and Aluminum Company of Canada (Alcan). The process economics of P/M creep forging technique was compared with conventional forging, and a final process specification was established.

2. TECHNICAL BACKGROUND

2.1 Conventional P/M Processing

Conventional P/M processing consists of compacting the powder to the desired geometry and then sintering the compact. The main purpose is to produce parts with a high degree of precision requiring little or no finish machining.

Characteristics of the starting powder influence the end product of a P/M component greatly. Some of the important powder particle characteristics are mean particle size and size distribution, dendritic cell size and pattern, internal voids, and for the elemental powder ingredients their size, shape, and distribution.

The powder mass properties of major concern are flow rate, bulk and tap densities, and compacting pressure-green density-strength relationships. The temperatures and pressures required for compacting aluminum alloys are fairly low. An example(2) for aluminum alloy 201AB which is similar in composition to 2014 alloy is shown in Fig. 4. Notice that 90% of the theoretical density is achieved at room temperature at a compacting pressure of only about 25,000 psi.

The compaction can be carried out in dies or in an isostatic pressing chamber. In both, the powder flow property is of great interest. Naturally, higher bulk density and higher green density at low compaction pressures are desirable. For die pressed parts, a lubricant is needed either in the powder or on the die wall. With isostatic compaction no lubricant is needed, thereby eliminating the lubricant burn-off step in the sintering cycle. For large and complex parts, isostatic compaction is definitely more advantageous provided, of course, suitable facilities are available.

Nitrogen, dissociated ammonia, and vacuum atmospheres are all used in aluminum P/M sintered part production. All the atmospheres are acceptable and produce comparable properties in sintered and heat treated parts, as shown in Table 1.(3) Dry nitrogen shows certain advantages over others, while vacuum sintering is also gaining wider acceptance.

Another property of importance is dimensional change due to sintering. The dimensions(3) are affected by green density, atmosphere, temperature, and dew point, as shown in Fig. 5. At 90% green density, vacuum sintering produces very little change in dimensions whereas sintering in nitrogen produced substantial shrinkage.

---

(2) "Aluminum Powder Products for Powder Metallurgy Parts," Form F38-12816 (Rev. 6-71), p. 8, Aluminum Company of America.

(3) "Improved Sintering Procedures for Aluminum P/M Parts," Form F38-12964, p. 9, Aluminum Company of America.

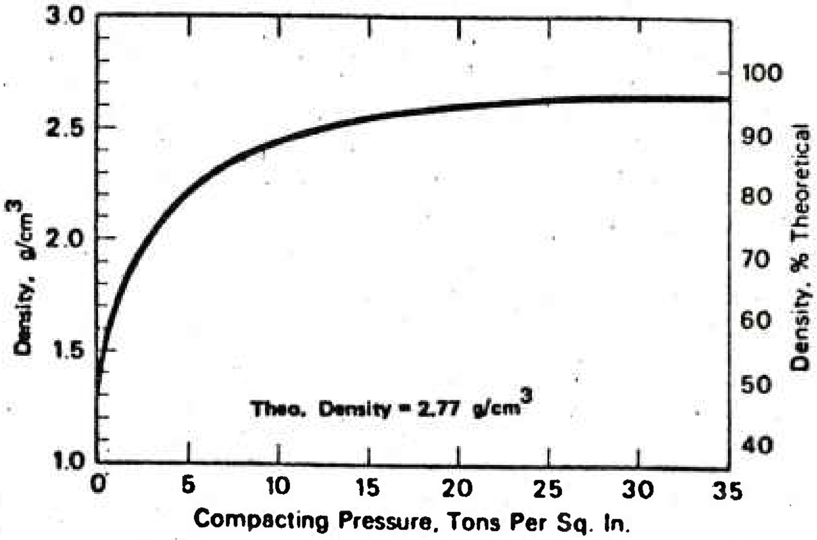


Figure 4

Compacting Pressure vs. Green Density of Alcoa 201AB Blend[2]
(Equivalent to alloy 2014, without Mn)

Table 1

EFFECT OF SINTERING ATMOSPHERE ON STRENGTH PROPERTIES OF ALUMINUM P/M PARTS[a] (3)

Temper	Strength Properties	Atmosphere: Nitrogen	Atmosphere: Dissociated Ammonia	Atmosphere: Vacuum
T1	UTS, psi	24,200	23,300	26,800
	YS, psi	21,300	20,500	20,700
	El., %	3.0	2.0	4.0
T4	UTS, psi	29,200	28,800	35,000
	YS, psi	24,300	23,700	27,100
	El., %	3.0	2.5	5.5
T6	UTS, psi	38,500	35,800	43,000
	YS, psi	38,000	--	41,000
	El., %	1.5	0.5	2.0

[a] Alcoa 201AB, green density 90% of theoretical (2.50 g/cm^3).

(3) "Improved Sintering Procedures for Aluminum P/M Parts," Form F38-12964, p. 9, Aluminum Company of America.

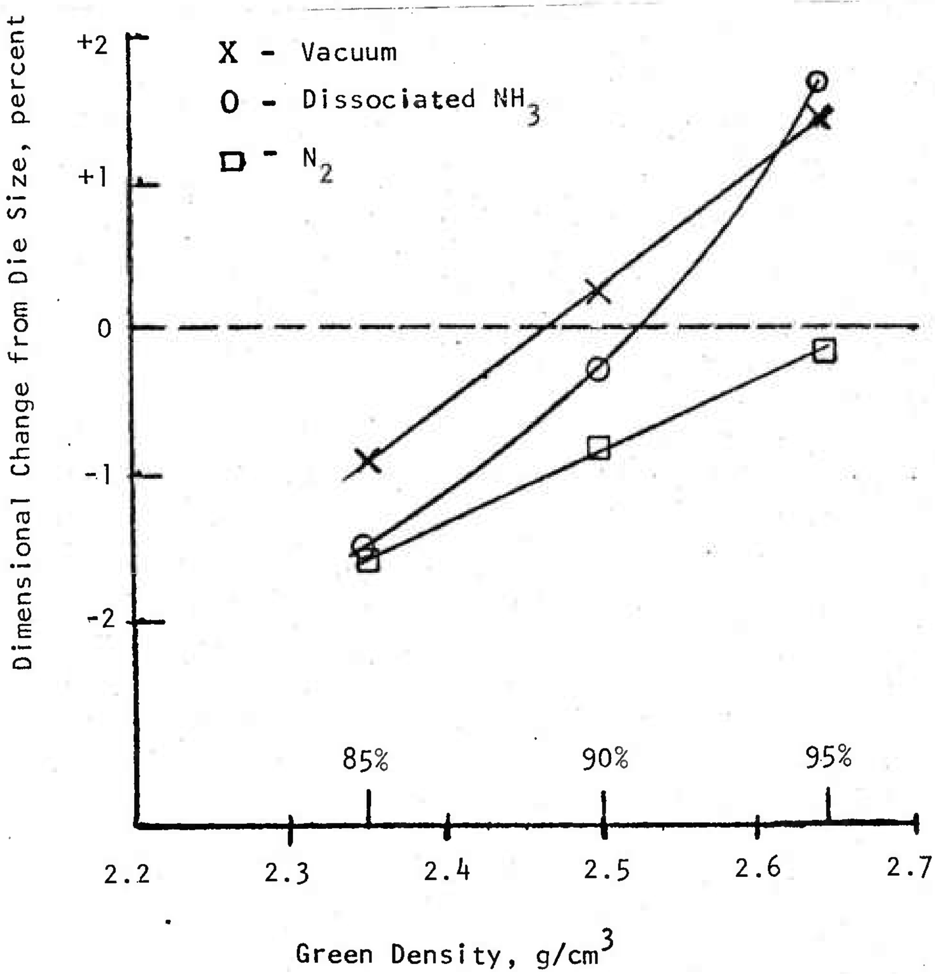


Figure 5

Effect of Green Density and Atmosphere on Sintered Dimensions of Alcoa 201AB alloy[3]

The properties obtained in aluminum P/M parts are naturally dependent on the alloy, density, and sintering conditions. Parts are in routine production with commercially available powders with tensile strength of 50,000 psi. By conventional processing and sintering, the parts rarely have a density of over 95%. Re-pressing after sintering can raise that to 98% with somewhat better properties. As a consequence of the aluminum oxide in the powder, the ductility is often very low even when strengths near to that of the wrought product can be obtained.

2.2 Forging of P/M Preforms

The forging operation is carried out on the conventionally processed P/M parts for further improvement in mechanical properties. To withstand the forging operation without cracking, the preform must have at least 80%, and preferably, 90% of the theoretical density. The final properties of forged P/M parts are affected by the degree of deformation during forging even though the initial preform density is the same for all parts (Table 2).(4) The property improvement, particularly in ductility, is quite significant at the higher deformation and forging pressure.

Work on alloys comparable to 6061 and 2014 shows(3) that pressing pressures of 20,000 to 50,000 psi were necessary in forging at 800°F. Recent work(5) on alloys comparable to 7075 has shown that hot working (extrusion and/or forging) of powder compacts can give properties generally better than the wrought product. These experimental 7075 type forgings were up to 30 in. x 8 in. in an aircraft-related shape.

Forging of P/M preforms to date has followed the usual procedures of wrought alloy forging. Steel dies have been used at temperatures up to 800°F in mechanical or hydraulic presses operated at conventional, relatively rapid speeds. Review of published literature did not reveal any systematic usage of slower deformation speed as in creep forging discussed in the next section.

The forging process definitely leads to an improvement of P/M product as shown in Tables 2 and 3. However, commercial applications so far have been few and confined to small parts less than 10 sq in. in plan area with weights less than 1 lb.

2.3 Creep Forging--Basic Principle and Advantages

The flow stress for many materials is sensitive to speed of deformation and increases with it. For such materials, it is often beneficial to use slower rates of deformation, that is, slower press speeds. The process is then described as creep forging. Of course, since the work material

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(4) K. E. Buchovecky and M. R. Rearick, "Aluminum P/M Forgings," Metal Progress, Feb. 1972, p. 75.

(5) J. E. Hockett, "On Relating the Flow Stress of Aluminum to Strain, Strain Rate, and Temperature," Trans. Met. Soc. AIME, July, 1967, pp. 969-976.

Table 2

PROPERTIES OF FORGED P/M PARTS[a(4)]

Height Reduction, %	Forging Pressure, psi	UTS, psi	YS, psi	Elong. in 1 in., %
10	50,000	62,000	58,000	2
25	50,000	63,000	59,000	4
50	50,000	66,000	60,000	8
10	20,000	57,000	56,000	0.5
25	20,000	57,000	56,000	0.5
50	20,000	63,000	58,000	4

[a]Alcoa 201AB, T6 temper. 90% green density, heated in air at 800°F and forged in a confined die.

(4) K. E. Buchovecky and M. R. Rearick, "Aluminum P/M Forgings," Metal Progress, Feb. 1972, p. 75.

Table 3

PROPERTIES OF ALUMINUM P/M FORGINGS
COMPARED WITH CONVENTIONAL P/M PARTS AND FORGINGS
(Data compiled from references 3 and 4)

Processing	Tensile Strength, psi	Yield Strength, psi	Elong. in 1 in., %
Composition and Heat Treatment Similar to 6061-T6			
Sintered P/M	36,000	35,000	2
Forged P/M	50,000	46,000	8
Conventional Forging	47,000	43,000	17
Composition and Heat Treatment Similar to 2014-T4			
Sintered P/M	38,000	31,000	5
Forged P/M	58,000	37,000	8
Conventional Forging	61,000	34,000	22
Composition and Heat Treatment Similar to 7075-T6			
Forged P/M	86,000	80,000	9
Conventional Forging	82,000	78,000	11

strength increases as it cools, realizing the benefit from the creep forging process requires that the difference between the workpiece and the die temperature be small, thus minimizing any temperature or heat loss from the work material. When the die and the work material temperatures are equal, the process is known as isothermal forging.

The main advantage of the creep forging technique is that it enables forming of complex and high precision components that cannot be formed by other (conventional) forging techniques. In addition, the forging pressure is greatly reduced--in effect, increasing the capacity of existing presses to make larger forgings. The process can lead to substantial improvement in the overall material utilization and a significant decrease in the amount of required finish machining. Naturally, the process can be applied only to materials whose flow stress is sensitive to strain rate, and aluminum alloys fall in this category.

2.4 Temperature and Strain-Rate Effects in Aluminum

Aluminum and aluminum alloys are known to be strongly strain rate sensitive at temperatures of forging interest.[6-13] It is believed that the

---

(6) K. Tanaka, T. Nojima, and M. Kinoshita, "The Effect of Temperature and Strain Rate on the Strength of Aluminum," 13th Japan Congress on Materials Research, March 1970, pp. 101-105.

(7) J. L. Chiddister and L. E. Malvern, "Compression-Impact Testing of Aluminum at Elevated Temperatures," Experimental Mechanics, April, 1963, pp. 81-90.

(8) R. R. Arnold and R. J. Parker, "Resistance to Deformation of Aluminum and Some Aluminum Alloys," J. Inst. Metals, Vol. 88, 1959-60, pp. 255-259.

(9) A. M. DiGioia, Jr., and R. G. Crum, "Yielding at Varying Load Rates," J. Eng. Mech. Div., Amer. Soc. Civil Eng., June, 1962, pp. 45-74.

(10) K. G. Hoge, "Influence of Strain Rate on Mechanical Properties of 6061-T6 Aluminum Under Uniaxial and Biaxial States of Stress," Experimental Mechanics, April, 1966, pp. 204-211.

(11) R. Mignogna, C. D'Antonio, R. Maciag, and K. Mukherjee, "The Mechanical Behavior of 6063 Aluminum," Met. Trans., June, 1970, pp. 1771-1772.

(12) C. R. D'Antonio, R. J. Maciag, K. Mukherjee, and G. J. Fischer, "The Effect of Strain Rate and Temperature on the Flow Stress of 7075 Aluminum," Trans. Met. Soc. AIME, Nov., 1968, pp. 2295-2297.

(13) K. Tanaka, M. Kinoshita, and T. Matsuo, "Compressive Deformation of Aluminum at High Strain Rate," Proceedings of 7th Japan Congress on Testing Materials, March, 1964, pp. 91-93.

strain rate sensitivity is due to the solutioning of second-phase strengthening particles in the matrix. The effect of strain rate on flow stress[12] of Al 7075 is shown in Fig. 6, and the effect of temperature on tensile properties is shown in Table 4.[14]

Table 4

TYPICAL TENSILE PROPERTIES AT VARIOUS TEMPERATURES[14]

Alloy and Temper	Test Temp., °F	0.2% Y.S., psi	UTS, psi	Elong., %
7075-T6	75	73,000	83,000	11
	500	9,000	11,000	65
	700	4,500	6,000	70

An extensive literature search has revealed no publications on creep forging technique applied to P/M components. However, since the P/M preform will have substantially finer grain size resulting in much greater strain rate sensitivity, the advantages of applying the creep forging process to P/M preforms should be even greater than those obtained by creep forging of wrought preforms.

2.5 Component Investigated

The part investigated in this program--the cam--is shown in Rock Island Arsenal Drawing No. 8433752, Fig. 2. The part is about 9 1/4 x 6 in. in plan area with about 1/2 in. thickness over much of the area, and projections ranging up to 2 1/4 in. high. This component is currently made by forging and machining. For comparison, two views of a forging and the component machined from it are shown in Fig. 7, and it is quite obvious that the finished component requires a substantial amount of machining. The weight of the conventional forging after trimming is 2.9 lb and that of the finish-machined component is 1.8 lb. The target for this program was to make many, but not all, of the surfaces net. The cam slot with a complex contour and ±0.002 in. tolerance and the mounting pads and holes will need to be machined. The surface -A- (Fig. 2) may need to be flattened if it distorts during heat treatment.

The preform for this forging will have a complex shape. Since it must resemble, at least partly, the finished part in outline, isostatic pressing seems to be the only practical process for compaction of the preform.

(14) Aluminum Standards and Data, 4th Ed., 1974, The Aluminum Association, Inc., Table 2.2, pp. 31-34.

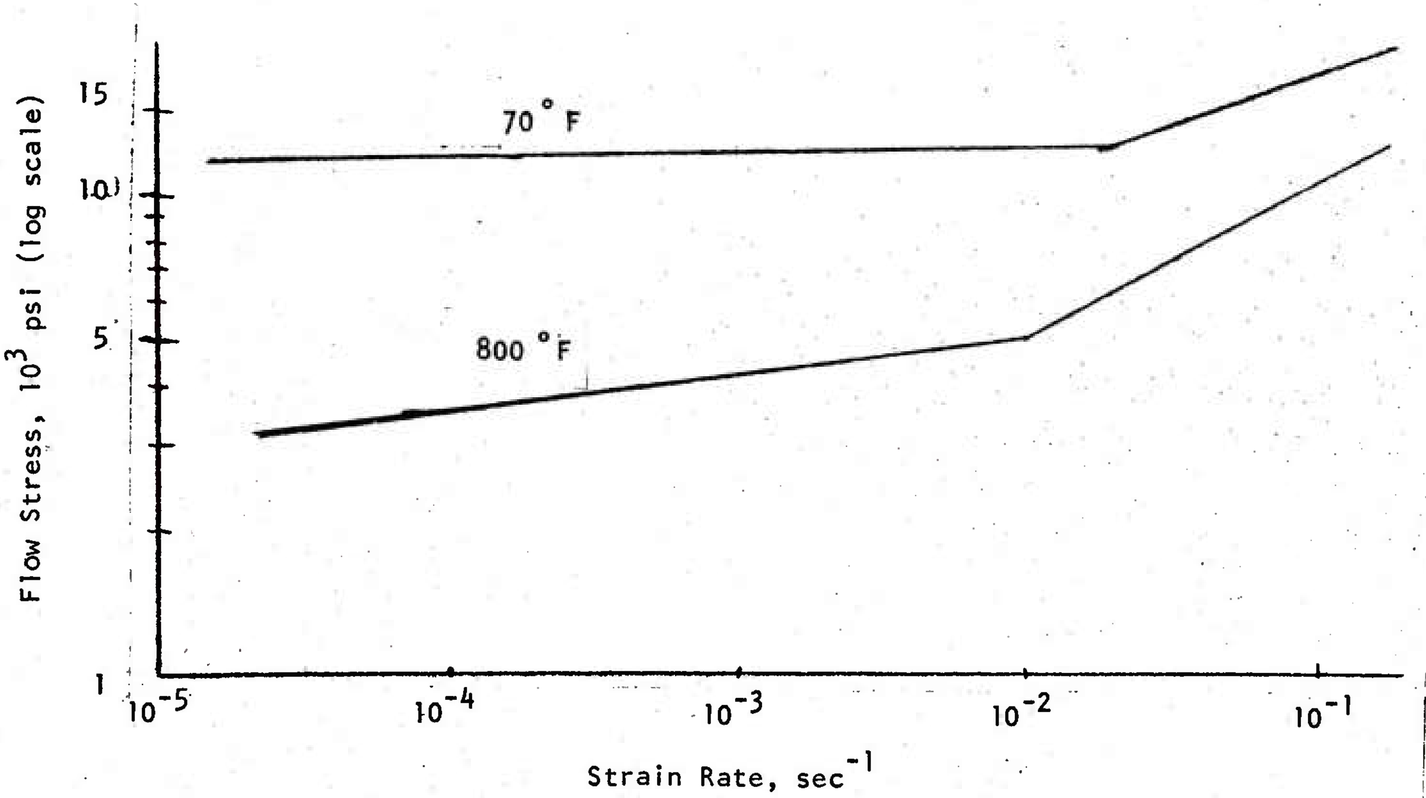
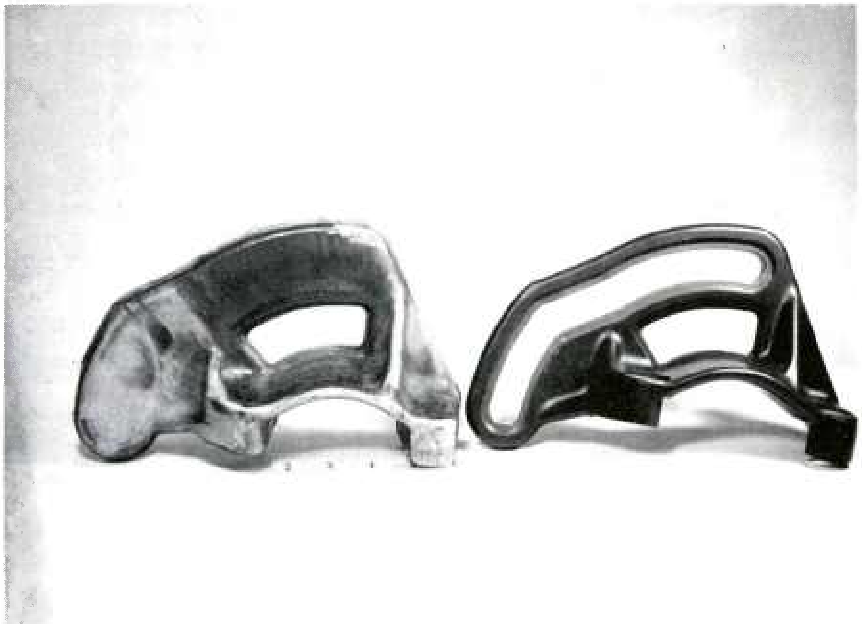


Figure 6

Strain Rate/Temperature Effect on Flow Stress for Al 7075[12]



Neg. No. 43253

Neg. No. 43254

Figure 7

Two Views of the Conventional Forging
and the Cam Finish-Machined from It

2.6 Target Mechanical Properties

The property specification for the cam, as shown in Fig. 2, is 7075T6 as per QQ-A-367H. This is for a wrought material since the cam is at present produced by the conventional forging technique. There is no comparable specification for this alloy and application for the cam to be produced by powder metallurgy technique. The Federal Specification QQ-A-367H, dated December 26, 1973, entitled "Aluminum Alloy Forgings," gives the property specifications for wrought material up to 1 in. thickness. For test specimens parallel to forging flow (grain) lines, the specifications are 75,000 psi minimum tensile strength, 64,000 psi yield strength, and 7% elongation; and for specimens not parallel to forging flow lines, the corresponding properties are 71,000 psi, 61,000 psi, and 3%. The latter set of properties is applicable to transverse directions. In the P/M processing technique, even after heavy reductions, the "type" of grain structure found in wrought materials is normally not obtained resulting in a more isostropic property distribution in P/M longitudinal and transverse specimens. In the absence of any definitive property specifications for P/M products, we have used that for the wrought product as the specification to be aimed at for the purpose of this program.

3. PHASE I, TASK A: POWDER CHARACTERIZATION AND UPSETTING STUDIES

The purpose of Phase I, Task A, was to characterize the powder, to optimize isostatic pressing, sintering, and upsetting parameters, and then on the basis of this work to select preliminary process specifications for Task B. The detailed program is summarized in Fig. 8.

3.1 Powder Selection and Characterization

Atomized elemental aluminum powder blended with other elemental powders to form the desired alloys are commonly used for P/M compacted and sintered products. Prealloyed powders require higher pressure for compaction. Also, recent work[15] done on prealloyed 7075 aluminum powders made by rotating electrode process showed poor integrity of extruded products. Therefore, atomized elemental blended, unlubricated Al 7075 powder was purchased from Alcoa in two distinct sieve sizes--coarse (-40 mesh) and fine (-100 mesh). The nominal and analyzed chemistry and particle size distributions are given in Tables 5 and 6, respectively. The chemical analyses and particle size distributions conform to nominal composition and supplier's specification. Subsequently, in Phase II studies, powder from Alcan was also utilized.

The powders were examined using a scanning electron microscope (Fig. 9). Both powders reveal the rounded, irregular, smooth, and slightly elongated typical shapes of atomized aluminum powder which is the main ingredient of the blended aluminum powder. Both the coarse and fine fractions were totally non-flowing under standard flow tests. The bulk densities were 1.34 and 1.12 g/cc for coarse and fine powders, respectively.

3.2 Statistical Experiment Design

The major variables and their levels selected for the evaluation are shown in Table 7. The variables include particle size, preform density, sintering temperature, forging temperature, and forging deformation. Generally, the properties of a product are complex functions of the different processing variables. Such interactions can best be identified by multiple stepwise regression analysis.[16] For such analysis, a fractional factorial plan is often adequate and minimizes the number of experiments to be performed. In this program, a half factorial design was selected as shown in Table 8, and this led to a total number of experiments of 36.

---

(15) F. J. Gurney, D. J. Abson, and V. DePierre, "The Influence of Extrusion Consolidation Variables on the Integrity and Strength of the Product from Prealloyed 7075 Aluminum Powder," Powder Metallurgy, 1974, Vol. 17, No. 33, p. 46.

(16) W. S. Connor and S. Foung, "Fractional Factorial Design of Experiments with Factors at Two and Three Levels," NBS Applied Mathematics Series No. 58, 1961, Washington, D.C. (U.S. Govt. Printing Office).

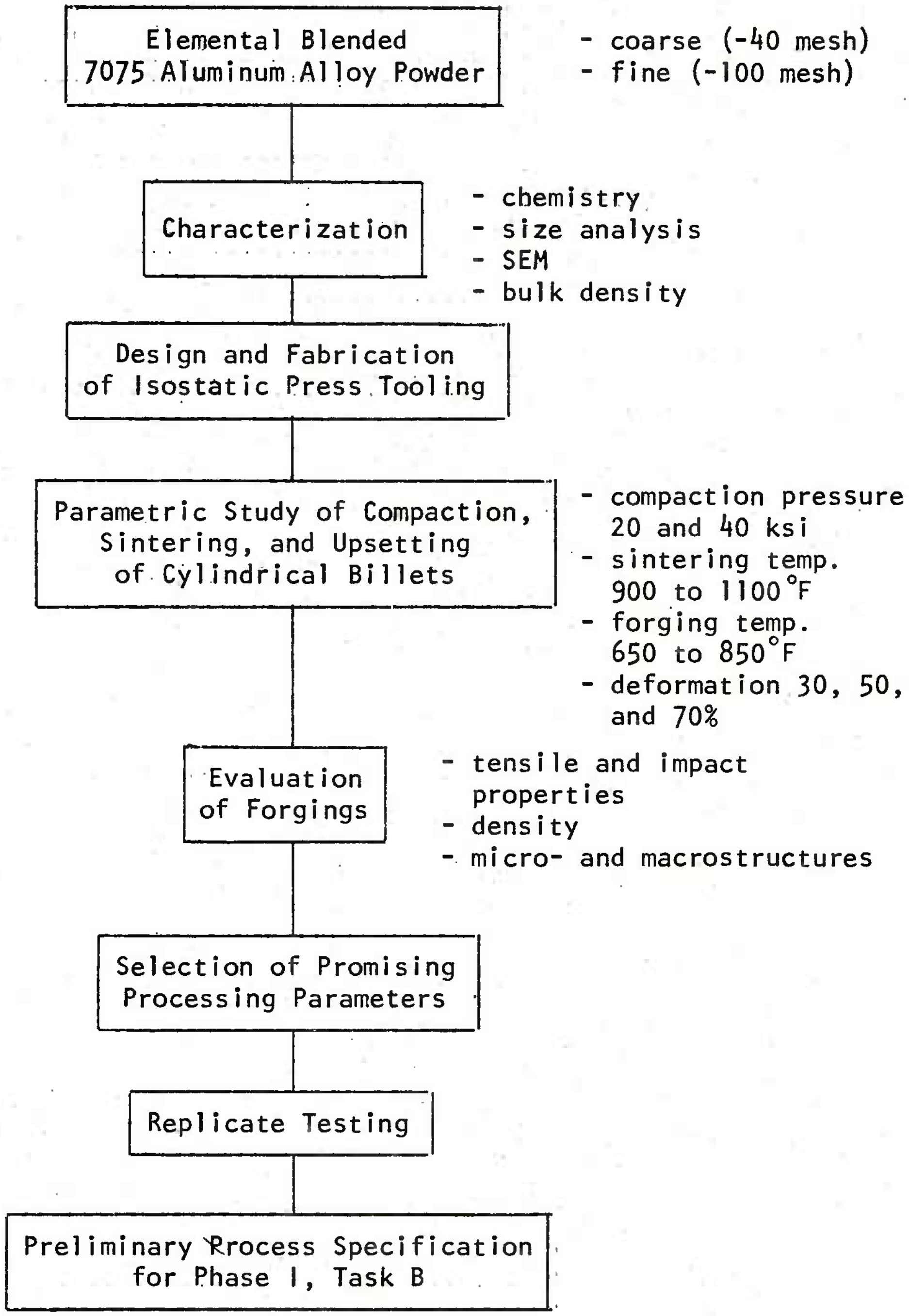


Figure 8

Phase I, Task A. Powder Characterization
and Upsetting Studies

Table 5

CHEMICAL ANALYSIS OF 7075 ALUMINUM ALLOY POWDER

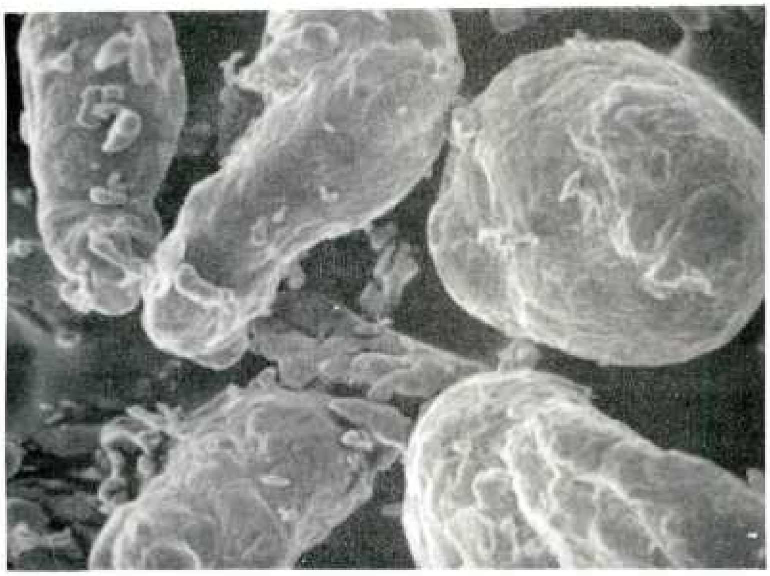
Element	MIL-A-22771C and Federal Specification QQ-A-367H, %	Powder Chemical Analysis, % Coarse	Powder Chemical Analysis, % Fine
Cu	1.2-2.0	1.56	1.60
Si, max	0.4	0.17	0.07
Fe, max	0.5	0.1	0.1
Mn, max	0.3	na	na
Mg	2.1-2.9	2.46	2.46
Zn	5.1-6.1	5.93	6.01
Cr	0.18-0.35	0.21	0.20
Ti-max	0.20	na	na
O_2	--	0.21	0.25

na - Not analyzed.

Table 6

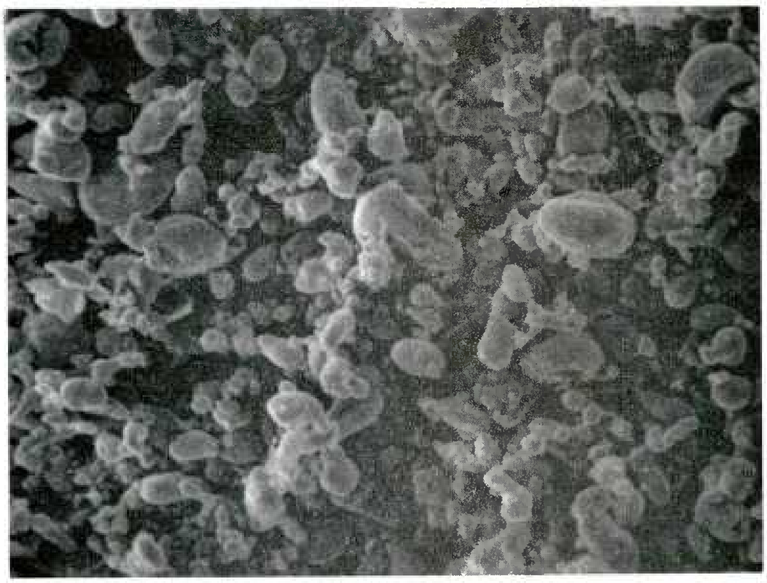
SIEVE ANALYSIS OF 7075 ALUMINUM ALLOY POWDER

U.S. Sieve Size (μm)	Specification, % Coarse	Specification, % Fine	IITRI Analysis, Related on Sieve, % Coarse	IITRI Analysis, Related on Sieve, % Fine
40 (420)	0	--	0.1	trace
60 (250)	--	--	0.1	trace
100 (149)	--	0	17.1	trace
200 (74)	--	--	26.6	0.5
270 (53)	--	--	14.3	3.1
325 (44)	--	--	8.3	4.5
-325 (<44)	25 to 40	75 to 90	33.7	92



SEM No. 8226 200X

(a)



SEM No. 8228 200X

(b)

Figure 9

SEM Photographs of Elemental Blended Atomized Aluminum Powder Made to 7075 Alloy Composition. (a) Coarse, (b) fine.

Table 7

MATERIAL AND PROCESS PARAMETER LEVELS

Parameter	No. of Levels	Code	Remarks
1. Particle Size	2	Coarse(1) Fine(2)	Coarse (100% -40 mesh) Fine (100% -100 mesh)
2. Preform Density	2	Low(2) High(1)	Low (pressure 20,000 psi) High (pressure 40,000 psi)
3. Sintering Temperature	2	Low(1) High(2)	Low (950°F) High (1025°F)
4. Forging Temperature	3	Low(1) Med(2) High(3)	Low (650°F) Medium (725°F) High (800°F)
5. Forging Deformation	3	Low(1) Med(2) High(3)	Low (30%) Medium (50%) High (70%)

Note: The specific values of sintering and forging temperatures were decided after Phase I, Task A, was completed. They are, however, given here for convenience.

Table 8

STATISTICAL DESIGN FOR PHASE IA STUDY

Combination	Particle Size Distribution	Preform Density	Sinter Temperature	Forging Temperature	Forging Deformation
1	1[a]	1	1	1	1
2	1	1	1	2	3
3	1	1	1	3	2
4	2	2	1	1	1
5	2	2	1	2	3
6	2	2	1	3	2
7	2	1	2	1	1
8	2	1	2	2	3
9	2	1	2	3	2
10	1	2	2	1	1
11	1	2	2	2	3
12	1	2	2	3	2
13	2	2	2	2	1
14	2	2	2	1	2
15	2	2	2	3	3
16	2	1	1	2	1
17	2	1	1	1	2
18	2	1	1	3	3
19	1	2	1	2	1
20	1	2	1	1	2
21	1	2	1	3	3
22	1	1	2	2	1
23	1	1	2	1	2
24	1	1	2	3	3
25	2	2	2	3	1
26	2	2	2	1	3
27	2	2	2	2	2
28	2	1	1	3	1
29	2	1	1	1	3
30	2	1	1	2	2
31	1	2	1	3	1
32	1	2	1	1	3
33	1	2	1	2	2
34	1	1	2	3	1
35	1	1	2	1	3
36	1	1	2	2	2

[a]See Table 7 for corresponding parametric values.

3.3 Experimental Details

3.3.1 Design of Isostatic Press Tooling and Pressing Scheme

The size of the preforms for forging is dictated by the size of the pancake desired after forging. In an open die forging, the outside layer does not densify as well as the inner core. Therefore, to allow enough sound material for test specimens, it was decided to forge the pancakes to 3.8 in. diameter and 0.75 in. thickness, as shown in Fig. 10.

To obtain a 0.75 in. forged thickness under 30, 50, and 70% deformations, the corresponding thicknesses prior to forging should be 1.07, 1.5, and 2.5 in. For a 90% density sintered preform for 30% deformation, its diameter (d) will thus be given by equation 1:

$$(0.9)\ (d^2_{\rho 0.9})\ (1.07) = (3.5)^2_{\rho 1.0}\ (0.75)\ . \ . \ . \qquad (1)$$

or $d_{\rho 0.9} = 3.09$ in.

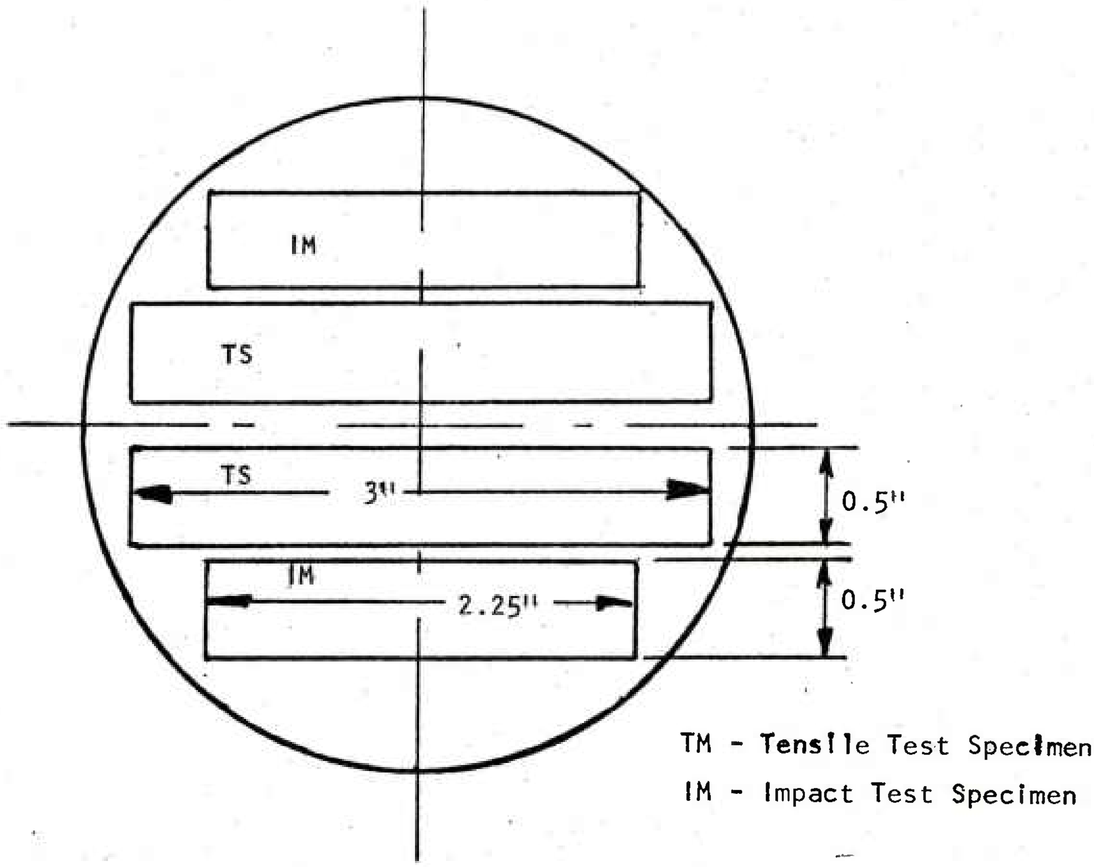
Similarly, for 50 and 70% deformations, the sintered preform diameters will be 2.61 and 2.02 in., respectively. On the basis of an estimated compression ratio of about 1.5 to 1.6, the isostatic press bag sizes selected were 4 and 11 in. in length and 3 1/2 in. diameter, and 5 in. long and 4 in. diameter, and multiple preforms from each pressing were obtained.

The rubber bags with 1 1/6 in. wall thickness, rubber closures, perforated aluminum containers to support the bags, and aluminum sealing rings were obtained from Trexler Rubber Company in Ravenna, Ohio. In all, 12 samples were prepared as shown in Table 9. The procedure involved filling a bag to the required height, vibrating it, placing a filter paper on top of the powder to prevent powder loss during evacuation, placing a sealing ring and clamp, evacuating the bag, and then tightening the clamp. Then the bags were isostatically pressed in an oil system in a 6 1/2 in. diameter x 18 in. deep chamber. Pressurization to 40,000 psi took about 6 to 10 min. The pressure was maintained for 2 min, the chamber was depressurized, the bags were removed and cleaned, and then the billet was removed. The isostatic press tooling and typical compacted preforms are shown in Fig. 11.

On some samples, the increase in bulk density after filling and vibrating but prior to isostatic compaction was checked. The vibrated densities of coarse and fine powders were as follows (the values in parentheses are the corresponding loose filled bulk densities mentioned earlier):

coarse - 1.78 g/cc (1.34 g/cc)

fine - 1.62 g/cc (1.12 g/cc)



Diameter 3 1/2 in.
Thickness 3/4 in. } at 100% Density

Figure 10

Target Dimensions of the Forged Pancake for Parametric Study
(Note also the location of tension and impact specimens.)

Table 9

ISOSTATIC PRESSING SCHEME

Powder-Filled Bag Dimensions	Number of Samples	Powder and Pressure Combination	Billet Serial No.
4 in. dia., 5 in. high	4	Coarse x low pressure	7
		Coarse x high pressure	1
		Fine x low pressure	10[a]
		Fine x high pressure	4
3 1/2 in. dia., 7 in. high	4	Coarse x low pressure	8
		Coarse x high pressure	2
		Fine x low pressure	11[b]
		Fine x high pressure	5
3 1/2 in. dia., 11 in. high	4	Coarse x low pressure	9[c]
		Coarse x high pressure	3
		Fine x low pressure	12
		Fine x high pressure	6

[a]Compacted billet loose inside bag. Small amount of oil leakage at top and bottom.

[b]Slight trace of oil on compact. Bags deteriorating after second pressing.

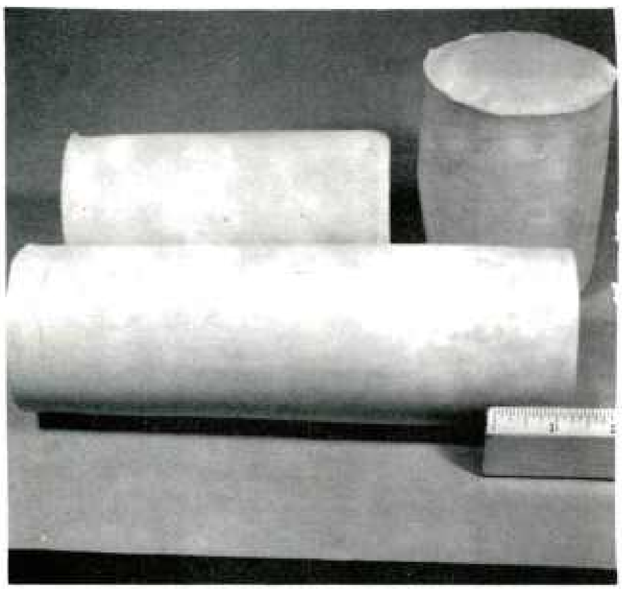
[c]Rubber was perforated by protruding metal tube while closing cover; sample discarded.

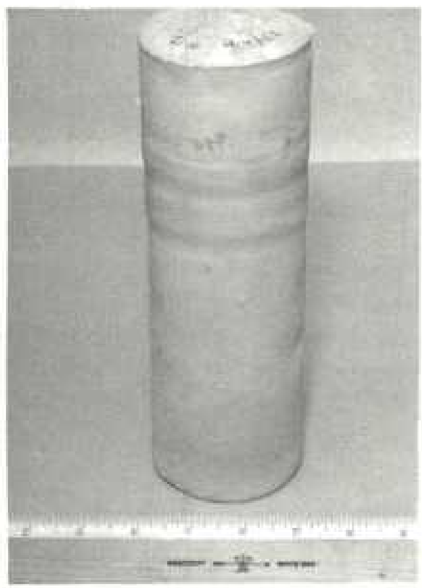
Neg. No. 42348

(a)

Neg. No. 42349

(b)





Neg. No. 42017

(c)

Neg. No. 42389

(d)

Figure 11

Isostatic Pressing Tools and Pressed Billets. (a) Bag, perforated container, plug with vent, sealing ring, and clamp; (b) a sealed bag; (c) billets pressed at 40,000 psi (coarse powder); and (d) billet pressed at 20,000 psi, (fine powder).

For replicate tests, the isostatic pressing procedure was very similar to that described above except that in these tests plastic tape was used to seal the rubber bags instead of aluminum sleeves used in the early part of the tests. This change was made to minimize the possibility of any tearing of the rubber bags during isostatic pressing.

3.3.2 Sintering of Preforms

Since Al 7075 alloy contains zinc which melts at 790°F and forms a eutectic with aluminum at 720°F, it was necessary to perform preliminary trials to select sintering conditions and experimental combinations for the Phase IA parametric study. The sintering for this investigation was done in a small vacuum furnace at about 50 µm pressure. Small pieces were cut from the top and bottom discards of the pressed billets. The temperatures selected for this study were 900°, 950°, 1000°, 1050°, and 1100°F. The sintering parameters were evaluated on the basis of optical metallography and scanning electron microscopy. The results of this work are presented in Section 3.4.2.

Sintering for all the forging work was conducted using a large Inconel muffle placed inside a large electric furnace. The inside dimensions of the muffle were 13 in. width, 4 in. height, and 58 in. length, and it was designed for heating with any atmosphere. The samples to be sintered were placed in a stainless steel tray with a long handle and could be inserted to any desired location inside the muffle. A chromel-alumel thermocouple was inserted to the center of a 1 1/4 in. diameter x 1 1/4 in. high piece of aluminum which was placed next to the samples being sintered. This thermocouple was used for temperature control. All the samples (preforms) for the forging trials were sintered in nitrogen.

3.3.3 Forging Trials

The forging procedure is described briefly in this section. The preforms for forging were cut from sintered cylindrical billets after discarding the low density portions* near the ends of the billets. The preforms were heated in the muffle furnace in air for at least 15 min after the correct temperature was indicated by the control thermocouple. Then, each preform was quickly transferred to the press and forged between heated flat dies at a press speed of approximately 1/2 ipm. The preforms were forged with aluminum sheet wrapped around the periphery to minimize heat loss.

The preform dimensions and forging experimental plan for the parametric study were discussed in Sections 3.3.1 and Table 8, respectively. Of the 36 tests planned (Table 8), eight were aborted because of sintering furnace malfunction. The results of the parametric study are discussed

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*Some of the discarded ends were subjected to preliminary forging tests to help selection of forging temperatures for the parametric study. See Section 3.4.3 for discussion of these preliminary tests.

in Section 3.4.4. The procedure for replicate forging tests was identical to that for parametric study, and the results of the former are presented in Section 3.4.5.

3.4 Results and Discussion

3.4.1 Effect of Powder Size and Isostatic Pressure on Density

After isostatic compaction of the cylindrical billets, dimensional and density measurements were made. Based on theoretical density of 2.8 g/cc, average density values for 40,000 psi and 20,000 psi pressing pressures are given in Table 10. The data show that, as expected, the higher compaction pressure (40 ksi) gives better densification.

3.4.2 Effect of Sintering Temperature and Time on Microstructure

A study of sintering temperatures from 900° to 1100°F and times from 20 to 45 min in vacuum was conducted (see Section 3.3.2). Temperatures above 1050°F showed the presence of a liquid phase after sintering and, at 1100°F, the presence of volatilized zinc was observed. Two typical microstructures of as-sintered specimens are shown in Fig. 12.

SEM examination revealed the presence of unreacted alloying particles as well as particles extremely rich in Cr, Cu, and Zn. The 900°F sintering leaves undiffused Cr as well as Cu particles, as shown in Fig. 12c, and the fine dendritic substructure of Fi-Si-Zn-Cu-rich precipitates is shown in Fig. 12d. The larger porosities at the particle boundaries and the very fine microporosities (<2 μm) inside the particles are also clearly visible. It is worth mentioning that even at the 1100°F sintering temperature, many chromium particles did not diffuse completely.

The sintering study was conducted with both fine and coarse powders and, as expected, ease of diffusion for the fine particle size was quite evident. A typical example of comparison between coarse and fine powder sintered compacts is shown in Fig. 13. Both the compacts were sintered at 950°F (2 hr) in argon atmosphere.

On the basis of this study, 950°F and 1025°F were selected as the two sintering temperatures for the more detailed forging parametric study planned according to Tables 7 and 8. These temperatures are high enough to provide extensive diffusion but not so high that much zinc would be lost. For the forging trials, nitrogen was selected as the sintering atmosphere and, as discussed in Section 3.4.4, the preforms sintered in nitrogen and then forged led to good properties.

3.4.3 Preliminary Forging Tests

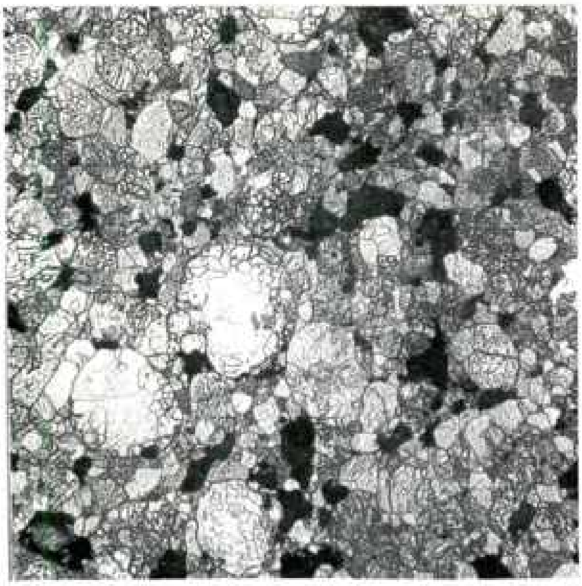
These tests were conducted to help selection of forging temperatures for parametric study and for evaluation of density and microstructure of

Table 10

GREEN DENSITY AS A FUNCTION OF COMPACTION PRESSURE AND POWDER PARTICLE SIZE, ALUMINUM 7075 ALLOY BILLET

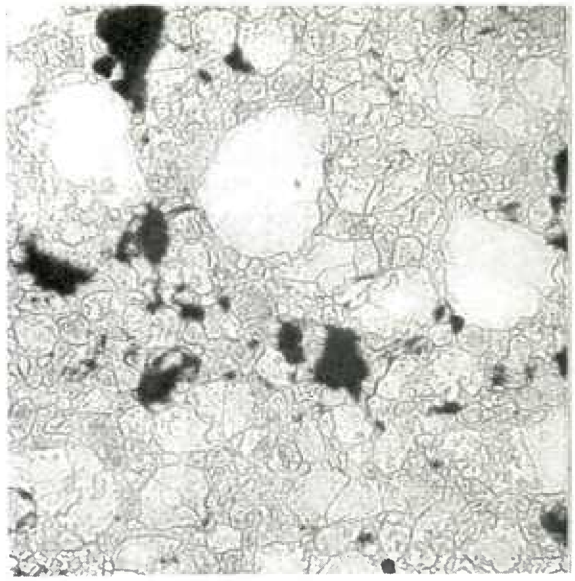
Specimen No.	Powder Size, mesh	Pressure, ksi	Green Density	
			Actual,[a] g/cc	Percent of Theoretical
1	Coarse (-40)	40	2.70	96
2	Fine (-100)	40	2.60	93
3	Coarse (-40)	20	2.51	90
4	Fine (-100)	20	2.36	84

[a]Average of three billets each.



Neg. No. 42223 100X

(a)



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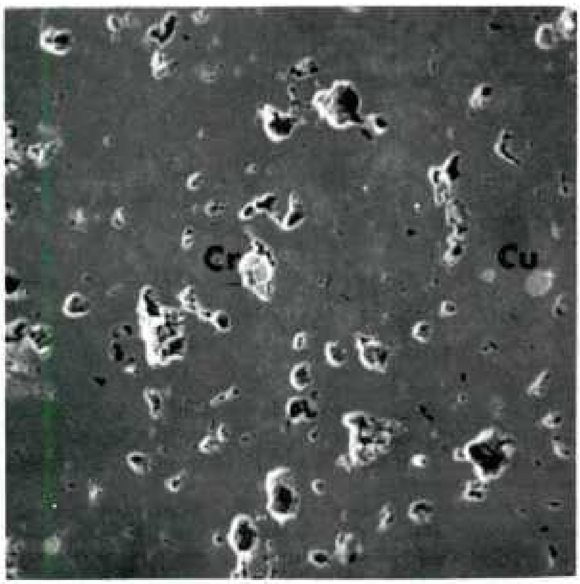
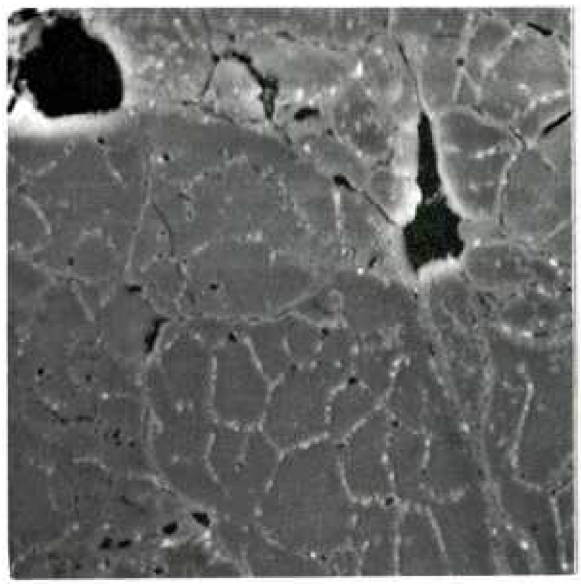
(b)



SEM No. 8052 100X

(c)

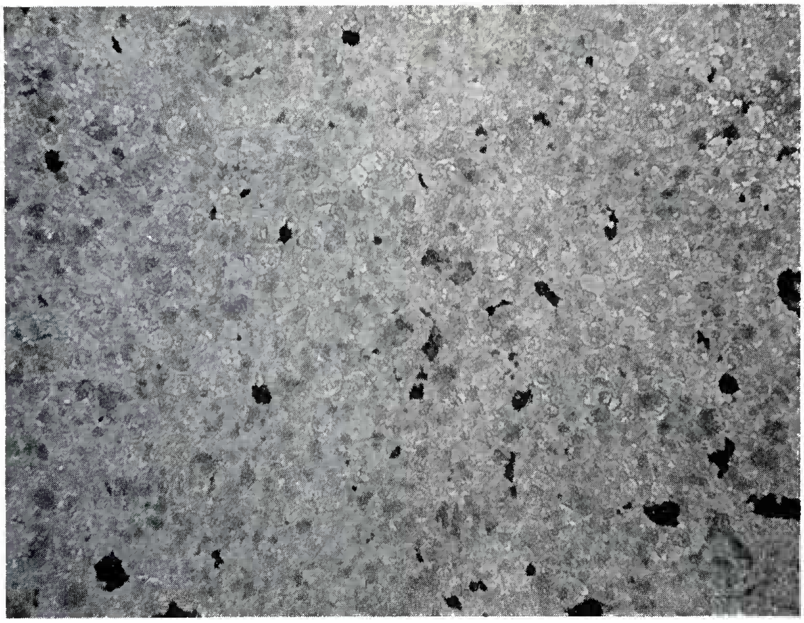


SEM No. 8050 1000X

(d)

Figure 12

Photomicrographs of Sintered Al 7075 Alloy. Coarse powder pressed at 40,000 psi. Samples taken from top of the billet. (a) 950 °F, 45 min; (b) 1100°F, 20 min; (c) 900°F, 45 min; (d) very fine substructure, precipitation, and microporosity inside the particles shown in (c).



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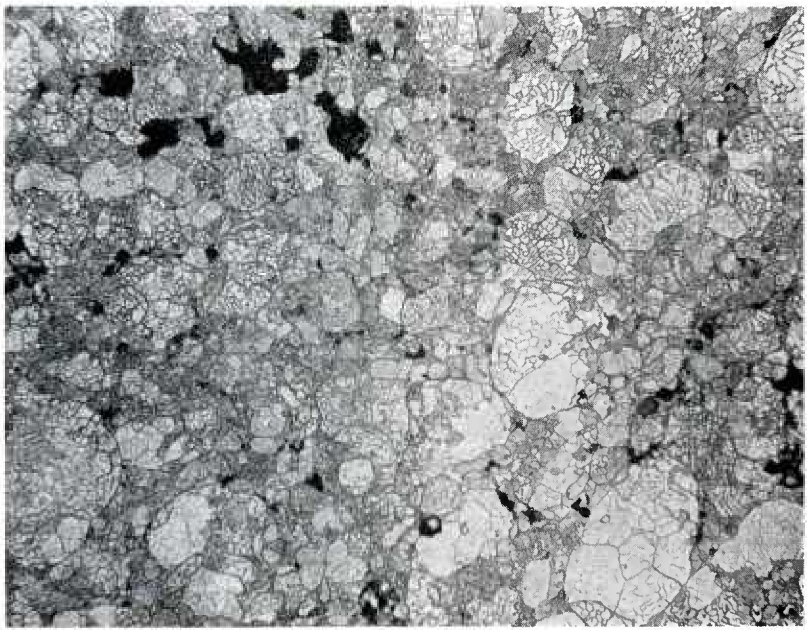
(a)



Neg. No. 42351 100X

(b)

Figure 13

As-Sintered Microstructure of P/M Al 7075 Alloy. 950°F, 2 hr in argon. (a) Fine, and (b) coarse.

forged P/M parts. The ends of cylindrical billets isostatically pressed at 40,000 psi were used as preforms. In all, 13 pieces were forged representing various combinations of powder size, sintering temperature (950 to 1050°F) and forging temperature (650 to 850°F). The deformation was 50% in height on all preforms. A few wrought preforms were also similarly forged for comparison.

In general, fine powder and lower sintering and forging temperatures led to less edge cracking. Therefore, forging temperatures of 650, 725, and 800°F were selected for the parametric study discussed in Section 3.4.4.

The density of the P/M forgings was 100 percent of the theoretical. Microstructures were also studied for various combinations of processing conditions. The samples forged 50% at 750°F (Figs. 14a and b) did not reveal any remnant effect of hot forging in the form of elongated grains. However, with 650°F forging temperature (Figs. 14c and d), the typical elongated appearance of grains can be clearly seen. The irregular-shaped areas are particles of much higher hardness, e.g., chromium, which had remained unreacted and undeformed at these temperatures. The microstructure of the forged wrought products shown in Figs. 14e and f is similar to that in Figs. 14c and d.

3.4.4 Parametric Forging Study

This section presents the results of the parametric study conducted according to the plan in Tables 7 and 8 along with procedure described in Section 3.3.3. From the preliminary sintering study of Section 3.4.2, two sintering temperatures, i.e., 950 and 1025°F, were selected. The sintered preforms were upset for three different reductions, i.e., 30, 50, and 70% in height as per statistical design of Table 8 in Section 3.2. Both coarse and fine powders were utilized and the forging temperatures investigated were 650, 725, and 800°F. The flat dies used were the same as those used for forging (upsetting) earlier in the preliminary tests. The locations of tensile and Charpy test specimens in the disks were as shown in Fig. 10.

Visual observation of the forged pancakes shows (Fig. 15) that the high deformation of 70% invariably led to severe cracking, whereas it was much less at lower reductions. The extent of deformation was the dominant factor and other process variables showed little systematic effect on the surface cracking in the forgings.

Tables 11, 12, and 13 present data on 0.2% offset yield strength, ultimate tensile strength, and tensile elongation, respectively. By simple comparison of these data with the minimum values required by the specifications, it is observed that there are several processing combinations which meet the minimum requirements, and they are shown in Table 14. Tables 11, 12, and 13 clearly indicate that none of the preforms obtained by isostatically pressing at 20 ksi met the minimum requirements, suggesting that a minimum initial consolidation is required to obtain the desired properties in the final product. This investigation showed that the

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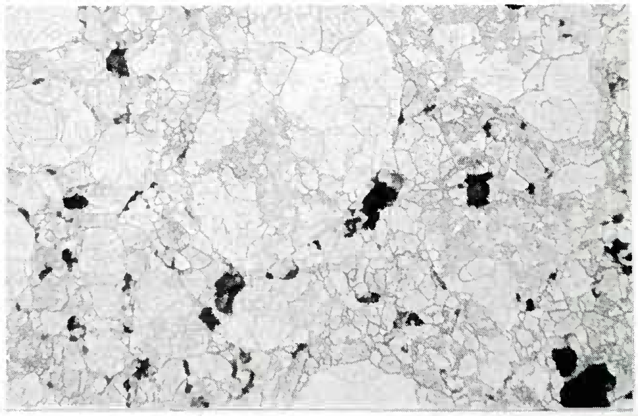
(a)



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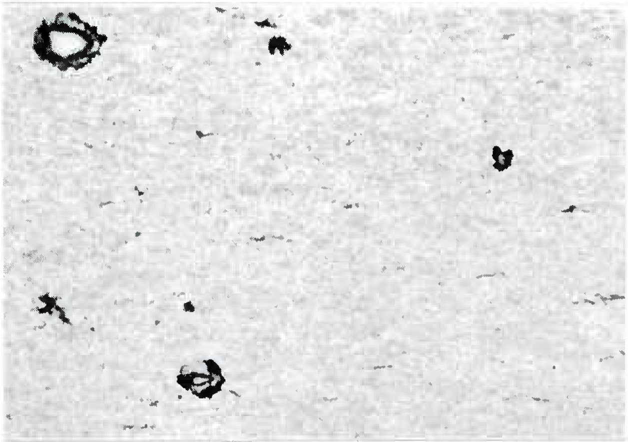

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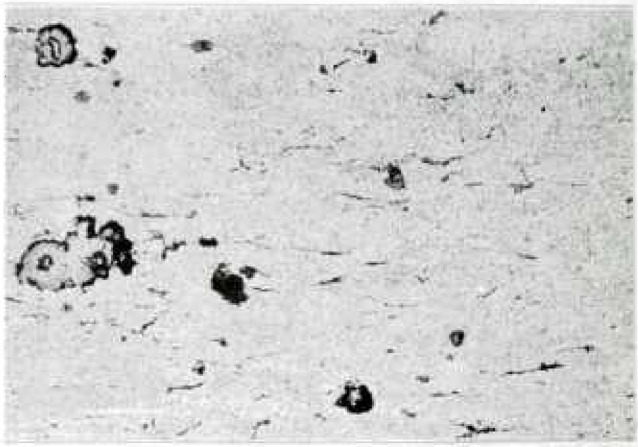

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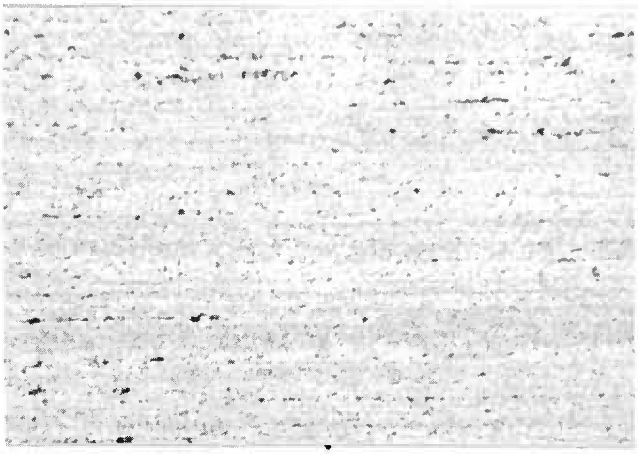
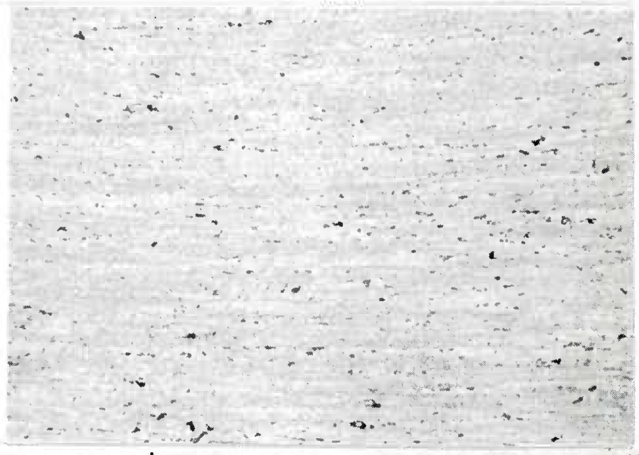
(d)



Neg. No. 42355 100X
(e)



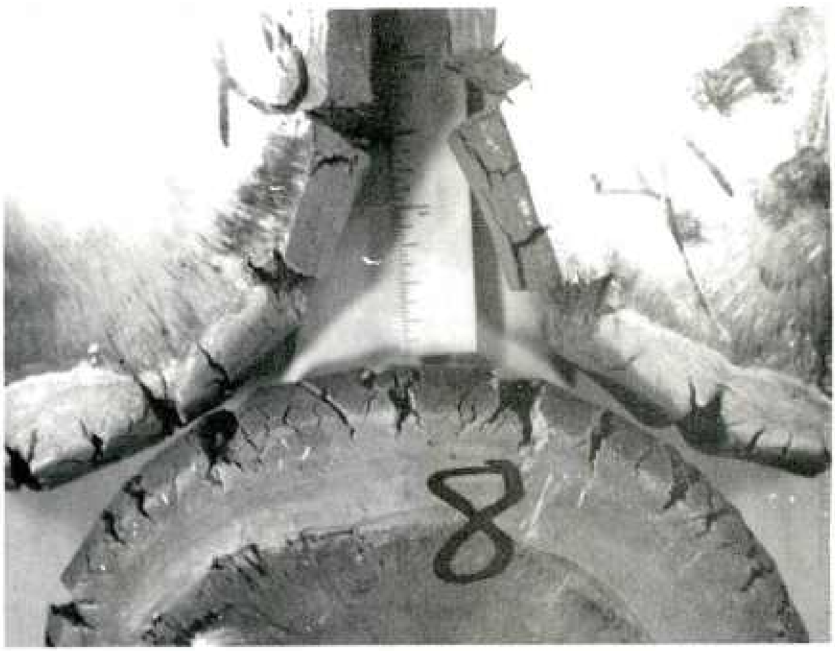
Neg. No. 42350 100X
(f)

Figure 14

Sintered and Forged Microstructures of P/M and Wrought Al 7075 Alloy Specimens. ST 1025°F, FT 750°F: (a) fine, (b) coarse; ST 950°F, FT 650°F: (c) fine, (d) coarse; wrought material: (e) FT 650°F, and (f) FT 850°F.

Neg. No. 42544

(a)



Neg. No. 42542

(b)

Figure 15

Cracking in Forged Pancakes. (a) Less cracking under 30 and 50% height reduction in upsetting, (b) more cracking under 70% reduction. (Numbers on samples refer to combination number in Table 8.)

Table 11

0.2 PERCENT YIELD STRENGTH (KSI) OF FORGINGS FROM PARAMETRIC STUDY OF PROCESS VARIABLES

Forging Def., %	Mesh/psi -40/20,000 Sinter Temp., °F 950	1025	Mesh/psi -40/40,000 Sinter Temp., °F 950	1025
30	(19)-/-	(10)-/-	(1)-/-	(22)-/-
	(31)-/-			
50			(3)63.4/64.0	(23)63.8/63.7
70	(21)63.6/65.6		(2)67.5/68.0	(24)65.9/65.7
	(32)63.2/60.8			
	Mesh/psi -100/20,000		Mesh/psi -100/40,000	
30	(4)-/-	(13)-/-	(16)67.0/66.4	(7)67.3/67.2
		(25)-54.1	(28)-/64.4	
50	(6)63.5/62.6	(14)62.2/-	(17)67.4/67.8	(9)67.0/67.4
		(27)63.6/-	(30)68.1/68.1	
70	(5)65.7/65.2	(15)64.9/64.7	(18)68.2/67.4	(8)69.7/69.2
			(29)68.7/69.9	

Specification Minimum = 61,000 psi

Notes: 1. The numbers in parentheses indicate the combination number of statistical model (Table 8).
2. The values are for two specimens tested.
3. Solution treated and aged = 900°F (2 hr), water quench, age 250°F (24 hr),
4. Gage diameter 0.25 in.

Table 12

ULTIMATE TENSILE STRENGTH (KSI) OF FORGINGS FROM PARAMETRIC STUDY OF PROCESS VARIABLES

Forging Def., %	Mesh/psi -40/20,000 Sinter Temp., °F 950	1025	This Block Avg.	Mesh/psi -40/40,000 Sinter Temp., °F 950	1025	This Block Avg.	All Def. Avg.
30	(19)44.9/47.8 (31)39.2/43.2	(10)51/7/51.5	46.3	(1)22.8/25.3	(22)49.5/48.1	36.4	42.3
50				(3)66.7/64.9	(23)70.5/68.2	67.6	67.6
70	(21)69.1/70.2 (32)65.5/65.4		67.6	(2)75.5/76.4	(24)73.8/73.6	74.8	71.2
	55.7 Avg.	55.3 Avg.		55.3 Avg.	64.0 Avg.		
	55.6 Avg.			59.6 Avg.			
	Mesh/psi -100/20,000			Mesh/psi -100/40,000			
30	(4)30.3/48.3	(13)56.2/60.8 (25)55.1/54.4	50.9	(16)69.4/70.6 (28)65.3/53.3	(7)76.0/76.2	63.5	59.7
50	(6)63.1/64.7	(14)60.1/63.0 (27)43.4/63.7	59.6	(17)69.8/71.4 (30)74.4/73.6	(9)74.8/74.2	73.0	66.3
70	(5)70.3/68.9	(15)70.8/71.3	70.3	(18)77.0/77.2 (29)78.8/77.2	(8)77.4/78.4	77.7	74.7
	57.6 Avg.	59.9 Avg.		71.5 Avg.	76.2 Avg.		
	59.0 Avg.			73.1 Avg.			

Specification Minimum = 71,000 psi.

Notes: 1. The numbers in parentheses indicate the combination number of statistical model (Table 8).

2. The values are for two specimens tested.

3. Solution treated and aged = 900°F (2 hr), water quench, age 250°F (24 hr), air cooled.

4. Gage diameter 0.25 in.

Table 13

TENSILE ELONGATION (%) OF FORGINGS FROM PARAMETRIC STUDY OF PROCESS VARIABLES

Forging Def., %	Mesh/psi -40/20,000 Sinter Temp., °F 950	Mesh/psi -40/20,000 Sinter Temp., °F 1025	Mesh/psi -40/40,000 Sinter Temp., °F 950	Mesh/psi -40/40,000 Sinter Temp., °F 1025
30	(19)0/0	(10)0/0	(1)0/0	(22)0/0
	(31)0/0			
50			(3)1.0/2.0	(23)2.0/2.0
70	(21)2.0/2.0		(2)6.0/4.3	(24)4.0/5.0
	(32)3.0/3.0			
	Mesh/psi -100/20,000		Mesh/psi -100/40,000	
30	(4)0/0	(13)0/0	(16)1.0/1.0	(7)6.0/6.0
		(25)0/1.0	(28)0/1.0	
50	(6)1.0/1.0	(14)01.0	(17)1.0/2.0	(9)5.0/5.0
		(27)0/1.0	(30)2.0/2.0	
70	(5)1.0/1.0	(15)3.0/2.0	(18)5.0/6.0	(8)7.0/6.0
			(29)6.0/5.0	

Specification Minimum = 3.0%

Notes: 1. The numbers in parentheses indicate the combination number of statistical model (Table 8).

2. The values are for two specimens tested.

3. Solution treated and aged = 900°F (2 hr), water quench, age 250°F (24 hr), air cooled.

4. Gage diameter 0.25 in.

Table 14

PROCESSING COMBINATIONS FOR AL 7075 P/M ALLOY FORGINGS WITH TENSILE PROPERTIES ABOVE TARGET VALUES

Processing Combination[a]	Mesh Size	Isostatic Pressing, ksi	Deformation During Forging, %	Temperature, °F		Tensile Properties[b]		
				Sintering	Forging	.2% Y.S., ksi	UTS, ksi	% Elong.
2	-40	40	70	950	725	67.7	75.9	5.1
7	-100	40	30	1025	650	67.2	76.1	6.0
8	-100	40	70	1025	725	69.4	77.9	6.5
9	-100	40	50	1025	800	67.2	74.5	5.0
18	-100	40	70	950	800	67.8	77.1	5.5
24	-40	40	70	1025	800	65.8	73.7	4.5
29	-100	40	70	950	650	69.3	78.0	5.5

[a]Combination numbers are given in Table 8.

[b]Average values of two specimens. Specification minimum: Elong., 3.0%; 0.2% Offset Y.S., 61.0 ksi; UTS, 71.0 ksi.

preform density should exceed 90% of theoretical density to meet and exceed the wrought product tensile properties. Also, the coarse powder required 70% deformation during forging irrespective of sintering or forging temperatures, while the fine powder sintered at 1025°F met the specifications at all the deformations and forging temperatures under consideration. Lower sintering temperature of 950°F for fine powder required 70% deformation regardless of forging temperature.

From the above discussion and the fact that the amount of deformation in the actual part varies from one section to another, it is apparent that the processing combinations 7, 8, and 9 are the best suited for further evaluation. Thus, the optimum processing conditions are those involving usage of -100 mesh powder, 40,000 psi pressure for cold isostatic pressing, and 1025°F sintering temperature.

In addition to the tensile properties, hardness and Charpy impact values were also obtained on the specimens forged in the parametric study. The hardness showed trends similar to the tensile properties in that the hardness increased with the degree of deformation and with the sintering temperature. For all of the conditions studied, the hardness varied from a low of R_B 69 to a high of R_B 90. Significantly, with the -100 mesh powder and 40,000 psi isostatic pressing pressure, the hardness was above R_B 80 with even the low forging deformation of 30%, whereas with other processing conditions the hardness was in many cases less than 80.

Charpy V-notch impact tests were conducted at room temperature using full-size specimens on over 50 different specimens. The impact value was in the majority of cases 1 ft-lb and, in a few cases 2 ft-lb. These somewhat lower values may be related to the usually high oxygen level in the aluminum alloy powder.

3.4.5 Replicate Tests and Preliminary Process Specification

The results of the process parameter study (Section 3.4.4) indicated the promising processing conditions. To check performance reproducibility and also to select the optimum forging temperature, replicate tests were carried out using the promising conditions. The specific conditions used for these tests were fine (-100 mesh) powder, 40 ksi isostatic pressing pressure, 1025°F sintering temperature, and 50% deformation with two samples forged at each of the forging temperatures of 650, 725, and 800°F. The preform size was 3 in. in diameter and 1 1/2 in. in thickness, and the six preforms required for these tests were machined from two isostatically pressed compacts, each measuring 3 1/2 in. in diameter and 7 in. in height.

The room temperature tensile properties for the specimens machined from round pancakes obtained by forging at three different temperatures are shown in Table 15.

The sample identification numbers in the tables consist of one numeral which is the identification of the isostatically pressed preform from which

Table 15

TENSILE PROPERTIES OF AL 7075 P/M ALLOY FORGINGS

Sample Identification	0.2% Offset Y.S., ksi	UTS, ksi	Elong., %	R.A., %
	Forging Temperature, 650°F			
1T-B	72.5	76.4	3.0	4.0
1T-C	72.9	77.8	4.0	4.0
1T-D	73.1	77.2	3.0	3.2
2T-B	73.4	78.4	5.0	6.1
2T-C	73.5	77.4	4.0	5.5
2T-D	73.6	77.2	3.0	4.0
Average	73.2	77.4	3.7	4.5
	Forging Temperature, 725°F			
1M-B	71.1	76.0	4.0	3.4
1M-C	72.1	77.6	5.0	5.5
1M-D	71.0	76.2	4.0	4.0
2M-B	71.5	76.8	4.0	4.7
2M-C	71.8	76.2	3.0	3.4
2M-D	71.5	76.0	4.0	4.7
Average	71.5	76.4	4.0	4.3
	Forging Temperature, 800°F			
1B-B	70.6	75.8	4.0	3.2
1B-C	70.7	76.0	4.0	3.2
1B-D	69.9	75.0	3.0	3.0
2B-B	71.6	76.2	4.0	3.2
2B-C	71.4	76.6	5.0	3.4
2B-D	70.7	75.4	3.0	4.0
Average	70.8	75.8	3.8	3.3

Notes: 1. Mesh size, -100 mesh; isostatic compaction, 40 ksi; sintering temperature, 1025°F; deformation, 50%.

2. T - top, M - middle, B - bottom; location in compacted billets from which the forging preforms were taken.

3. Test specimens were obtained from pancake forgings and were tested in STA condition at room temperature.

the sample was cut and two letters. The first letter is T, M, or B, which stands for top, middle, or bottom, respectively, and shows the location of the sample within the isostatically pressed billet since three samples were cut from each billet. The second letter--B, C, or D--merely distinguishes the three different tensile test specimens cut from each forged pancake. Thus, at each forging temperature there were essentially six identical tensile test specimens, and the uniformity of the properties achieved within these six samples at each of the three forging temperatures is quite remarkable. These tests conclusively show the reproducibility of the results obtained by using optimum processing conditions and further confirm the selection of the conditions as optimum.

It can be observed that there is no appreciable difference in the final tensile properties and the properties are independent of both the location of pieces taken from the compact cylinder and the forging temperatures applied for 50% deformation in height. From a practical viewpoint, usage of higher forging temperature is therefore suggested to minimize the forging load.

The entire work of Phase I, Task A, thus leads to the following preliminary process specification for creep forging of P/M preforms for 7075 aluminum alloy:

1. Elemental blended powder, size -100 mesh

2. Cold isostatic compaction at 40,000 psi

3. Sinter at 1025°F in N_2 for 2 hr

4. Forge at or near isothermal conditions in the range of 750-800°F with at least 30% reduction.

4. PHASE I, TASK B - T-SHAPE FORGING

The work done in Phase I, Task A, was conducted primarily with cylindrical preforms. In actual practice of making a complex forging, the metal flow is considerably more nonuniform than in the case of upsetting of simple cylindrical pieces where there is perfect circular symmetry. Therefore, the purpose pf Phase I, Task B, was to test and evaluate the forgings made with a special die incorporating elements of forward and backward extrusion along with longitudinal flow and, if necessary, to modify preliminary process specifications. The detailed scheme is shown in Fig. 16.

4.1 Experimental Details

4.1.1 Design and Fabrication of Forging Dies for T-Shape

The sample for evaluation and the corresponding preform shape selected is shown in Fig. 17. The preform selected had approximately the same width as the forging so that there would be little transverse deformation during forging. The deformation was primarily of extrusion type in the longitudinal direction as well as in the vertical direction to form the short legs of the "T" by backward and forward extrusion. Keeping the above-mentioned factors in mind, the dies for the T-shape forgings were designed and the die assembly is shown in Fig. 18. Since only a few pieces were to be forged from this die, it was made from a common die steel--A. Finkl and Sons Grade FX heat treated to R_C 38. These dies were mounted in a standard die set and assembled in the 1000-ton press.

4.1.2 Isostatic Press Tooling and Making of Preforms

The design of isostatic press tooling was similar to that of cylindrical billets as described in Section 3.3.1 The tooling for trapezoidal billet is shown in Figs. 19a and b. For comparison, both cylindrical as well as trapezoidal billets are shown in Fig. 20. The trapezoidal billets were prepared by cold isostatic pressing at 40,000 psi and subsequent sintering at 1050°F for 2 hr. After discarding the top and bottom ends, each billet was cut into three equal pieces to be used as preforms for forging. The location of the preform in the sintered billet was identified by a letter in the forging number, viz., T for top, M for middle, and B for bottom.

4.1.3 Forging of "T" Shapes

The preforms for forging were heated in an electric furnace in air. The dies were assembled in IITRI's 1000-ton press and heated to the requisite temperature as checked by surface pyrometer directly on the die cavity surfaces; then the die surfaces were coated with a graphite grease-type of forging lubricant, the preform was transferred to the dies, and it was forged.

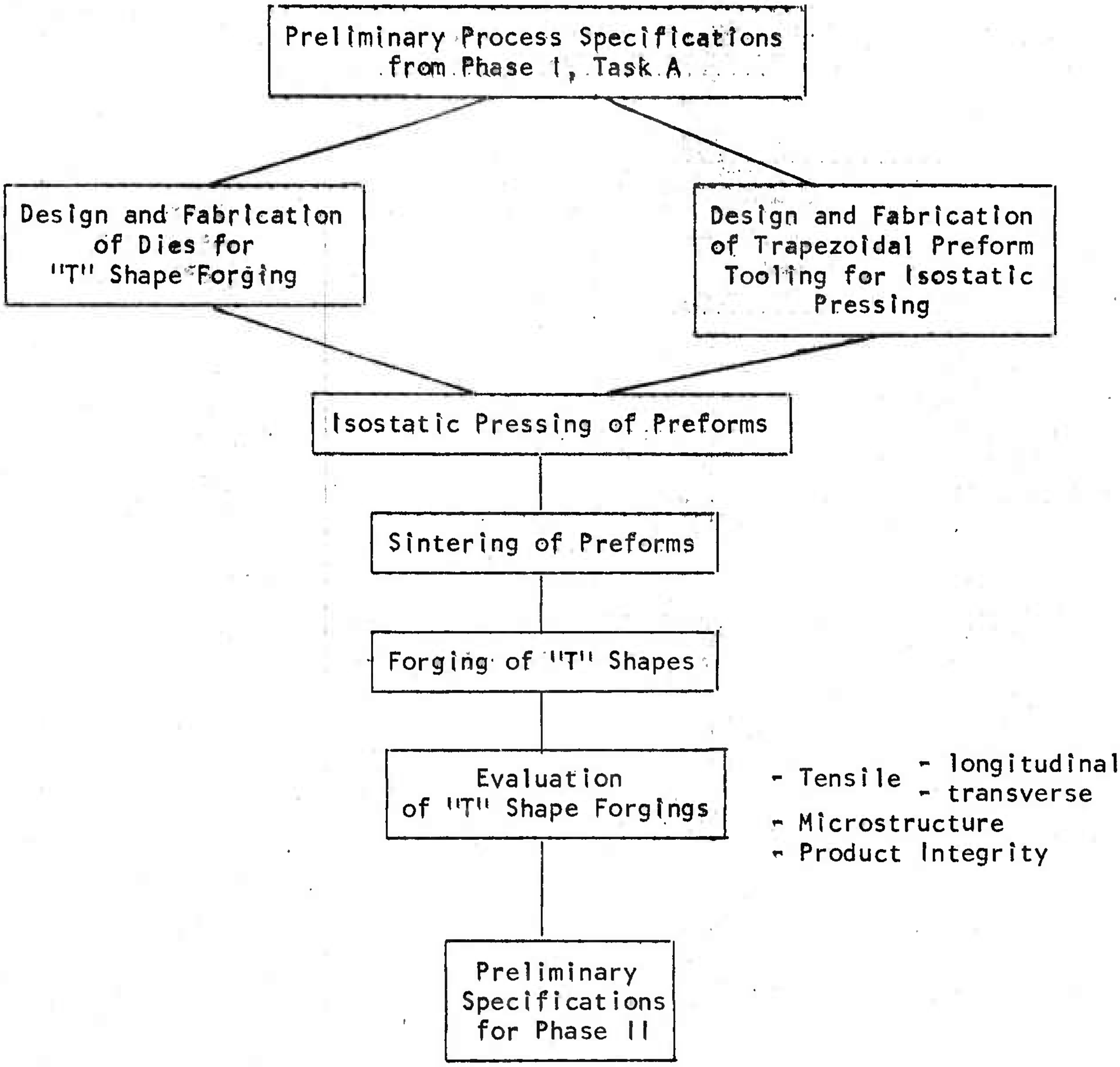
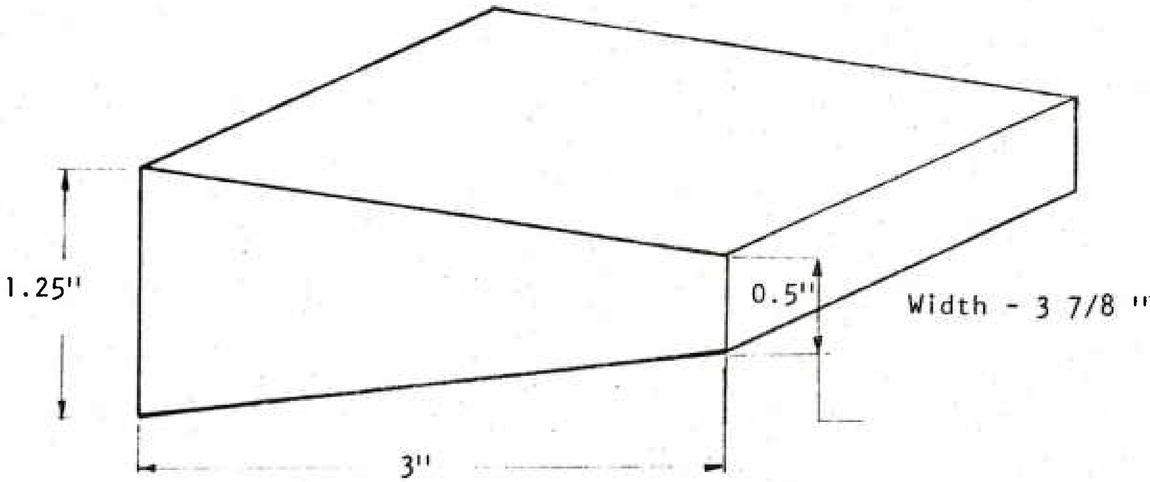
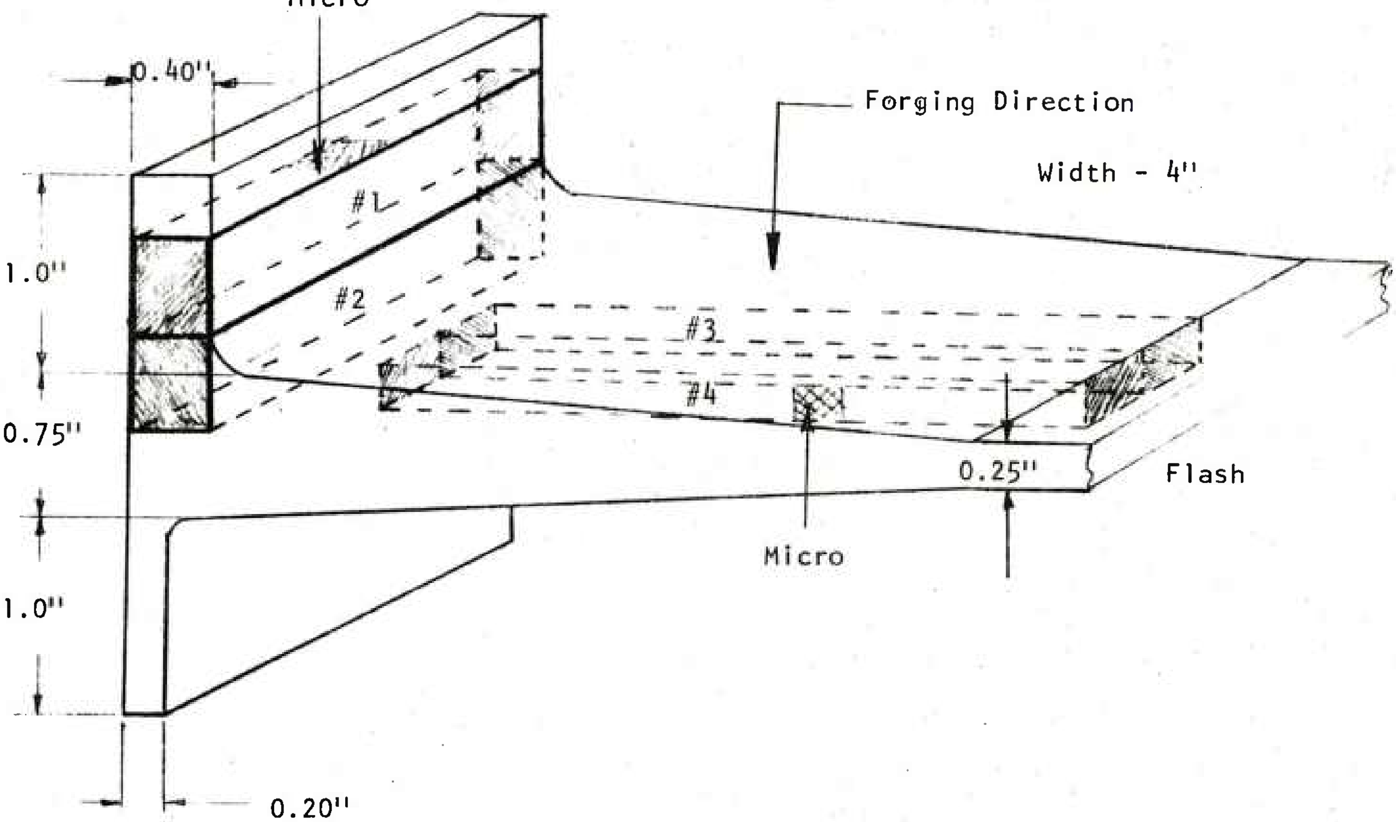


Figure 16

Phase I, Task B - T-Shape Forging and Its Evaluation



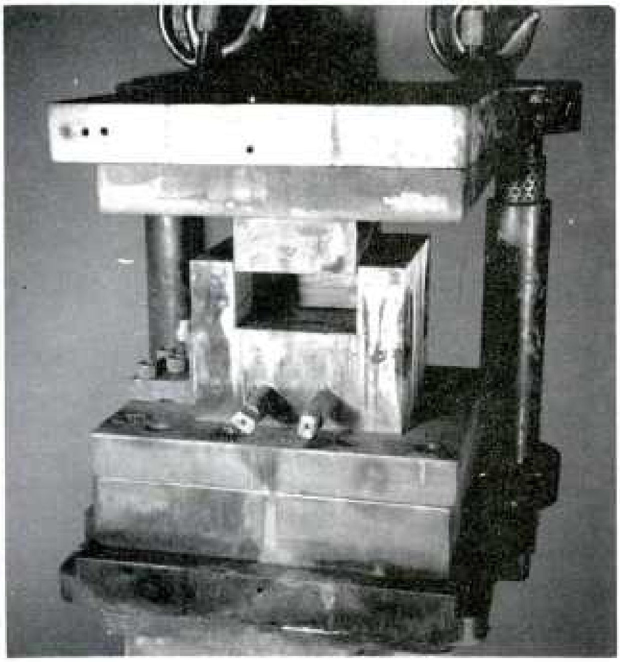
(a) Preform Shape



(b) Creep Forged Evaluation Sample

Figure 17

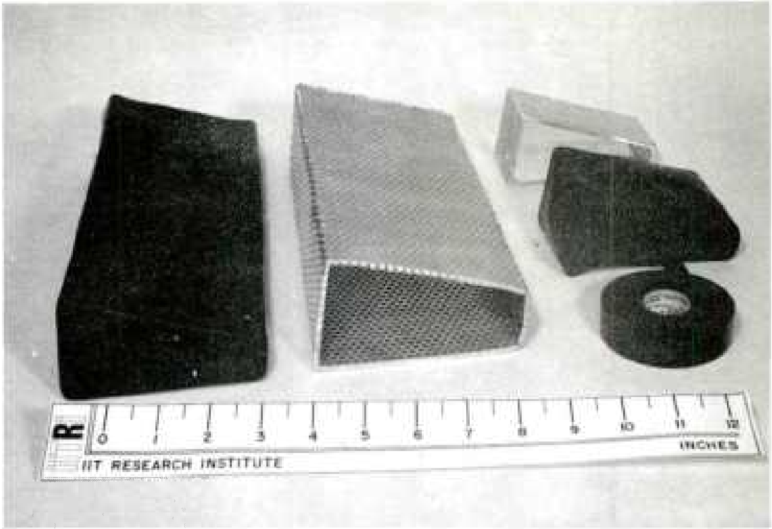
Schematic of T-Shape Forging for Phase I-B and the Preform (#3 and 4 are longitudinal and #1 and 2 are transverse tensile samples. Locations for micrographs are also shown.)



Neg. No. 43351 Approx. 1/6 scale

Figure 18

Die Assembly for Forging of T Shape. (Long arm of T forged in horizontal plane. Short arm forged at the rear of the die cavity.)



Neg. No. 43353

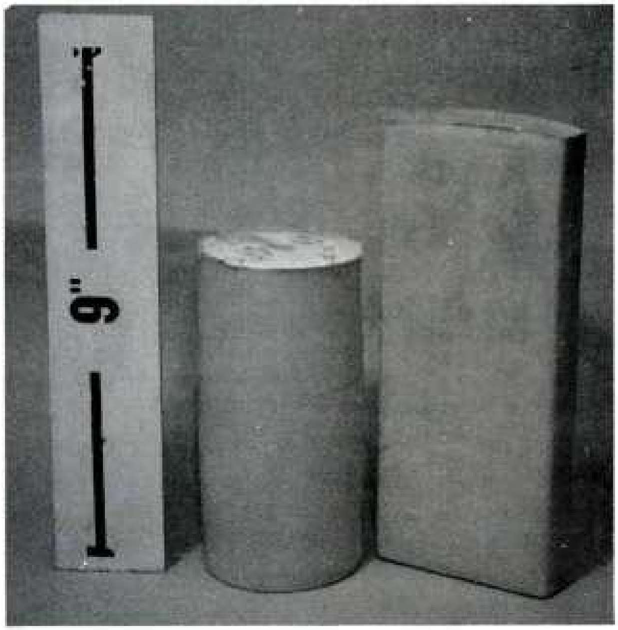
(a) Tooling for trapezoidal billets

Neg. No. 42759

(b) Bags ready for pressing

Figure 19

Tooling for Isostatic Pressing of Trapezoidal Billets



Neg. No. 42760

Figure 20

Comparison of Isostatically Pressed
Cylindrical and Trapezoidal Billets

Note that during forging the preform was on its side with the long arm of the "T" formed in the horizontal plane and the short arms formed by backward and forward extrusion in the vertical direction towards the back of the die system. The press was moved in a slow manual mode with the approximate speed estimated to be of the order of 3 ipm or less.

In the first forging test, the preform had excessive material and the stop blocks were not set precisely. This caused excessive thinning of the web and extrusion of thin flash between die clearances which made removal of the forging difficult. In all the subsequent trials, the preforms were machined to a width of 3 3/4 in. and a weight of 1.4 to 1.5 lb. With these optimized dimensions, no difficulty was encountered in the forging tests. Two preforms were overheated because of a furnace malfunction but did not appear to be damaged and were used in the tests. These preforms were Nos. 5T and 7T. Apart from the initial test on preform No. 6B, all the remaining forgings were made with a work material and die temperature of 750°F (Table 16). Figure 21 shows some of the forgings made.

4.2 Results and Discussion

4.2.1 Evaluation of Mechanical Properties

As shown in Fig. 17, samples 1 and 2 were cut for the transverse properties, and samples 3 and 4 for longitudinal properties. There was a significant amount of extrusion flow in the direction of the sample length for the longitudinal samples, whereas the metal flow was transverse to the length of samples 1 and 2. Because the width of the trapezoidal preforms was very similar to the width of the T-shaped forging, there was practically no metal flow along the length of the samples 1 and 2. Creep forging was conducted at 750°F die and workpiece temperatures, and tensile specimens were taken from six T-shaped forgings. The average values are shown in Table 17 along with the ranges of the individual values. Averages are given for six tests except for location 1 where three of the specimens had forging defects and had consequently poorer properties. The defective specimens were not included in the averages given for location 1.

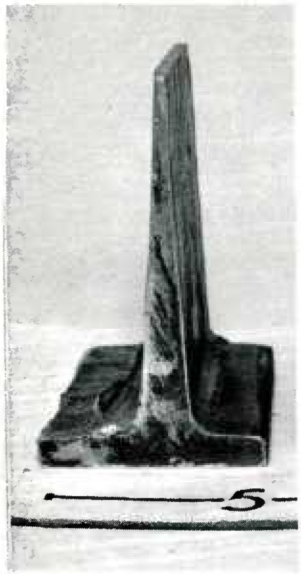
The results of the tests were truly remarkable in that the tensile properties in the longitudinal direction are, in many cases, in excess of the minimum specified properties for the wrought materials in the direction of the grain. Indeed, in view of the high yield stress of the samples, it is conceivable that with somewhat different heat treatment, all the specimens would have exceeded the minimum specified elongation of 7% set by the Federal Specification QQ-A-367H (see Section 2.6). The transverse specimens 1 and 2 exceed the specified properties for the transverse direction in most cases, and the maximum elongation is as high as 5%. Considering that the Federal property specification was for wrought material, this combination of high strength and satisfactory elongation formed in the P/M processed samples is quite remarkable--this, in spite of the fact that in the lateral direction, the trapezoidal

Table 16

FORGING DATA FOR MAKING T-SHAPES

Forging No.	Preform Weight, lb	Web Thickness after Forging, (A), in.	Remarks
6B	1.74	0.190	Initial test
4B	1.49	0.325	
4T	1.43	0.260	
5B	1.46	0.315	
5T	1.41	0.253	Forging ground to allow reentry into die cavity for a restrike.
7B	1.41	0.260	
7T	1.45	0.316	

Notes:
1. Lubricant FEL-PRO graphite base spray applied to dies.
2. Forging load 125-140 tons except for inadvertent overshoot to 320 tons for forging 4T.
3. Die and workpiece temperature was 750°F for all tests except for 6B when workpiece was at 800°F and dies at 350°F.
4. Press speed approximately 3 ipm at the start of forging operation.



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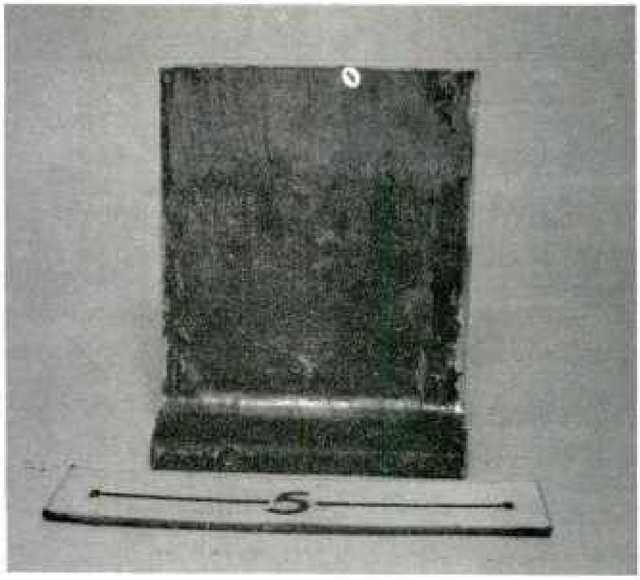


Neg. No. 42992

(a,b) Two Views of the First T-Shaped Forging 6B (after trimming)

Neg. No. 43002

(c) Two T-Shaped Forgings (as-forged, without any trimming or cleaning)

Figure 21

Examples of T-Shaped Forgings

Table 17

TENSILE PROPERTIES OF SPECIMENS FROM T-SHAPED AL 7075 P/M ALLOY FORGINGS

Specimen No.	0.2% Offset Y.S., ksi	UTS, ksi	Elong., %	R.A., %
4B-1[a]	67.6	70.5	2.0	2.4
4T-1	--	--	-	-
5T-1	67.2	72.2	2.0	3.9
5B-1	67.0	69.0	1.0	1.6
7B-1[b]	--	--	-	-
7T-1[b]	--	--	-	-
Avg	$67.2^{+0.4}_{-0.2}$	$70.5^{+1.6}_{-1.6}$	$1.7^{+0.3}_{-0.7}$	$2.6^{+1.3}_{-1.0}$
4B-2[a]	67.6	73.8	3.0	4.0
4T-2	68.5	75.4	5.0	6.8
5T-2	68.4	73.8	2.0	6.8
5B-2	68.2	71.6	2.0	3.1
7B-2	68.3	73.0	2.0	4.7
7T-2	67.1	70.2	2.0	2.4
Avg	$68.0^{+0.5}_{-0.9}$	$72.9^{+2.4}_{-2.8}$	$2.7^{+2.3}_{-0.7}$	$4.6^{+2.2}_{-2.2}$
4B-3[a]	69.7	77.8	7.0	10.1
4T-3	71.5	78.8	6.0	10.8
5T-3	69.7	79.0	8.0	11.6
5B-3	72.4	79.0	6.0	10.1
7B-3	72.5	78.4	7.0	9.4
7T-3	71.4	81.2	10.0	15.2
Avg	$71.2^{+1.3}_{-1.5}$	$79.0^{+2.1}_{-1.2}$	$7.3^{+2.7}_{-1.3}$	$11.2^{+4.0}_{-1.8}$
4B-4[a]	70.6	78.0	7.0	10.1
4T-4	70.8	78.4	6.0	10.1
5T-4	69.7	78.2	7.0	11.6
5B-4	72.4	78.8	5.0	9.4
7B-4	71.3	77.8	6.0	10.1
7T-4	71.6	80.4	8.0	13.0
Avg	$71.1^{+1.3}_{-1.4}$	$78.6^{+1.8}_{-0.8}$	$6.5^{+1.5}_{-1.5}$	$10.7^{+2.3}_{-1.3}$

[a]-1 and -2 are transverse specimens; -3 and -4 are longitudinal specimens.

[b]Failure before yielding.

Notes: 1. Powder mesh size, -100 mesh; isostatic compaction, 40 ksi; sintering temperature, 1025°F, forging deformation, 50-70%; isothermal forging temperature, 750°F. 2. The tensile test specimens were in STA condition and were tested at room temperature.

preforms were made so wide as to have practically no flow in that direction. Even in conventional forging, the lateral direction is subjected to some metal flow.

The data obtained thus far clearly indicated that, if the cam were made with the optimum processing conditions selected in this work, it would have excellent properties. The properties should exceed the specification used for this program based on the specifications for the wrought material.

4.2.2 <u>Microstructure and Internal Integrity</u>

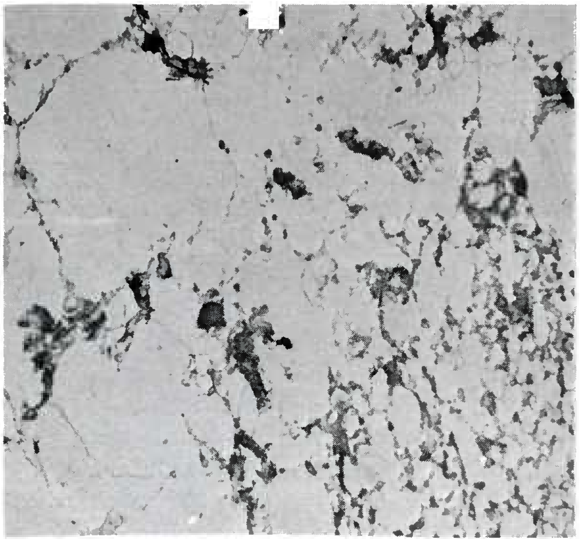
In view of the high density of the isostatically pressed and sintered preforms and the significant amount of mechanical work that these preforms are subjected to in the forging operation, it was expected that the forgings would show no porosity. This was confirmed by observation of microstructural specimens and by radiography of the first forging. No internal defects were indicated by the radiograph, and the remainder of the evaluation, therefore, was directed towards the microstructural and morphological features. The locations of micrographs in the forging are indicated in Fig. 17.

Figure 22 shows micrographs of tensile test specimens in the longitudinal and transverse directions. The directionality of the structures is quite noticeable in specimen 7T-3 (Fig. 22b) and 5B-4 (Fig. 22c) with the samples in the longitudinal direction. In contrast, specimen 7T-1 in Fig. 22a and specimens 4T-1 and 4T-2 in Fig. 23 show no such directionality. Thus, to a certain extent, the same directional effect that one finds in wrought products is seen in these P/M forgings and may account for the differences in ductility observed in the longitudinal and transverse specimens, with lower ductility in the latter.

Note the rounded structure in Fig. 22c, specimen 5B-4, and similar structures in Fig. 23. Observation of similar structures through SEM is shown in Fig. 24, along with an X-ray spectra of the whole surface as well as of the rounded phases. The X-ray spectra suggest that these spherical particles are chromium-rich and, as discussed earlier, remain in the matrix because of the poor diffusibility of the chromium into the aluminum matrix at the low processing temperatures. The fact that the particle does not show elongated shape in Fig. 22 (specimen 5B-4) also indicates that, because of the hardness of the particle, it does not deform with the matrix.

In many specimens, such as those shown in Fig. 25, some cracking was noticed in the hard chromium-rich particles. However, since such cracking appeared in the particles in both the longitudinal and transverse sections, it is probably not related to the relatively low ductility in the transverse specimens.

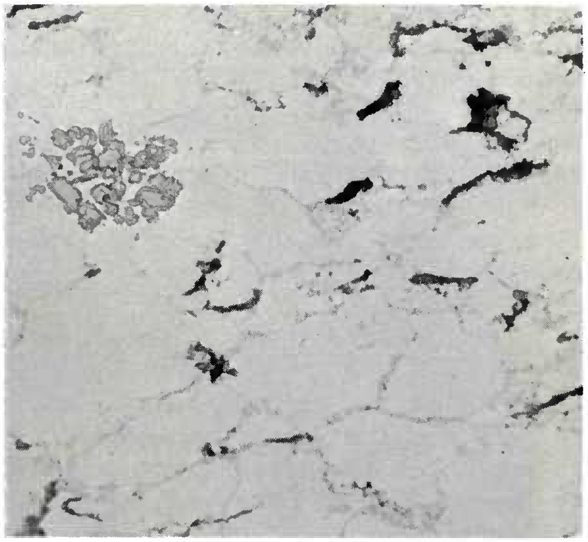
The differences in ductility in different samples do not appear to be caused by grain size or its variation either. For example, in Fig. 23



Neg. No. 42334 200X

(a)

Metal flow normal to photograph



Neg. No. 42335 200X

(b)

← Metal flow →

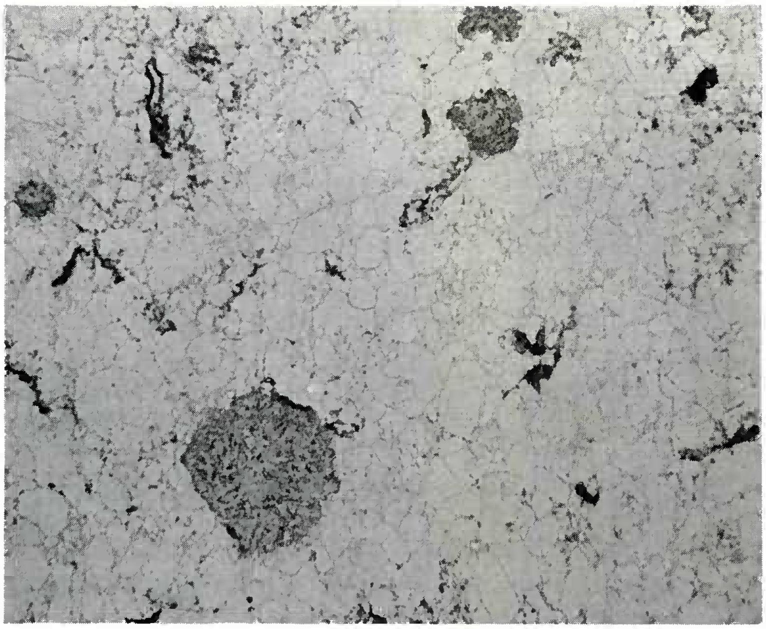
Neg. No. 42336 200X

(c)

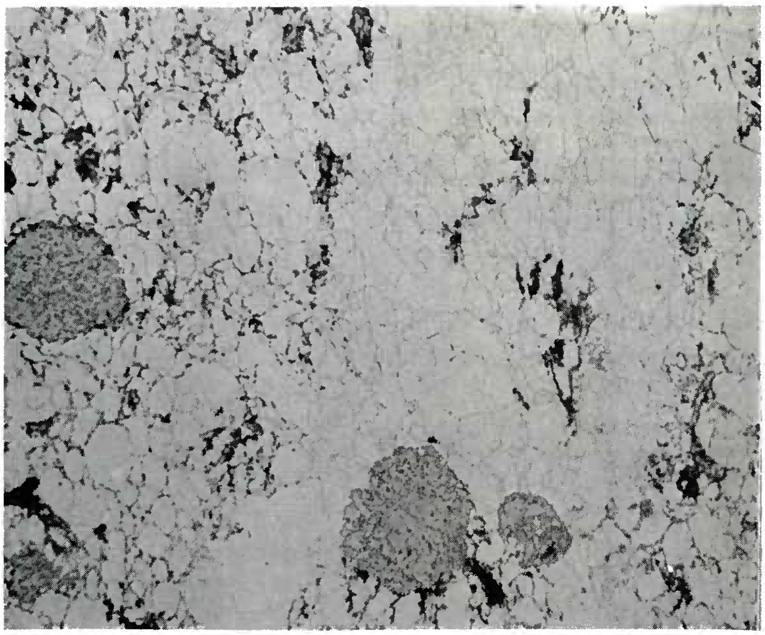
← Metal flow →

Figure 22

Micrographs of T-Shaped Forgings in STA Condition (Note metal flow directionality in the longitudinal samples.) (a) Transverse specimen 7T-1, (b) longitudinal specimen 7T-3, (c) longitudinal specimen 5B-4.



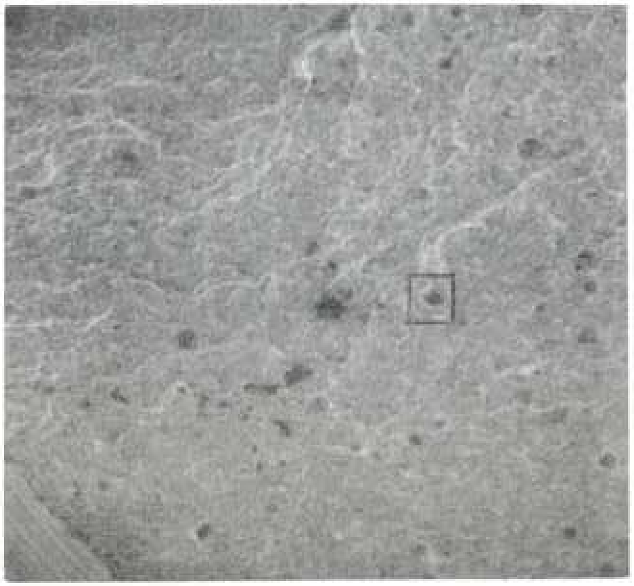
Neg. No. 42333 200X



Neg. No. 42337 200X

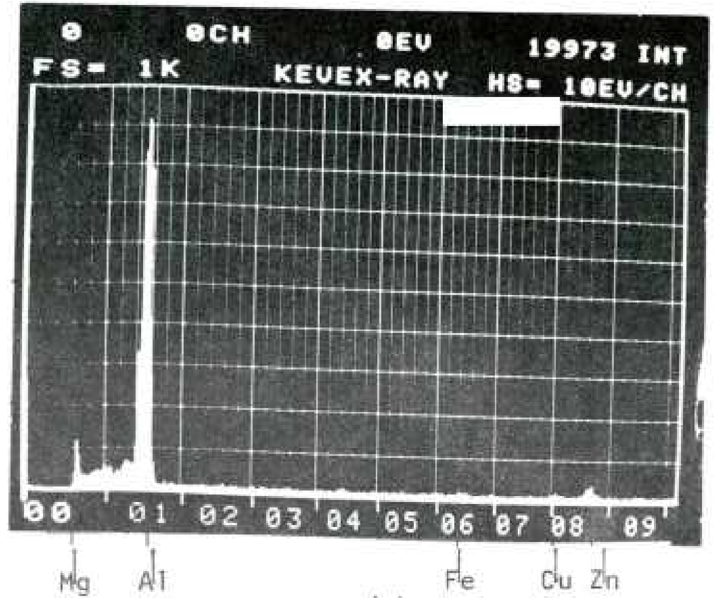
Figure 23

Photomicrographs of Two Transverse Samples (4T-1 and 4T-2) from a T-Shaped Forging. Metal flow normal to photograph.

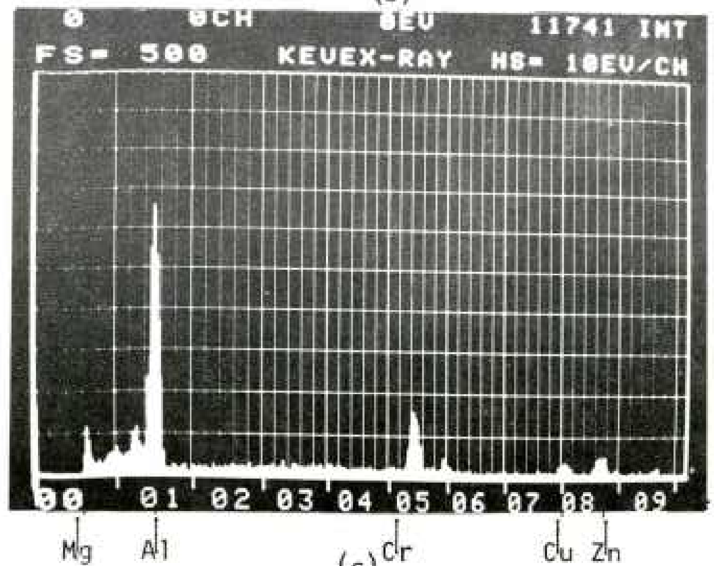


SEM No. 9248 20X

(a)



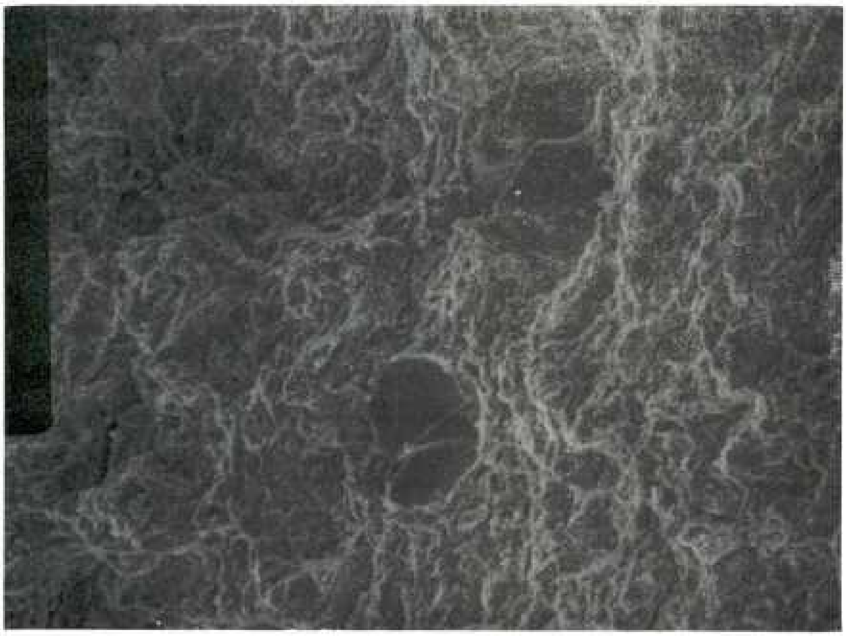
(b)



(c)

Figure 24

SEM and X-Ray Spectra of Samples from T-Shaped Forgings. (a) SEM of fractured surface of transverse specimen (4T-1); (b) X-ray scan of the whole matrix of same specimen (c) X-ray scan of the particle shown in (a).



200X

(a)

SEM No. 9252

200X

(b)

Figure 25

Appearance of Cracks in Hard Chromium-Rich Particles.
(a) SEM of fractured surface of transverse specimen 4T-2;
(b) SEM of fractured surface of longitudinal specimen 5B-4.

both specimens 4T-1 and 4T-2 have similar grain size, but specimen 4T-2 has a reasonable ductility of 5% whereas specimen 4T-1 failed immediately on loading because of a forging defect. Generally, the finer grain size is associated with better elongation but, in the samples tested in this program, the highest tensile elongation of 10% was observed in specimen 7T-3 which, as can be seen in Fig. 22, shows fairly large grains. It appears that the predominant factor affecting the elongation was the orientation of the tensile specimen with respect to the direction of metal movement. Understandably, if and when any forging defects appear, they adversely affect the ductility.

4.3 Preliminary Process Specification

The following process specifications were drawn up for components to be made by isothermal creep forging of Al 7075 P/M alloy preforms. They pertain to elemental blended powders wherein the preforms are made by cold isostatic pressing, sintered, and then subjected to isothermal forging operation at slow speeds.

Powder size: -100 mesh

Isostatic compacting pressure: 40,000 psi

Sintering temperature: 1025°F for 2 hr

Sintering medium: Nitrogen

Isothermal forging temperature: 750°F

Deformation: minimum 30%

Press speed: approximately 5 ipm or lower

Solution treat: 900°F-2 hr, water quench, age 24 hr at 250°F

The process specification is prepared with the properties in the wrought product specification as the targets. They are 64 ksi yield stress, 75 ksi ultimate strength, and 7% elongation for the longitudinal direction, and 61 ksi yield stress, 71 ksi ultimate strength, and 3% elongation in the transverse direction. These properties should be met by specimens tested in the longitudinal direction, that is, with the gauge length in the direction of the predominant metal deformation. In the transverse direction, somewhat lower ductility may be encountered depending on the degree of deformation imposed on the preform in that direction.

5. PHASE II - PROCESS OPTIMIZATION FOR PRODUCTION RUN OF THE CAM

5.1 General Approach

In conventional forging, much of the final dimensional detail is obtained by forging so that the preform shape is considerably different from the dimensions required on the forged component. In conventional P/M processing, the dimensions of the die pressed compact are very close to the required final dimensions. In this program the preform would be closer to a preform for forging. However, since the P/M preform is to be then forged, the limitations posed by the low ductility of a P/M preform had to be taken into account. The problem is further compounded by the relatively large size and complexity of the cam in relation to the components normally produced by P/M processing.

The first-phase work showed that a minimum of 30% height reduction is necessary during forging to obtain satisfactory tensile properties. But it is not clear whether a pressed and sintered preform, which normally has a low ductility, is capable of withstanding such high deformation without extensive cracking. Furthermore, it was decided to use isostatic pressing to prepare the preform because of the overall size and complexity of the component. The problem of being able to remove the pressed preform from the bag poses some more limitations on the geometry of the preform that can be made.

In view of the factors discussed above, it was decided to follow two different approaches for the Phase II work. The first approach involved two different forging operations in which a relatively simple preform geometry requiring a simple bag configuration was used. Initially, the preform was forged in the so-called blocker (first-stage) die, which distributes the material by imposing only a small amount of deformation that can be achieved even with the limited ductility of the P/M preform. The resulting first-stage forging had nearly full density and a greatly increased ductility. It was then subjected to a second forging operation in the finishing (second-stage) die having the configuration of the target geometry.

The second approach involved making a considerably more complex preform, which required a more complex bag geometry. Then, this pressed and sintered preform was to be forged in one single operation using the finishing die. The scheme for Phase II is summarized in Fig. 26.

5.2 Target Geometry of Forging

As a target, it was planned to make the isothermal creep forging with most of the surfaces net. Only a few portions of the forging will require machining. The high precision cam slot for the roller will have to be machined out. The step "ab" (Fig. 27) will be forged net, but the "cd" portion will be made with about a 1/8 in. thick web which can be punched out later to form the window. The surfaces (e,f,c,g,h,i,j and p,q) and

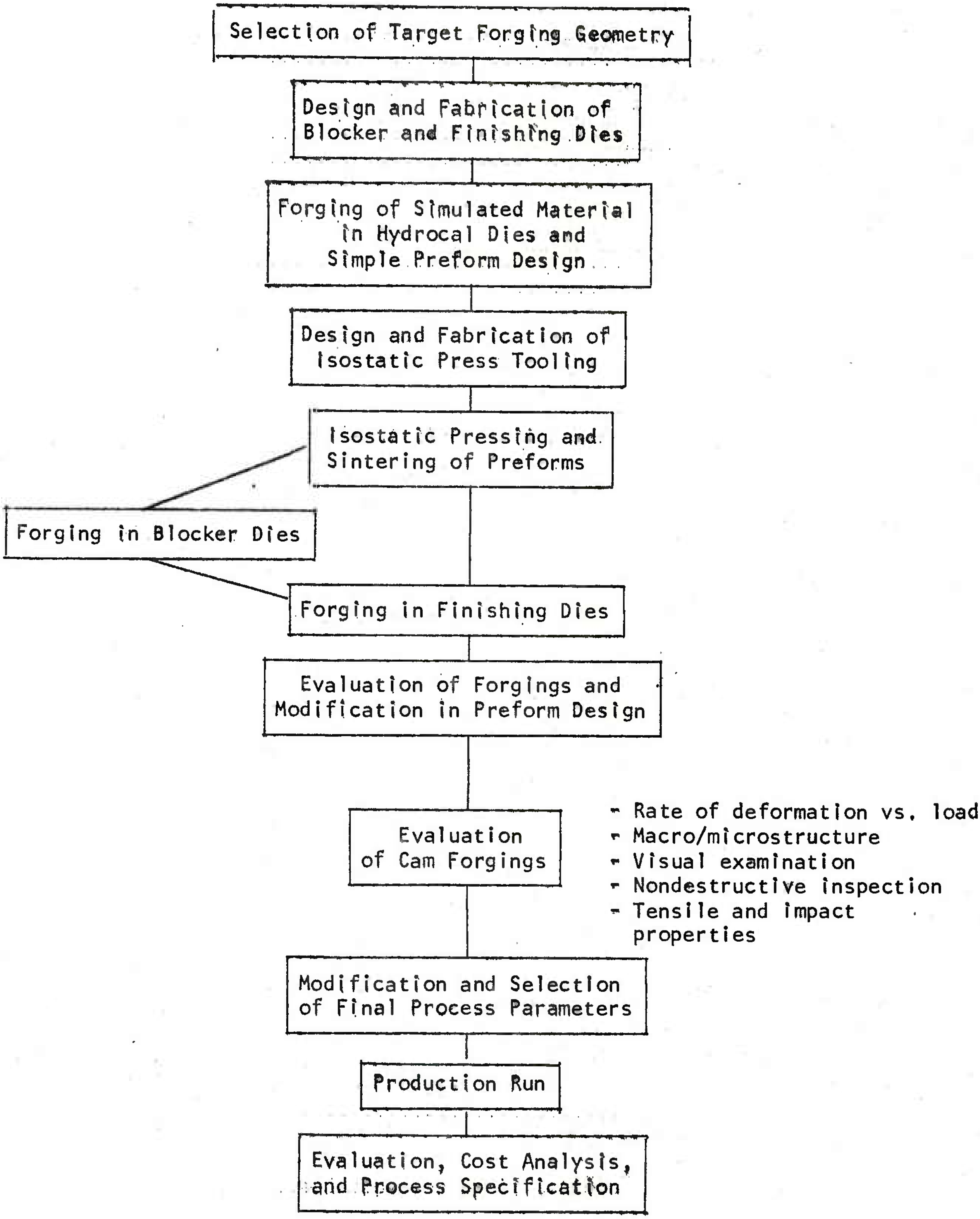
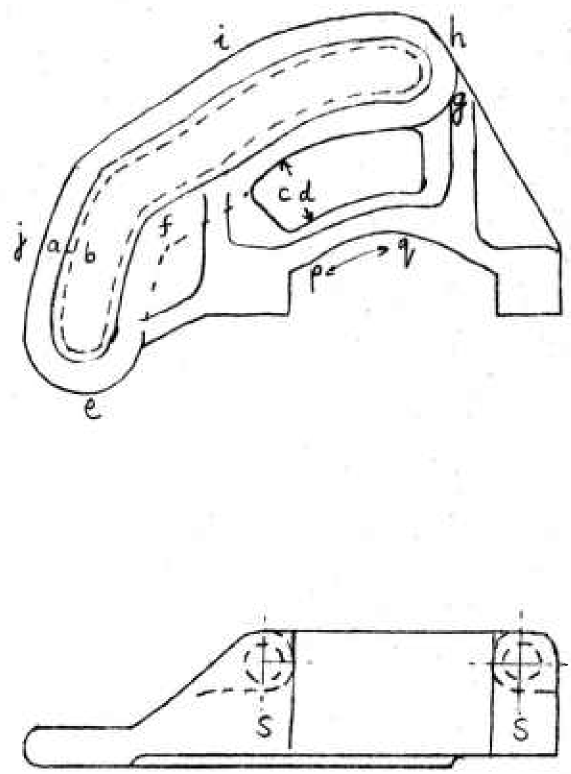


Figure 26

Phase II: Process Optimization for Production Run of Cam



See Fig. 2 for detailed dimensions.

Figure 27

Target Cam Geometry for P/M Forging
(Make all surfaces net except as follows:

1. Cam slot b to be machined, but step a-b will be net.
2. Punch out window d and trim flash all around.
3. Surfaces S and bolt holes need machining but machining on S will be much less than on conventional forging.)

ribs will also be made net. However, the holes and the material (around the areas SS in view BB) will require some machining.

5.3 Experimental Details

5.3.1 Design and Fabrication of Forging Dies

As discussed earlier, since powder materials are prone to fracture during forming, one of the approaches considered was to accomplish the creep forging in two steps so as to have a controlled amount of deformation in each step. The forging obtained from the blocker die will become the preform for the finishing (second-stage) die.

The detailed design of the bottom and top dies for the first stage are shown in Figs. 28 and 29, respectively. In the blocker die, dimensional tolerances were not critical; therefore, low alloy steel SAE 4140 heat treated to R_C 35 was selected as the die material. The finishing bottom and top die designs are shown in Figs. 30 and 31, respectively. For the finishing dies the dimensions were critical. Therefore, H13 tool steel heat treated to R_C 38 was selected. Because of the ejection system necessary in finishing dies, the positions of the bottom and top dies were reversed as compared to the blocker dies.

Figure 32 shows the photographs of blocker dies, machined at IITRI, whereas finishing dies, fabricated to IITRI's design by Atols Tool and Mold Corporation, Chicago, are shown in Fig. 33. Both lower and upper support plates along with ejection plate and pins were fabricated at IITRI and are shown in Fig. 34.

It is worth mentioning here that the technique of fabricating dies by casting to approximate dimensions followed by finish machining was considered but was not found to be cost-effective. Therefore, both the blocker and finishing dies were produced by machining from wrought die blocks.

These dies were assembled on existing support bases which, in turn, were assembled in IITRI's 1000-ton press. The finishing die assembly with induction heating coil on the side is shown in Fig. 35.

5.3.2 Forging of Simulated Material and Design of Preform

It was felt that, in view of the nonsymmetric shape of the cam, some simulated material forging tests would be valuable for designing and preform shape for the blocker die. Plaster (Hydrocal) molds were produced using the conventionally forged cam as the pattern. The parting line was the same as for the conventional forging. The pattern was placed in a wooden core box and attached through the base by drilled and tapped holes in the pattern. To form the parting line, the area around the pattern was built up by wax. The plaster (100 parts plaster + 35 parts water by

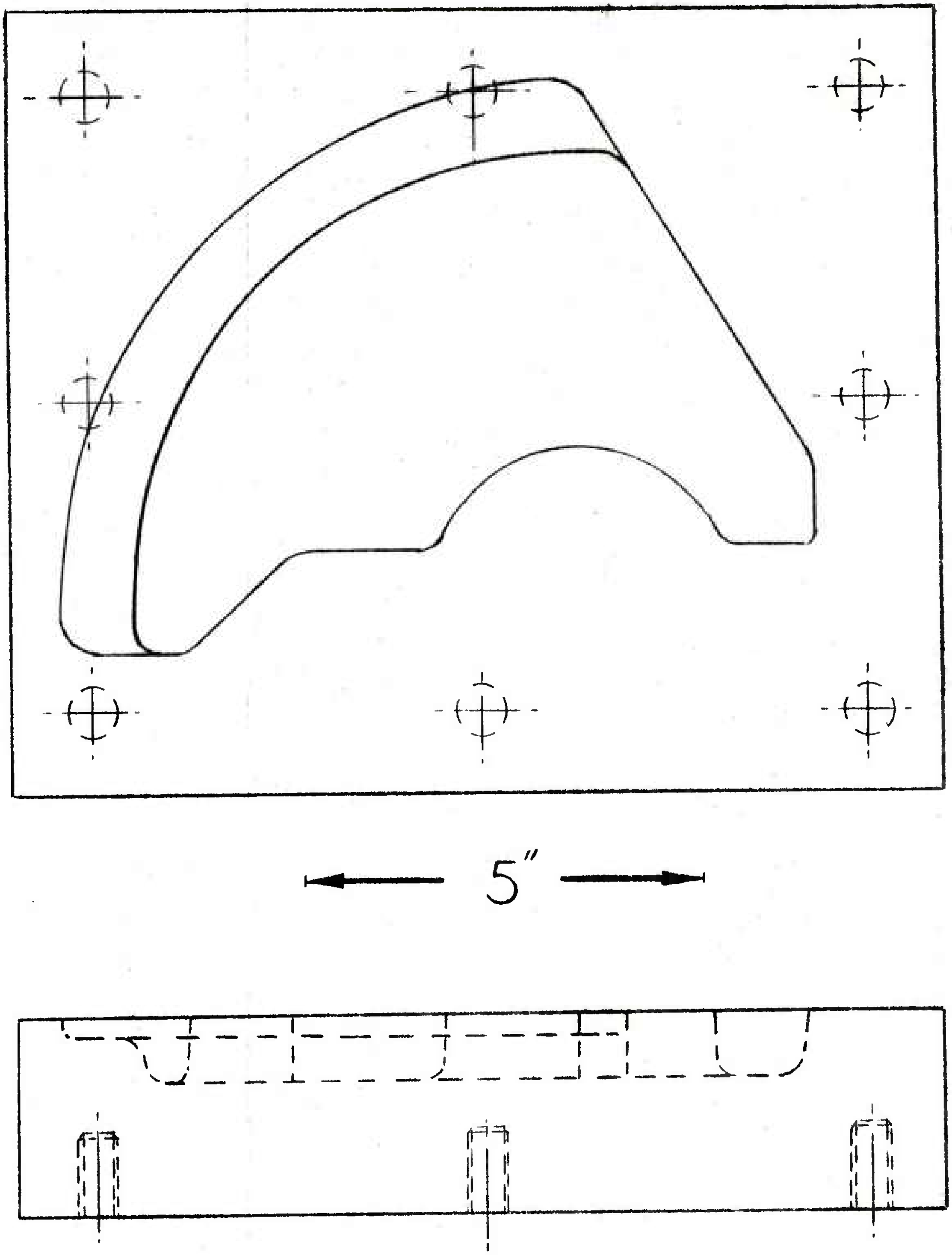


Figure 28

Schematic of Blocker Bottom Die

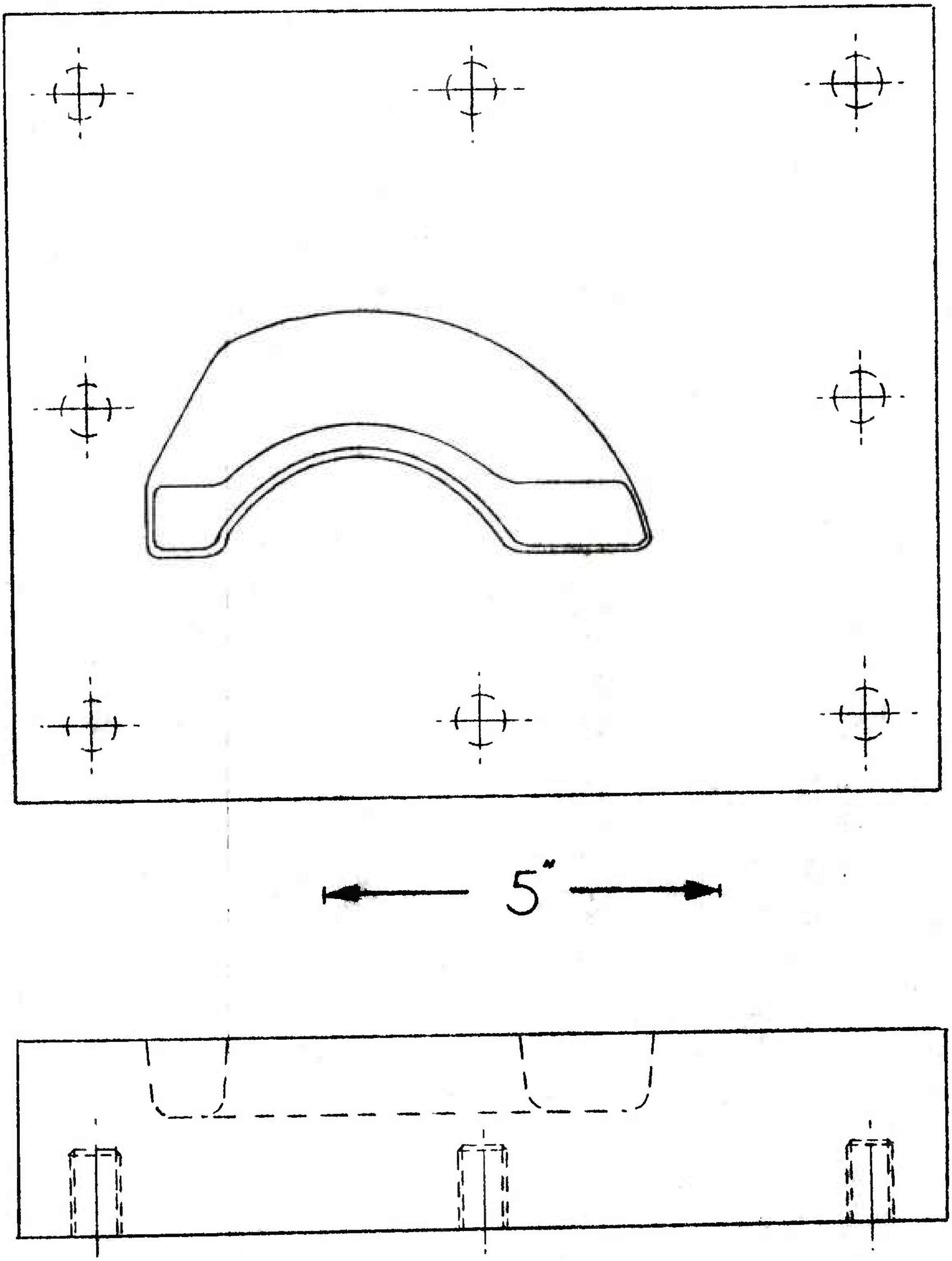
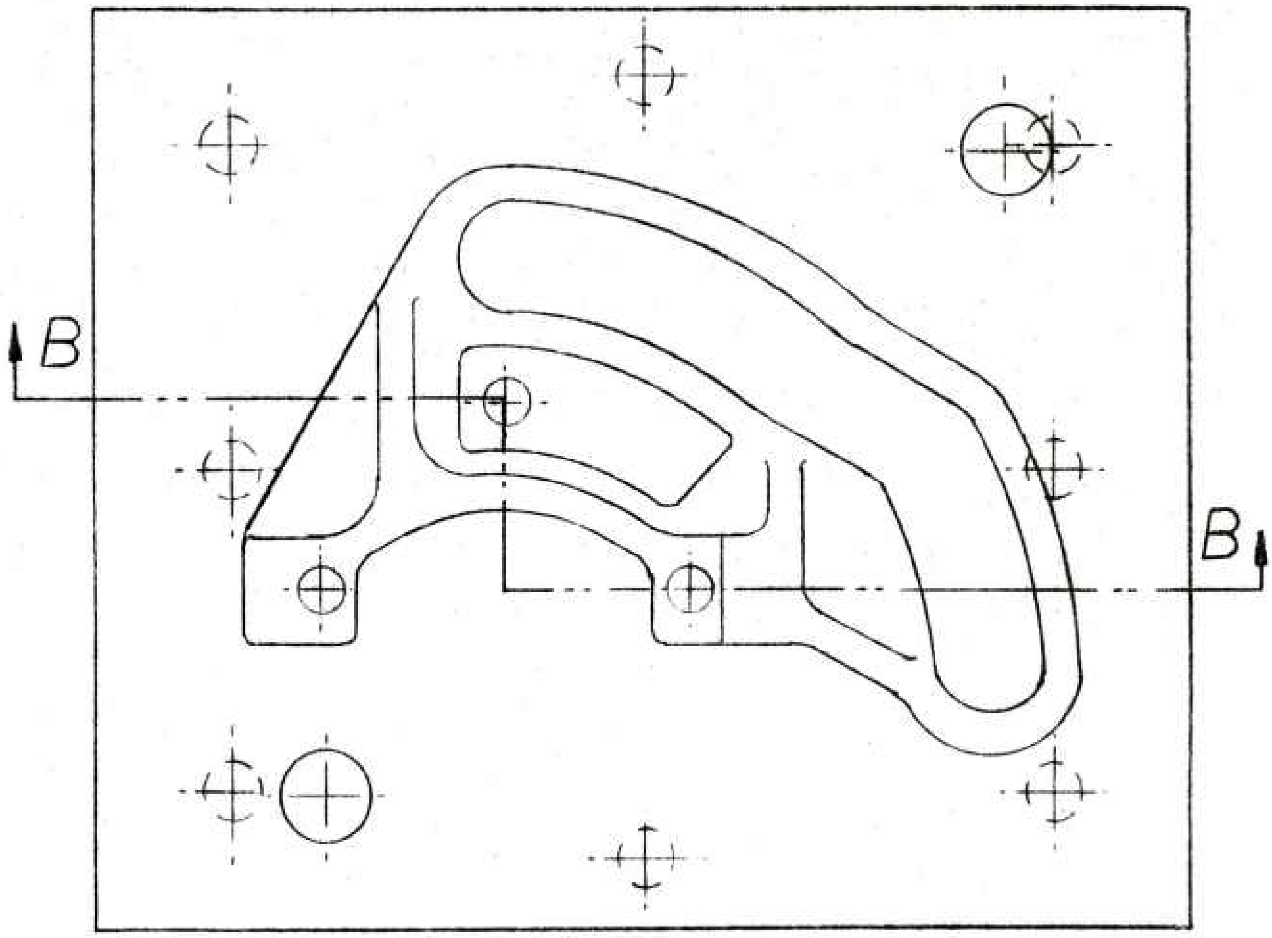


Figure 29

Schematic of Blocker Top Die



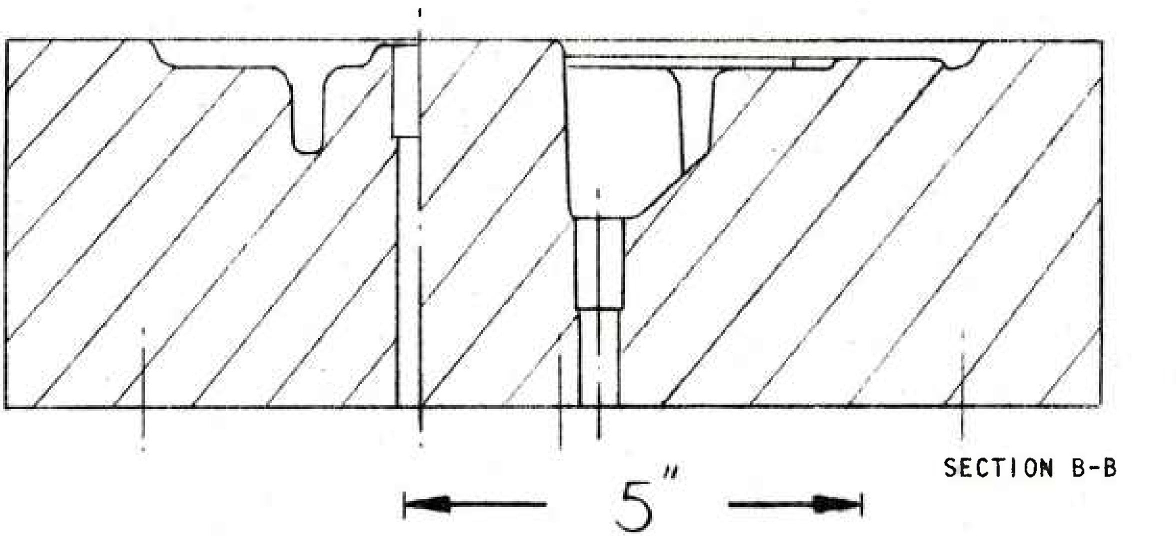


Figure 30

Schematic of Finishing Bottom Die

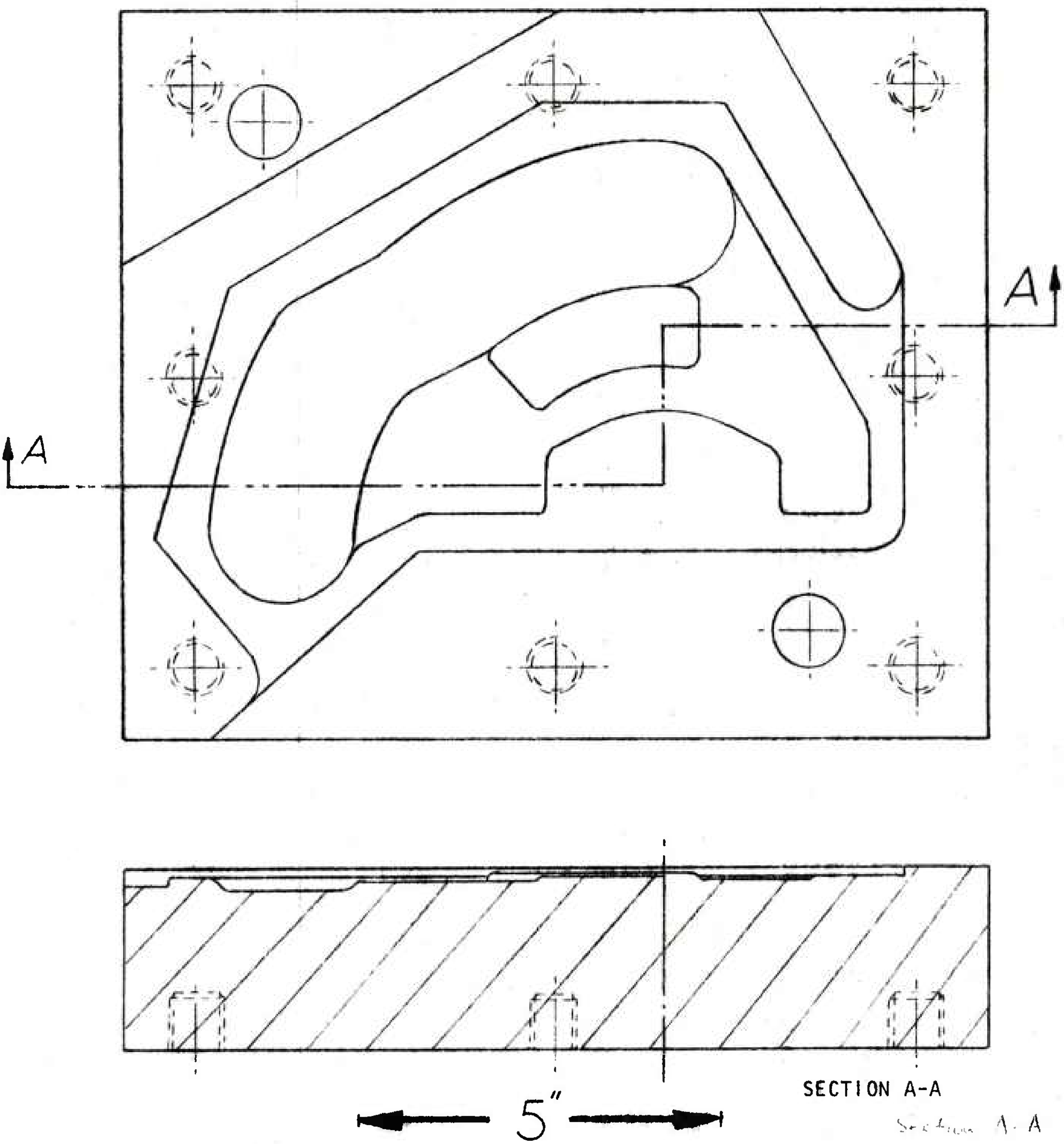
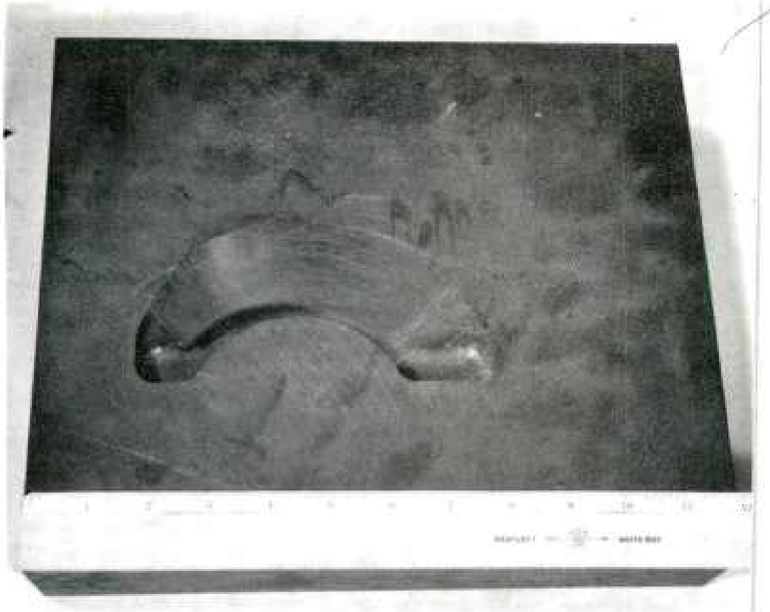


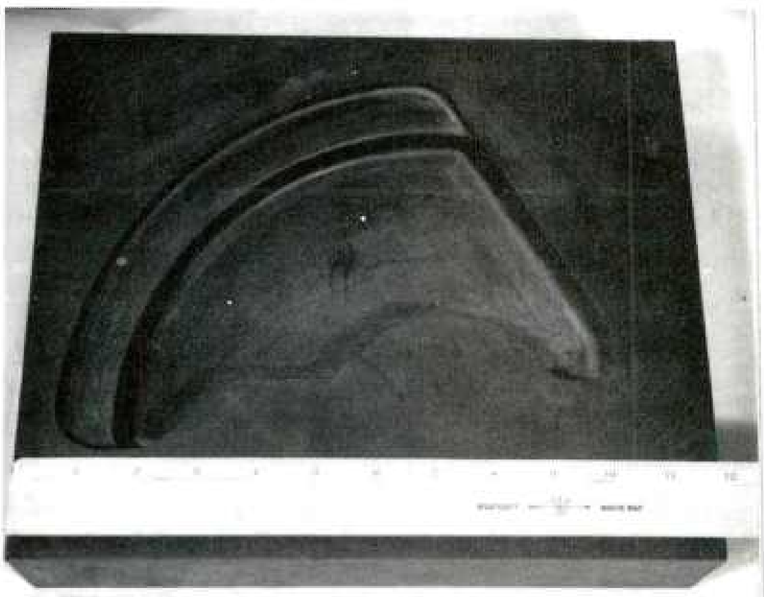
Figure 31

Schematic of Finishing Top Die



Neg. NO. 44752

(a) Top die

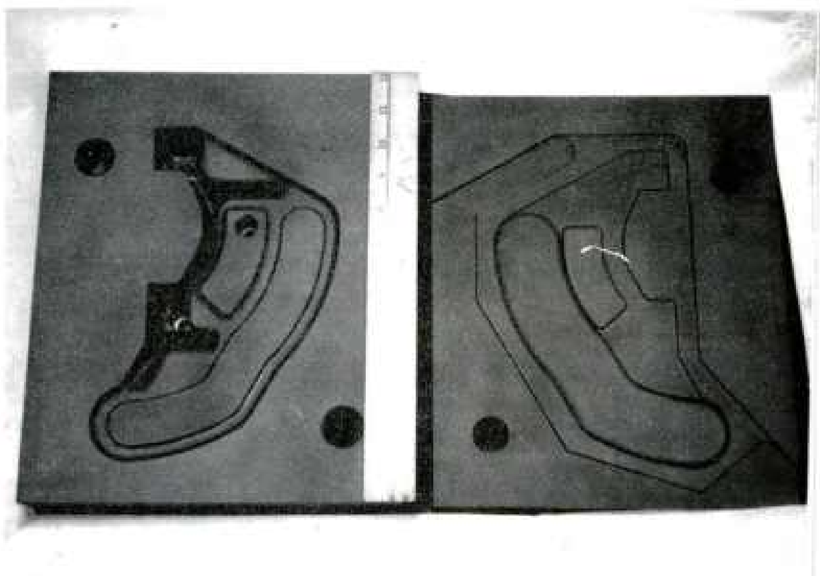


Neg. No. 44751

(b) Bottom die

Figure 32

Blocker Dies

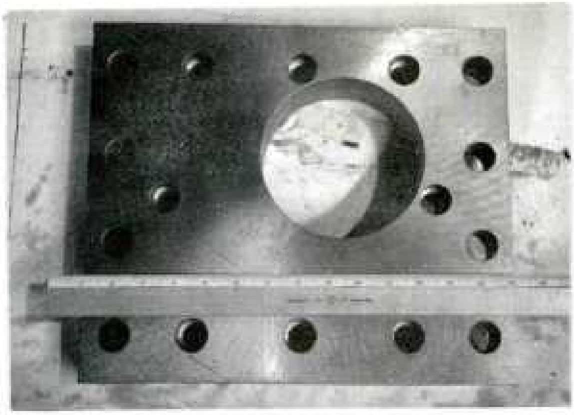


Neg. No. 44757

Bottom Top

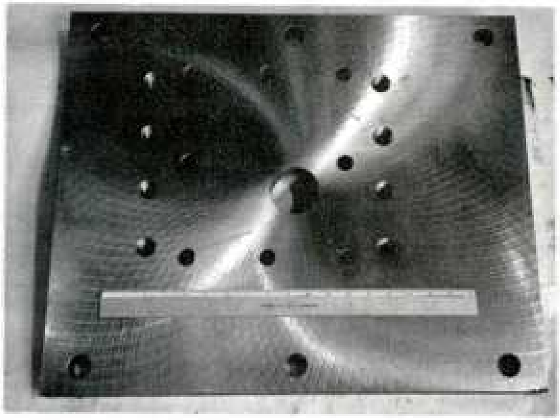
Figure 33

Finishing Dies



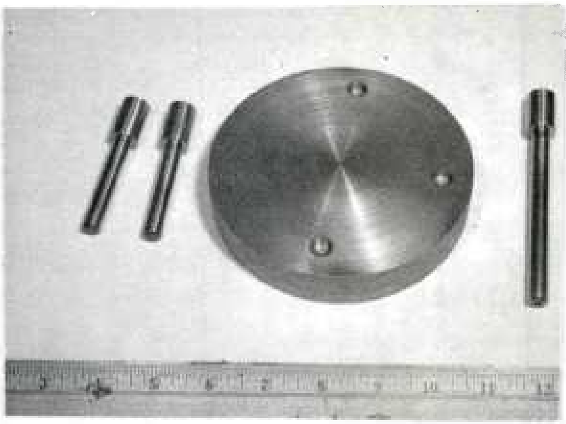
Neg. No. 44749

(a) Top plate



Neg. No. 44750

(b) Bottom plate

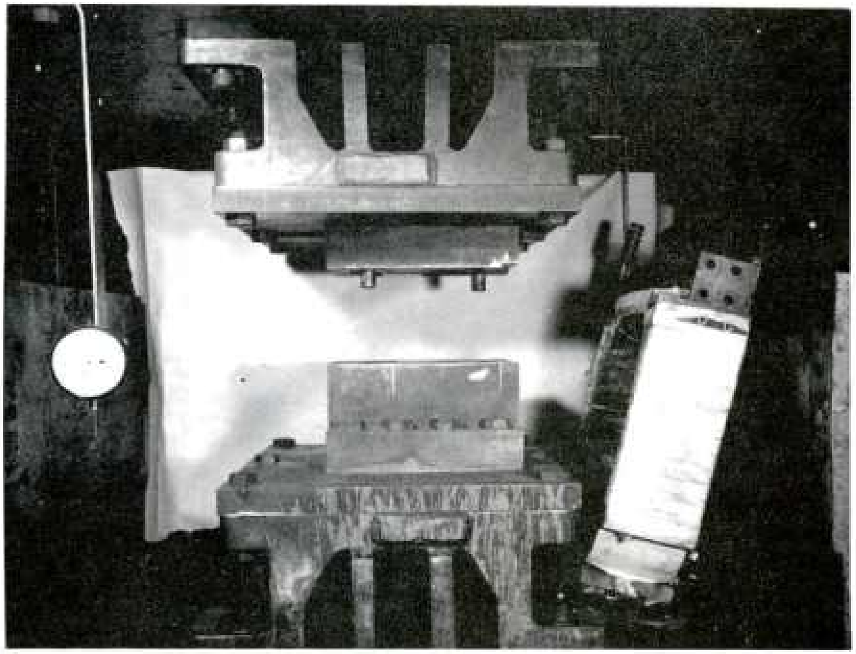


Neg. No. 44764

(c) Ejection plate and pins

Figure 34

Supporting Plates and Ejection System
for the Finishing Dies



Neg. No. 45398

Figure 35

Finishing Die Assembly in 1000-ton Press
(The heating coil is on the side.)

weight) was thoroughly mixed and then poured into the box and allowed to set overnight. For reinforcing the plaster mold, steel wire was used in the cope. Then the cope was removed from the core box, while the pattern remained in the plaster mold. The drag (lower die) was produced in a similar manner with nail and wire reinforcements. To prevent sticking of the cope and drag, lubricating grease was used on the cope surface. Both cope and drag were dried in an oven at 150°F for a couple of days. The Hydrocal dies are shown in Fig. 36.

Play dough was used as the simulated material. After some initial tests, graphite spray on wax worked quite satisfactorily as a lubricant, and facilitated easy removal of the play dough forging. The results of different shapes of preforms tried are summarized in Table 18, and some of the preforms and final forgings of play dough are shown in Fig. 37. Cylinder shape (No. 1) with 2.5 in. diameter showed complete filling of the cavity but could not be considered for preform shape because of heavy deformation (approximately 80% in height) which may crack the component. Therefore, a semicircular disc with a varying height (Nos. 7 and 8) was considered for preform shape. As can be seen in Fig. 37, they have good reproducibility also. A modification was then made (Table 18, No. 9) to accommodate the filled bag in IITRI's isostatic pressing facility. The volume of the pressed preform (in this preliminary design) was estimated to be about 43 $in.^3$ whereas that of a trimmed conventional forging is 29 $in.^3$ The excess is provided to allow some minor modifications of the preform dimensions, to form a flash, and to allow removing cracks, if any, after the first forging operation.

5.3.3 Design of Bags for Isostatic Compaction

From the first-phase work, it was known that the density of sintered product will be nearly 93% and the -100 mesh blended elemental Al 7075 alloy powder has a tapped (loose filled) density of about 55% of theoretical. Hence, for the preform shape No. 9 in Table 18, the design of the bag should be as shown in Fig. 38. The volume of such a bag is about 80 $in.^3$ It has an extended portion and open end for filling and evacuation. The cap for the bag has a 1/4 in. diameter rubber evacuation tube. The wall thickness of the tube and the cap were 1/16 in. As can be seen in Fig. 38, the bag design does not have the semicircular detail (as in shape No. 9 of Table 18) which is left out on purpose so that it can be modified as necessary. Also, a bag with such detail would have made it difficult to remove the compact from the bag. The rubber bags were fabricated by Trexler Rubber Company, and the tooling for isostatic compaction is shown in Fig. 39.

As discussed in Section 5.4, it was later necessary to modify the bag design to that shown in Fig. 40. The height of the preform was increased and a few modifications were made, as shown in Fig. 40, because of the incomplete filling of the final forgings. (See Section 5.4.) The circular section was not necessary because of one-step forging in the finishing dies.

Neg. No. 43793

(a) Cope (top die)

Neg. No. 43792

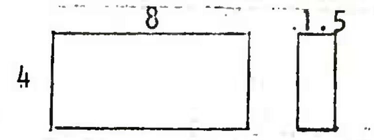
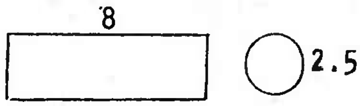
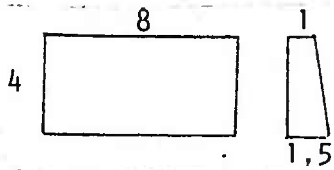
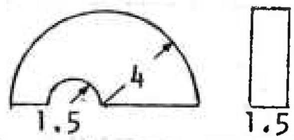
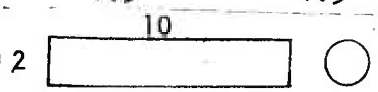
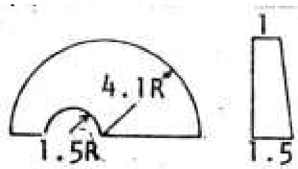
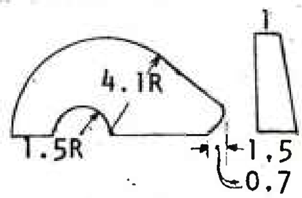
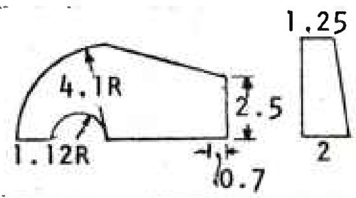
(b) Drag (bottom die)

Figure 36

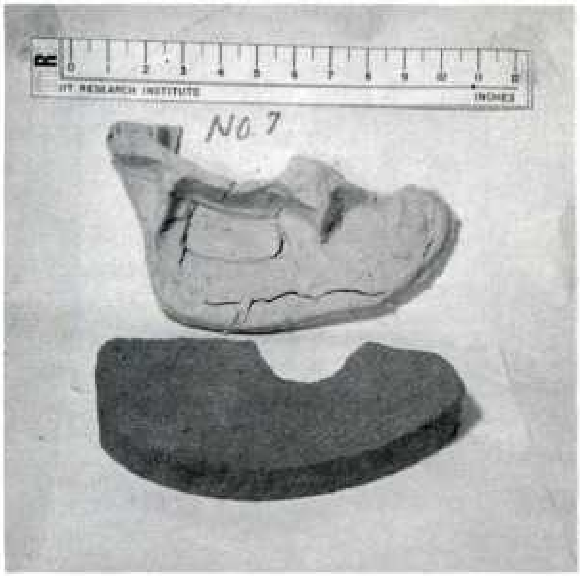
Hydrocal Dies for Forging of Simulated Material

Table 18

SIMULATING MATERIAL FORGING TESTS WITH PREFORMS OF VARIOUS GEOMETRIES

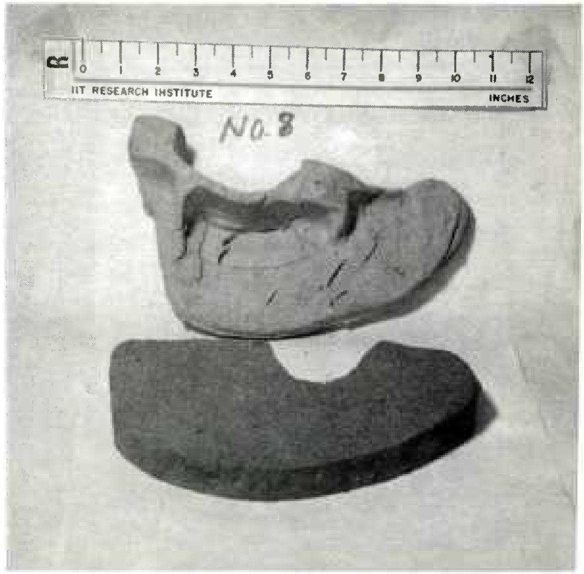
No.	Sample	Schematic Drawing with Dimensions in in. (appr.)	Vol., in.^{3}	Comments
1a	Plate		48	Broke during ejection from the Hydrocal die.
1	Cylinder		39	Showed complete filling of the cavity.
2	Trapezoidal plate		40	Incomplete filling of the cavity.
3	Semicircular disc		32	Incomplete filling of the cavity.
4	Cylinder		31	Incomplete filling of the cavity and broke during ejection from the die.
5	Cylinder	Same as 4	31	Position of cylinder was different than position 4. Broke during ejection.
6	Trapezoidal semicircular disc		39	Incomplete filling.
7	Trapezoidal semicircular disc		42	Excellent filling of the cavity.
8	Trapezoidal semicircular	Same as 7	42	Excellent reproducibility
9	Trapezoidal disc		43	Excellent filling of cavity.

Note: Volume of the conventionally forged and trimmed cam is ∿29 in.^{3}
Play dough is the simulating material.



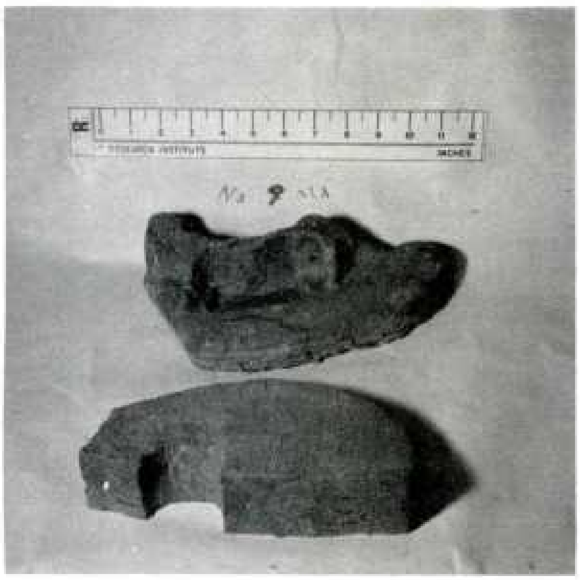
Neg. .No. 43796

(a) No. 7



Neg. No. 43798

(b) No. 8



Neg. No. 43800

(c) No. 9

Figure 37

Simulated Material Preform Shapes
and Creep Forgings

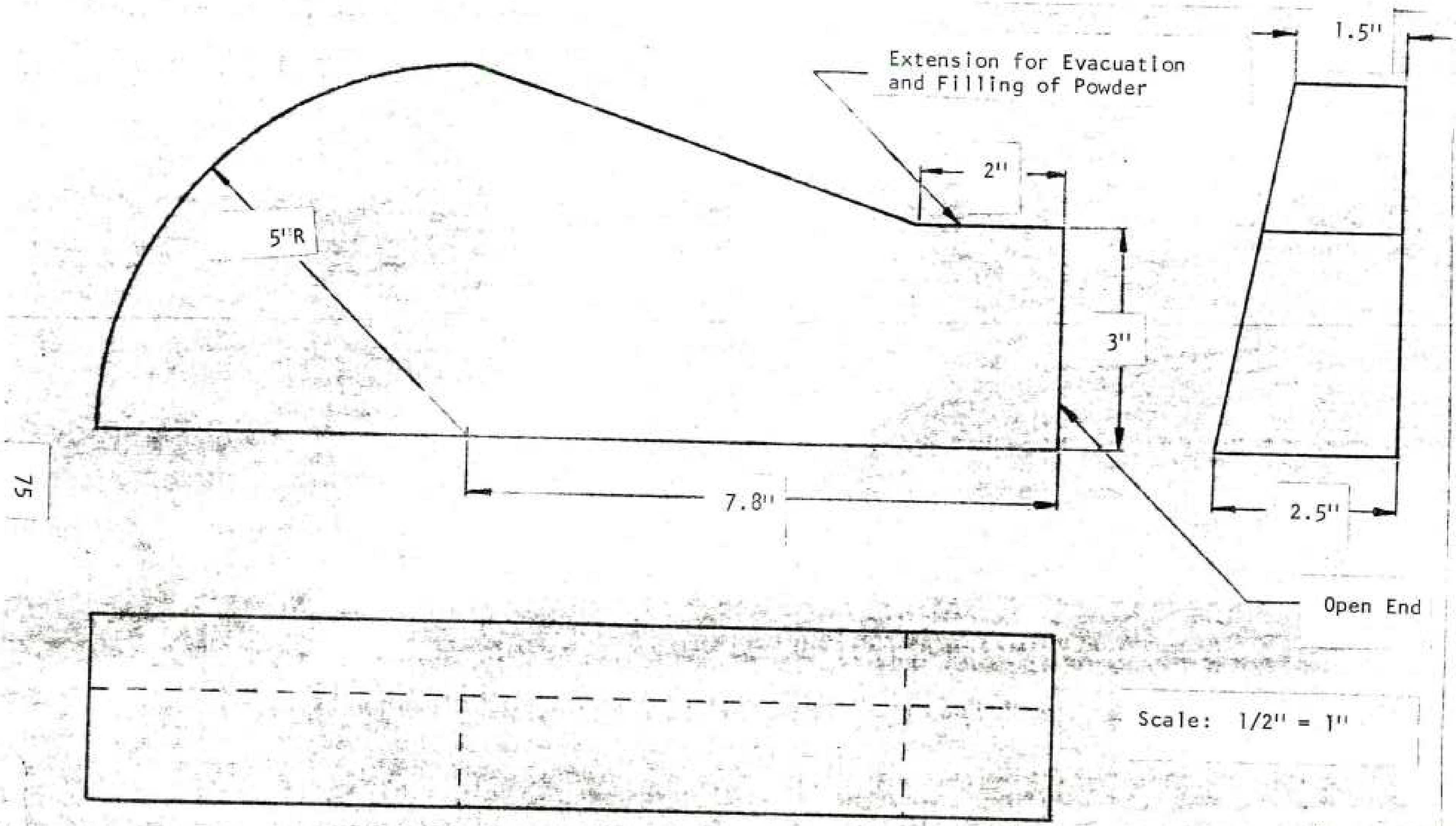
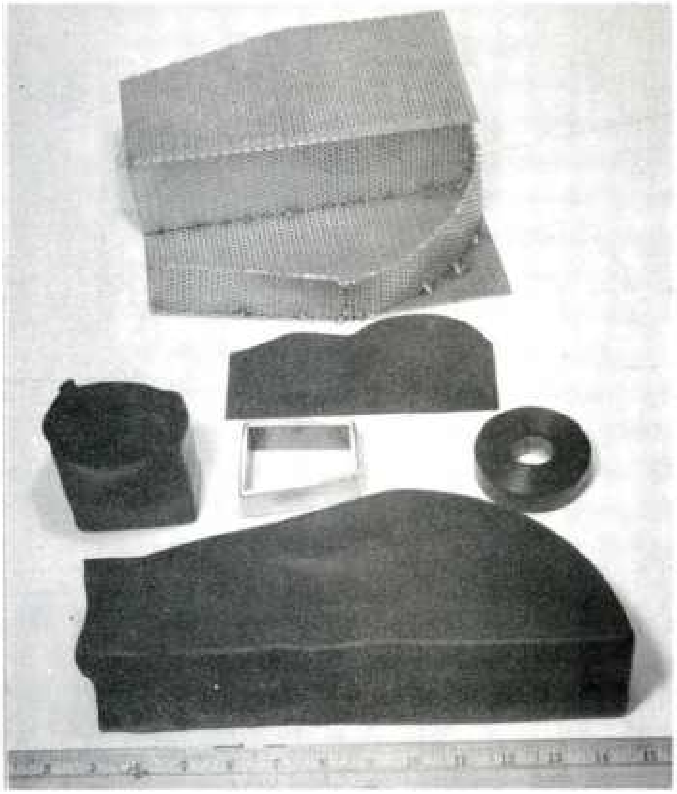


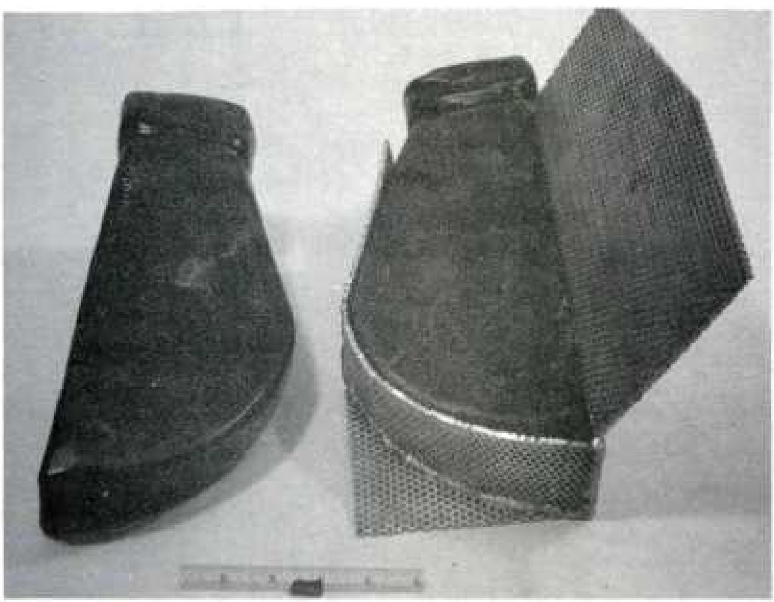
Figure 38

Initial Design of Aluminum Form for Rubber Bag



Neg. No. 44765

(a)



Neg. No. 44766 (b)

Figure 39

Tooling for Isostatic Pressing Preforms for Cam (a)
and Bags after Evacuation, Ready for Isostatic Pressing (b)

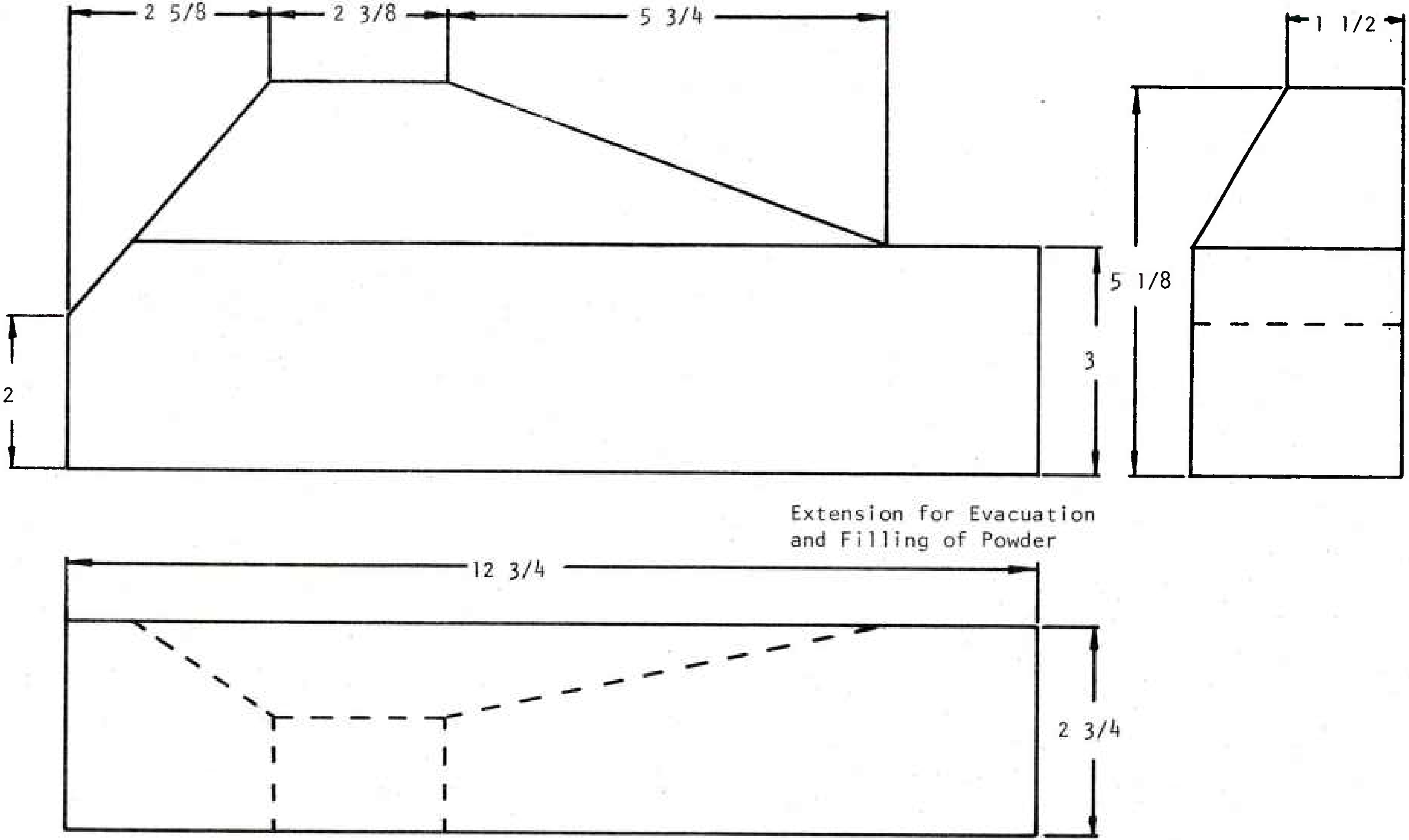


Figure 40

Modified Aluminum Form Design for Rubber Bag

5.3.4 Development of Reusable Inserts

Since the shape of the component is nonsymmetrical and complicated, in turn making the preform shape complex, it would require several iterations on preform shape before a satisfactory shape could be finalized. This means several rubber bag designs, preform trials, and bag design modifications. To carry this out would be expensive and time-consuming. Therefore, a highly innovative idea of using rubber inserts to alter the internal shape of the preform while keeping the outer bag dimensions the same was rapidly developed and effectively used throughout Phase II of the program. These rubber inserts were reusable, worked very effectively, and are shown in Fig. 41. This idea offers two major advantages:

1. The inserts can be changed easily and can be made to different geometries. This permits varying the geometry of the pressed preform without the necessity of changing the bag geometry. This facilitiates optimizing the preform geometry quickly.

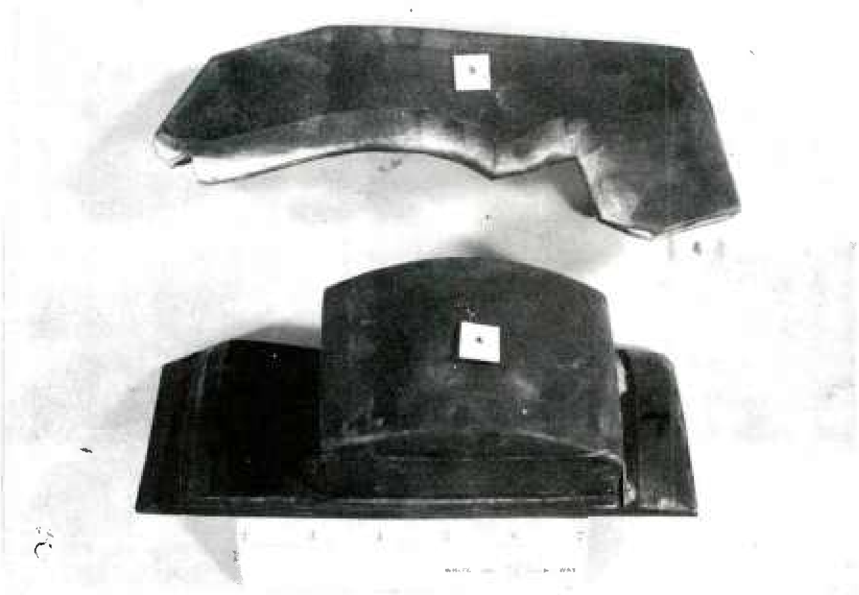
2. The complexity of a preform is normally severely restricted by the need to remove pressed preform from the bag. Yet, often a more complicated preform geometry may be desirable for its ultimate usage. This is the case, for example, for P/M preform forging. The development of rubber inserts allows production of preforms with practically unlimited complexity. This is perhaps the most important advantage.

5.3.5 Comparison of Alcoa and Alcan Powders

The Phase I work was conducted with powder supplied by Alcoa. Another major supplier of the powder is Alcan. In Phase II, the two types of powders were compared to a limited extent. Many of the Phase II tests were conducted on powder supplied by Alcan. The Alcan powder (-100 mesh) had a bulk density of 1.18 (Alcoa 1.12), and the size distribution given below with Alcoa analyses given in parentheses:

Size, U.S. Mesh	%	Size, U.S. Mesh	%
+100	0.1 (trace)	-200 +325	10.2 (7.6)
-100 +200	8.7 (0.5)	-325	81 (92)

The Alcan powder had lesser (81%) fines (-325 mesh) as compared to Alcoa powder which contained 92% of -325 mesh. The chemical composition (%) was 1.6 Cu, 2.5 Mg, 0.2 Cr, 5.6 Zn, and the rest aluminum, which is within the specifications of Al 7075 alloy. The powder was checked after sintering and had microstructure similar to that of Alcoa powder. Thus, from a technical viewpoint Alcan powder was deemed as good as Alcoa powder.



Neg. No. 45746

Figure 41

Rubber Inserts Developed to Control Geometry of Preform
Made by Isostatic Pressing

5.3.6 Isostatic Pressing and Sintering of Preforms

The processing conditions used for pressing and sintering were the same as established during Phase I.

Powder:	-100 mesh
Isostatic Compaction:	40 ksi
Sintering Temperature:	1025°F, 2 hr in N_2 atmosphere

The details of the preforms studied during this investigation are given in Appendix 1. After sintering, the preform density was 93% which is the same as found in Phase I of the program. The microstructure was also similar to that obtained in Phase I of the program. A total of 52 preforms were made, including those for the production run.

The initial study made on preforms involved the following variations:

1. Different shapes of preforms by changing the shapes of the inserts as described in Section 5.3.4.
2. Two designs for isostatic pressing bags.
3. Control of final preform shape by trimming or grinding of preform after sintering.
4. Comparison of performance of powders supplied by Alcan and Alcoa.
5. Effect of temperature and deformation rates on forging characteristics, load, and microstructure.

5.4 Forging Results and Discussion

5.4.1 Two-Step Forging

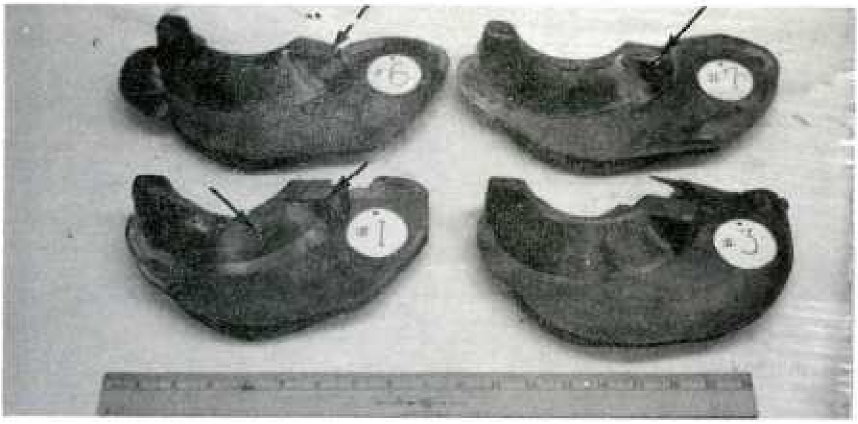
Initially, four preforms (Nos. 1, 3, 6, and 7 described in Appendix 1) with a general shape as in Fig. 42 were subjected to first stage or blocker forging operation. The preforms were coated with Fiske 604 die lubricant and heated in the furnace for 1 hr. The dies were heated by induction up to 750°F and the total variation in temperature within the die was ± 50°F. The detailed data for isothermal creep forgings are given in Appendix 2, and the blocker die forgings obtained are shown in Fig. 43.

Except for forging No. 3, all the rest had some cracks at the places shown by the arrows in Fig. 43a. The data in Appendix 2 show the trend in load. With the press speed of 0.1 ipm the load was 350 tons, and with the speed at 0.2 and 0.3 ipm the load increased to 400 ton. Except for the

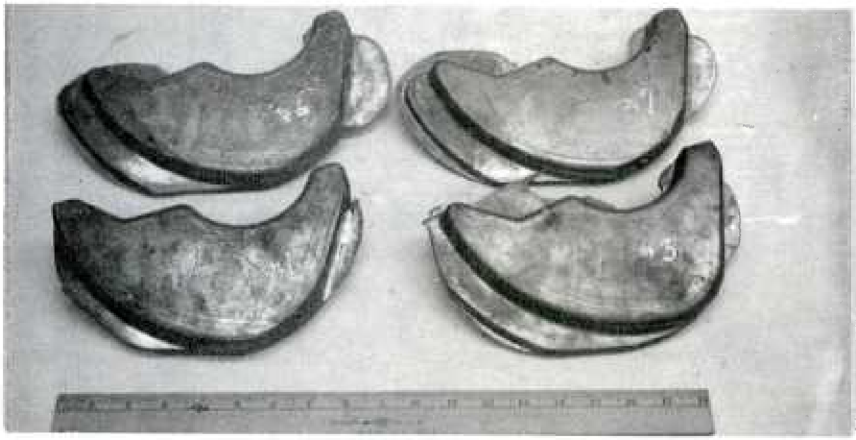
Neg. No. 44759

Figure 42

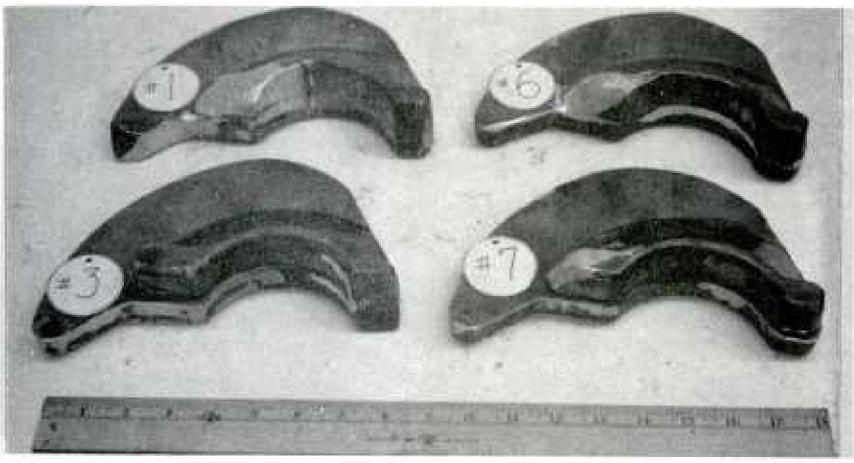
Isostatically Pressed and Sintered Preform



Neg. No. 44893 (a)



Neg. No. 44892 (b)



Neg. No. 44900 (c)

Figure 43

Four Blocker Die Forgings. As-forged (a and b) and as-prepared for finish forging (c).

minor cracks the blocker die forgings appeared to be sound. The cracks were ground and preparations were made (Fig. 43c) for finishing die forging.

Blocker die forgings became the preforms for the finishing dies. The forging data for finishing dies are shown in Appendix 2. Forging No. 1 had the same speed and temperature as in the blocker die forging. It showed extensive cracking, Fig. 44a. With the same speed but with an increase in temperature from 750 to 830°F, less cracking was observed (Fig. 44c) on Forging No. 3. To check for smaller cracks, both forgings were examined with dye penetrant tests and the results of a typical forging (No. 3) are shown in Fig. 45. Besides the cracks which could be visually seen, two other kinds of defects were also observed. Defects marked by the arrows in the left of Fig. 45a do not seem to be deep enough and are most probably due to the lubricant entrapment, whereas the defect to the right of Fig. 45a (shown by an arrow) seems to be a "fold over" type of defect. Therefore, it was decided to forge preforms Nos. 6 and 7 in steps (incrementally) to find the stages at which formation of defects starts.

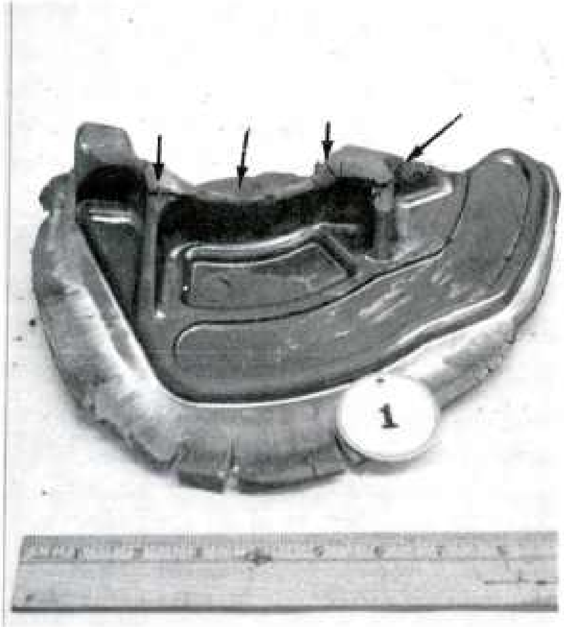
The forging data for Nos. 6 and 7 are shown in Appendix 2 and one of the isothermal forgings is shown in Fig. 46. The type of metal flow that causes the formation of fold-over is quite evident and is indicated by the arrow. The unsatisfactory metal flow suggests the need for modification in the preform design for more favorable material distribution.

5.4.2 One-Step Forging Directly in Finishing Dies

Four forgings (Nos. 2, 5, 8, and 9) were made directly in the finishing dies at two different temperatures and two deformation rates, and the data on forgings are shown in Appendix 2. One of the typical forgings as well as dye penetrant tested forgings are shown in Fig. 47. Some of the common defects observed were pinching of the material at the place shown by the arrow, incomplete filling of the deep cavity corresponding to the rib, cracks at thin sections of the rib, and some minor defects because of the lubricant entrapment. Within their respective ranges investigated, the forging temperature or the deformation rate (0.1 and 0.3 ipm) did not make any appreciable difference in either the quality of forgings or the load.

From the studies in Sections 5.4.1 and 5.4.2, the following conclusions were reached:

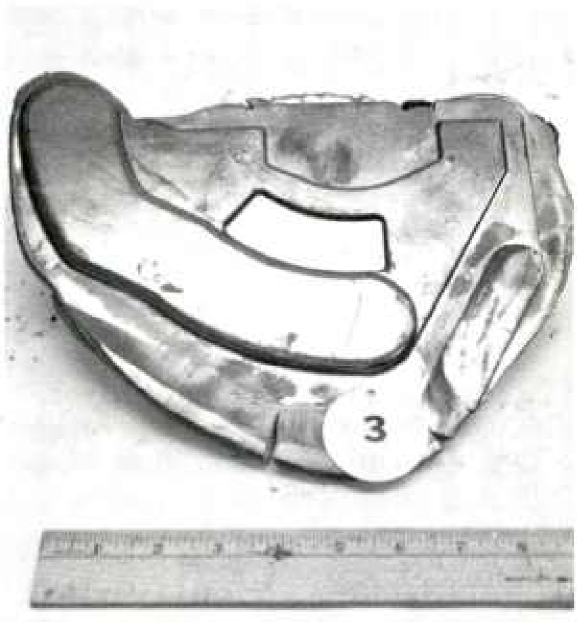
1. Forging the sintered preform directly in finishing dies shows excellent chance for success in terms of being able to make a crack-free forging with complete die fill. Naturally, from a cost reduction point of view, such an approach would be highly desirable provided the mechanical properties are satisfactory.



Neg. No. 44934
(a)

Neg. No. 44935
(b)

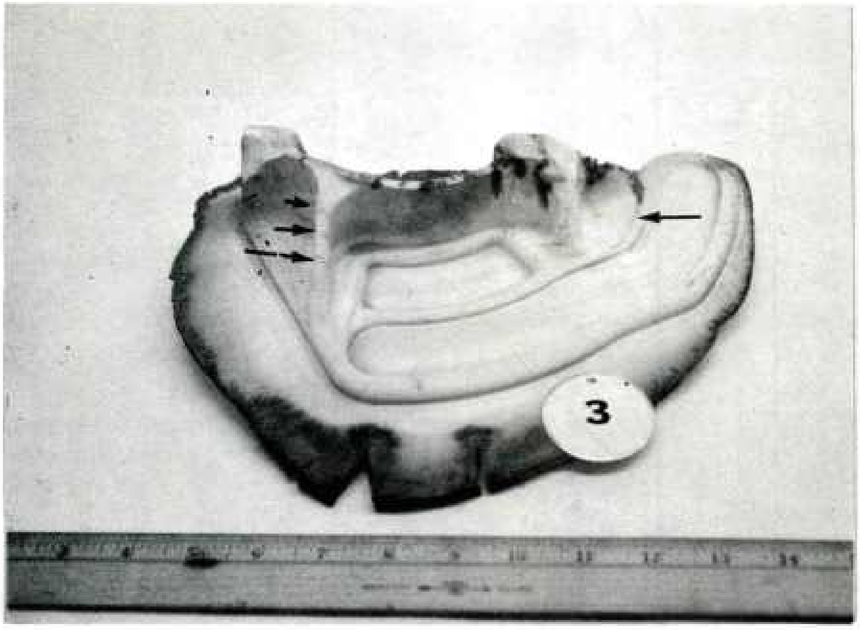
Neg. No. 44936
(c)



Neg No. 44937
(d)

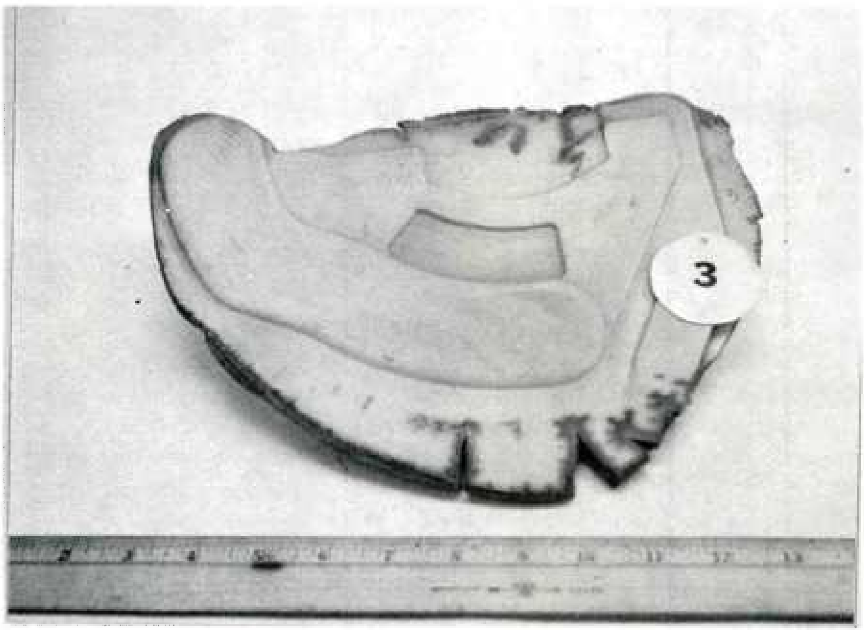
Figure 44

Two Views of Forging Nos, 1 and 3 after Finish Die Forging



Neg. No. 44983

(a)

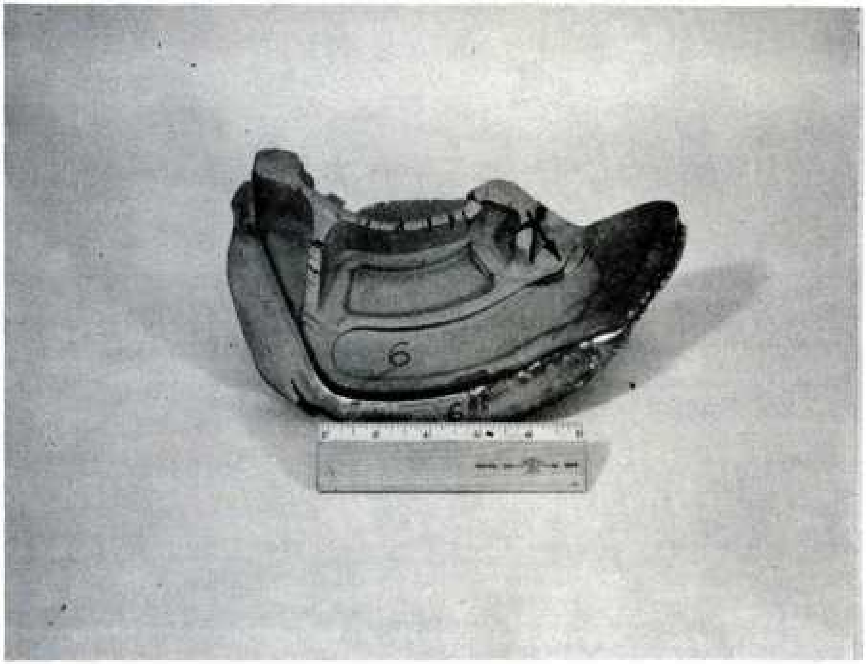


Neg. No. 44984

(b)

Figure 45

Finish Die Forging No. 3 after Dye Penetrant Test



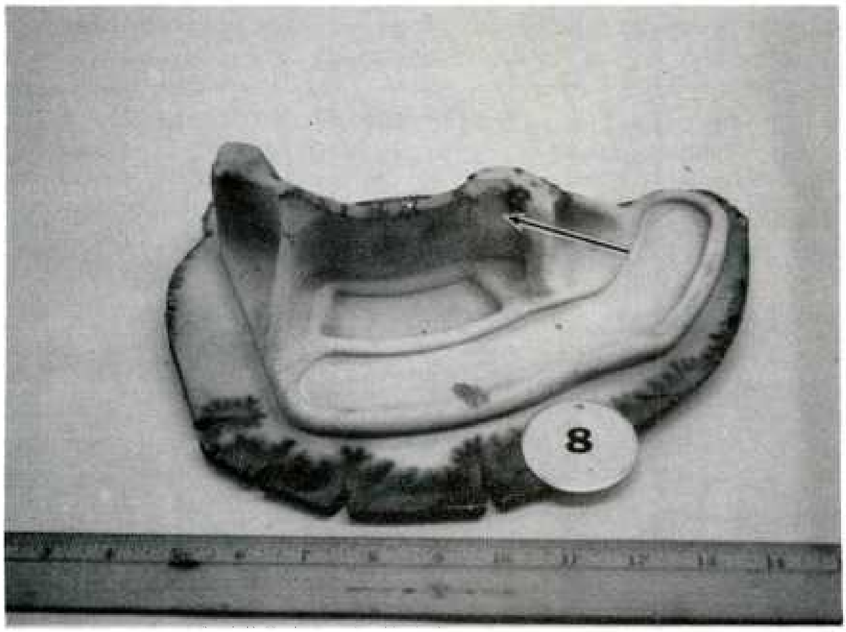
Neg. No. 45388

Figure 46

Finish Die Forging No. 6 at 1/4 in. from Full Die Closure

Neg. No. 44938

(a) As-forged



Neg. No. 44987

(b) After dye penetrant test

Figure 47

One-Step Forging in the Finishing Die

2. The original preform (bag) design No. 1 needs modification to improve die filling and reduce cracking.

3. Forging at around 830°F shows less cracking than at 750°F.

4. The slow deformation rates require longer forging times which will cool the preform during deformation and may, in turn, give rise to cracking.

5. Entrapment of lubricant should be avoided for better surface quality of the forging.

In order to decide on the proper preform geometry, a few more forgings were made with preforms made in the bag of design No. 1, but after grinding the preforms to different shapes. Also, to minimize entrapment, lubricant was thinned down with trichlorethylene. The forging temperature was again 830°F, but to avoid cooling of preform during forging, a faster press speed--1.5 ipm--was selected. The general shape of the preform is shown in Fig. 48. Four forgings described in Appendix 2 were made with slight variations in dimensions of the preform and are shown schematically in Fig. 49. Forging Nos. 14, 16, and 20 are shown in Fig. 50.

The results obtained on these forgings were quite remarkable. The cracks were reduced substantially with the modified preform geometries even with the use of high deformation rate. However, the lack of material at the web C (Fig. 50) clearly indicated the need for modification of the preform bag design. The forging parameters seemed to be quite satisfactory for the direct forging of preforms in the finishing die. Before going through the modification of preform bag design, it was thought necessary to examine the microstructural integrity and the mechanical properties.

5.4.3 Product Integrity and Mechanical Properties

Forging No. 14 was sectioned at three different places as shown in Fig. 50a, and the macroscopic views are shown in Fig. 51 at two magnifications. Note the similarity of the macrostructure with that in conventional wrought products. A few surface defects were observed but they were quite shallow. The defects appeared to have been formed in the deep cavity of the bottom die--most probably due to the entrapment of the lubricant. Density measured on the forgings was 100% of the theoretical.

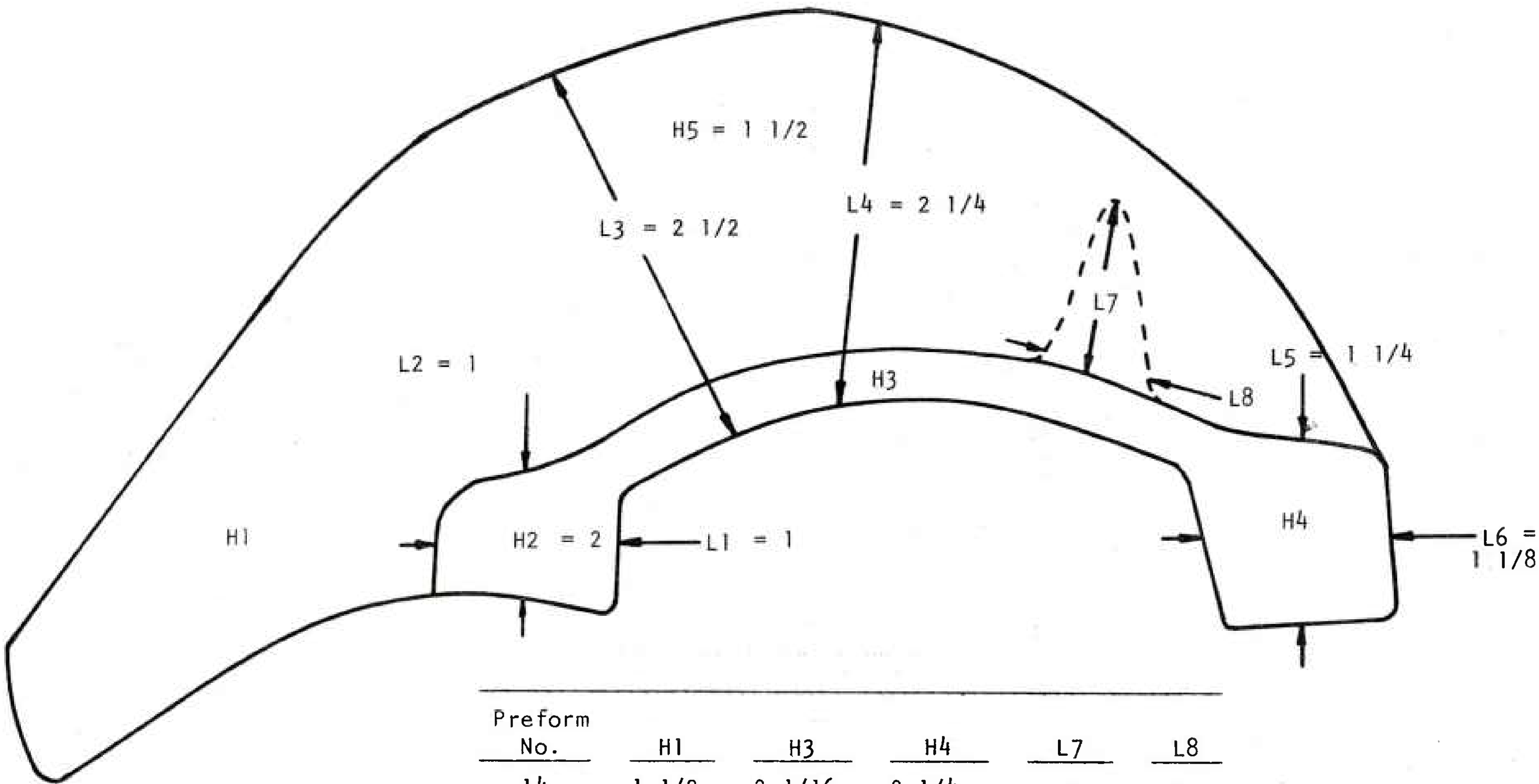
Since powders from two manufacturers and one- and two-stage operations were used for establishing initial forging parameters, a thorough investigation of microstructures was done for the as-forged (AF), solution treated (ST), and solution treated and aged (STA, T6) conditions. Three forgings were selected.

Neg. No. 45056

Approx. 1/3
Full Size

Figure 48

Preform for Forging No. 14

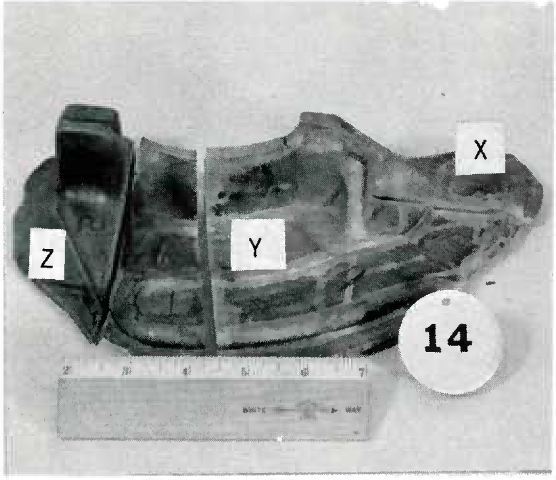


Preform No.	H1	H3	H4	L7	L8
14	1 1/2	2 1/16	2 1/4	--	--
16	1 5/8	1 15/16	1 15/16	1 1/16	11/15
17	1 5/8	1 3/4	1 3/4	--	--
20	2 3/16	1 7/8	2 3/16	--	--

Note: 1. Dimensions are inches.
2. H - Dimensions perpendicular to plane of paper.

Figure 49

Four Preforms Prepared to Study Effect of Preform Geometry

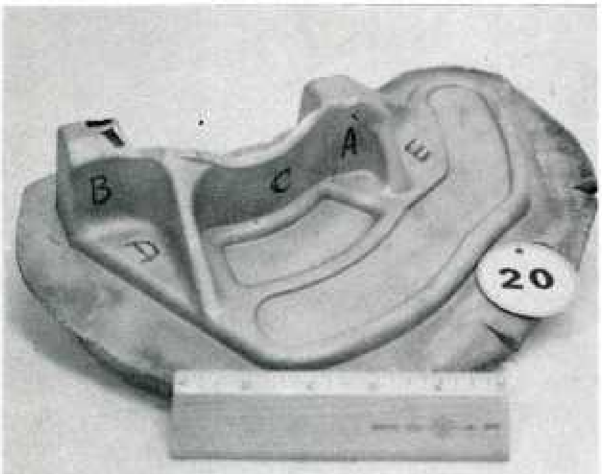


Neg. No. 45390

(a)

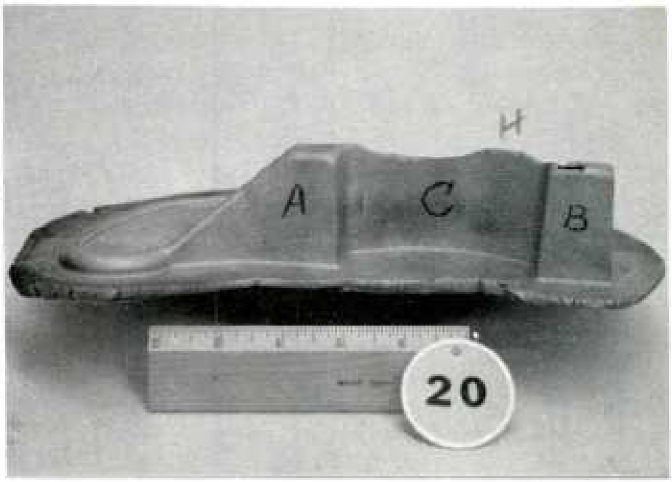
Neg. No. 45391

(b)



Neg. No. 45073

(c)



Neg. No. 45074

(d)

Figure 50

Forging No. 14 (sectioned), 16, and Two Views of Forging No. 20 (See details of Fig. 50a in Fig. 51. Section X in Fig. 51-top; Section Y looking towards right in Fig. 51-center; and Section Z - Fig. 51 - bottom)

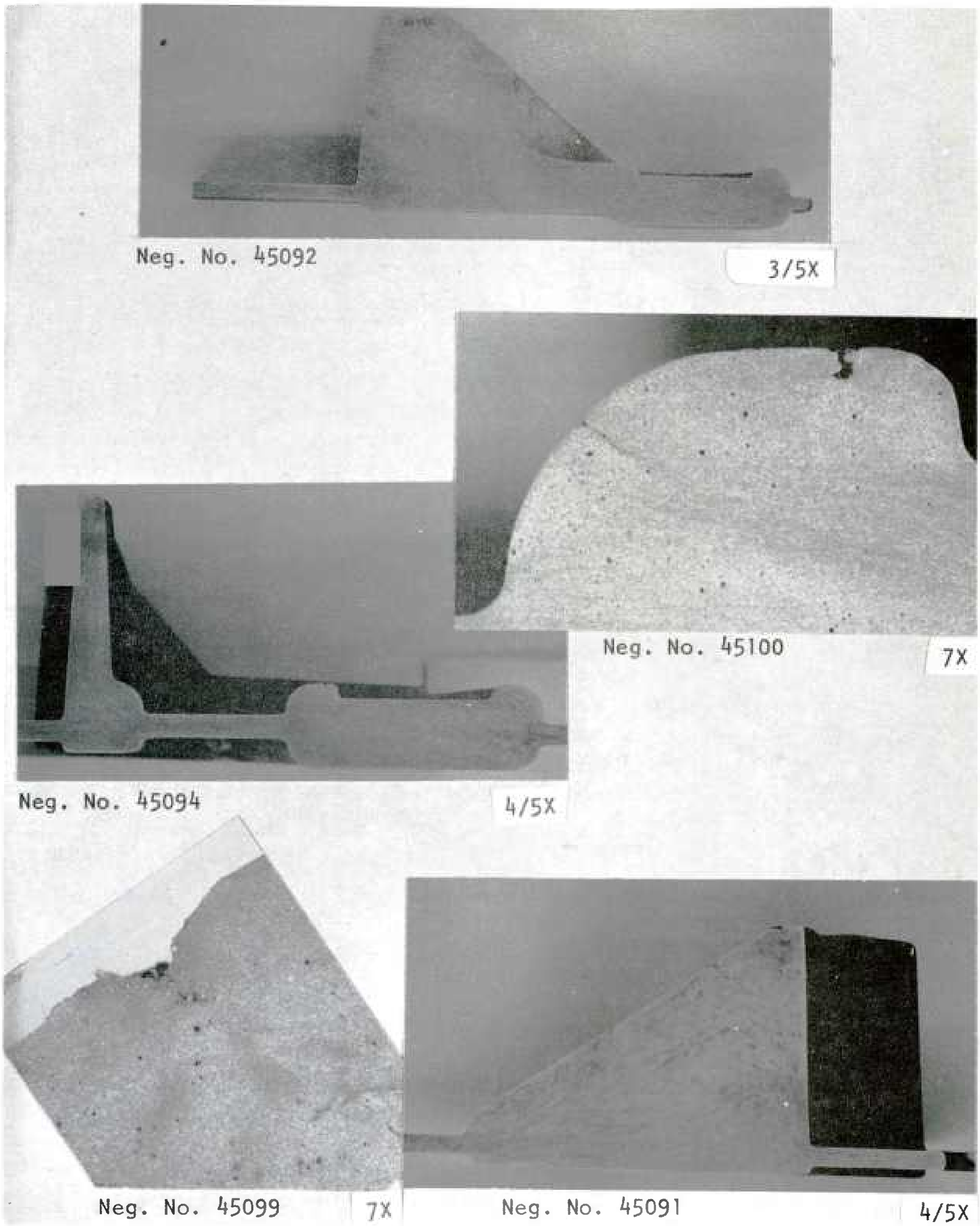


Figure 51

Sections of Forging No. 14. The black dots are most probably the unreacted Cr-Rich Particles. (See Fig. 50 for key to part locations.)

Forging No. 1 - Made from Alcoa powder with the two-stage forging operation.

No. 8 - Made from Alcoa powder with the one-stage operation.

No. 17 - Made from Alcan powder with the one-stage operation.

The photomicrographs for the three forgings with different heat treatments are shown in Fig. 52. The two types of powders and the two types of forging operation did not make any appreciable difference in the microstructure. As expected, micrographs of as-forged samples show (Fig. 52a) severely deformed structure. On solutioning and aging, recrystallized grains with much sharper boundaries can be seen. Significant substructure along with some undissolved precipitates is present. Also, chromium-rich particles are quite evident, and these were unaffected by heat treatment as was already noted in Phase I.

The hardness values of both Alcan and Alcoa powder forgings were very close, e.g., forging No. 8 had an average hardness of R_B 89, whereas forging No. 17 had an average of R_B 86 in the STA condition. Room temperature tensile tests for forging No. 17 in the STA condition show (Table 19) properties closely approaching longitudinal wrought specifications and exceeding those for the transverse direction.

An analysis of forgings made from both powders, given below, shows them to be within the specification limit:

Element	Chemical Analysis, % Forging No. 1 (Alcoa)	Chemical Analysis, % Forging No. 16 (Alcan)
Cu	1.53	1.59
Mg	2.31	2.14
Zn	5.85	5.52
O	0.48	0.37

The above-mentioned results clearly demonstrated that the Alcan powder was just as satisfactory as the Alcoa powder. Also, the mechanical properties and product integrity were quite remarkable with one-stage finishing die operation. Thus, it seemed feasible that sound forgings could be made with the one-stage operation, which was highly desirable for the cost-effectiveness of the process. This led to the following conclusions:

1. It may be feasible to forge the preform directly in the finishing dies.

2. Alcan and Alcoa powders were equivalent in terms of their response to the P/M forging process.

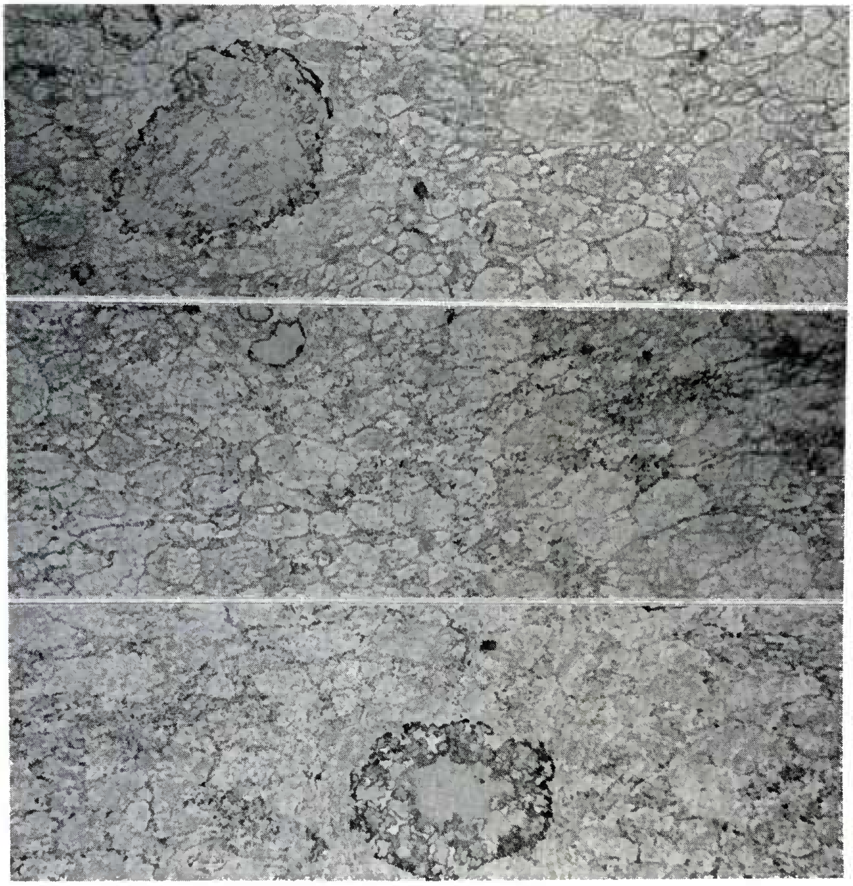
Neg. No.

Forging No.

17 45156

8 45161

1 45159



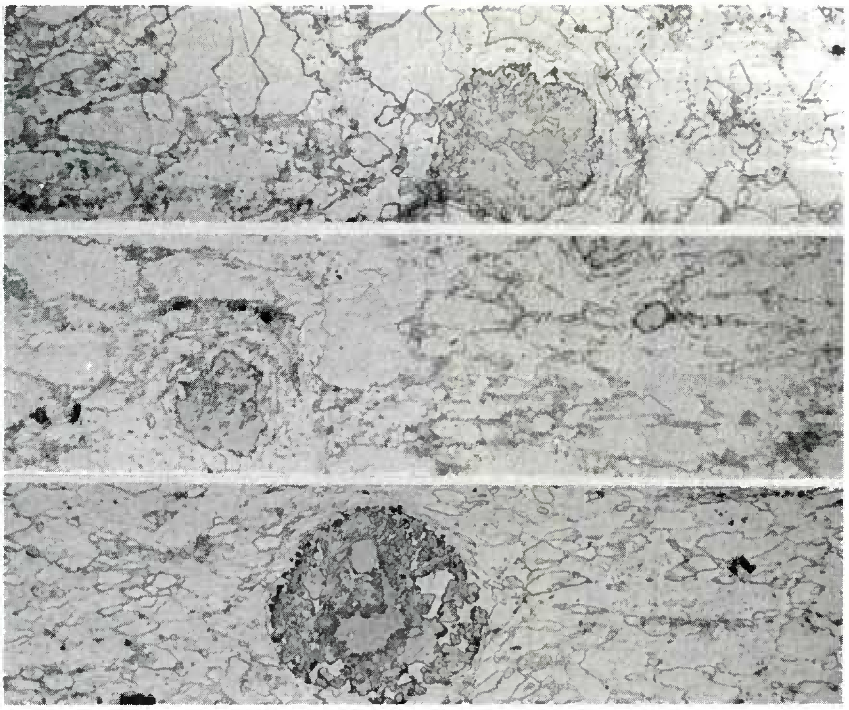
(a) As-Forged 200X

Figure 52

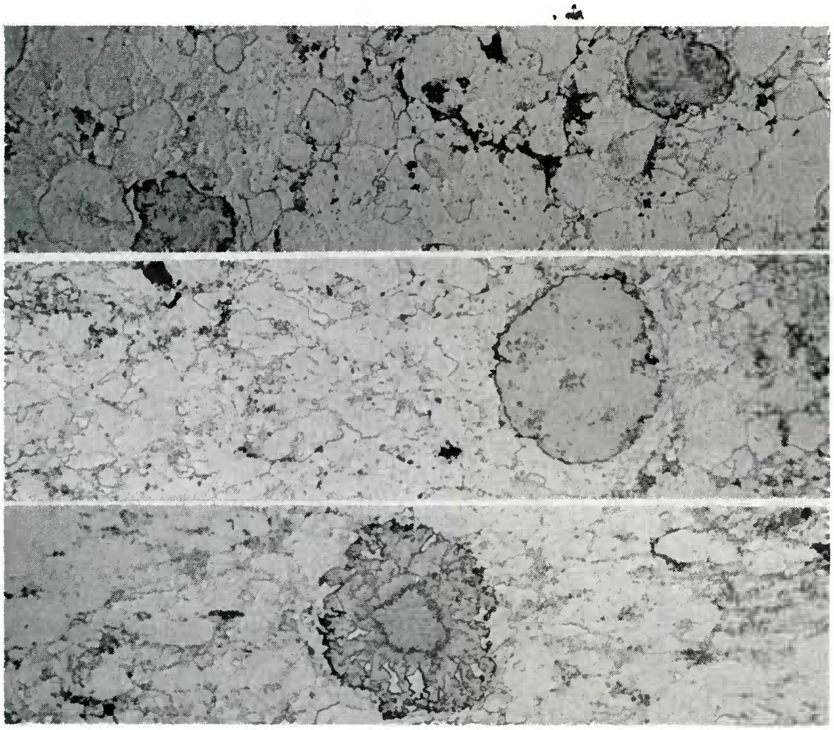
Micrographs of Forgings with Different Processing and Heat Treatments. (Forging No. 17, Alcan powder, one-stage operation, forging No. 8, Alcoa powder, one-stage operation, forging No. 1, Alcoa powder, two-stage operation.)

Neg. No.

Forging No.



(b) Solution Treated 900°F, 2 hr



(c) Solution Treated 900°F, 2 hr, Water Quenched, and Aged 250°F, 24 hr.

Figure 52 (cont.)

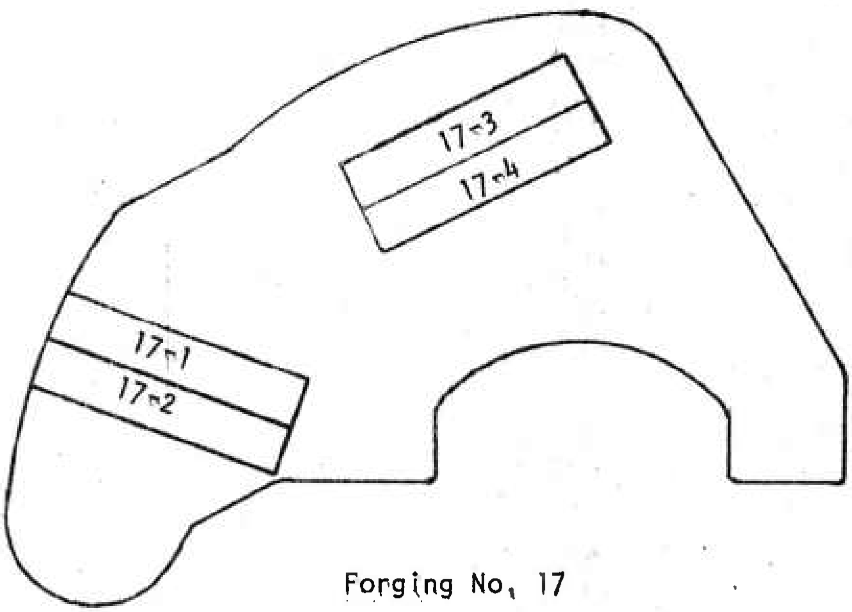
Table 19

TENSILE PROPERTIES OF A FORGING MADE DIRECTLY IN FINISHING DIES

(Tensile samples cut from forging No. 17 and tested in the T6 condition)

Sample No.	Directionality	0.2% Offset Y.S., ksi	UTS, ksi	Elong., %	R.A., %
17-1	Longitudinal	63.2	72.7	8.0	11.4
17-2	Longitudinal	62.1	72.1	9.0	11.7
17-3	Transverse	63.1	71.2	6.0	7.8
17-4	Transverse	63.8	73.0	8.0	10.8
Target[a]	Longitudinal	64.0	75.0	7.0	--
	Transverse	61.0	71.0	3.0	--

[a]Based in MIL-Spec. QQ-A-367H for wrought materials for samples from forgings of up to 1 in. thickness.



Forging No. 17

3. Modifications on preform bag shape are necessary for complete die filling.

5.4.4 Direct Forging of Modified Preforms in Finishing Dies

The modified bag design of Fig. 40 in Section 5.3.3 was used for the rest of the program. Several preforms starting with No. 22 in Appendix 1 were made with minor variations in the shapes by controlling the position of the inserts during pressing. The pressing and sintering parameters were kept the same as in the early part of Phase II. Preform Nos. 22, 23, 36, and 27 were forged directly in the finishing dies. The forging parameters and results are given in Appendix 2. The temperature and ram speed were maintained the same. Figure 53 shows two of the forgings and the preforms they were made from.

5.4.5 Modification of Flash Geometry

Forging No. 26 (Fig. 53) showed excellent die filling except for a slight underfill at the tallest rib. Minor cracking also occurred over a small length near the periphery. The latter did not occur on forging No. 22 (Fig. 53), showing that it was just a matter of providing enough material in the preform. It was more difficult to improve the filling of the rib detail. To achieve this, the flash geometry was modified by weld depositing some material on the top die (Fig. 30). This restricted metal flow into the flash near the rib and forced it into the rib detail of the cavity in the lower die. As discussed later, this die modification improved the die filling in the rib area.

5.4.6 Effect of Forging Speed and Temperature on Load

In all, 21 more identical preforms were made using the modified design. They were sintered and hand ground slightly to prepare them for production run and for the series to study the effect of forging speed onload. The latter forging series was conducted with a constant preform temperature of 830°F and with three press speeds of 0.1, 0.3, and 1.5 ipm. The effect of forging speed on the load is shown in Fig. 54. As expected, the loads are high at higher speeds. The maximum load applied was 700 tons and the average projected area of the forging, including the flash, was about 70 sq in.; therefore, the maximum pressure applied was about 20 ksi. Near the die closure the press speed showed less influence on load. Also, usage of a slower speed makes the cycle time considerably longer. Therefore, a press speed of 1.5 ipm was selected as the practical forging speed. This speed is significantly lower than 100 to 600 ipm speed commonly used with hydraulic forging presses. That speed range can increase the forging load substantially. Thus, the 1.5 ipm speed gives an optimum combination of low forging load and reasonable production rate.

Neg. No. 45207

(a)

Neg. No. 45392

(b)

Neg. No. 45218

(c)

Neg. No. 45394

(d)

Figure 53

Examples of Forgings Made Directly in Finishing Dies
and Preforms for the Forgings

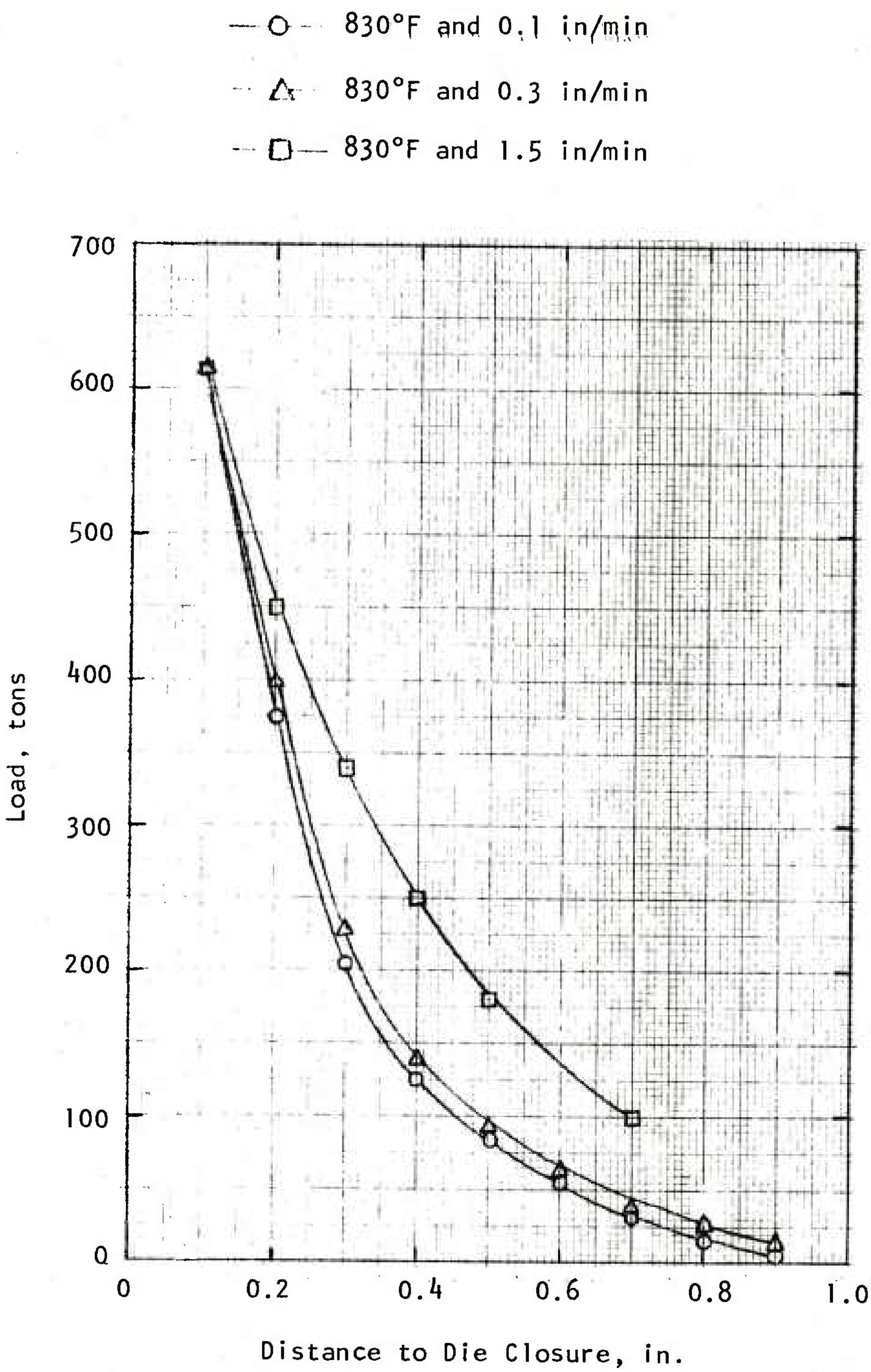


Figure 54

Load vs. Distance to Die Closure
for Different Forging Speeds

5.5 Production Run Forgings and Their Quality

Once it was established that preform design was adequate anough to produce a cam, it was decided to make a short production run with ten preforms. The optimum preform dimensions based on those actually measured on these preforms are shown in Fig. 55. All the processing parameters were maintained the same, i.e.:

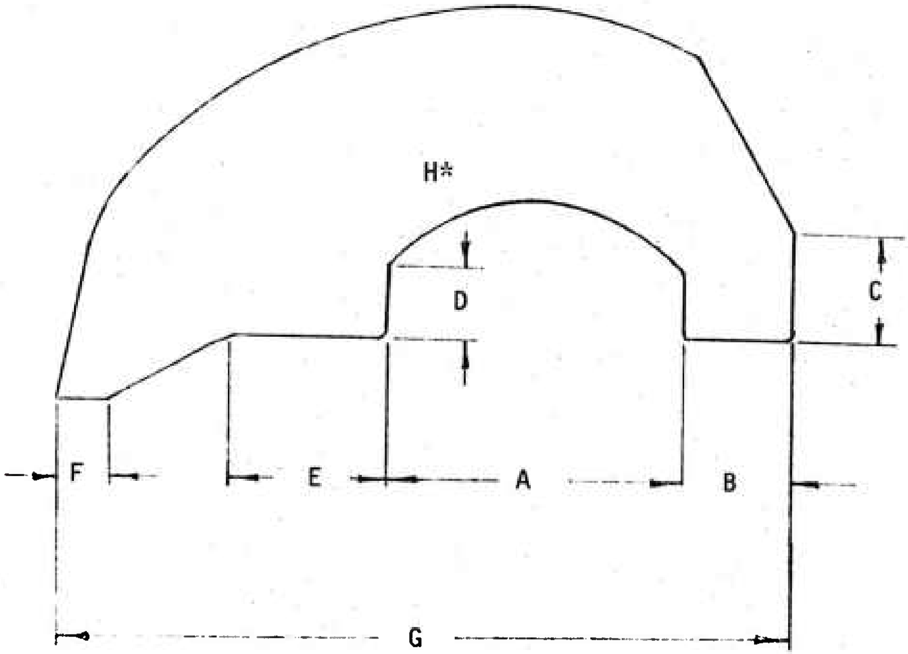
Preform temperature	- 830°F
Die temperature	- 750°F
Forging speed	- 1.5 ipm
Forging load	- 700 tons
Duration of load	- 2 min
Lubrication	- Fiske 604 and trichlorethylene, 50:50

Some of the preforms used for the production run and for load vs. deformation study are shown in Fig. 56a in the as-sintered condition. The production run forgings are shown in Fig. 56b.

The detail obtained in the forgings was excellent as can be seen in Fig. 56b. The first seven forgings, however, showed a slight lack of fill at the top of the tallest rib, Fig. 57a. The problem was attributed to buildup and entrapment of excessive lubricant in the deepest section of the lower die that corresponds to the top of the rib. Therefore, for the last three forgings, lubricant was applied to the preform only prior to placing it in the furnace. Also, the lower die was not lubricated again since there was adequate lubricant layer from previous runs. With these changes, complete die filling was achieved on forging Nos. 46, 49, and 51, the last of which is shown in Figs. 57b and c.

The reproducibility of the process was checked by measuring the thickness of the forging at point h (Fig. 27). The thickness for the ten forgings was in the narrow range of 0.725 to 0.740 in., thus indicating an excellent reproducibility of the process. The rib detail and several surfaces were forged net as planned (see target geometry in Fig. 27). The thickness at h was, however, larger by 0.085 to 0.100 in. then the maximum 0.640 in. dimension specified for the finish-machined part.

A simple and inexpensive machining operation on the flat back face will bring the thickness to the desired dimension. Alternatively, through usage of larger load and slightly modified preform geometry, this machining can be eliminated. It may be noted that, because of a machining error on the finishing dies, the P/M forging was made with a thinner tall rib than was necessary. Thus, this program suggests capability of making even more complex parts than the cam. Five of the forgings were trimmed to remove the flash. The trimmed forgings weighed an average of 2.76 ± 0.02 lb.



H* - Height perpendicular to paper at location shown

$A = 3.54^{+.08}_{-.14}$

$B = 1.08 \pm .08$

$C = 0.66^{+.14}_{-.10}$

$D = 0.85^{+.13}_{-.05}$

$E = 1.39 \pm .09$

$F = 0.94 \pm .09$

$G = 8.03^{+.10}_{-.15}$

$H = 2.32^{+.06}_{-.02}$

$\text{Weight} = 3.46^{+.13}_{-.15}$

Figure 55

Optimum Preform Dimensions
(Derived on the basis of measurements on ten preforms used for production run)

Neg. No. 45345

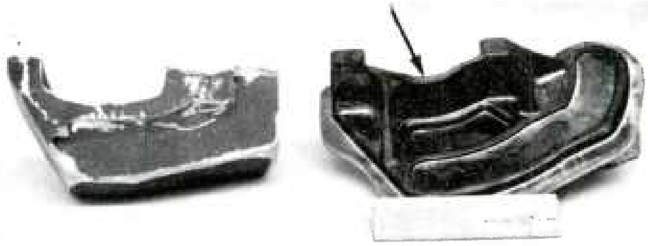
(a) Preforms in as-sintered condition

Neg. No. 45360

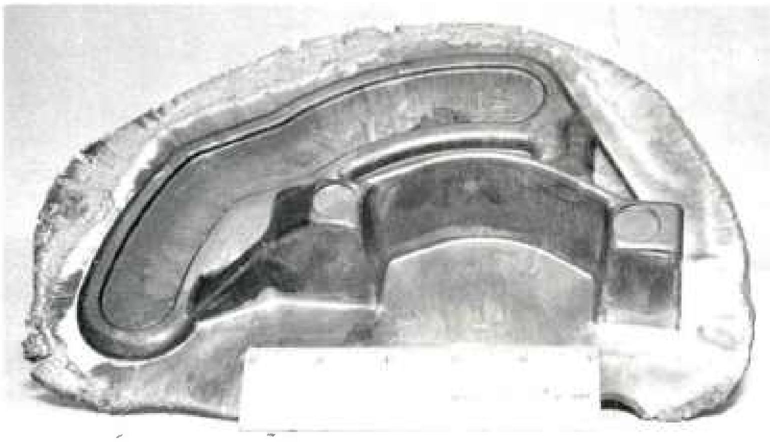
(b) Production run forgings (as-forged)

Figure 56

Overall Views of Several Preforms and Forgings



Neg. No. 45347 (a)



Neg. No. 45356 (b)

Neg. No. 45358 (c)

Figure 57

Comparison of Two Forgings. (a) Preform and forging No. 30 showing incomplete filling at the rib (arrow); (b,c) two views of forging No. 51 showing complete filling.

The weight of the flash was thus nearly 25 percent of the trimmed weight. This allowance was adequate to limit any cracking (Fig. 56b) of the P/M forging to the flash and give a sound trimmed forging.

The superior finish of the creep-forged P/M cam (Fig. 58a) is obvious when compared with the conventionally forged cam (Fig. 58b). The finish-machined cam (Fig. 58c) is also shown to highlight the near-net shape configuration of the P/M forging. Close-up views of the rib-web areas from both ends of the P/M and conventional forgings are shown in Fig. 59. These figures clearly indicate the capability of isothermal creep forging of a P/M preform to obtain a near-net shape component in contrast to the oversize conventional forging.

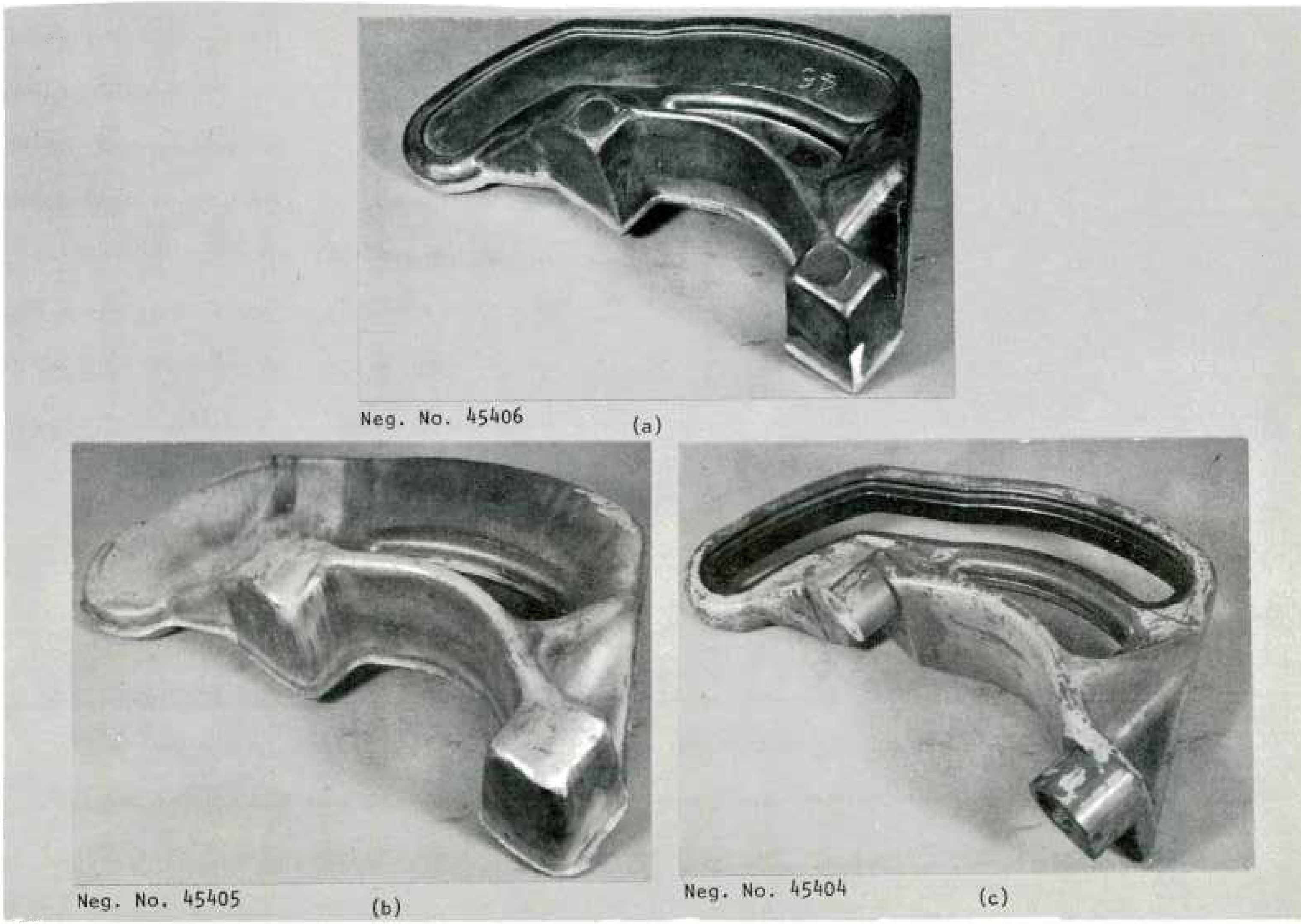


Figure 58

Comparison of the Creep-Forged P/M Cam (a) with a Conventional Forging (b) and the Finish-Machined Part (c). (Note the near-net shape of the creep-forged P/M cam.) (Approx. half scale.)

Neg. No. 45408

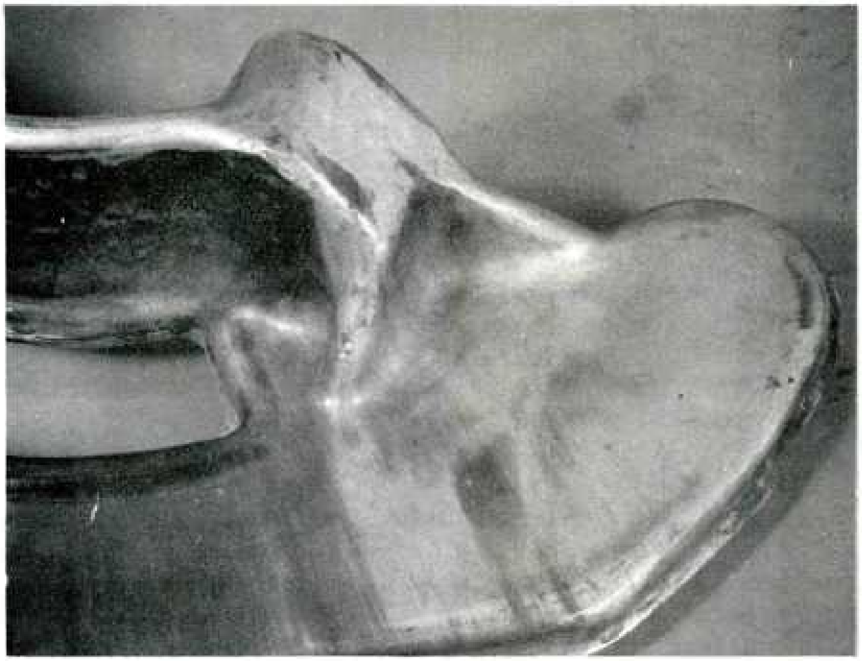
(a)

Neg. No. 45407

(b)

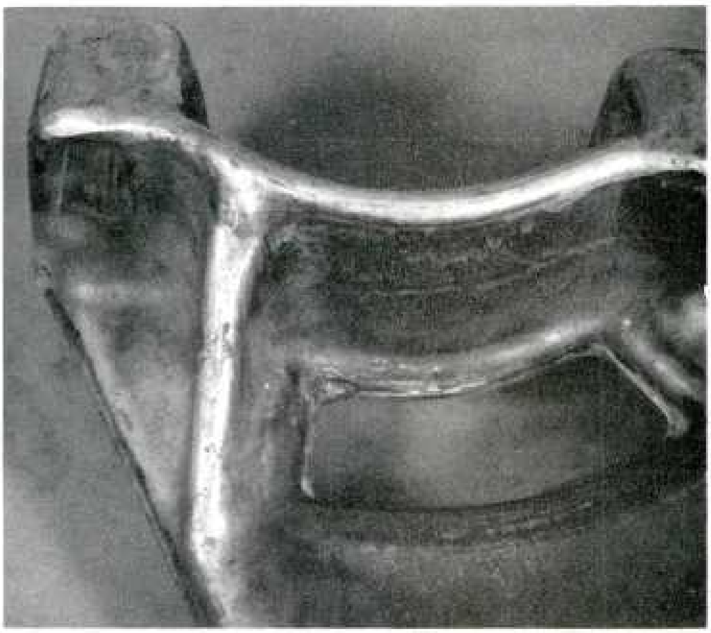
Figure 59

Close-ups of the Creep Forged P/M Cam (a and b)
and the Conventional Forging (c and d)
(Approx. half scale)



Neg. No. 45402

(c)



Neg. No. 45401

(d)

Figure 59 (cont.)

6. COST ANALYSIS

This section provides a preliminary cost analysis of the isothermal creep forging of the Al 7075 P/M cams in relation to conventional forging. An attempt is made to include all the cost elements normally associated with the production of forgings. The large equipment costs, such as for the forging press or the isostatic pressing facility, are however not considered. The costs for P/M forging were estimated on the basis of actual quotations or the costs incurred in the program except as noted below. The costs for conventional forging were based mainly on the data provided by the sponsor. The summary of the analysis is presented in Table 20.

In comparing the two processes, the labor cost was assumed to be \$25/hr. This unit cost includes direct labor, overhead, and supervision for each hour of direct labor. To estimate the cost of the P/M preform forging, engineering estimates are used for setup, isostatic pressing, and forging. Actual costs or quotations provide the basis in other cases. Engineering estimates are used for the cost of dies and N/C tape preparation for conventional forging. The other data were provided by the sponsor for forging in lots of 20. In our analysis, it is assumed that each lot consists of 100 pieces per setup. Since the sponsor's overall requirements are only of the order of 2000/yr, the per-forging costs for the various essentially manual operations are unlikely to change much from a lot size of 20 to a lot size of 100. The per-piece cost for heat treatment or N/C machining are also unlikely to change over this range of lot sizes. The tooling costs are amortized over one year's production of 2000 cams.

The analysis in Table 20 shows that the isothermal creep forging of P/M preforms will lead to a substantial saving of nearly 30% over the cost of a cam machined from a conventional forging. Note that the saving comes primarily from the reduced cost of finish machining. Additionally, the forging cost is also lower for the single P/M forging operation because conventional forging involves two forging operation in two different die sets. Note that the conventional forging uses over twice the material required for P/M forging. Interestingly, the material cost on a per-pound basis is also substantially higher for the wrought forging billet because of the uncommon section size used for the billet.

It is clear that the isothermal creep forging process can lead to substantial reduction in production cost of complex aluminum alloy components. The analysis is based on the work for the cam with linear dimensions of up to 10 in. and finished component weight of about 1.8 lb. The cost-effectiveness of the process is likely to be valid for a wide range of component size, but must be analyzed individually for each application under consideration.

Table 20

COST COMPARISON FOR CAMS MACHINED FROM P/M AND CONVENTIONAL FORGINGS

	Cam Machined from a P/M Forging		Cam Machined from a Conventional Forging	
Description	Cost Basis	Cost, \$/cam	Cost Basis	Cost, \$/cam
Tooling[a]	Finishing die, \$5,600 N/C tape, \$1,300 Isopress form, \$175 Rubber bags at \$23/bag for every 10 forgings	5.84	Blocker die, \$2,000 Finishing die, \$5,000 N/C tape, \$1,500	4.25
Material	3.5 lb/pc at \$0.92/lb	3.22	1 1/2 x 5 x 10 in. bar/pc at \$1.40/lb	10.50
Setup	16 hr/100 pc at \$25/hr	4.00	37 hr/100 pc at \$25/hr	9.25
Isopreform Preparation	Filling and evacuation, 1 hr/5 bags Sintering, \$3.60/pc Trimming, 1 hr/5 pc	13.60	(None required)	--
Forging and Trimming	(6 + 8) min/pc	5.83	36 min/pc	15.00
Heat Treating	3.75/pc	3.75	1.71 hr/pc for heat treat and N/C machining	42.75
N/C Machining	\$21/pc	21.00		
TOTAL		57.24		81.75

[a]Tooling amortized over one year's total requirement of 2000 cams.

7. FINAL PROCESS SPECIFICATION

7.1 Applicability and Scope

The following process specifications were drawn up for components to be made by isothermal creep forging of 7075 aluminum alloy P/M preforms. They pertain to elemental blended powders wherein the preforms are made by cold isostatic pressing, sintered, and then subjected to isothermal forging operation at slow speed. The topics covered are those important for the new processing technique. Details commonly known in forging and/or P/M industries or facility-related items necessary for high production rate are not covered.

7.2 Material

The work material will be elemental blended powders compounded to 7075 composition.* There will be no lubricant as is used for die pressing of P/M compacts. The powder size will be -100 mesh. The distribution of size is probably not important. As a guideline, in the subject work on which this specification is based, nearly 90% of the powder was of -325 mesh size.

7.3 Preform Preparation

The preform for forging will be prepared by cold isostatic pressing and sintering. The compaction pressure will be at least 40,000 psi and will be maintained for approximately 2 min. On removal from the bag, the compact will be inspected for contamination by pressurizing oil. Any indication of oil contamination (beyond slight trace) or cracking will be reasons for rejection of the preform from further processing. The preforms will be sintered in nitrogen, argon, or vacuum at 1025 ± 25°F for 2 hr. The duration is after the center of the preform reaches the sintering temperature. A limited amount of trimming and hand-grinding may be employed after sintering to more closely control the shape and weight of the preforms.

The preform design deserves careful attention. It should be such that, in the subsequent forging stage, the stress system will be predominantly compressive. At the same time, a minimum of 30% reduction in thickness should be achieved at all portions in the preform for getting good properties in the forging.

7.4 Forging and Heating Equipment

Any conventional hydraulic forging press can be employed for the new process. The press should have adequate tonnage of about 20 to 25 tons/

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*There is a likelihood that the chemistry can be modified to reduce or eliminate chromium content on the basis of further development work. This will reduce the material cost and make the end product more homogeneous.

sq in. for the plan area of the forging including the flash. The press should be capable of being operated at slow speeds of 5 ipm or lower, and of maintaining the load for the desired duration of 2 min on the forging. The preform can be heated in air in any furnace with suitable temperature range. The dies can be heated by any technique capable of heating the dies to and maintaining them in the desired temperature range of about 750 to 830°F.

7.5 Forging Procedure

The forging procedure is basically similar to conventional forging except for the closer control on die temperature and press speed. The sintered preform is coated with a commercially available graphite-base forging lubricant. (This lubrication step may be eliminated on the basis of some initial tests.) It is then heated in a furnace to 830 ± 25°F. The heating will be for at least 30 min after the center of the preform is anticipated to have reached the furnace temperature. It will then be removed from the furnace, transferred to dies* preheated to 750 to 830°F and forged. The dies will have been coated with the lubricant just prior to placing of the preform. However, depending on the condition of the die, it is not essential to coat the die before each forging. Care must be taken to avoid buildup or entrapment of excessive lubricant in the deepest sections of the dies. Venting may be desirable for particularly deep dies. The load will be built up to the desired level using a press speed of 5 ipm or less--preferably about 1 to 2 ipm--and maintained for 2 min.

7.6 Target Properties

The properties of the P/M forging should meet those specified for wrought 7075 aluminum alloy forgings by MIL-Spec. QQ-A-367H. The heat treatment recommended on the basis of the wrought product specification is solution treating at 900°F for 2 hr, water quenching, and aging at 250°F for 24 hr. For P/M forgings some modification of this practice may lead to better properties. The processing leads to extremely fine grain size and no specification for grain size is warranted.

7.7 Inspection

The forgings will be inspected by dye penetrant tests and a dimensional check. Particular attention will be paid to ensure that any cracking in the flash does not extend to the trimmed forging area. Small surface imperfections can be ground off as judged by subsequent dye penetrant tests if the dimensional tolerances can still be met. The forgings should be free of customary forging defects such as laps, cold shuts, and cracks. Radiography is not warranted if inspection of initial forgings by radiography or destructive testing indicates that there is little chance of internal fractures.

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*At this stage, the opening between the dies should be adequate to insert the preform. Too large an opening should be avoided to keep temperature loss to a minimum.

8. PRINCIPAL RESULTS AND CONCLUDING REMARKS

The foregoing sections have presented the details of isothermal creep forging of 7075 aluminum alloy P/M preforms with special emphasis on a nonsymmetrical component, namely, a cam. This section summarizes the principal results and offers comments concerning the potential of the process for large-scale production.

8.1 Accomplishments and Main Results

1. The technology of isothermal creep-forging was successfully developed for 7075 aluminum alloy P/M preforms and demonstrated with the production of a complicated nonsymmetric component--a cam.

2. The cam is a complex component, weighing about 1.8 lb after machining. A conventional forging for the cam weighs about 2.9 lb. In conventional forging, the starting material is 10 x 5 x 1.5 in. bar stock weighing 7.5 lb which is forged in two different die sets. In the P/M process, the weight of the starting material, about 4.1 lb, can be further reduced to about 3.5 lb by modifications of the bag for isostatic pressing. The forging is made in one-step finishing dies. Therefore, utilization of material is 51% using the P/M creep forging technology, whereas, by the conventional route, it is only 24%.

3. Tooling systems were designed and fabricated from H13 die steel and showed to perform satisfactorily.

4. The process parameters were optimzied in a systematic manner, and a suitable lubricant and application technique were selected to optimize the product quality.

5. The isothermal forgings were inspected by dye penetrant method, and were also subjected to room temperature tensile testing in the T6 condition. Forgings made were defect-free and virtually met the wrought product specifications.

The excellent mechanical properties obtained without extensive chromium diffusion indicate the possibility of new alloy development using P/M technology. As a start, the costly strategic alloying element, chromium, can be eliminated when using P/M technology.

6. This study showed that, in fabrication of complex weapon components, the new technology of isothermal creep-forging of P/M preforms can reduce finish machining labor substantially. Some machining will still be necessary, such as drilling of holes and machining of slots to critical dimensions.

7. The isothermal creep-forging technique extended to P/M 7075 aluminum components shows tremendous potential for reduction in the overall cost of the finish-machined components. In addition, the process also has a potential for significant reduction in total energy consumption.

8. A process specification was prepared for isothermal creep-forging of P/M preforms. The specification is applicable to elemental powders blended to 7075 composition.

8.2 Comments on the Potential for Large-Scale Production

1. The work conducted under the project clearly demonstrates that the isothermal creep-forging technology using P/M preforms is capable of production of complex weapon components, such as the cam, at a production rate of 2000/yr or more that is of interest to the Arsenal. Satisfactory production of these components does not require any expensive equipment; the cost of an autoclave is not significant when compared to the press cost. The rubber bags are commercially available at a very reasonable price and are reusable several times.

2. A conventional hydraulic forging press is satisfactory for isothermal creep-forging. At 10 tons/in.^{2} forging load, very large components can be fabricated with currently available presses.

3. In this process, the duration of pressure on the preform (the hold time) is short, i.e., about 2 min, and the production rate is mainly controlled by this hold time once the preform is ready. However, by combining sintering with forging step and using an automatic belt conveyor-type furnace, the production time can be significantly reduced. Similarly, by automatic filling and compaction, the overall preform production rate can be substantially increased.

4. Since the dimensions of the creep-forged P/M components can be controlled closely by proper die dimensions, close tolerances can be obtained on the finished surfaces.

5. The die systems for isothermal creep-forging can be fabricated from common die steels, and the dies can be heated by well-established heating methods.

6. The isothermal creep-forging process combines conventional P/M processing with creep-forging. Successful application of the technique will be dependent on the training of personnel to familiarize them with both techniques.

7. Commercially available elementally blended aluminum P/M alloy powders are adequate for production. Sufficient aluminum P/M powder capacity exists. It is possible that strategic and costly alloying elements, such as chromium, may be eliminated altogether from alloy chemistry when aluminum alloy P/M technology is used.

8. The process specification prepared in the program will be valuable for using the process for large-scale production.

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APPENDIX 1

DATA ABOUT PREFORM WEIGHTS

Table I-1

DATA ABOUT PREFORM WEIGHTS

Preform No.	Weight of Preform after Compaction, lb	Weight of Preform after Trimming, lb	Preform No.	Weight of Preform after Compaction, lb	Weight of Preform after Trimming, lb
		Initial Bag Design			
Alcoa Powder			Alcan Powder		
1	4.51	3.41	14	4.35	2.66
2	4.21	3.51	16	4.32	2.90
3	4.40	3.50	17	4.22	2.71
5	3.73	3.05	20	4.34	3.55
6	4.10	3.20			
7	4.10	3.29			
8	3.59	3.08			
9	3.60	2.77			
		Modified Bag Design			
48	3.94	3.31	31	4.11	3.42
49	4.10	3.39	32	4.11	3.31
50	4.22	3.63	33	4.40	3.47
51	4.20	3.46	34	4.25	3.50
52	4.23	3.49	35	4.35	3.39
			36	4.48	3.45
Alcan Powder			37	4.26	3.24
22	3.89	3.66	38	4.45	3.59
23	4.40	3.28	39	4.51	3.56
24	4.32	3.92	41	4.45	3.59
26	4.22	3.00	42	4.81	3.54
27	4.02	2.82	43	4.30	3.52
28	4.33	3.65	46	4.40	3.54
30	4.20	3.67	47	4.26	3.47

Note: 1. The preforms used for the production run were 31-35, 39, 41, 46, 49, and 51.

2. Preforms used to study the effect of speed on forging load were 28, 30, 36-38, 42, 43, 47, 48, 50, and 52.

3. Preforms through No. 25 were made while the proper rubber insert geometry was being developed. Preforms from No. 26 onwards were made with the rubber inserts shown in Fig. 41.

4. Good preforms that were not forged were 15, 18, 19, and 21.

5. Preforms rejected because of oil leakage or cracking during isostatic pressing were 4, 10-13, 25, 29, 40, 44, and 45.

APPENDIX 2

FORGING DATA

APPENDIX 2

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This Appendix provides raw forging data about the forging trials conducted to optimize the processing conditions and the preform geometry. The details of preform geometry were covered in the text, and the data about the preforms were summarized in Appendix 1. The preforms used for the production run were forged under conditions described in the text in Section 5.5, and the data about the forging series conducted to study the effect of speed on forging load were summarized in Fig. 54. The data for these two series are not repeated in this Appendix.

The preforms for forging were heated for 1 hr after they reached the desired temperature. The die temperature was, in all cases, in the range of 700 to 800°F. The forging lubricant was Fiske's 604 for both the dies and the preforms, and for forgings made from preform No. 22 onwards, the lubricant was thinned with 50% trichloroethylene.

Table 2-1

FORGING DATA

Preform No.	Press Speed, ipm	Preform Temp., °F	Load, tons	Duration, min	Comments
		Two-Step Forging, Alcoa Powder			
1	0.3	750	400	0	Some cracking. Trimmed weight, 3.2 lb.
	0.3	750	390	0	Severe cracking and underfill in rib detail.
3	0.1	750	350	1	No cracks observed by visual inspection. Trimmed weight, 3.2 lb.
	0.1	830	380	1	Much cracking and underfill in rib detail.
6	0.2	750	400	1	Some cracking Trimmed weight, 3.0 lb.
	0.1	830	150	-	Forged incrementally stopping at 1.5, 1, and 1/4 in. from dies. Cracks appeared 1 in. from die closure. 10 min heating between steps.

Table 2-1 (cont.)

Preform No.	Press Speed, ipm	Preform Temp., °F	Load, tons	Duration, min	Comments
7	0.1	750	350	1	Some cracking. Trimmed weight, 3.1 lb.
	0.1	830	-	-	Forged incrementally stopping at 1 1/4 and 3/4 in. from die closure. Cracks appeared at 3/4 in. from die closure. May be due to extensive cooling of preform. 10 min heating between steps.
		One-Step Forging, Alcoa Powder			
2	0.1	900	350	1	0.25 in. to die closure. Extensive cracking and incomplete filling of cavity.
5	0.1	900	360	1	Incomplete filling of cavity and less severe cracks than No. 1. Pinching of material.
8	0.3	830	350	1	Incomplete filling and cracking at web. Pinching of material.
9	0.1	830	350	1	Incomplete filling of cavity and cracking at thin web sections. Some pinching of material.
		One-Step Forging, Alcan Powder			
14	1.5	830	500	1	About 1/8 in. less material at rib C (see Fig. 50 for key to letter designation). Small cracks at the top of rib C.
16	1.5	830	600	0	Rib C is more deficient in material than No. 14.

Table 2-1 (cont.)

Preform No.	Press Speed, ipm	Preform Temp., °F	Load, tons	Duration, min	Comments
17	1.5	830	400	1	Lack of material at B and C. Cracks at top of rib C.
20	1.5	830	500	1	Incomplete filling at rib C. Cracks at the top of rib C. Die closure incomplete by 0.03 in.
22	1.5	830	500	2	Much cracking at area B and incomplete fill in rib C.
23	1.5	830	500	2	Incomplete filling of rib C because of lack of material, also some cracking. Excessive flash in some areas. 0.03 in. to die closure.
24	1.5	830	600	2	Incomplete filling at rib C. Excessive flash in some areas. 0.05 in. to die closure.
26	1.5	830	600	2	Incomplete filling and cracking at rib C. Too little flash.
27	1.5	830	600	2	Some cracking and inadequate filling.

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Unclassified report.

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The second phase involved further optimization of the processing variables by use of proper preform and tooling design. Effectiveness of the process was demonstrated by a prototype production of a cam component, P/N 8433752, for the 105 mm howitzer. Excellent cam forgings, free of any cracking and with complete die filling, were made in a single forging operation. The forging had many net surfaces and a smooth finish. Mechanical properties of the cam in longitudinal and transverse directions were practically the same and were UTS 72 ksi, 0.2% Y.S. 63 ksi, and elongation of 8.5% for longitudinal and 7% for transverse specimens. These properties exceeded those of specification QQ-A-367H for wrought materials in the transverse direction and approached those in the longitudinal direction. A finalized process specification was recommended defining powder size, preform density, and sintering and forging conditions. Preliminary cost analysis shows projected cost saving of 30% when the cam is made from a P/M forging as compared to making it from a conventional forging.

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