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DEVELOPMENT OF ISOTHERMAL FORGING OF TITANIUM CENTRIFUGAL COMPRESSOR IMPELLER

T. Watmough

IIT Research Institute

Prepared for:

Army Materials and Mechanics Research Center

May 1973

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May 1973

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13. ABSTRACT

The technology of isothermal forging of titanium has been successfully extended to the production of impeller forgings. A four-part nickel-base superalloy die set weighing approximately 2000 lb was made and utilized to produce ten Ti-6Al-4V alloy forgings. The ten forgings were 13 1/2 in. OD, had a plan area of 114 sq. in., weighed between 24 and 25 1/2 lb, and had 36 blades radially emanating from the hub. The blades were 0.160 in. thick at the thinnest portion and had depths ranging from 3/4 to 1/2 in. depending upon location. The thickness of the hub portion of the forging at the 13 1/2 in. OD was typically 0.210 in. Preform temperatures were typically 1750°F and die temperatures 1600°F. Press forging loads were usually 1000 tons, equivalent to 17 kpsi forging pressure.

The finish-machined impeller weighs approximately 12 lb; the isothermally produced forging typically weighs 25 lb, while the forging conventionally produced for this impeller weighs approximately 60 lb. Significant savings in raw material and machining time would therefore accrue if isothermal titanium forgings are used for this part.

Details of illustrations in this document may be better studied on microfiche.

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Technical Report by

T. WATMOUGH

IIT Research Institute
10 West 35th Street
Chicago, Illinois 60616

May 1973

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FOREWORD

This Final Technical Report covers the work performed under the Contract DAAG46-72-C-0067 from December 7, 1971 to May 21, 1973 and is designated internally as IITRI-B6115-16.

This contract with IIT Research Institute, 10 West 35th Street, Chicago, Illinois 60616, was initiated by the Army Materials and Mechanics Research Agency, Watertown, MA 02172. It was under the technical supervision of Mr. E. N. Kinas of that facility.

The work was conducted at IIT Research Institute under the direction of Mr. T. Watmough, Assistant Director, Metals Research Division. Dr. K. M. Kulkarni, Manager of the Metalworking Section, assisted in the forging effort. Others who contributed to the overall program were Dr. N. M. Parikh, Director of Metals Research Division; J. Dorcic, Experimentalist; Mr. M. Malatesta, Metallurgist; and Mr. D. A. Stawarz, Experimentalist.

This project has been accomplished as part of the U.S. Army Manufacturing Methods and Technology Program, which has as its objective the timely establishment of manufacturing processes, techniques or equipment to insure the efficient production of current or future defense programs.

DEVELOPMENT OF ISOTHERMAL FORGING OF TITANIUM CENTRIFUGAL COMPRESSOR IMPELLER

ABSTRACT

The objective of this program was to develop processing methods, equipment, and dies for producing--by the isothermal forging technique--a complex Ti-6Al-4V alloy impeller forging requiring minimum machining. The impeller is approximately 13 in. diameter and is characterized by 36 thin blades.

A two-phase program was undertaken to accomplish these objectives. The first phase involved the production of a simplified version of the impeller to establish processing parameters, metal flow characteristics, and ability to meet specification requirements. The second phase was concerned with the development of a full-scale impeller forging based on the findings of the first phase.

The isothermal forging process requires the forging dies to be heated to the forging temperature. Because there is no danger of cooling of the workpiece by the dies, slow press speeds can be used to accommodate the strain-rate sensitivity of titanium alloys. The forging temperature for titanium alloys typically ranges from 1600° to 1800°F, and the dies must be made from superalloys.

In Phase I a series of Ti-6Al-4V forgings of a simplified version of the impeller were produced. These forgings were 8 1/2 in. diameter, weighed approximately 8 lb, and incorporated 20 blades arranged in four clusters of five. The blades ranged in thickness from 0.100 to 0.200 in. and were 3/4 in. in height and had zero draft. The relevant processing parameters were preform/die temperatures of 1700°F, press forging pressures of 20 to 22 kpsi, and a trapped die forging technique.

In Phase II a four-part die set weighing approximately 2000 lb was produced: an upper die which formed the upper or top face of the forging, a die insert in which the blades were formed, a die insert holder, and an ejection pin which also formed the detail on the inside diameter of the forging. The various components were precision cast in nickel-base superalloys, either IN-100, MAR-M 200, or Inconel 718.

Ten Ti-6Al-4V forgings of 13 1/2 in. outside diameter, having a plan area of 114 square inches, weighing between 24 and 25 1/2 lb, and having 36 blades radially emanating from the hub were produced. The blades were 0.160 in. thick at the thinnest portion and had depths ranging from 3/4 to 1/2 in. depending

upon location. The thickness of the hub portion of the forging at the 13 1/2 in. outside diameter was typically 0.210 in. Preform temperatures were typically 1750°F and die temperatures typically 1600°F. Press forging loads were usually 1000 tons, equivalent to 17 kpsi forging pressure.

The finish-machined impeller weighs approximately 12 lb; the isothermally produced forging typically weighs 25 lb, whereas the forging conventionally produced for this impeller weighs approximately 60 lb. Significant savings in raw material and machining time would therefore accrue if isothermal titanium forgings are used for this part.

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1. INTRODUCTION

Titanium alloy forgings are finding increasingly wide usage because of their high strength-to-weight ratios and good integrity. However, the production of titanium alloy forged structural shapes of reasonable complexity is not without difficulty. These difficulties revolve around the present requirement of forging near the beta transus to obtain favorable microstructural (and therefore mechanical property) features, and the associated high flow stress at these temperatures. With the present forging technology this severely limits the degree of reduction which can readily be imposed during the forging operation as well as the complexity of the forging, the depth of webs, and the degree of draft on such webs and similar parts of the forged shape.

The Metals Division of IIT Research Institute has, over the last four years, developed a method of forging titanium alloys using cast-to-shape superalloy dies heated to the workpiece temperature.(1-4) This isothermal forging technique represents a major breakthrough in forging technology since it overcomes the difficulties experienced in more conventional practices. Forgings of great complexity can be produced from relatively simple workpiece shapes in a single stroke of the press and in a single die set. These forgings are well beyond the capabilities of conventional forging technology, where die filling is severely inhibited by cooling of the workpiece in dies of lower temperature, or by the very marked increase in resistance to deformation when higher strain rates are used to shorten the die-workpiece contact time (for example, in hammer forging).

The objective of this program was to develop processing methods, equipment, and dies for producing by the isothermal forging technique a Ti-6Al-4V alloy forging from which the impeller shown in Figures 1, 2, and 3 could be economically machined. The impeller is approximately 13 in. in diameter and is characterized by 36 thin blades.

A two-phase program was undertaken to accomplish these objectives. The first phase involved the production of a simplified version of the impeller, to establish processing parameters, metal flow characteristics, and ability to meet specification requirements. The second phase was concerned with the development of tooling and the production of a full-size impeller based on the findings in the first phase. This full size Ti-6Al-4V impeller is identified as Part No. 1-100-078-03.

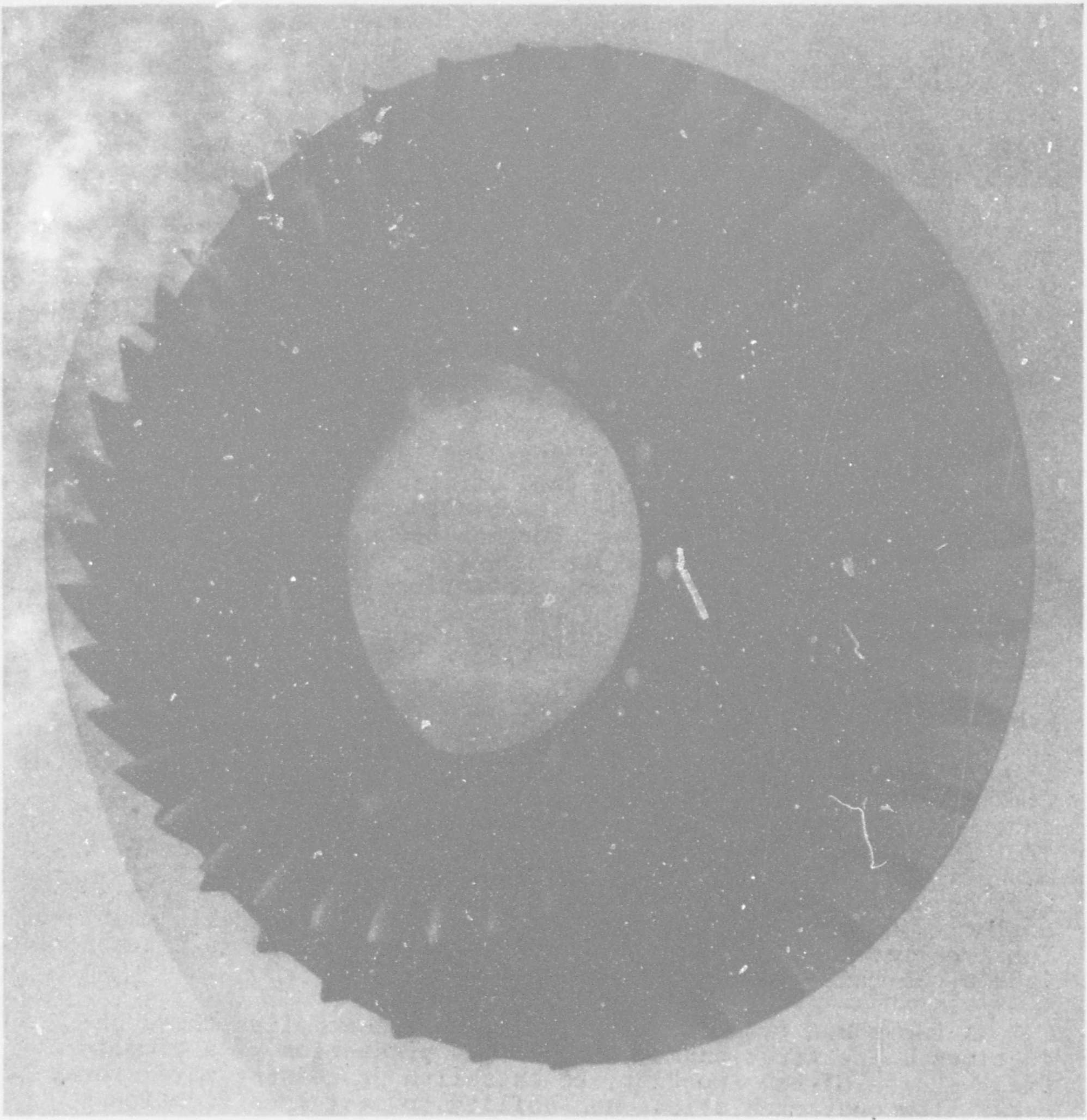


Figure 1

View of Finish-Machined Ti-6Al-4V Impeller

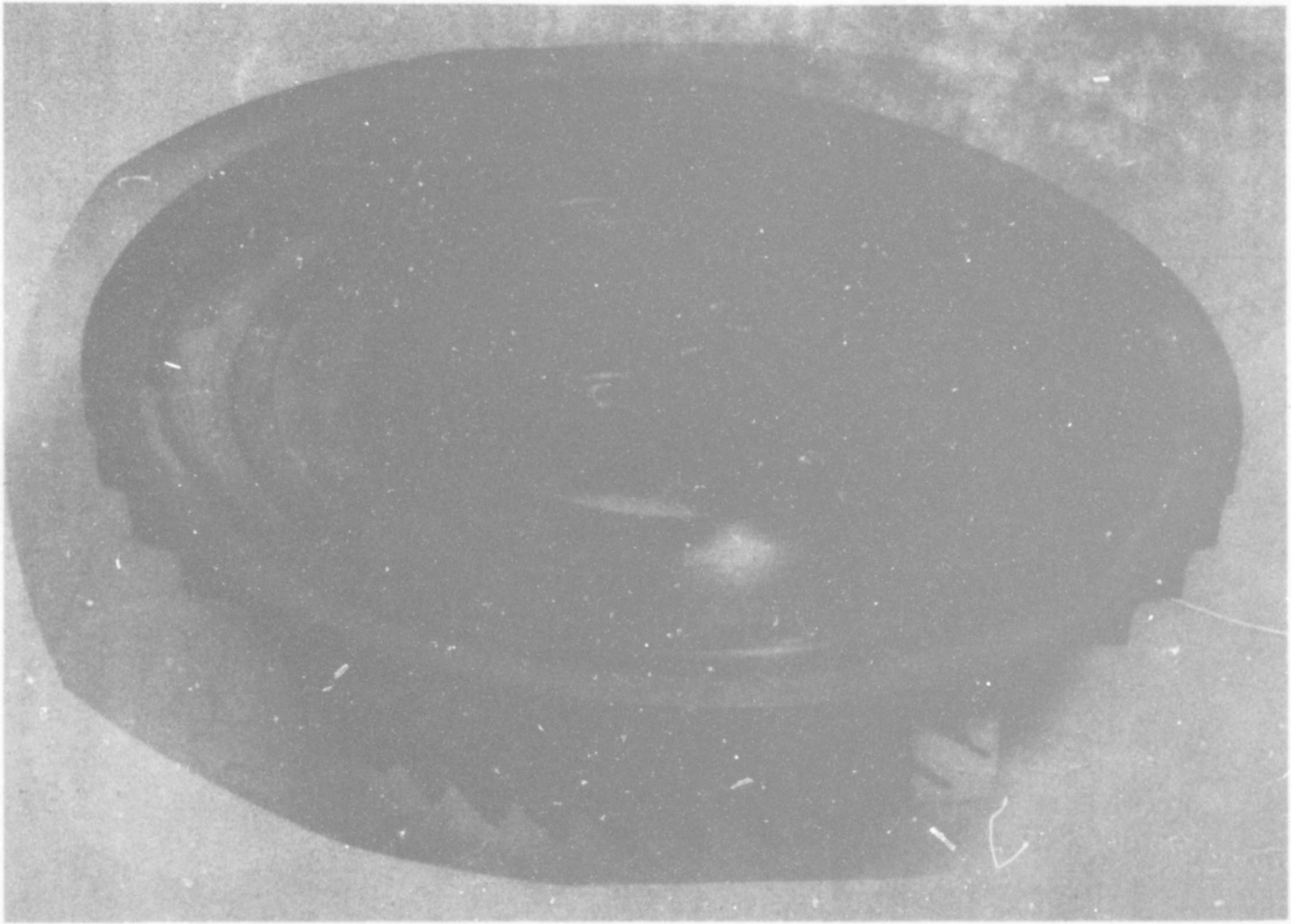


Figure 2
View of Top Face of Ti-6Al-4V Impeller

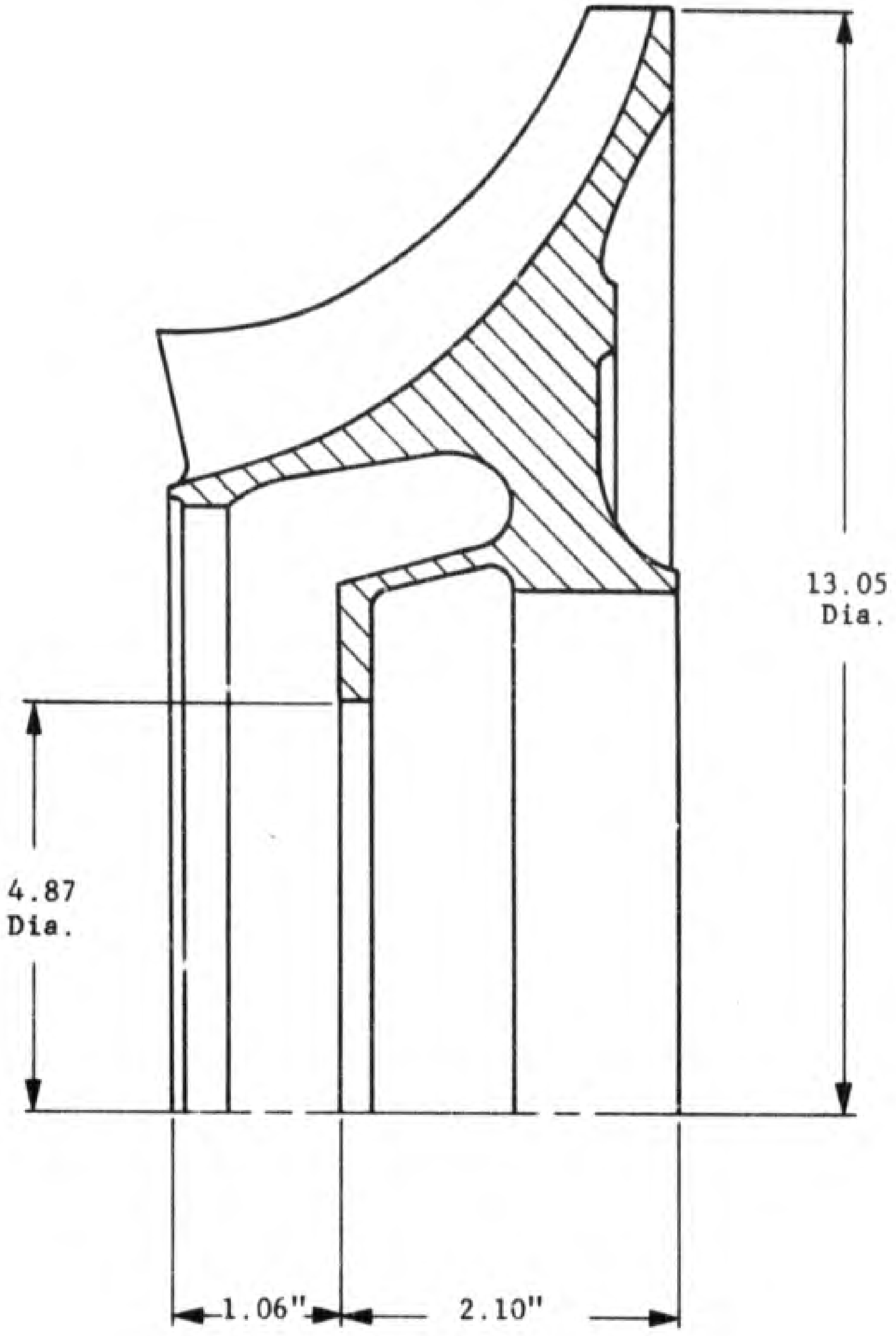


Figure 3

Longitudinal Cross Section of the Impeller. (Only half of the impeller is shown, and only a few representative dimensions are given.)

2. PRINCIPLES OF ISOTHERMAL SLOW SPEED (CREEP) FORGING

Generally, the forging temperatures for titanium alloys vary between the beta transus and 300°F below the beta transus (approximately 1400° to 1800°F). Since die temperatures normally range between 600° and 900°F in conventional forging, there is considerable difference between the die and the billet temperatures. To reduce the amount of cooling of the workpiece by the dies, there is a tendency to utilize fairly high forging speeds. It is then difficult--because of the strain-rate sensitivity of the titanium alloy as well as the increasing strength due to the chilling effect--to forge complex shapes or to forge sections with thin webs.

Complex titanium alloy forgings, therefore, require a number of forging steps in several sets of dies. Since these conventional forgings usually have to be machined to a final shape and size, the cost of the net forgings is high. Consequently, in many instances complex shapes of thin web forgings are impossible to produce by conventional forging practice.

The isothermal forging technique, where the dies are heated to the forging temperature, appears to be one possible solution to these problems. Naturally the dies must be made of superalloys to withstand the high temperatures, and, since superalloys are difficult to machine, the dies must be cast as close to finish dimensions as possible.

In isothermal slow-speed forging, the die and the billet are heated to the same temperature; therefore, there is no danger of specimen cooling, any suitable press speed can be chosen or selected for forging, and speed need not be controlled independently. Generally, the load is maintained at a preselected low value. Then the speed of forging is automatically controlled by the resistance to deformation of the material. Thus, since the load is maintained at a reasonably steady low value, the speed of the press decreases until the corresponding resistance to deformation of the material is also reduced and the press moves at such a speed that the preselected tonnage is balanced by the total load requirements of the forged material.

The strain-rate sensitivity of the yield strength of Ti-6Al-6V-2Sn alloy at different temperatures is shown in Figure 4. The data were obtained by simple upsetting tests in which a small billet was heated to the required temperature in a container completely enclosing it, and so the tests could be conducted without any appreciable cooling of the billet. It is obvious that the forging load requirements at a temperature (say, 1800°F) would be reduced by nearly a factor of 5 by changing the press speed from 50 ipm to approximately 0.6 ipm. The load requirements can be further reduced if the deformation speed is even slower. Similar trends are observed at other forging temperatures.

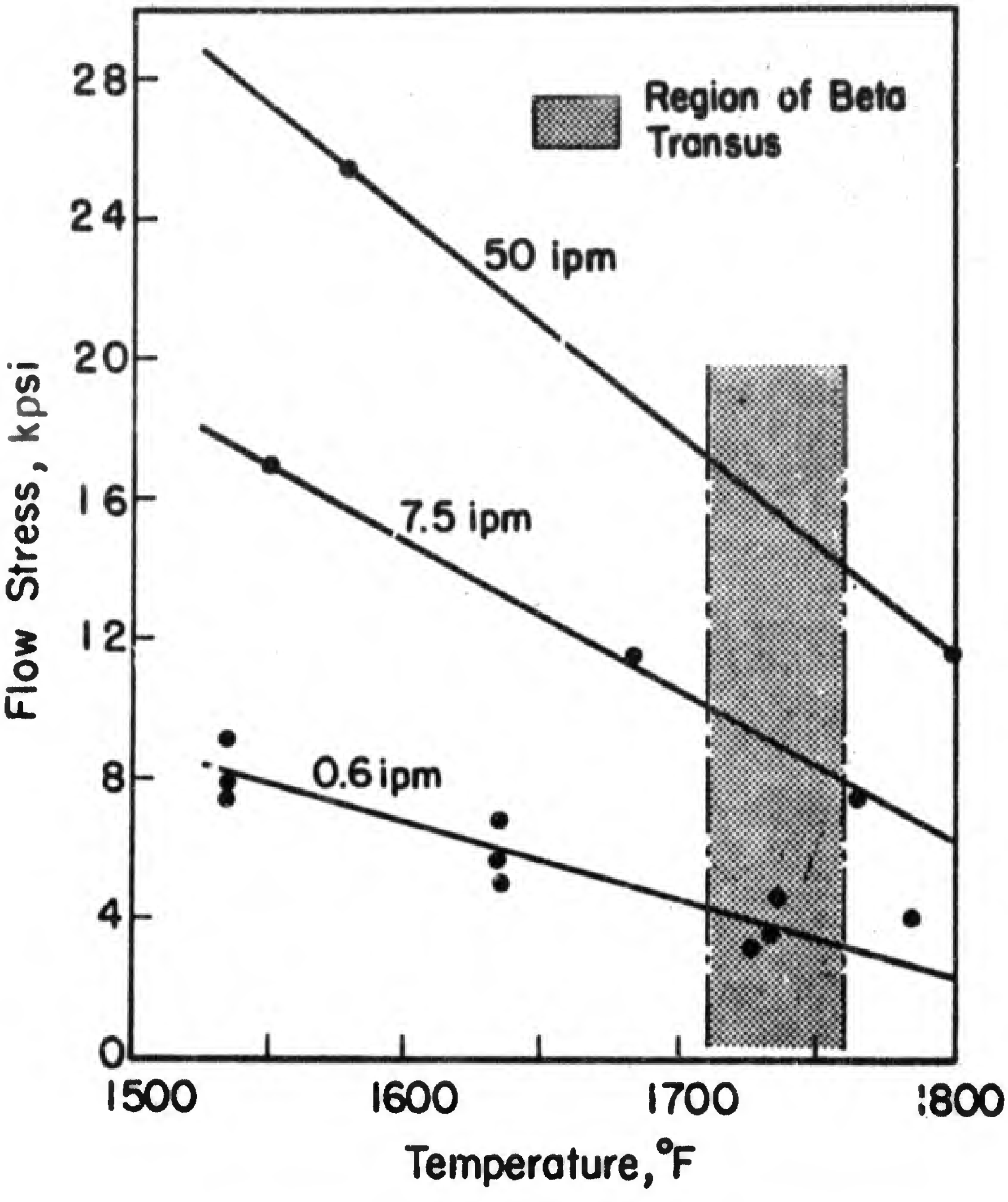


Figure 4

Influence of Press Speed on the Flow Stress of Ti-6Al-6V-2Sn Alloy.

It must be clarified that the entire forging operation does not take place at the very slow forging speed. During the initial stages of the forging, the various sections are quite thick and, therefore, for a given maximum load the press or the forging operation can take place at a fairly high speed. Only during the final stages, when the various sections tend to be quite thin or approach the complex finished shape, is the speed cut to the very small values. Therefore, the entire forging operation does not require more than a few minutes. On the other hand, the economic advantage can be very great due to a substantial reduction in the number of forging stages required and the reduction in the machining operations on the net forging.

The strain-rate sensitivity of the flow stress of work material, on which the success of the isothermal process is based, is common to all titanium alloys. In particular, the flow stress of Ti-6Al-4V alloy, used in the subject program, is highly strain rate dependent(5,6) as shown in Figures 5 and 6. Further, by comparing Figures 4 and 5 it is observed that (in the forging temperature range of 1600° to 1800°F) at the same temperature and strain rate Ti-6Al-6V-2Sn and Ti-6Al-4V have approximately equal flow stresses.

3. PRODUCTION OF SIMPLIFIED VERSION OF THE IMPELLER (PHASE I)

3.1 Design of Test Forging

To determine the potential of the isothermal forging process for the production of the subject impeller forging, a scaled down version was planned for the first phase of the program. This would allow for the determination of metal flow characteristics, the minimum thickness of blade which could be generated, what height of blade could be produced, and tooling design possibilities.

The forging schematically illustrated in Figure 7 was therefore designed to fulfill these objectives. It incorporates many of the features of the full-scale impeller including radial metal flow to fan the blades. Four sets of five blades were positioned at 15° intervals in the four quadrants of the forgings. As seen in Figure 7, the first set consisted of blades 0.100 in. thick, 1 1/8 in. long at the bottom and 1/2 in. long at the top; the second set, 0.150 in. thick and similar lengths to the 0.100 in. blades; the third set, 0.200 in. thick, and the fourth set, 0.150 in. thick but 1/4 in. longer than the other three sets.

3.2 Design and Production of Forging Dies and Tooling

In isothermal forging of titanium alloys, the dies are heated to and operate at temperatures up to 1800°F. Accordingly,

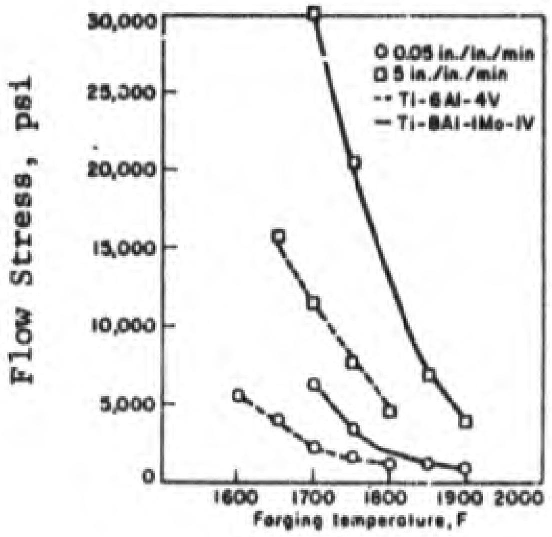


Figure 5

Flow Stresses of Ti-6Al-4V and Ti-8Al-1Mo-1V Forgings at Two Strain Rates.(5)

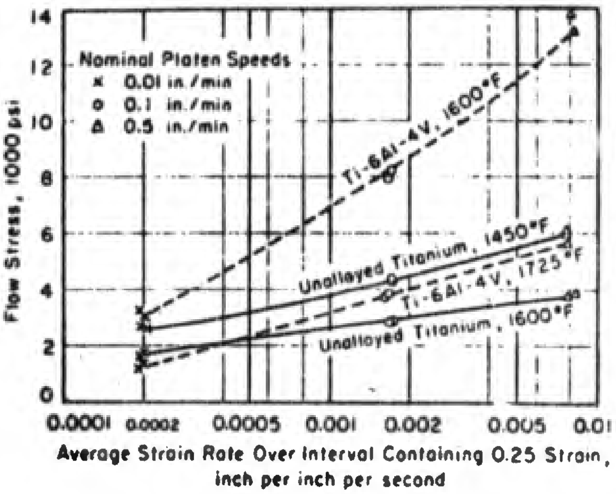
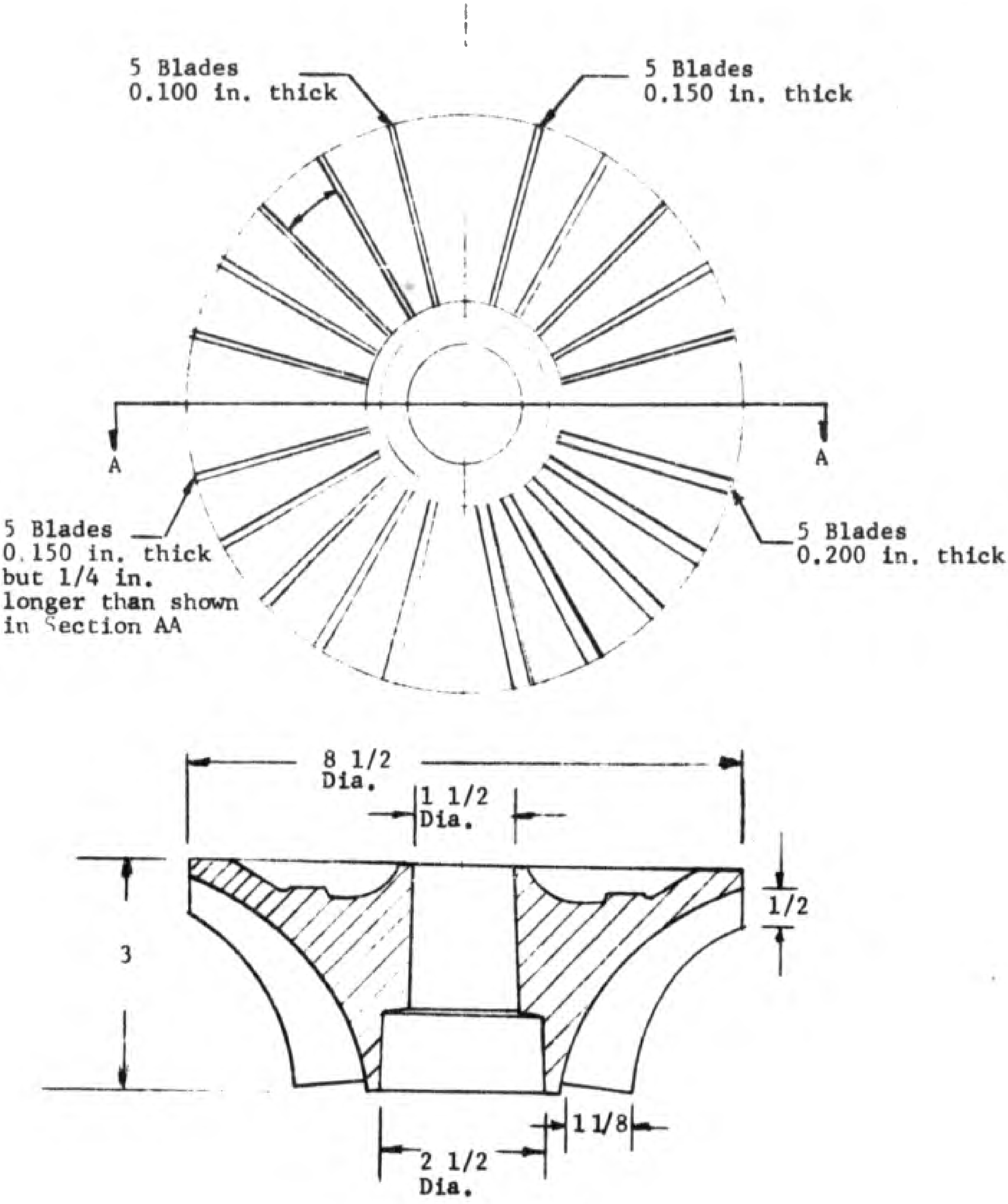


Figure 6

Effect of Strain Rate and Temperature on Deformation Resistance of Unalloyed Titanium and Ti-6Al-4V Alloy for 25% Compression.(6)



Section on AA

Figure 7

Schematic Illustration of Ti-6Al-4V Test Forging Used in Phase I superalloys or heat-resistant materials must be used as die materials. These alloys are extremely difficult to machine; consequently where possible, it is necessary for economy reasons to precision-cast the dies as close as possible to finish dimensions. The precision casting techniques involving ceramic molding have been developed on previous programs.(1-3)

The overall die design is schematically illustrated in Figure 8. The upper die, the hold-down ring, and the lower die and insert holder were cast in Supertherm heat-resistant alloy; the die insert which incorporated the blades was cast in IN-100 because of the more rigorous duty this component had to serve. The typical chemical analyses of these two alloys are shown in Table 1. The molding and casting techniques used to produce the die components are fully discussed in Phase II of the work where the full-size die components were produced.

3.3 Die Assembly and Installation in the Press

The various components of the die set were machined, and the dies were assembled in the IITRI 1000-ton hydraulic press. Figure 8 is a schematic illustration of the die assembly in position in the press with the induction coils and preform in position.

The dies were induction-heated to 1700°F in the press using a 200 kva 60-cycle transformer at top setting 6 to give a current of 1370 amps at 82 volts on the secondary to check that all die components were correctly nested, that adequate clearance between the heated die components was available, and that temperature gradients were a minimum (less than 20°F across the area of the die). Figure 9 shows the heated dies complete with ancillary tooling.

3.4 Ti-6Al-4V Preforms

A series of twelve Ti-6Al-4V preforms were machined from a 5 1/2 in. diameter forged, lathe turned billet. The supplier's test report on this material is shown in Table 2. The general preform dimensions were therefore 5 1/2 in. in diameter and 2.39 to 2.8 in. in thickness, and a 1.75 in. diameter hole was drilled through the center of all preforms. Two types of chamfer were machined on the lower outer edge of 11 of the 12 preforms; these were designated chamfer 1 and chamfer 2. Chamfer 1 was cut at a 45° angle 11/16 in. up from the bottom face of the preform, and chamfer 2 was cut at 45° and 15/16 in. up from the bottom face of the preform. Figure 10 is a schematic illustration of the general features of the various preforms.

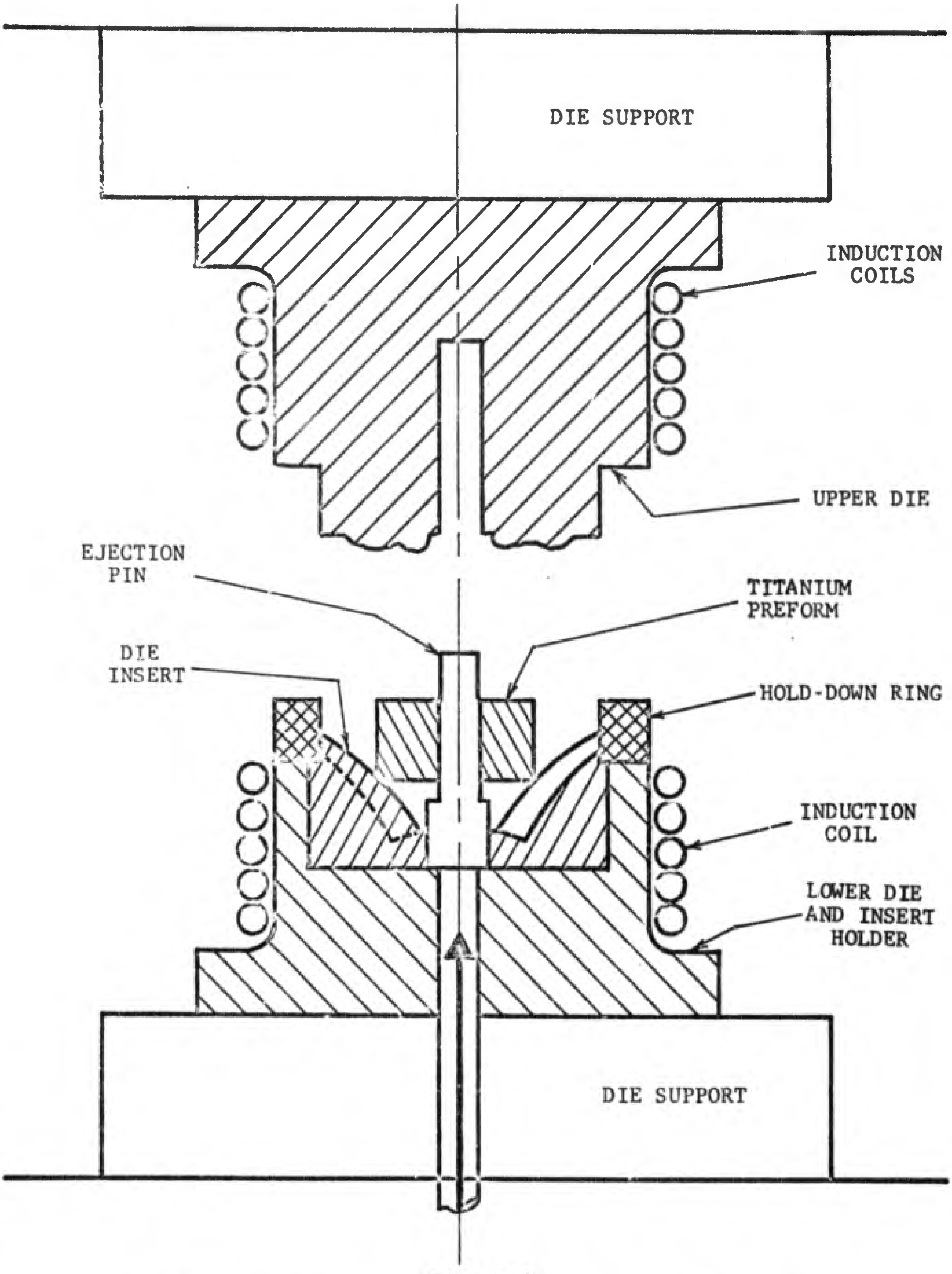


Figure 8
Schematic Illustration of Isothermal Forging Dies

Table 1

CHEMICAL COMPOSITION OF IN-100 AND SUPERTHERM

Alloy	Typical Analysis, wt%										
	C	Mn	Si	Fe	Ti	W	Mo	Cr	Ni	Co	Al
Supertherm	.45	.22	1.80	Bal.	--	4.7	--	26	36.4	18.3	--
IN-100[a]	.15	--	--	--	4.7	--	3.0	10	Bal.	15.0	5.5

[a] IN-100 also contains 0.015 B, 0.05 Zr, 1.0 V.

Figure 9
Heated Dies Installed in the Press

TEST REPORT

PAGE 1 OF 1

RMI TITANIUM

RMI Company - NILES, OHIO

DATE	March 17, 1972
MILL ORDER NO.	14523X
GRADE	6Al-4V
PACKING LIST NO.	71404
CUSTOMER NAME	IIT Research Institute
CUSTOMER ORDER NO.	92539
MATERIAL	Forged Lathe Turned Titanium Billet
SPECIFICATION	AMS 4967C

IDENTIFICATION & REFER.	INGOT NO.	LOT	S-R	INGOT NO.	LOT	S-R	INGOT NO.	LOT	S-R	INGOT NO.	LOT	S-R
MATERIAL NUMBER	704427	02	00									
TRAVEL CARD NO.	51333											

CHEMISTRY ☒ INGOT (AVERAGE OF TOP-CENTER-BOTTOM): ☐ FINAL PRODUCT.

	C %	.03			
	N	.009			
	Fe	.18			
	Al	6.6			
	V	4.4			
	Cr				
	Sn				
	Mn				
	Mo				
		BA	1BA		
FINAL PRODUCT	O	.191	.197		
	H (PPM)	33	46		

PROPERTIES

ULTIMATE KSI	L				
	T	174.9	174.8		
YIELD KSI	L				
(0.2%) OFFSET	T	161.2	160.4		
% ELONGATION	L				
(INCHES)	T	12.0	13.0		
% REDUCTION	L				
IN AREA	T	44.0	42.0		
BEND 105°	L				
	T				
HARDNESS RC		33.9/36.5			
STATIC NOTCH		185,000 psi for 5.0 hrs. without rupturing			
IMPACT					
ULTRASONIC		Ultrasonically tested and meets the requirements of the specification			
BETA TRANSUS		1825°			
TEST FORGE PROCEDURE		T/F 1/2 of 5.5" dia. x 2" Upset Forge to 1/2" Plate Lab STA 1750°F 1 Hr. W.Q. Age 1000°F 4 Hrs. Air Cooled			

OTHER DATA

SHIPPED

NO. OF PIECES	1			
WEIGHT	446.0#			
SIZE	5.5" Dia. x 117			
TEST PIECES				

FORM NO. 44 REV. 5/71

THIS IS TO CERTIFY THAT THE ABOVE TEST RESULTS ARE CORRECT AS CONTAINED IN THE RECORDS OF THE COMPANY.

SIGNED

Table 2
Test Report on Phase I Forging Stock

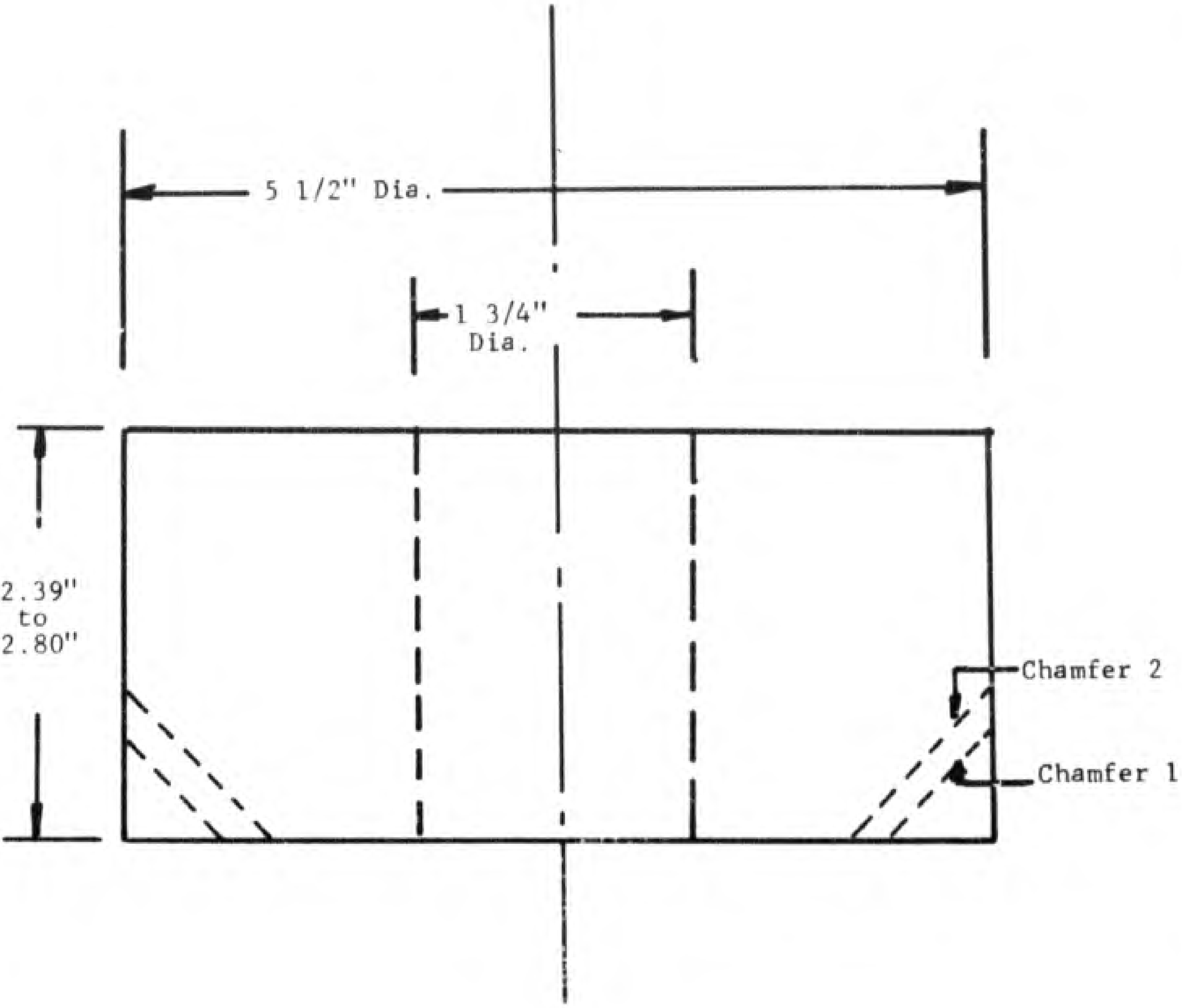


Figure 10
Schematic Illustration of General Features of Preforms.

3.5 Forging Trials

The twelve preforms were utilized in the isothermal forging trials. Table 3 gives details of the trials, and includes preform size, weight, type and volume, preform temperature, die temperature, finished forging load and time, and degree of fill. The remarks on degree of fill utilized a severe rating system which assumed that if all blades did not completely fill, the forging was classified as "incomplete fill." However, in many instances a full-size blade as per the Drawing No. 1-100-078-03, could be obtained from these "incomplete" filled blades on the trial forgings because they were forged 1/4 in. longer than required.

The forging practice adopted was to coat the preforms with a thin layer of Markal CRT-22 glass-based slurry, admit to the furnace, hold for 1 hr at 1700°F, transfer to the heated forging dies, close the press and build up to the preselected forging tonnage, and maintain this tonnage for the preselected length of time. The upper die was retracted after completion of the individual experiments, and the forging was ejected and allowed to air cool.

The variables encompassed in the forging trials were preform thickness, two types of chamfer on the preform, die temperature, forging load, and forging time. Figure 11 is a general view of nine of the forgings produced in the series of trials.

The first trial, specimen A, did not completely fill because no chamfer was mechined on the bottom edge of the preform and the preform rode too high in the die. Although the blades all filled on the upper large outer diameter, the blades produced in the lower part of the die did not fill. The chamfer on the succeeding preforms allowed the blank to sit lower in the die, and metal therefore did not have to be driven down as far in the die to obtain filling in the bottom regions while the spreading was taking place in the upper portions of the die.

The second trial, specimen B, gave a forging which showed excellent filling on all ribs, with the exception of some very minor lack of fill at the bottom of the 0.100 in. ribs. The lack of fill can be attributed to trapping of lubricant and could be accommodated by making the ribs somewhat deeper and reducing the quantity of lubricant on the preform. Figure 12 shows this particular forging along with a preform having the same general features as that used to produce it. Figure 13 is a closer view of the forging after sandblasting and preheating. It should be stressed that all the blades have zero draft and the fillet at the junction of the blade to body of the forging is extremely small.

Table 3

DETAILS OF FORGING TRIALS

	Preform[a]			Die	Forging[b]			
Spec. No.	Thickness, in.	Weight, lb	Volume, cu in.	Temp., °F	Load, tons	Pressure, kpsi	Time, sec	Remarks
A	2.39 No chamfer	8.2	51.2	1650	650	23.7	300	Incomplete fill on bottom of blade.
B	2.40 Chamfer 1	7.7	48.1	1750	600	21.8	300	Good filling except for 0.100 in. blades.
C	2.40 Chamfer 1	7.5	46.9	1600	600	21.8	180	No hold-down rings, incomplete fill.
D	2.49 Chamfer 1	7.9	49.4	1750	500	18.2	180	Incomplete fill, insufficient time and tonnage.
E	2.44 Chamfer 2	7.6	47.5	1775	500	18.2	300	Incomplete fill on top and bottom of blade, too small preform and insufficient tonnage.
F	2.40 Chamfer 2	7.5	46.9	1750	400	14.6	300	Same as E
G	2.40 Chamfer 1	7.7	48.1	1700	450	16.4	300	Incomplete fill, tonnage too low.
H	2.40 Chamfer 1	7.6	47.5	1700	550	20.0	300	Marginal fill except for 0.100 in. blades, low tonnage.
I	2.47 Chamfer 1	7.8	48.8	1650	600	21.8	300	Marginal fill except for 0.100 in. blades, preform small, low die temperature.
J	2.80 Chamfer 1	9.1	56.8	1750	550	20.0	300	Good fill, except for 0.100 in. blades.
K	2.40 Chamfer 1	7.6	47.5	1700	200	7.2	150	Incremental experiment.

[a] See Figure 10 for dimensions; preform temperature 1700°F for all trials.

[b] Plan area of forging 55 sq in.

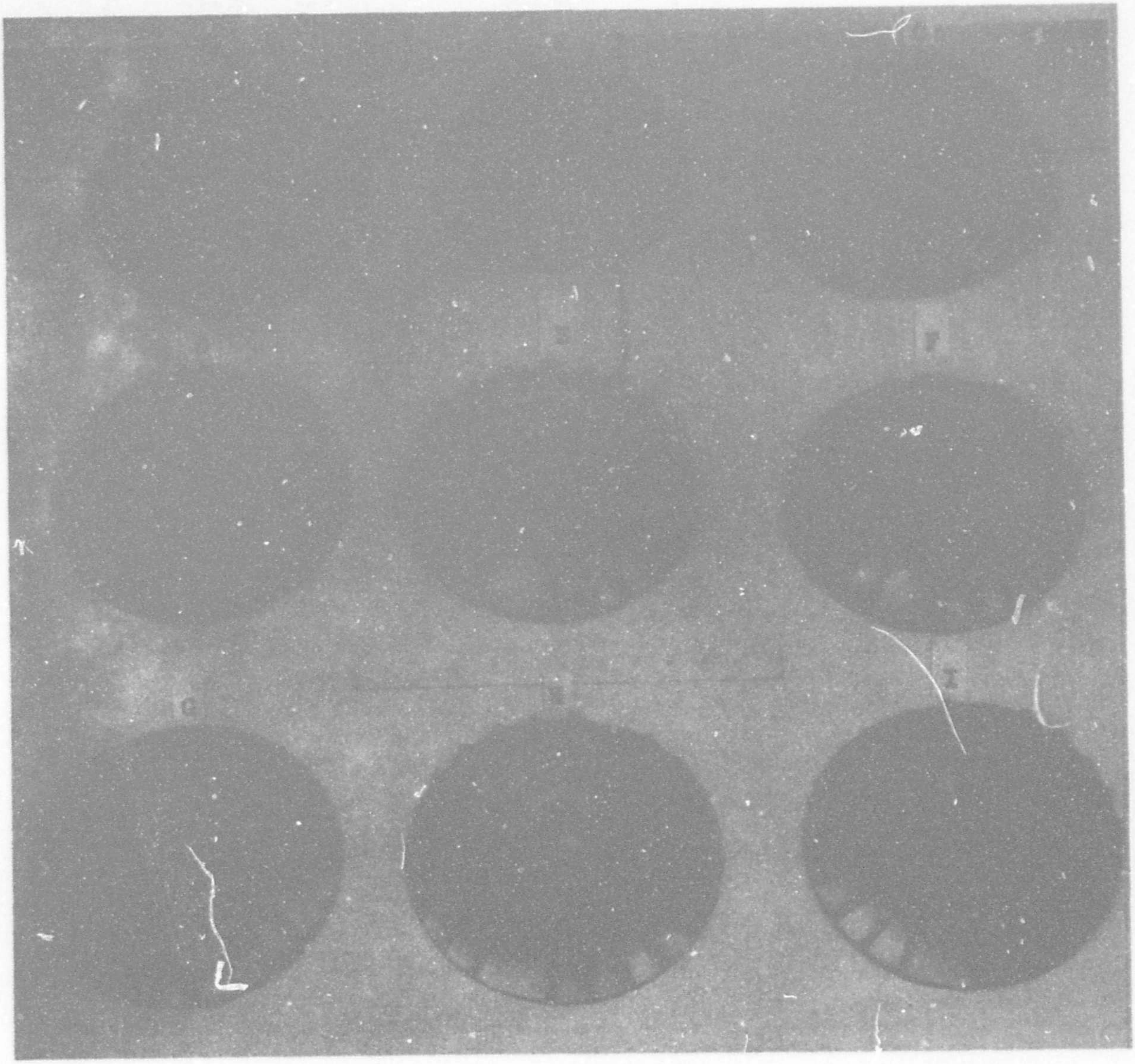


Figure 11
General View of Nine Isothermally Forged Titanium 6Al-4V Forgings

Figure 13
Ti-6Al-4V Forging Produced from Specimen B by Isothermal Forging

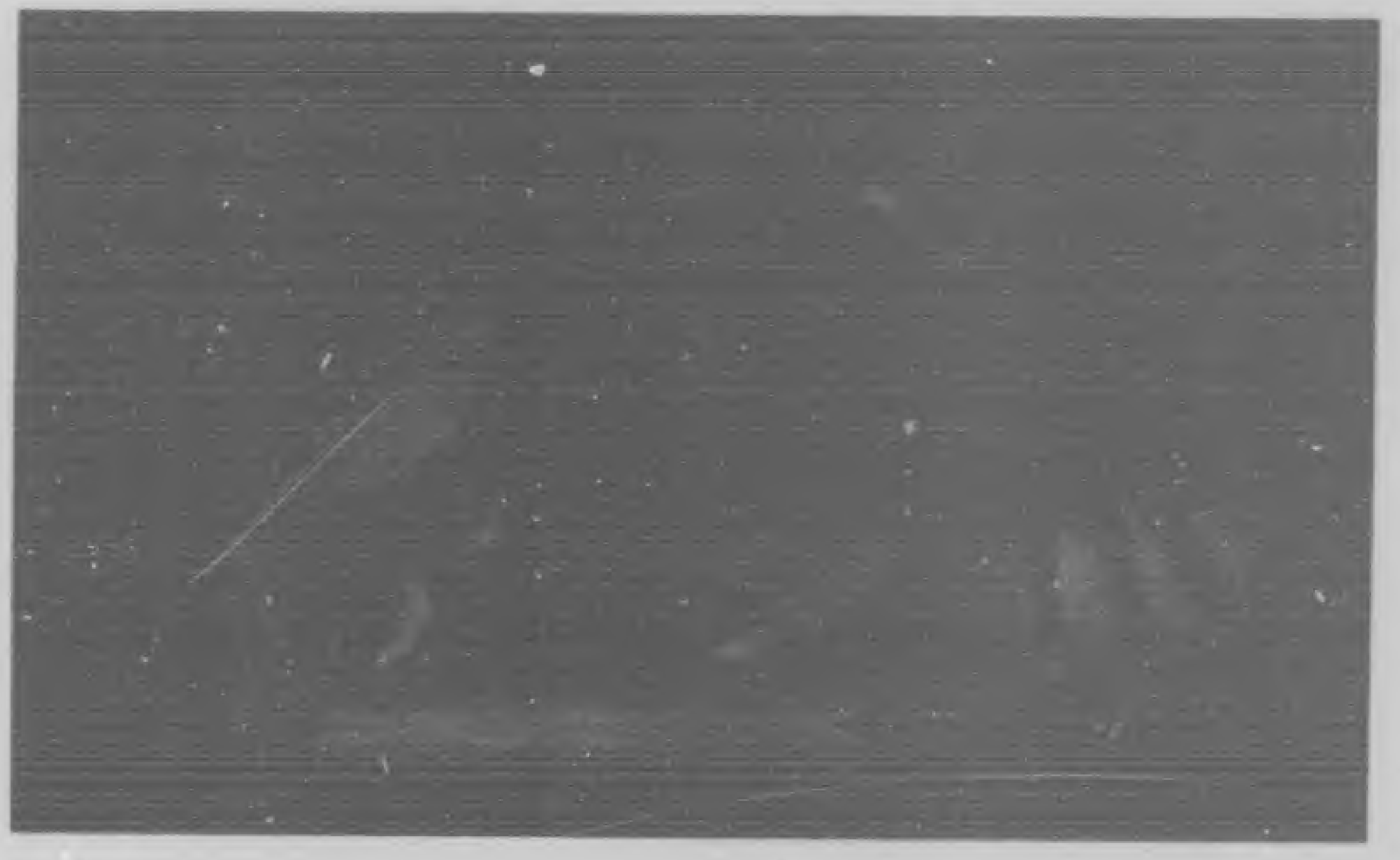


Figure 12
Preform B and Ti-6Al-4V Forging

In this third trial, involving specimen C, the hold-down ring was removed from the bottom die. This theoretically would allow for the production of a forging having flash around the periphery of the forging by allowing metal to escape from the area. This trial was conducted to determine whether the trapped die technique which was being utilized was required. Figure 14 shows the forging produced. It can be seen that there is a severe lack of fill on the tips of the blades at the top and bottom of the forging. This indicates that in order to ensure metal flow to the full depth of the blades, the titanium must be confined, as in the trapped die forging technique. In conventional forging this confinement is essentially achieved by the cold thin flash which "picture frames" the forging and effectively tends to restrict lateral metal flow. In isothermal forging any flash generated is not chilled and therefore does not inhibit lateral metal flow.

In the fourth trial, utilizing preform D, the forging load was reduced from 600 tons to 500 tons and time was reduced from 300 to 180 seconds. The blades were filled on the upper outer portion of the forging, but in the lower portion of the forging the blades were not complete, particularly in the corners. The cause for this lack of fill was probably insufficient tonnage and time.

The fifth trial, specimen E, utilized a preform with a somewhat greater chamfer on the lower edge and forging load was again 500 tons as in the fourth trial. This forging showed lack of fill at the tip of the thinner blades, at both the top and bottom of the forging. This could be attributed to a combination of insufficient tonnage and too small a preform.

The sixth trial, specimen F, again employed chamfer 2 on the preform, and the press load was reduced to 400 tons. Again, some minor lack of fill was noted at the tips of the blades which could be attributed to low press forging load and a small preform.

For the seventh trial, specimen G, the chamfer was reduced to 11/16 in. and press tonnage was increased to 450 tons. The fill on the blades was somewhat better than the preceding forging, but again the tips were not complete, indicating that the tonnage was too low for this particular preform size.

In the eighth trial, specimen H, the press tonnage was increased to 550 tons, and filling of the blades was considerably better than in the seventh trial with minor lack of fill at the tips of the blades generated in the bottom of the die, indicating that the press forging load was marginal.

Figure 14
Preform C and Ti-6Al-4V Forging

For the ninth trial, specimen I, the press tonnage was increased to 600 tons and die temperature was reduced to 1650°F. Good filling of the die was obtained with the exception of the extreme tips of the blades at the top and bottom of the forging. The die temperature, 1650°F, was probably marginal for this size of preform and forging load.

In the tenth trial, specimen K, the press load was restricted to 200 tons to determine the mode of plastic flow of the titanium during the early stages of loading. It was observed that the preform was driven down to the lower portions of the die and some lateral spreading of the blank occurred. Quite surprisingly, the metal flowed into the blade cavities to an appreciable depth, particularly in the center portions of the blades.

In the eleventh trial, specimen J, the preform thickness was increased to 2.80 in. from the 2.40-2.50 in. used in the preceding trials. An excellent forging was produced which showed good fill in all areas with the exception of the extreme tips of the 0.100 in. blades in the bottom of the forging. This indicates that preform mass is critical and that in some instances it was marginal in the preceding forging trials. Unfortunately, some difficulty was experienced during ejection of the forging from the dies, and this resulted in the forging being distorted.

3.6 General Observations on Forging Trials

The following general comments can be made as a result of the series of isothermal forging trials:

1. Full-size straight blades, having a thickness of 0.150 in. and up, can be produced in trial Ti-6Al-4V forgings when the isothermal forging technique is used.
2. Blades having a thickness of 0.100 in. present a marginal situation because some difficulty is experienced in obtaining complete fill at the lower tips of these blades. This difficulty is probably associated with accumulation of lubricant in these pockets of the die and could be accommodated by making the blades somewhat longer and reducing the amount of lubricant on the preform.
3. Preform temperatures of 1700°F and die temperatures of between 1700°F and 1750°F are optimum for obtaining the best filling. The beta transus of this alloy is approximately 1825°F, and these temperatures are therefore well within the alpha-beta region.

4. Press forging pressures of 20 to 22 kpsi are adequate, at optimum die-preform temperatures, to obtain good forgings. This is in contrast to forging pressures of over 100 kpsi which are typically used in conventional titanium forging practice.

5. To obtain complete blades by isothermal forging it is essential that the trapped die forging technique be used.

6. While a simple-shaped preform can be used to produce the forging, the mass, thickness, and general shape of the blank are critical.

7. A series of forgings were produced from a single stroke of the press which would be impossible to make by conventional forging techniques. Twenty straight blades having thicknesses ranging from 0.200 to 0.100 in., full size depth, and zero draft were generated in each forging.

4. PRODUCTION OF FULL-SCALE IMPELLER FORGINGS (PHASE II)

4.1 Design of the Full-Scale Impeller Forging

The successful completion of the Phase I effort showed that 0.150 in. thick blades could be produced with 100% fill, and 0.100 in. thick blades could probably be produced with some minor modification of the forging technique and die construction.

At the technical meeting held at AMMRC between the project technical supervisor and IITRI personnel, it was agreed that some difficulty might be experienced in producing the impeller forging with about 1/64 in. machining allowance on the blade thicknesses. This difficulty was not connected with metal flow to produce the blades. The problems revolved around geometric constraints associated with the curved sloping blade configuration and associated reentrant angles and the difficulty of vertically ejecting such a forging from the dies.

It is extremely difficult to visualize potential methods of overcoming these difficulties with the use of drawings. Consequently, a model of a potential forging configuration was made. This model was produced by removing a section from a machined impeller and filling all reentrant angles with wax so that a vertical lift from a forging die could be obtained. Figure 15 shows the section of the finish machined impeller, incorporating six vanes and filled with wax in the appropriate sections to allow for a vertical lift. The vertical lift is

Figure 15

Section of Machined Ti-6Al-4V Impeller with Wax Added to Fill Reentrant Angles assured by the steel rule being at an angle normal to the horizontal plane, and therefore parallel to the vertical axis, of the finished forging. Figures 16 and 17 further illustrate the method of adding and shaving the wax to ensure the absence of reentrant angles.

To determine that such a forging could be removed vertically from a forging die, a wooden box was constructed to accommodate the forging and into which plaster could be poured around the partially wax-filled vanes. This box with the impeller section in position is shown in Figure 18.

Plaster was poured into the cavity incorporating the vanes and allowed to air-set overnight. The simulated forging was extracted with no problems vertically from the simulated forging die shown in Figure 19. This indicates that such an approach with the areas filled as typified in Figures 15, 16, and 17 is viable for full-size impeller forging. Accordingly, the forging die set was designed to accommodate this forging.

4.2 Forging Die Design

Figure 20 is a schematic scaled representation of the die assembly concept for isothermally forging the titanium impeller. Figure 21 is the drawing for the IN-100 upper die for forging the subject impeller. The lower working die face was to be cast to size. Figure 22 is a detailed drawing for the IN-100 insert casting, which incorporated the impeller blades. The bottom part of the impeller blades was to be forged by the sawtooth portion of the casting as seen in Figure 22. Slots for the remainder of the blades to be forged were to be machined by EDM into the 3.857 in. radius shown in Section AA. Figure 23 shows the insert holder which accommodates the casting produced to the drawing shown in Figure 22. Figure 24 shows the Inconel 718 ejection pin.

4.3 Production of Die Set

4.3.1 Upper Die (B6115-C-21)

Figure 21 is the drawing for this component. The pattern for producing the casting is shown in Figure 25. Figure 26 shows the composite drag mold produced from this pattern. The facing (light area) on this mold is a mixture of fine-grained fused silica and zirconal bonded with ethyl silicate on a backup of fused silica bonded with sodium silicate. The mold is fired at between 1300° and 1400°F to give a dimensionally stable hard ceramic facing free from gas-forming constituents. The face of the die block, which forms the upper face of the impeller forging and is formed by the bottom part of the mold shown in

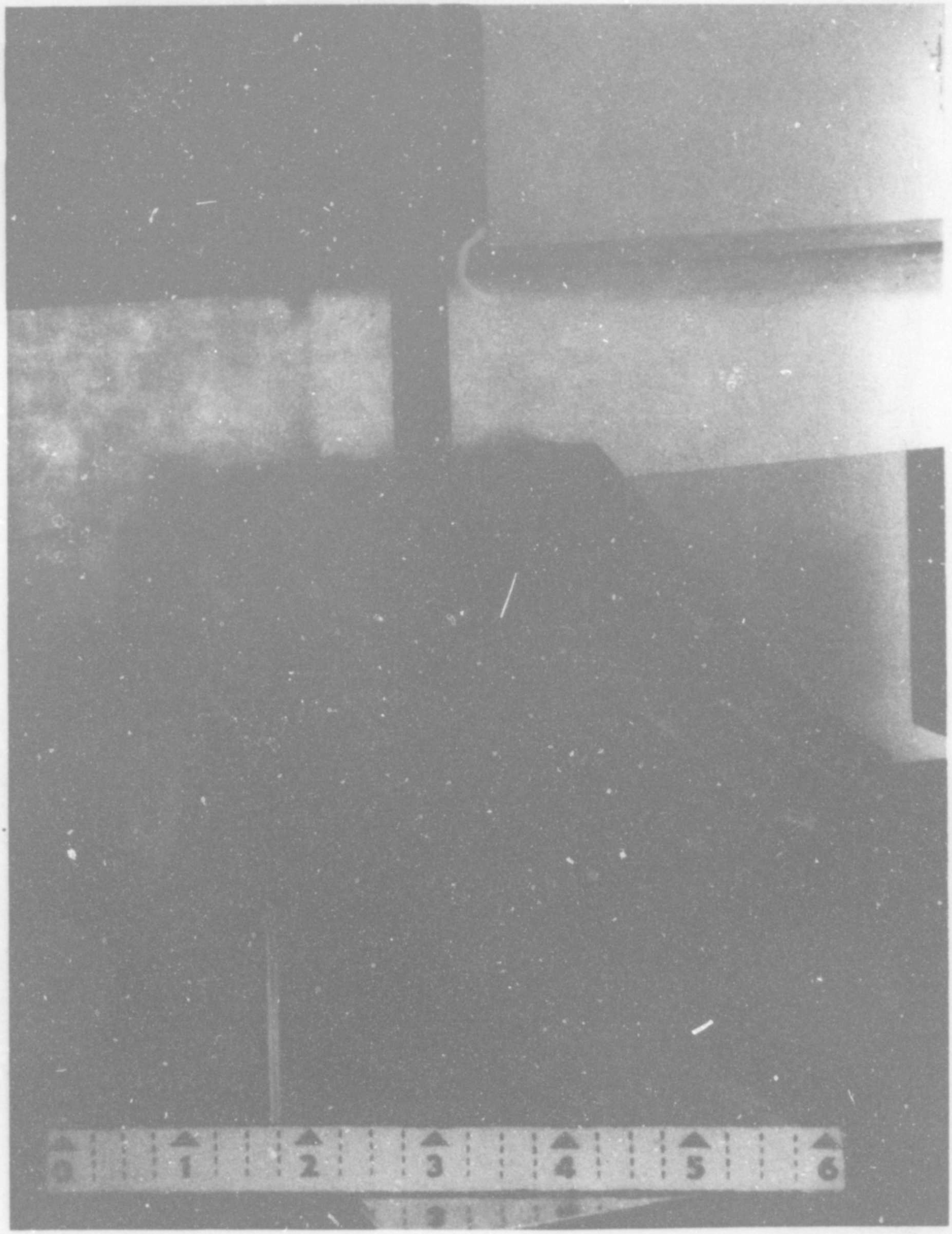


Figure 16

Section of Machined Ti-6Al-4V Impeller with Wax Added to Fill Reentrant Angles

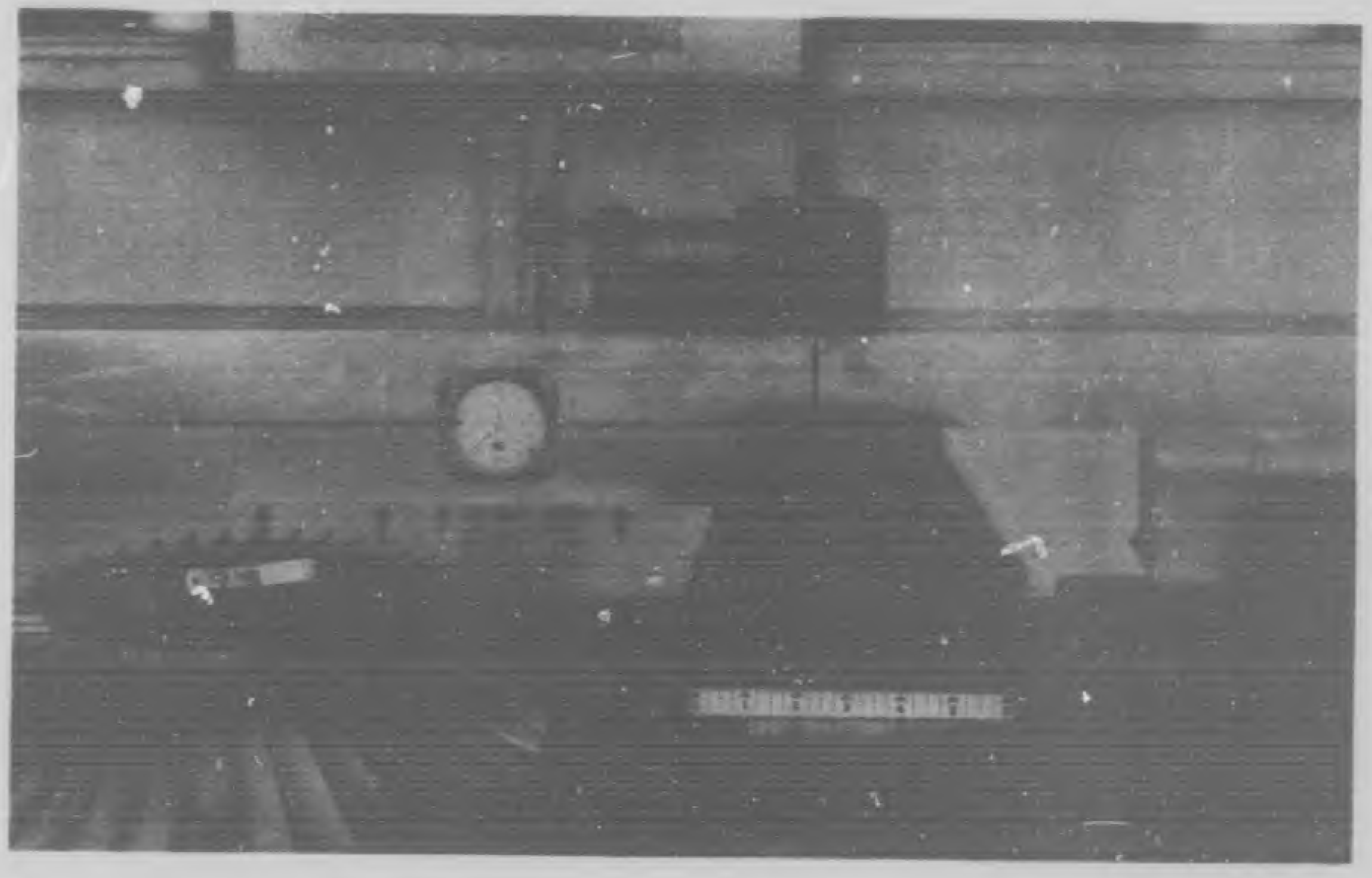
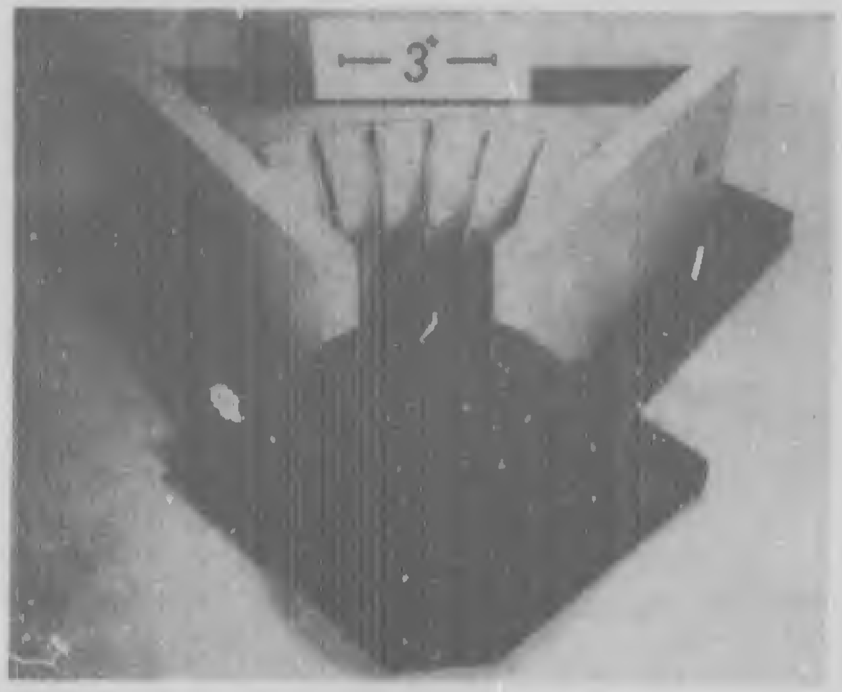


Figure 17

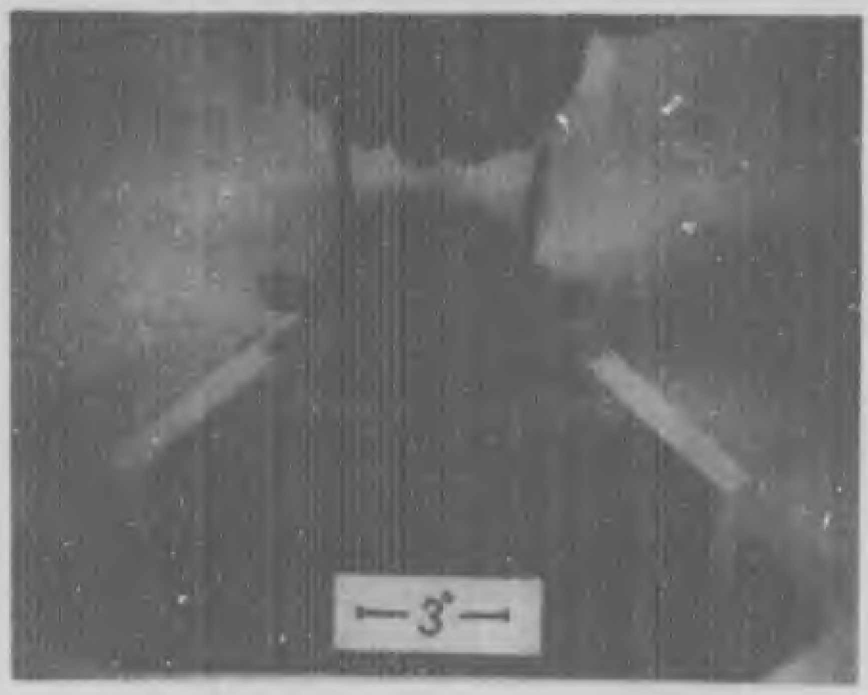
General View of Setup for Adding and Shaving Wax on Machined Ti-6Al-4V Impeller to Fill Reentrant Angles and Ensure Clean Lift of Forging from Dies

Figure 18

Wax-Filled Impeller Section in Position in Wooden Box, with One Side Removed, Ready for Pouring of Plaster into Cavity Incorporating Vanes



(a) Section of Plaster of Paris
Simulated Lower Forging Die



(b) Wax-filled Simulated Forging being Removed Vertically from the Simulated Forging Die Section

Figure 19

Two Views of Simulated Section of Lower Forging Die Cavity with Simulated Forging being Withdrawn

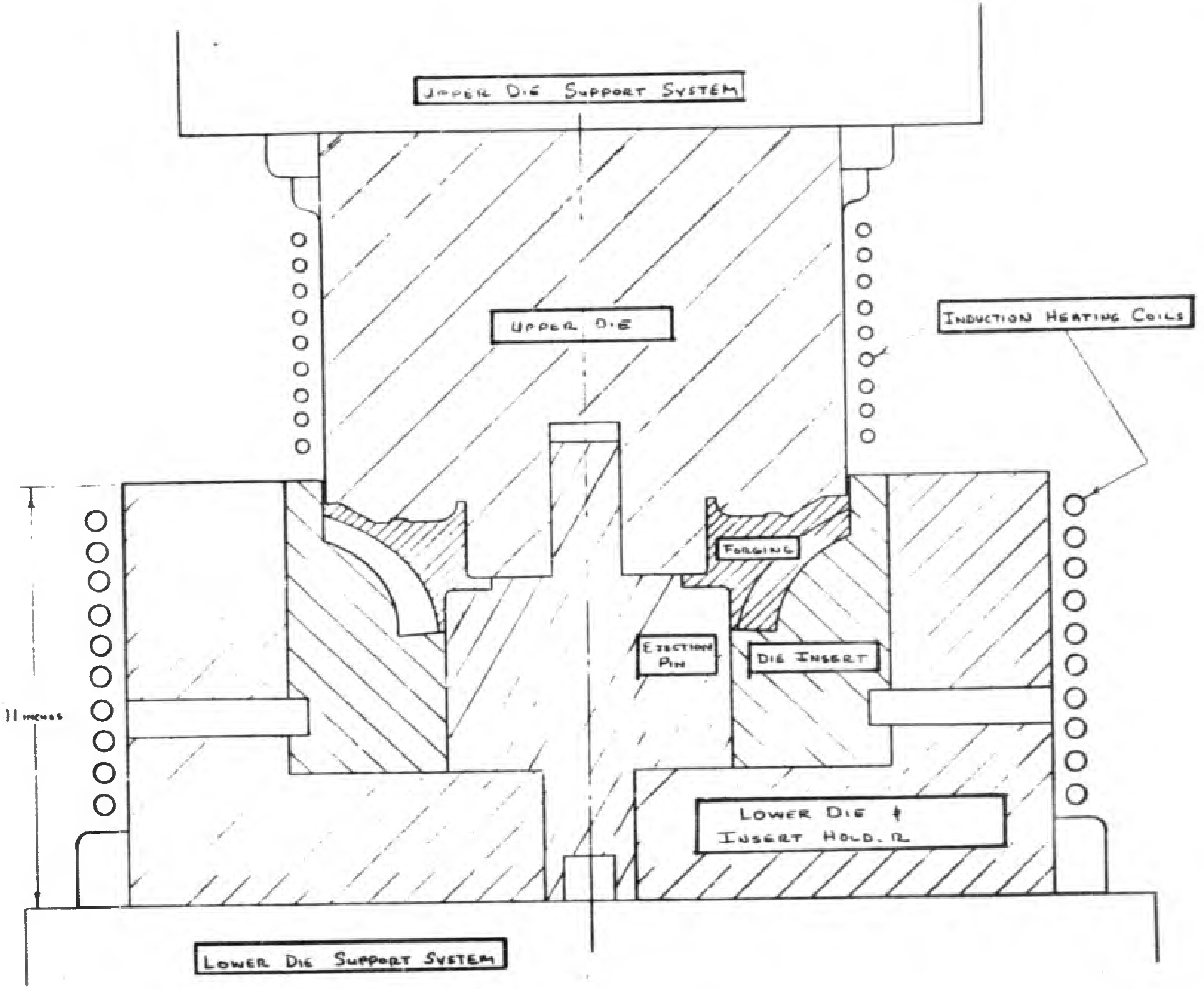


Figure 20
Schematic Representation of Die Assembly for Isothermal Forging of Full-Scale Impeller

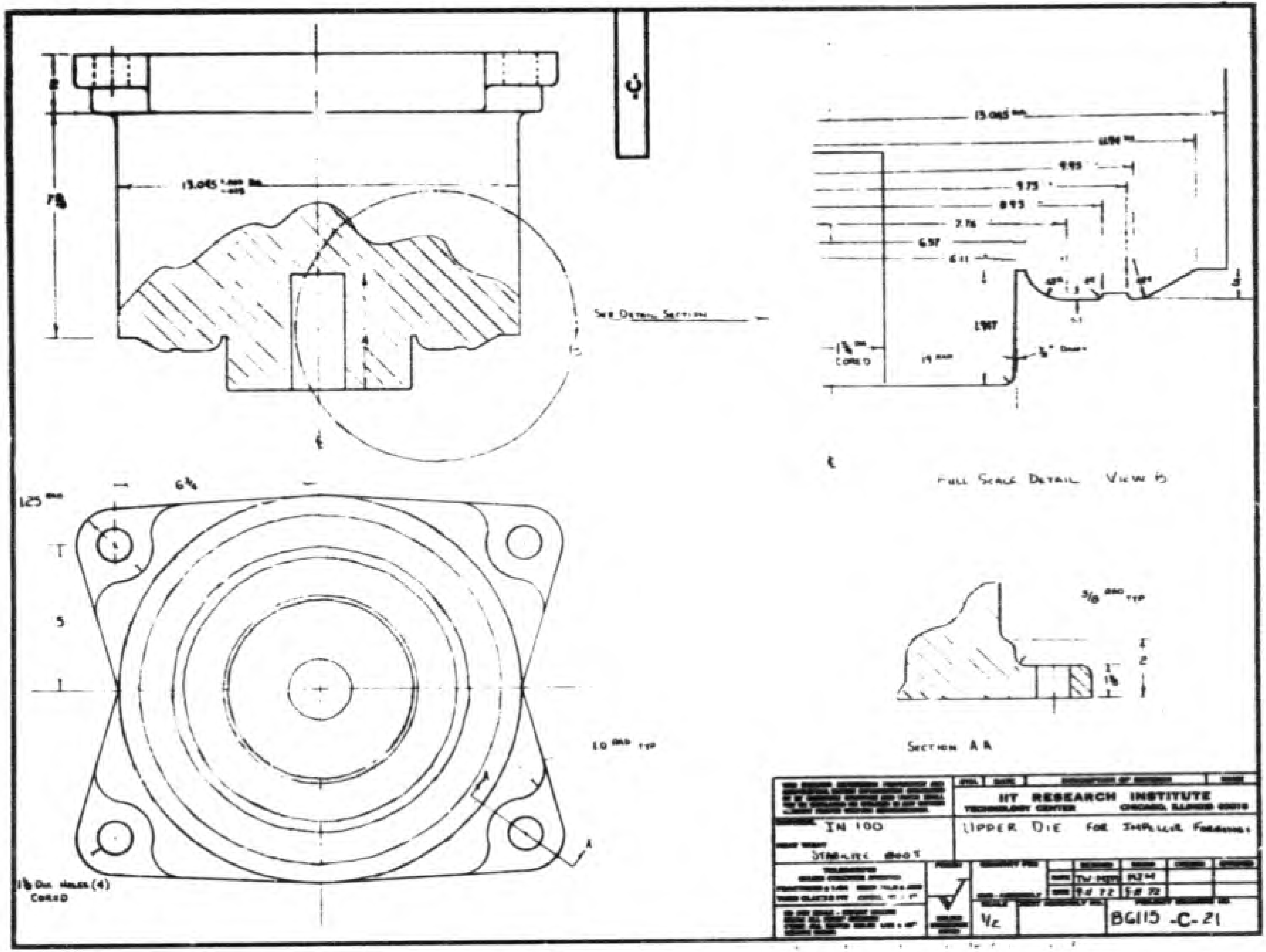


Figure 21
IN-100 Upper Die

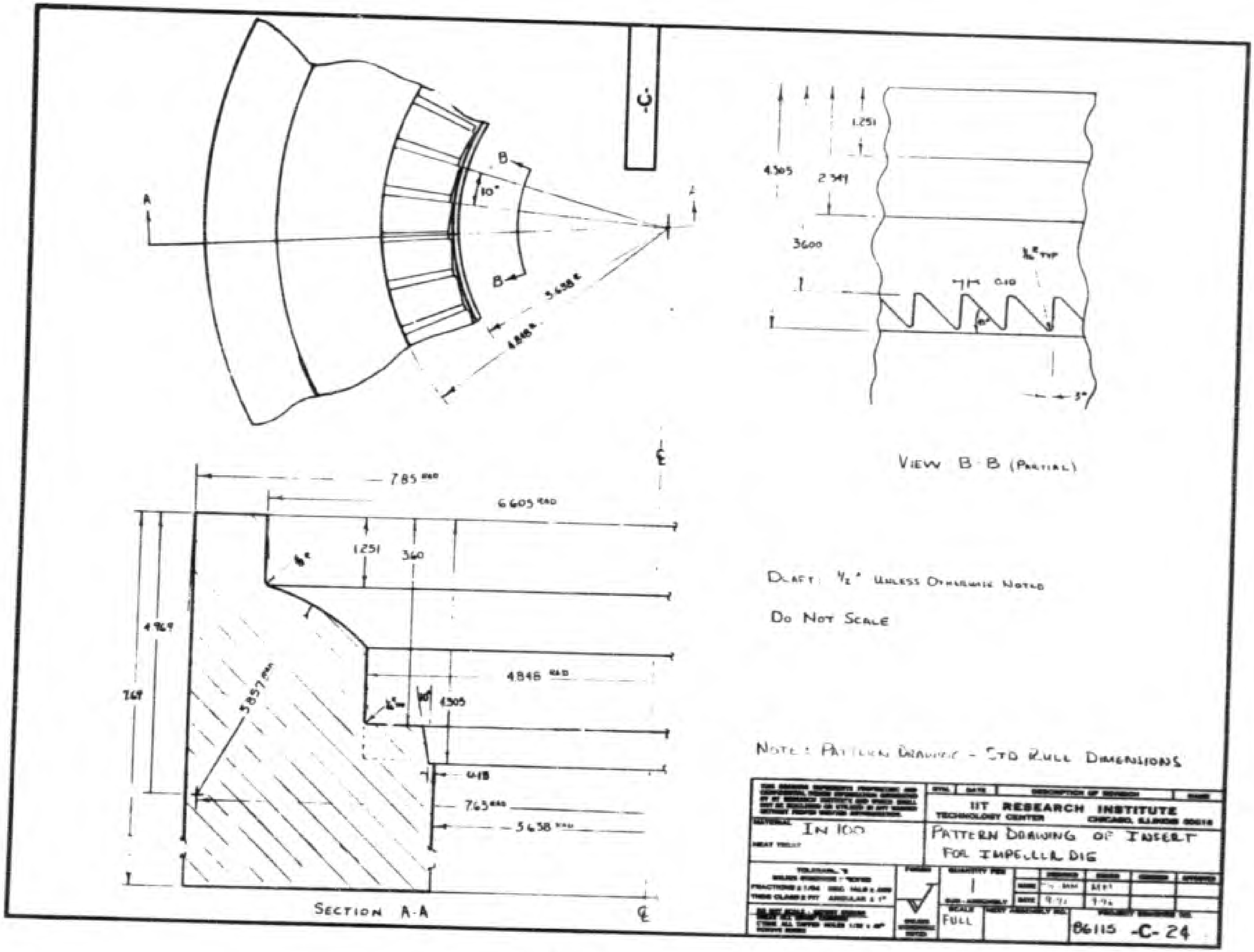


Figure 22
IN-100 Insert Casting

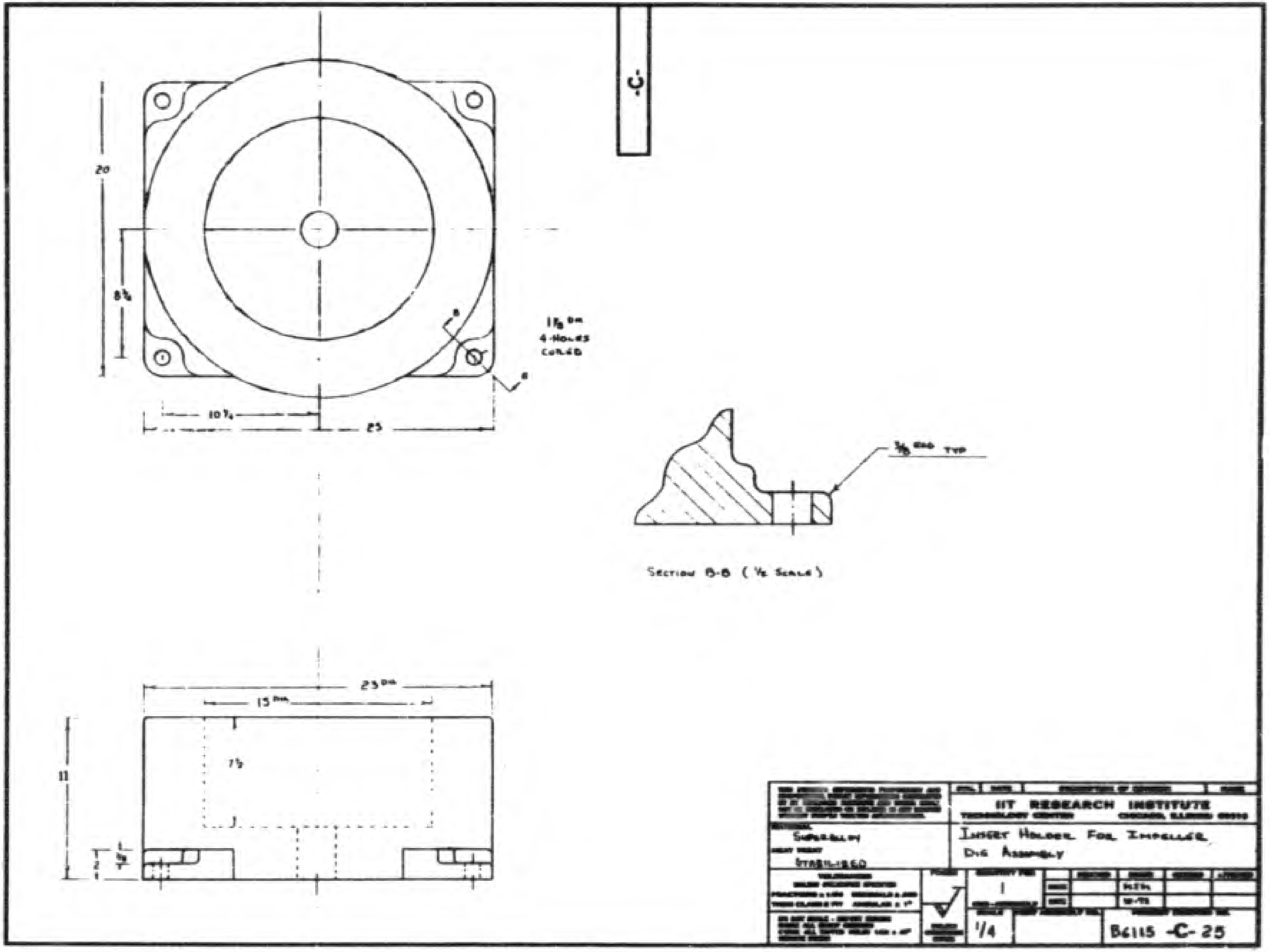


Figure 23
IN-100 Lower Die Insert Holder

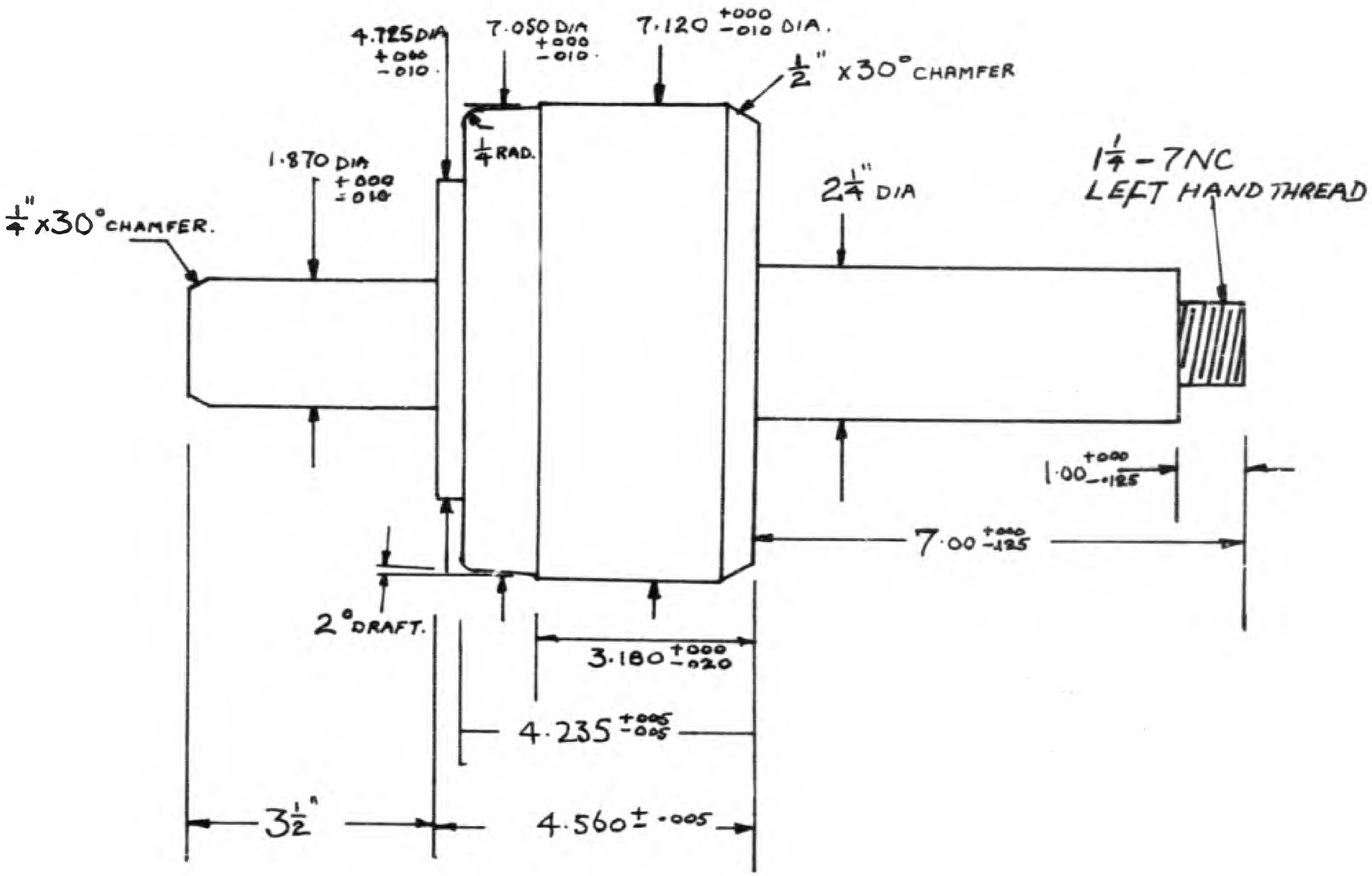
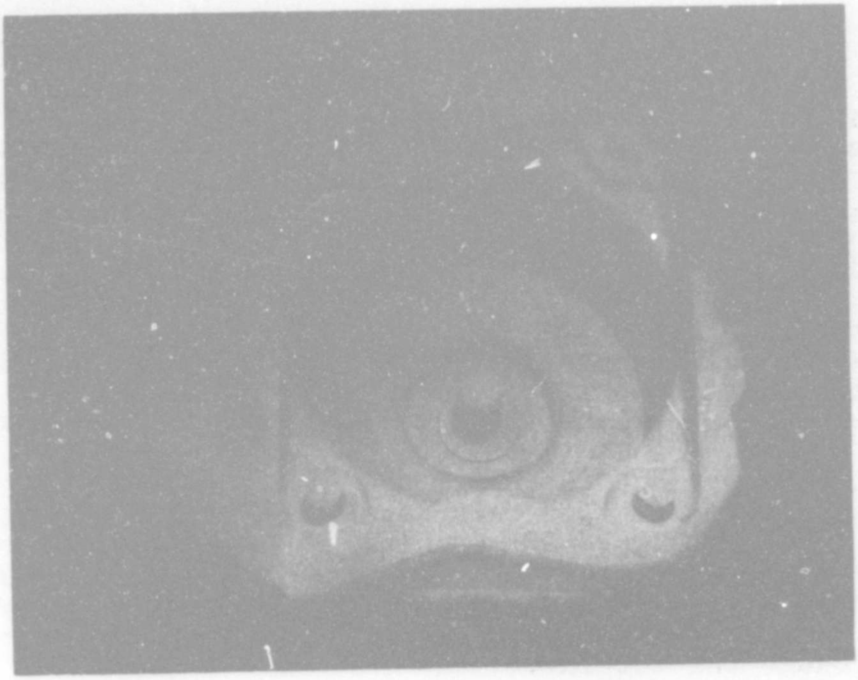
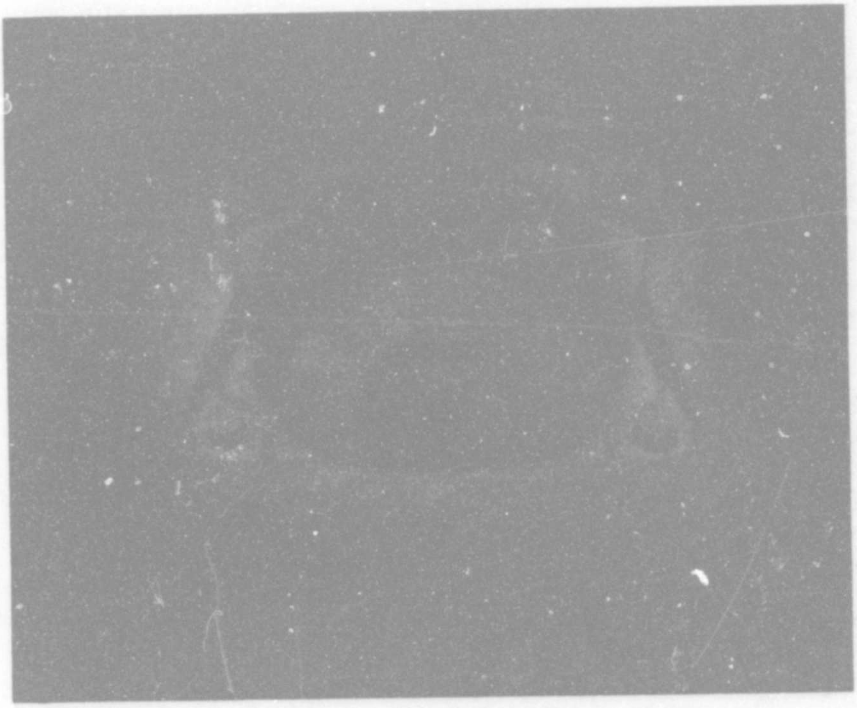


Figure 24
Inconel 718 Ejection Pin

Figure 25
Pattern for MAR-M 200 Upper Die



(a)



(b)

Figure 26
Two Views of Mold for MAR-M 200 Upper Die

Figure 26a, was to be used in the as-cast condition. The central core in the bottom of the mold formed a location hole in the upper die. The down sprue and ingate can be clearly observed in Figure 26b. The mold was cast in air-melted MAR-M 200 superalloy. Casting temperature was 2800°F. The risers and ingates were removed by burning bars. The casting weighed 465 lb with risers removed.

MAR-M 200 superalloy was used for this die component because a sufficient quantity of scrap material was available. This alloy has properties approximately equivalent to IN-100 and has been successfully used in this application on other programs.

Figure 27 shows the upper die block casting with feeder head and ingate removed. The only machining performed on this casting was as shown in Figure 28, machining of the face which mates with the ejection pin, machining of central location hole and mating outside diameter, and grinding of the back face of the die. It should be noted that no machining was performed on the die faces that produce the forging.

4.3.2 Die Insert (B6115-C-24)

This component of the die system was considered to be the most critical one. The pattern for the insert casting to drawing No. B6115-C-24 is shown in Figure 29. Figure 30 shows two views of the composite drag mold for this casting. The molding procedure was similar to that used for the upper die. The castellated portion of the mold and the resultant casting was to form the tips of the impeller blades. The other parts of the blade cavities were to be obtained by electro discharge machining the slots into the curved face of the casting. The down sprue and ingate can be seen in Figure 30b. This mold was cast in air-melted IN-100 superalloy. Casting temperature was 2800°F. Risers and ingates were removed, and the casting weighed 258 lb.

The casting produced is shown in Figure 31 after removal of gates and risers. The excellent surface finish on the working face of the die can be clearly observed. Machining of this casting consisted of grinding the cope face flat, turning of the outside diameter to match the lower die insert holder casting, turning of the larger internal diameter of the top of the casting to match the external diameter of the upper die, turning of the lower smaller internal diameter to match the ejection pin, and electro discharge machining of the 36 slots which formed the blades of the forging on the curved inner portion of the casting. The model developed in Figures 15 through 19 was used to produce the electrode for the electro discharge machining operation. Figure 32 shows the finish machined IN-100 lower die insert casting.

Figure 27
MAR-M 200 Upper Die Block Casting

Figure 28
Machined MAR-M 200 Upper Die Block Casting

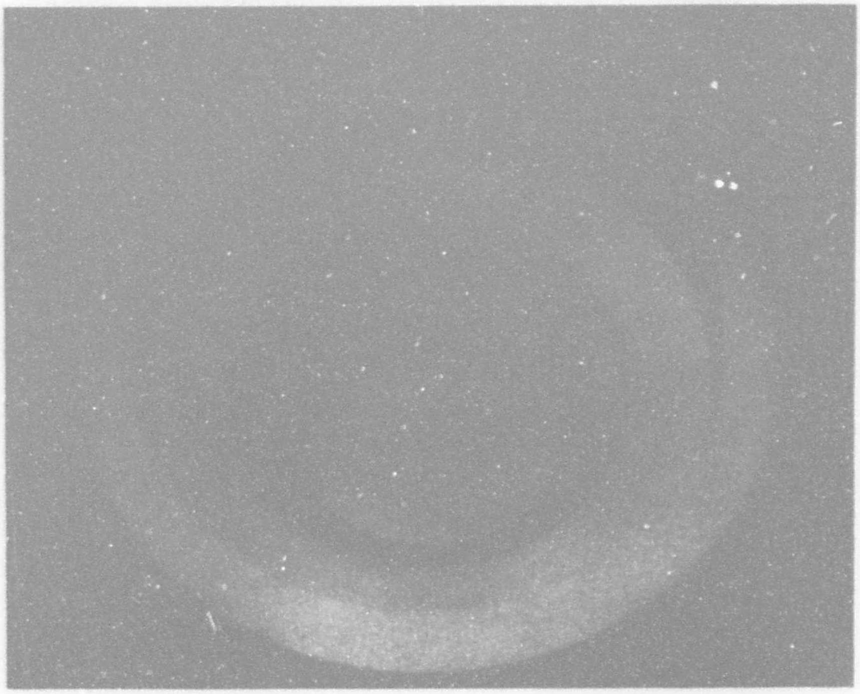
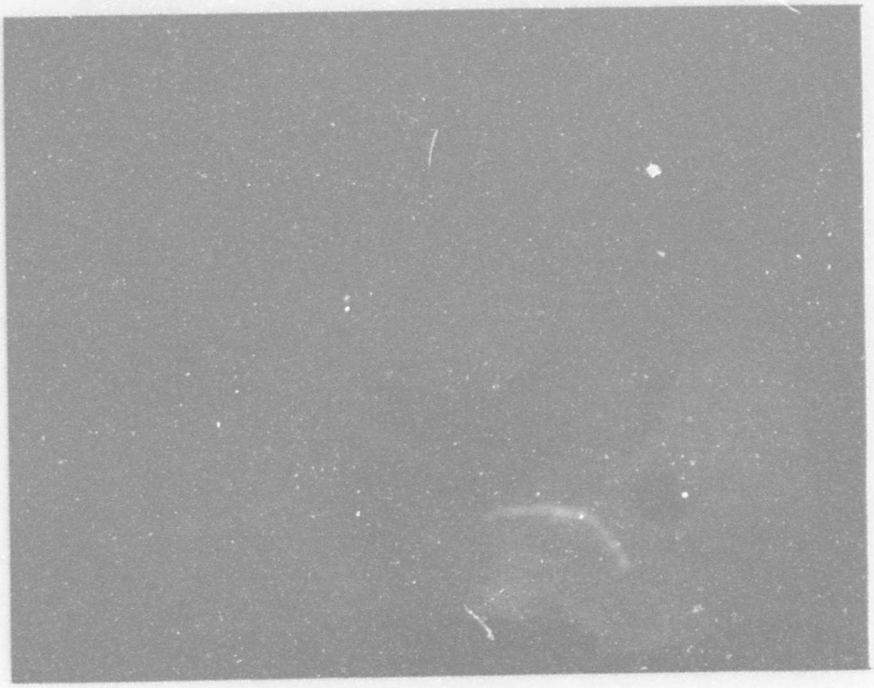
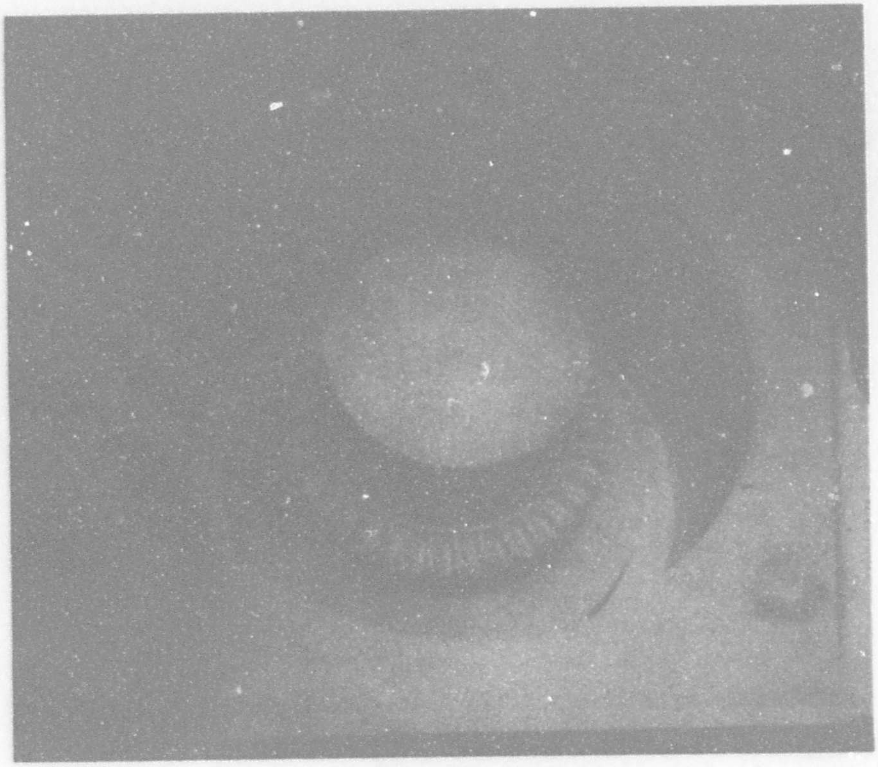


Figure 29
Pattern for IN-100 Insert Casting



(a)



(b)

Figure 30
Two Views of Mold for Producing IN-100 Die Insert Casting

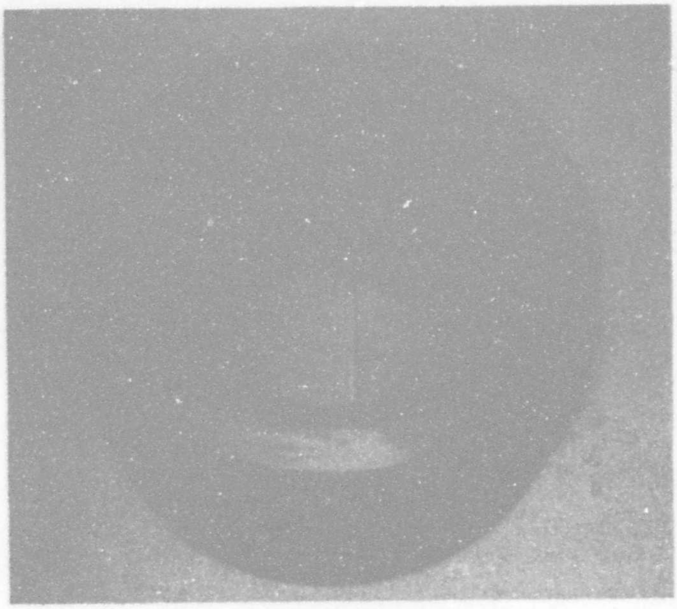


Figure 31
IN-100 Die Insert Casting

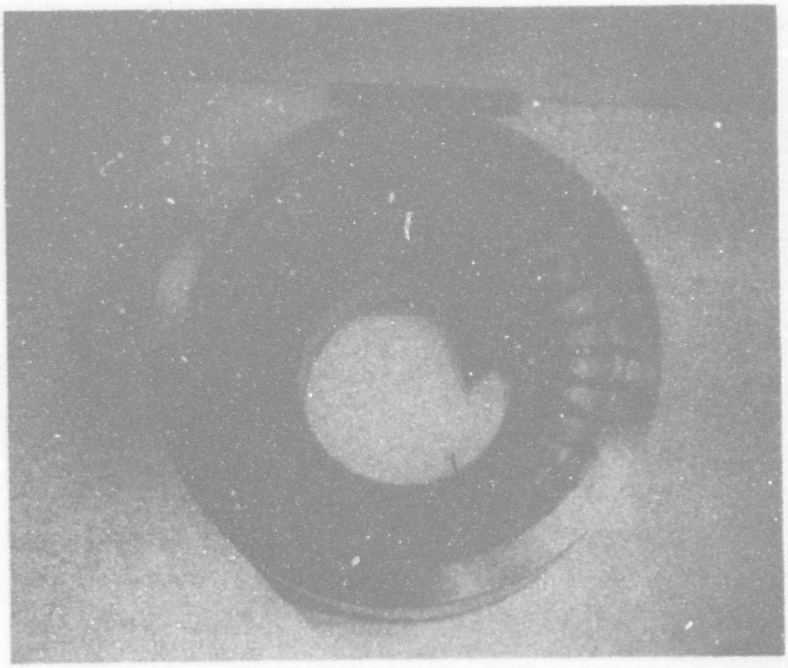


Figure 32
Finish Machined IN-100 Lower Die Insert

4.3.3 Lower Die Insert Holder (B6115-C-25)

This particular component accommodates the die insert shown in Figure 32. Two choices were available for the production of this component. The first involved the manufacture of a new superalloy IN-100 casting weighing approximately 1400 lb, and the second involved the modification of an existing IN-100 die block casting by electro discharge machining a cavity approximately 15 in. diameter by 7 1/2 in. deep from the upper face of the die block as shown in Figure 23. A study of the economic factors involved showed that the second approach was preferable, and consequently the obsolete die block casting was machined by a commercial source. Figure 33 shows two views of the IN-100 die block component so produced.

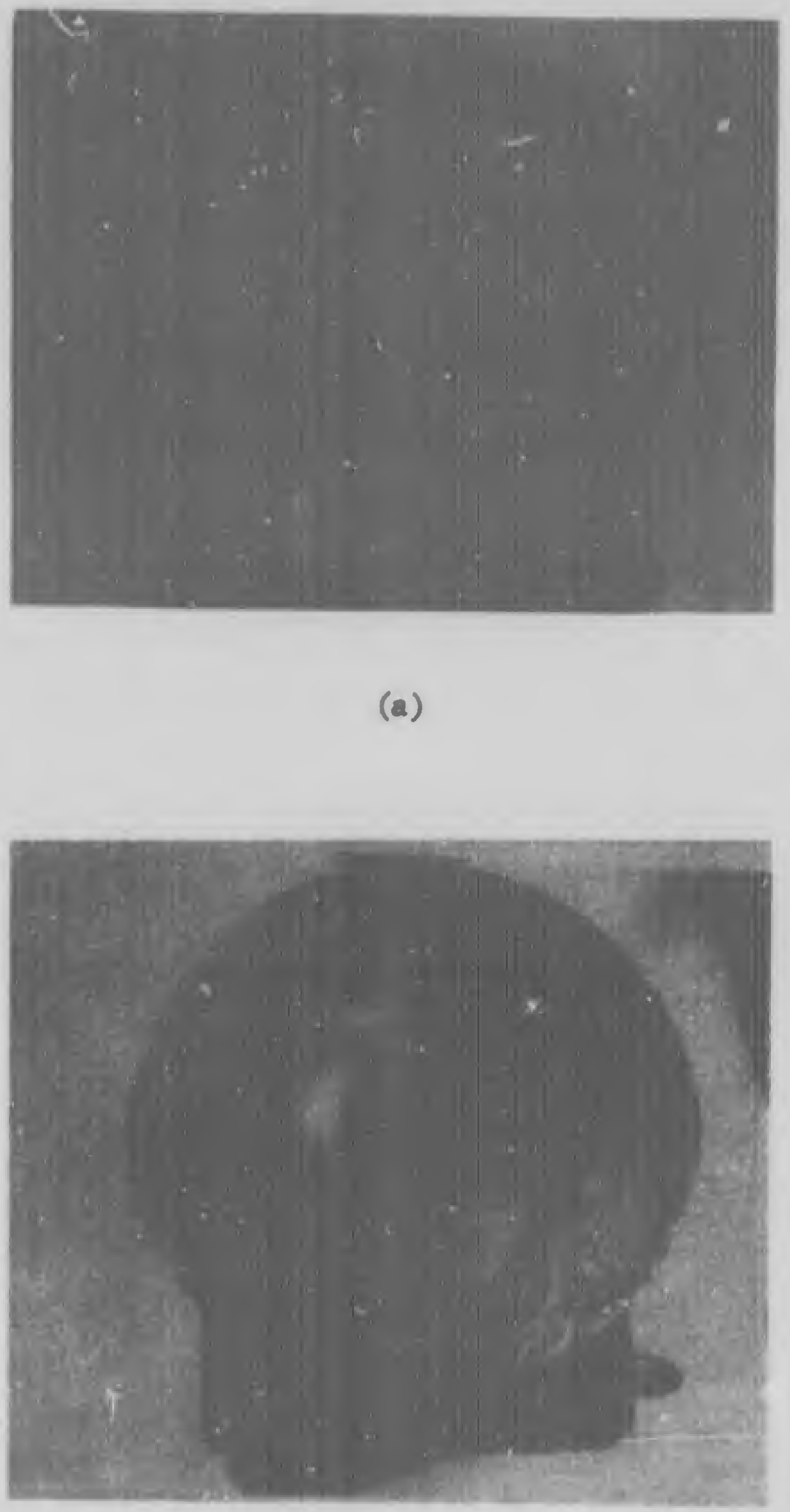
4.3.4 Ejection Pin

The ejection pin as drawn in Figure 24 served three purposes. It was used to align the upper and lower die components during assembly and forging, the upper portion formed the inside diameter of the forging, and it also was used to eject the forging from the die.

A composite casting was produced for this component. A 2 5/8 in. diameter Inconel 718 bar was used for the 2.25/1.870 in. diameter portions of the pin, and IN-100 was cast around this bar to form a 7 3/8 in. diameter x 5 in. thick collar from which the 7.120 in. diameter x 4.560 in. thick detail could be machined. This economical approach worked quite successfully, and the casting was machined to give the component shown in Figure 34.

4.4 Assembly of the Die Set for Producing the Full-Scale Impeller Forging

The sequence in assembling the die components to form the complete die set was as detailed below. The die insert was placed in the lower die insert holder as shown in Figure 35. A sliding fit was used, 0.010 in. difference, between the two interfacing diameters. The ejection/location pin was placed in the lower die as shown in Figure 36. The upper die was carefully lowered into position over the lower die as shown in Figures 37 and 38. The upper die support member was fastened to the upper die as shown in Figure 39. The die components so assembled were now placed in position in the 1000 ton HPM press, all die support members bolted to the upper and lower bolster plates and the high frequency induction heating coils installed as seen in Figure 40. To ensure that all components worked smoothly the ejection pin mechanism was cycled as seen in Figure 41 and a simulated forging blank was placed in the die set and ejected as seen in Figure 42. All components of the die set were found to work as designed.



(a)

(b)

Figure 33
Two Views of Finish-Machined IN-100 Lower Die Block Insert Holder

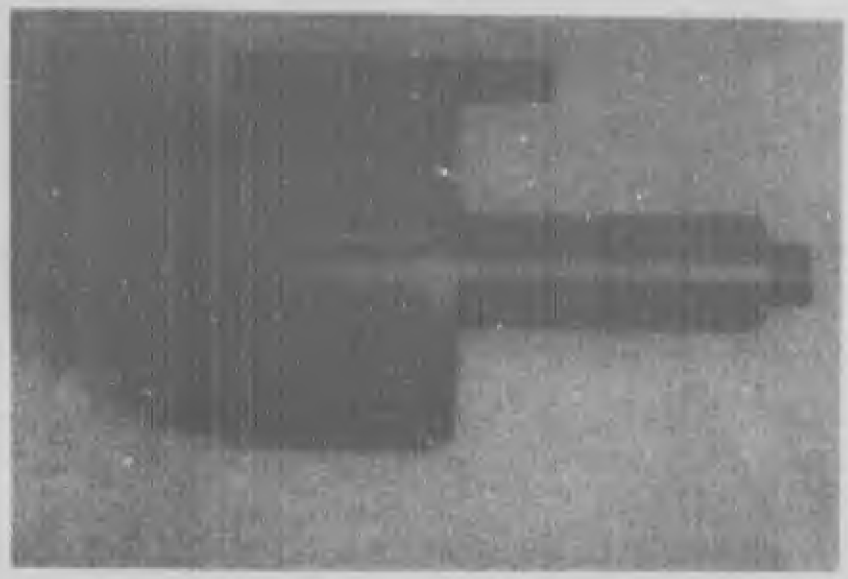


Figure 34
Finish-Machined IN-100/Inconel 718 Ejection Pin

Figure 35
Die Insert in Position in Lower Die Insert Holder

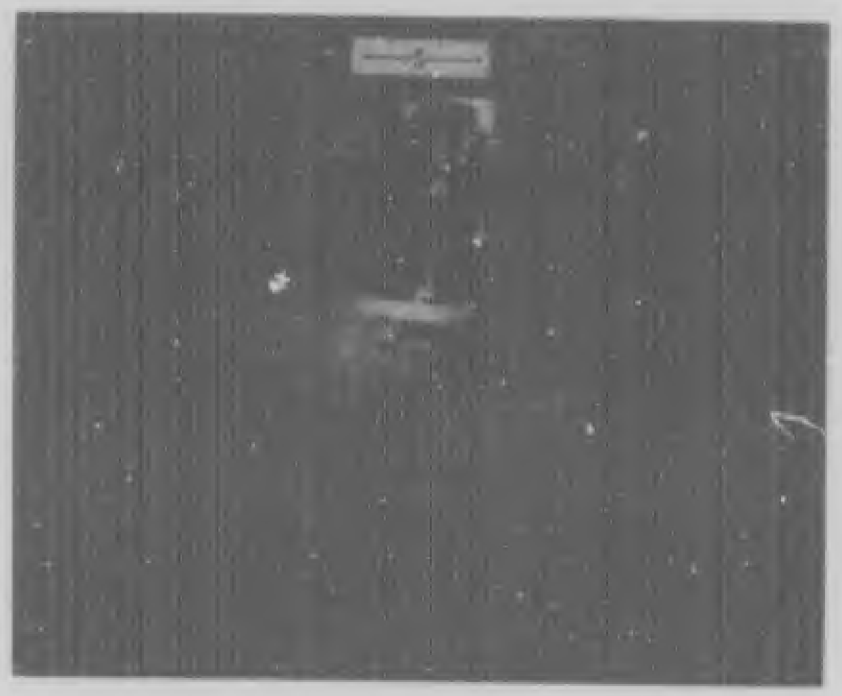


Figure 36
Ejection Pin in Position in Lower Die

Figure 37
Upper Die Being Lowered into Position Over the Lower Die

Figure 38
Upper Die in Position on Lower Die

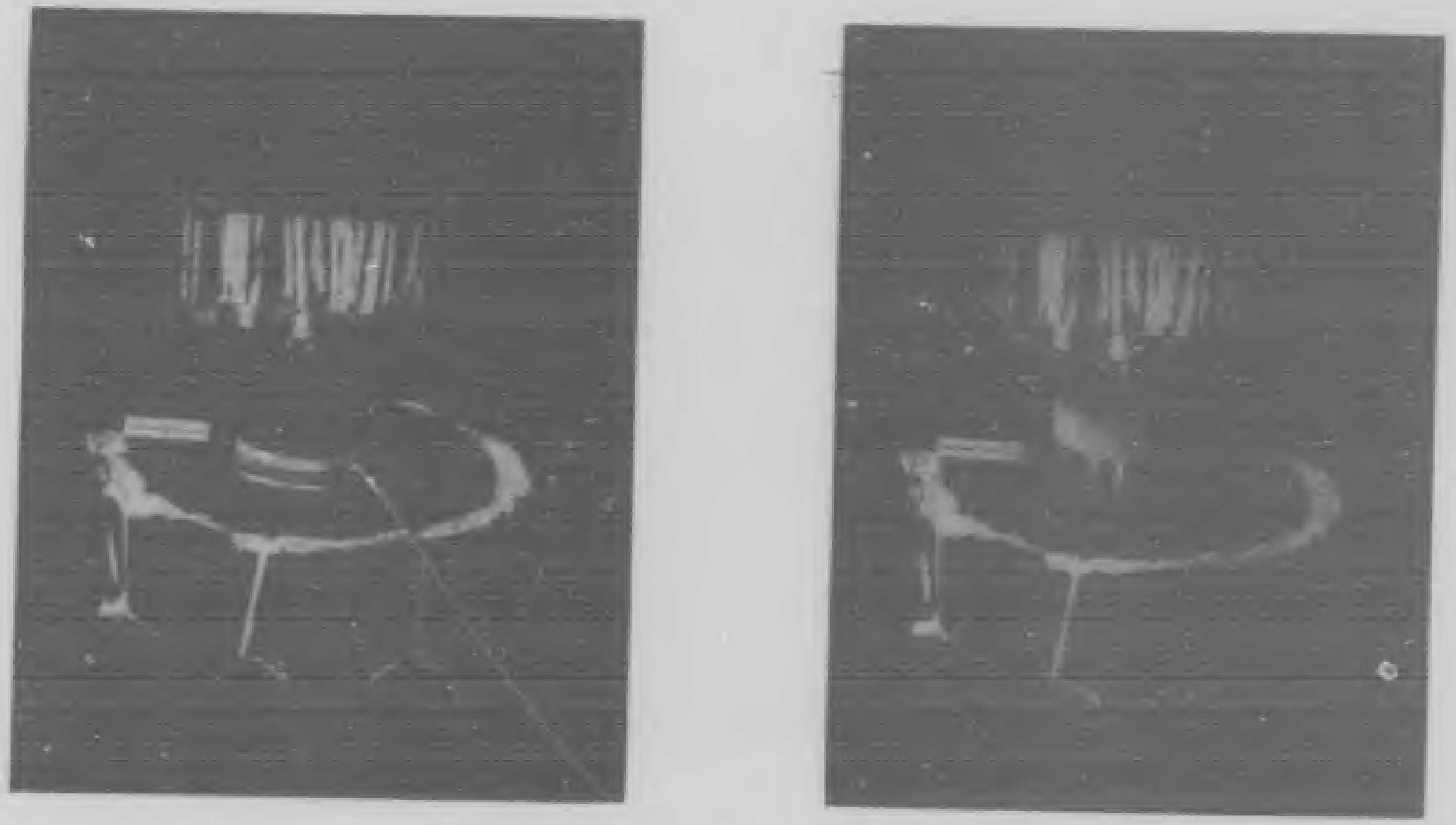
Figure 39

Upper Die Support Fastened to the Upper Die

Figure 40

Die Set with Induction Heating Coils
Installed in 1000-Ton HPM Press

Figure 41
Ejection Pin in Raised Position



(a) (b)

Figure 42
Simulated Forging Blank in Position in Dies and in Ejection Position

4.5 Preform Design

In isothermal trapped die forging the design of the preform is extremely critical as demonstrated in the Phase I forging trials. This criticality in design for the subject preform applies to the weight of the preform and the relationships between the thickness and internal and external diameters to obtain the estimated weight. In conventional production-run forging where several sets of dies are used, the development of preforms, blocker forgings, etc., is usually on a trial-and-error basis. Such development can be costly particularly with titanium alloys, both in terms of raw material usage and time for modification of preceding blockers, preforms, etc. This is particularly true for complex forging of the type involved in this program. Extensive full-scale efforts utilizing titanium trial preforms could not be justified on the subject work. It was therefore decided to construct a Plexiglas model to simulate a section of the full-scale die. This was to be used to "forge" Plasticine shapes which had a range of dimensions to simulate possible preform shapes. Figure 43 shows the Plexiglas model which allowed for the production of a Plasticine preform 3/8 in. thick. A series of Plasticine shapes were cut to simulate possible preform dimensions; Table 4 details the size of the simulating preforms used in the five experiments.

Figures 44 through 48 indicate the flow of the Plasticine at various stages of die closure for the five experiments. The various Plasticine shapes were prepositioned in the die to a position which corresponded to their diametric dimensions.

In experiment 1 (Figure 44) with a simulated preform 12 in. OD, 8 in. ID x 2 in. thick, die filling occurred at the outside portions of the die far too soon, as seen in Figure 44c. There was also insufficient material in the preform at the internal diameter of the preform.

Experiment 2, therefore, utilized a simulated preform with reduced external diameter and internal diameter: 10 in. OD, 6 1/4 in. ID by 2.75 in. thick. Figure 45 shows the die filling which occurred at various stages of die closure. In this instance die filling was occurring on the inside diameter too soon, as clearly demonstrated in Figure 45d. With a die gap of 3/8 in. (Figure 45e) excessive flash is trapped between the upper and lower die at the inside diameter, and there is also lack of fill at the outside diameter of the die.

A simulated preform 11 in. OD, 7 in. ID by 2.30 in. thick was utilized in experiment 3. These dimensions are nearly midway between those used in experiments 1 and 2. This preform size gave excellent results, as shown in Figure 46. The outer edge of the die filled at 1/4 in. die gap (Figure 46d) and, as can be observed in Figure 46e, all portions of the die were filled at die closure.

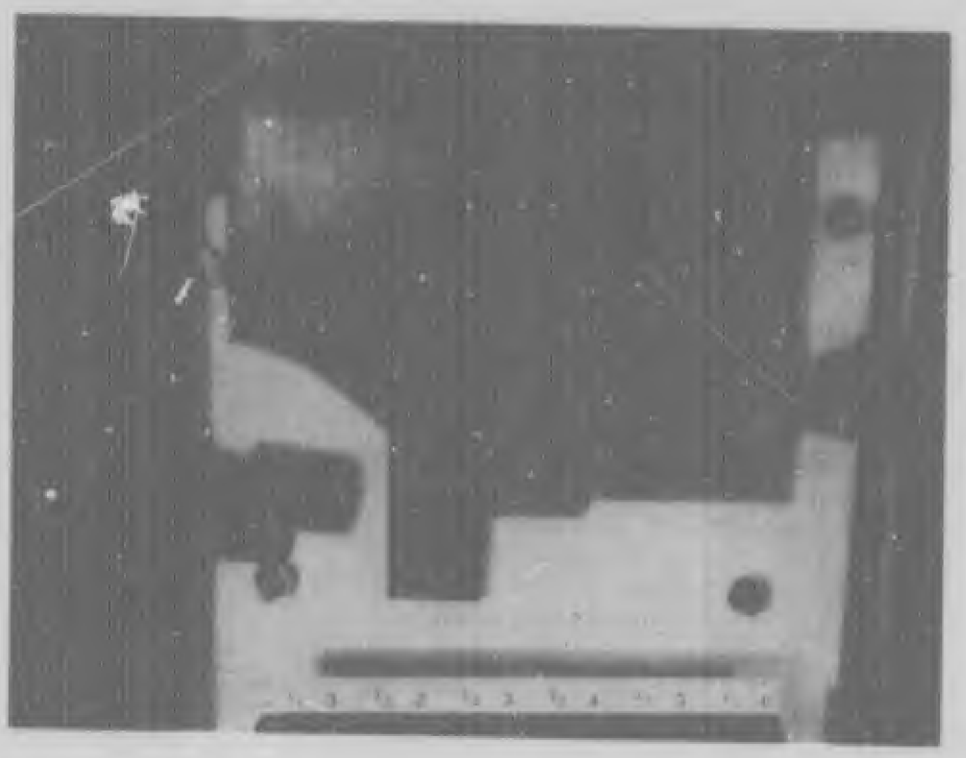


Figure 43
Simulated Plexiglas Die Set

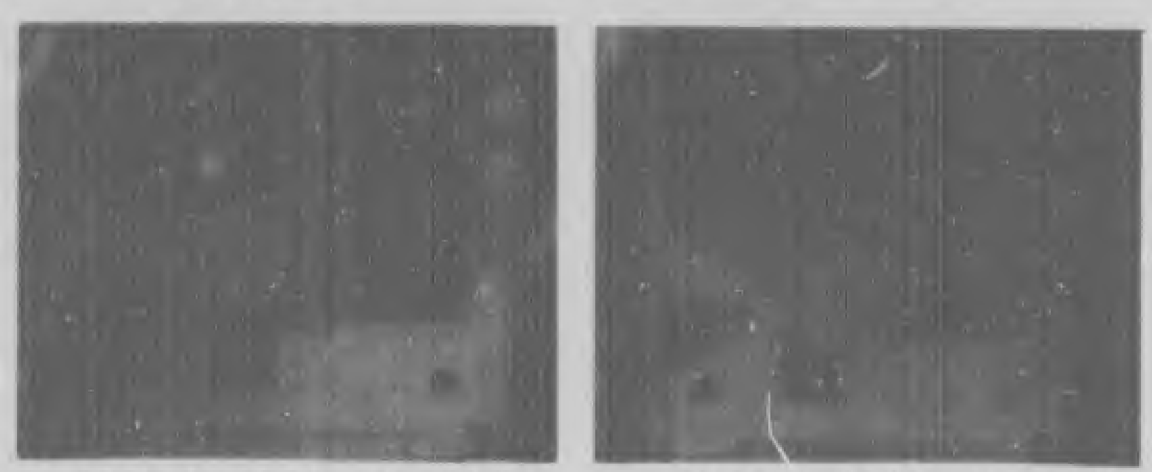
Table 4

SIMULATED PREFORM SIZES

Experiment No.	Simulated Preform Size	Remarks
1	12 inch OD, 8 inch ID, 2 inches thick	Lack of fill at bottom
2	10 inch OD, 6 1/4 inch ID, 2.75 inches thick	Center portions of die prematurely filled.
3	11 inch OD, 7 inch ID, 2.30 inches thick	Good overall die fill.
4	10 3/4 OD, 7 inch ID, 2.50 inches thick	Nearly complete fill at all locations.
5	Trapezoid 11 inch OD x 7 inch ID; 2 3/4 inches thick at ID, 1 3/4 inches thick at OD	Lack of fill at bottom and center of die.

(a) Simulated preform in position,
Die gap 2.25 in.

(b) Die closed 1 in., Die gap 1.25 in.



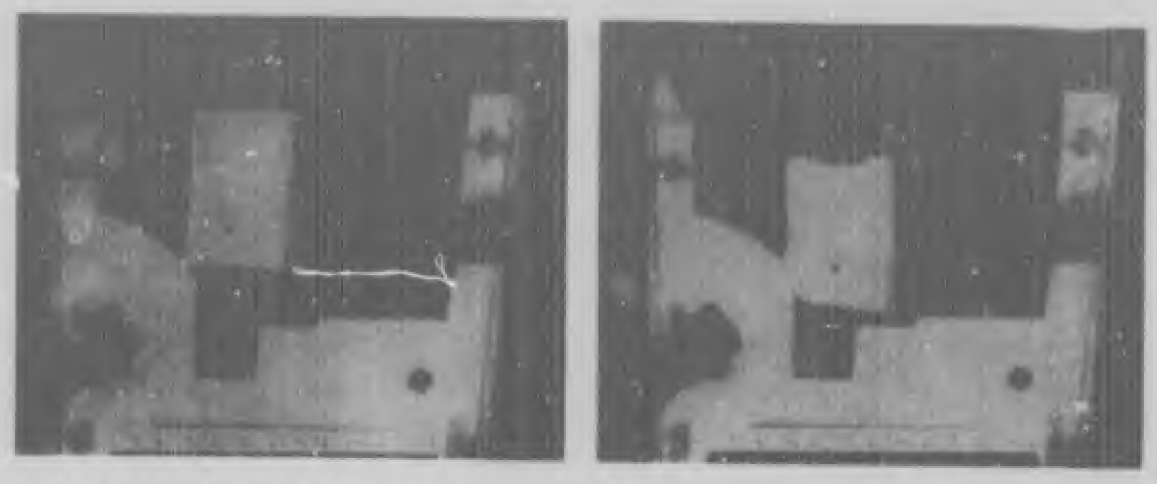
(c) Die closed 1.5 in., Die gap 0.75 in.
Note: Outside diameter of die filled

(d) Die closed 2.0 in., Die gap 0.25 in.

(e) Die closed 2.75 in., Die gap 0 in.
Note: Lack of fill at bottom, center, and top center of die.

Figure 44

Experiment 1 Simulated Forging Trials



(a) Simulated preform in position,
Die gap 2.75 in.

(b) Die closed 1 in., Die gap 1.75 in.

(c) Die closed 1.5 in., Die gap 1.25 in.

(d) Die closed 2 in., Die gap 0.75 in.
Note: Internal diameter of die prematurely filling.

(e) Die closed 2.375 in., Die gap 0.375 in.
Note: lack of fill at outer diameter
and excessive flash at inner diameter

Figure 45
Experiment 2 Simulated Forging Trials

(a) Simulated preform in position, Die gap 2.25 in.

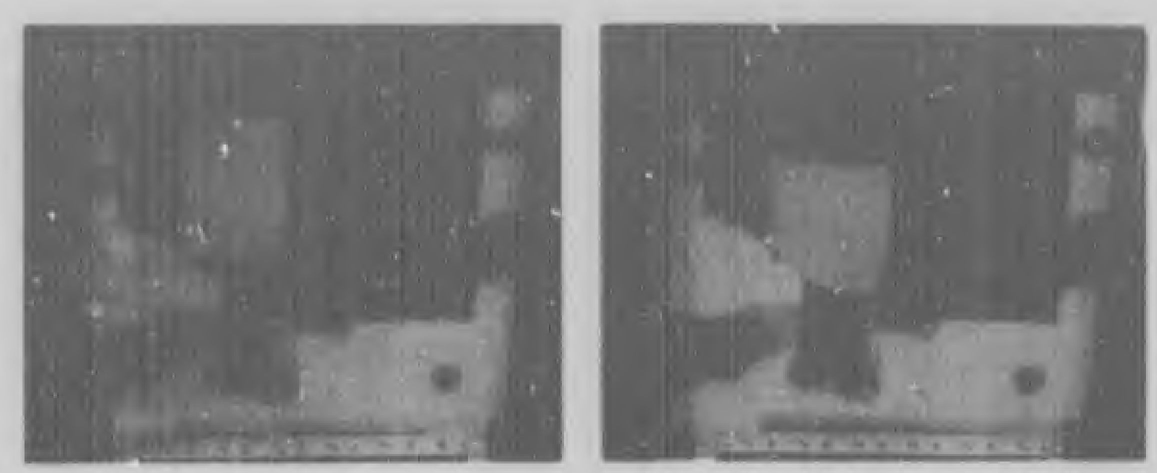
(b) Die closed 1 in., Die gap 1.25 in.

(c) Die closed 1.5 in., Die gap 0.75 in.

(d) Die closed 2.0 in., Die gap 0.25 in.
Note: Fill at outer diameter at 1/4 die gap.

(e) Die closed 2.25 in., Die gap 0 in.
Note: Good overall die fill.

Figure 46
Experiment 3 Simulated Forging Trials



(a) Simulated preform in position
Die gap 2.50 in.

(b) Die closed 1 in., Die gap 1.50 in.

(c) Die closed 1.5 in., Die gap 1.0 in.

(d) Die closed 2.0 in., Die gap 0.5 in.

(e) Die closed 2.25 in., Die gap 0.25 in.

(f) Die closed 2.50 in., Die gap 0 in.
Note: Nearly complete fill at all locations.

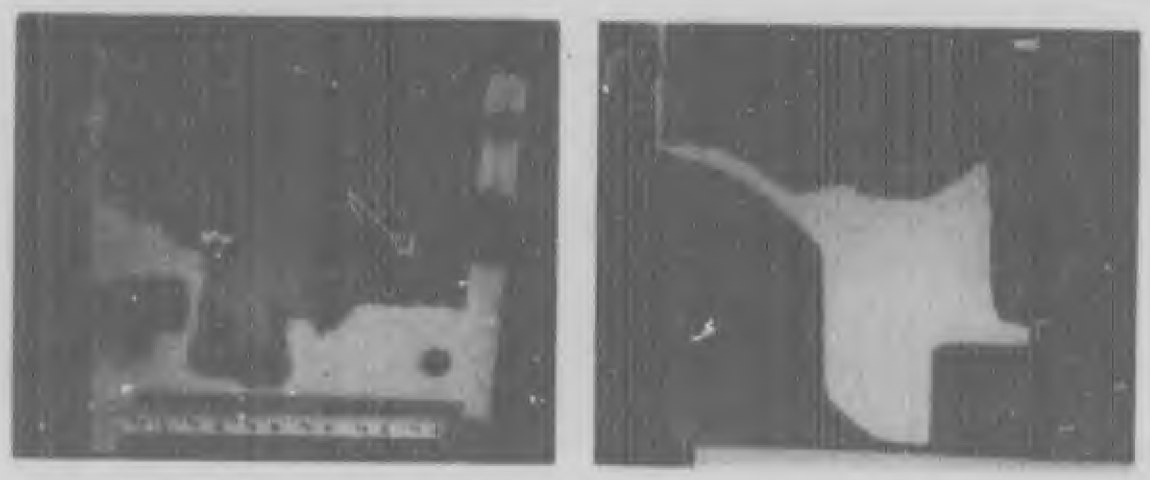
Figure 47
Experiment 4 Simulated Forging Trials

(a) Simulated preform in position, Die gap 1.75 in.

(b) Die closed 0.5 in., Die gap 1.25 in.

(c) Die closed 1.0 in., Die gap 0.75 in.

(d) Die closed 1.25 in., Die gap 0.50 in.



(e) Die closed 1.5 in., Die gap 0.25 in.

(f) Die closed 1.75 in., Die gap 0 in.
Note: Lack of fill in lower areas and inside diameter.

Figure 48
Experiment 5 Simulated Forging Trials

Experiment 4 utilized a simulated preform having dimensions 10 3/4 in. OD, 7 in. ID by 2 1/2 in. thick. The outside diameter was slightly less and the thickness was slightly greater than the preform used in experiment 3. The flow pattern of the Plasticine preform during die closure was again quite good, as can be seen in Figure 47, with nearly complete fill at all locations at die closure.

A simulated preform was produced for experiment 5 which would be thicker at the inside diameter than the outside diameter. The dimensions were 11 in. OD, 7 in. ID and 2 3/4 in. thick at inside diameter, 1 3/4 in. thick at outside diameter. The progression of die fill can be observed in Figure 48. With this shape of preform there is a lack of die filling in the lower area and the inside diameter of the die at die closure.

These experiments clearly identified the approximate dimensions which would be required for the preform without conducting expensive full-scale forging trials: 11 in. OD, 7 in. ID by 2.50 in. thick. Certain geometric factors in the full-scale titanium forging would probably require some modification to this preform size, but it was anticipated that these modifications would only be minor. The tests allowed for the procurement of the titanium forging stock and aluminum which was used for the die tryout.

4.6 Titanium and Aluminum Preform Material

In view of the simulated forging work performed in the Plexiglas dies, aluminum stock for die tryout and titanium forging stock were obtained. Six biscuits of 6061 aluminum, 11 in. OD, 6 1/2 in. ID by 3 in. thick were secured. Also 10 disks of Ti-6Al-4V were obtained having approximate dimensions 11 in. diameter by 2 3/4 in. thick. These disks were made by sawing 2 3/4 in. thick slices from a forged 11 in. diameter billet. Holes of 6 1/2 in. diameter were machined by trepanning in the center of the individual titanium biscuits. The supplier's certification for the titanium forging stock is shown in Table 5.

4.7 Forging Trials

4.7.1 Die Heating

The dies were installed in the 1000-ton HPM press as detailed in Section 4.6. The high frequency induction coils were connected in series to a 200 kva 60 cycle transformer at top setting 3 to give a current of 2000 amps at 100 volts on the secondary. Die temperatures of approximately 1650°F were obtained after 6 hr of heating. With the die cavity at the desired temperature of 1650°F the outside of the surface of the lower die insert holder was approximately 150°F higher.

Table 5

SUPPLIER'S CERTIFICATION OF Ti-6Al-4V FORGING STOCK USED FOR PRODUCING FULL-SCALE IMPELLERS

INVOICE # 21710966
DIE # 500016

*SEE REF NOTE	LOT NUMBER	SERIAL NUMBER	MECHANICAL PROPERTIES					
			TENSILE STRENGTH K.S.I.	YIELD STRENGTH K.S.I.	XX4D ELONG. % IN.	BHN		**BETA TRANSUS**
						% R.A.	R_C	
		SIZE OR GAUGE						
	3928101	**11"RD**						
	T Rad		133,500	143,200	14.0	42.4	28.0	**1830-40°F**
	Tang		135,200	144,800	19.0	43.1	29.0	
	B Rad		133,700	143,800	17.5	44.4	31.0	**1830-40°F**
	Tang		139,000	147,800	16.0	46.7	29.0	

PRESS UPSET 2 TO 3/4" @ 1750°F
ANNEALED 2 HRS. @ 1300°F - A.C.

CHEMICAL COMPOSITION										
HEAT NO.	ALLOY	C	N	FE	AL	V	O	H	CU	SN
G-9404	**6Al4V VF**	.025	.013	.06	6.4	4.1	.12T .[illegible] **FINAL**	.006T .[illegible]8		

4.7.2 Forging Trials with Aluminum

Six 6061 aluminum preforms were available for die tryout and forging trials. The basic configuration of these preforms was in the form of disks having an external diameter of 11 in., an internal diameter of 7 in. and 3 in. thickness. Table 6 summarizes the typical dimensions, weights, forging loads, and die and workpiece temperatures. Details of the individual forging trials are given below:

Forging No. 1 - This preform was 11 in. OD, 7 in. ID by 3 in. thick and weighed 17.1 lb. Die temperature was 700°F and workpiece temperature 800°F. This specimen was forged in two stages to obtain some idea of metal flow. Consequently, two tonnages were used, the first trial 210 tons and the second or restrike operation 400 tons. In both instances, the forging load was maintained for 5 minutes. The fins were not completely filled near the outer edge and near the inside diameter. No machining of the forging after first strike was performed. Figure 49 shows this particular forging.

Forging No. 2 - The internal diameter of the preform was increased to 7 1/4 in., and the preform weighed 15 1/4 lb. The die and workpiece were 800°F. In a single stroke of the press at 410 tons the forging shown in Figure 50 was obtained. Although better than No. 1, the fins were still not completely formed. The die was hotter for this specimen.

Forging No. 3 - Two strikes were used for this trial, and in the initial preform the material was redistributed to give a larger diameter starting piece, 11 3/8 in. diameter by 2 3/4 in. thick, weighing 17.1 lb. Die and workpiece temperatures were 950°F. The first strike used 475 tons; the forging as produced was machined on the outside diameter to remove approximately 1/4 inch and the inside diameter from the partially formed flange. On the second strike the tonnage was increased to 700 tons and maintained for 5 minutes. The excellent forging so produced is shown in Figure 51. The fins were completely formed on the outside edge, but the fins close to the ID were somewhat underfilled. The detail on the inside diameter was fully formed and prevented full die closure.

Forging No. 4 - The preform in this trial was 11 3/4 in. OD, 6 1/2 in. ID by 2 3/4 in. thick and a 3/4 in. 45° chamfer was removed from the upper outer diameter. Forging weight was 17.0 lb. Forging load was 550 tons applied for 5 minutes with die/workpiece temperature of 850 and 950°F, respectively. Figure 52 illustrates the forging so produced. The fins were completely formed at the outside edge, but the fins close to the ID were somewhat underfilled. The flange on the inside diameter was not filled.

Table 6

SUMMARY OF FORGING TRIALS FOR 6061 ALUMINUM

Forging Trial No.	Preform Dimensions, in.			Preform Weight, lb	Tonnage	Time, min	Die Temp., °F	Preform Temp., °F
	OD	ID	Thickness					
1	11	7	3	17.1	210	5	700	800
1-2					400	5	700	800
2	11	7 1/4	3	15 1/4	410	5	800	800
3	11 3/8	6 1/4	2 3/4	17.2	475	5	950	950
3-2	Trimmed OD and ID			17.1	700	5	950	950
4	11 3/8 3/4 x 45° chamfer	6 1/2	2 3/4	17.0	550	5	850	950
5	11 1/4 1 7/16 x 45° chamfer	6 1/4	2.8	15.0	700	7	950	950
6	11 1.35 x 45° chamfer	6 1/2	3	16.0	700	7	950	950

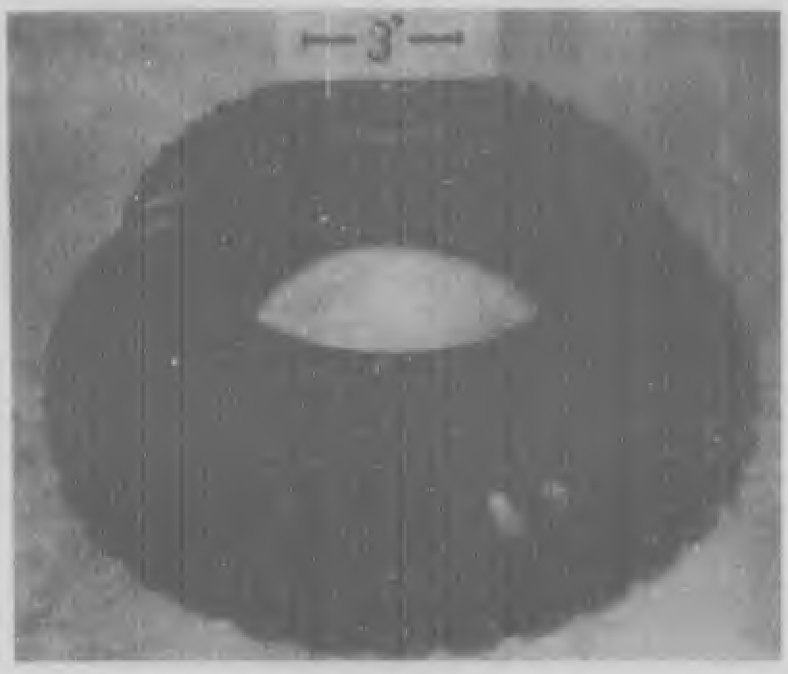


Figure 49
6061 Aluminum Forging after Trial 1

Figure 50
6061 Aluminum Forging after Trial 2

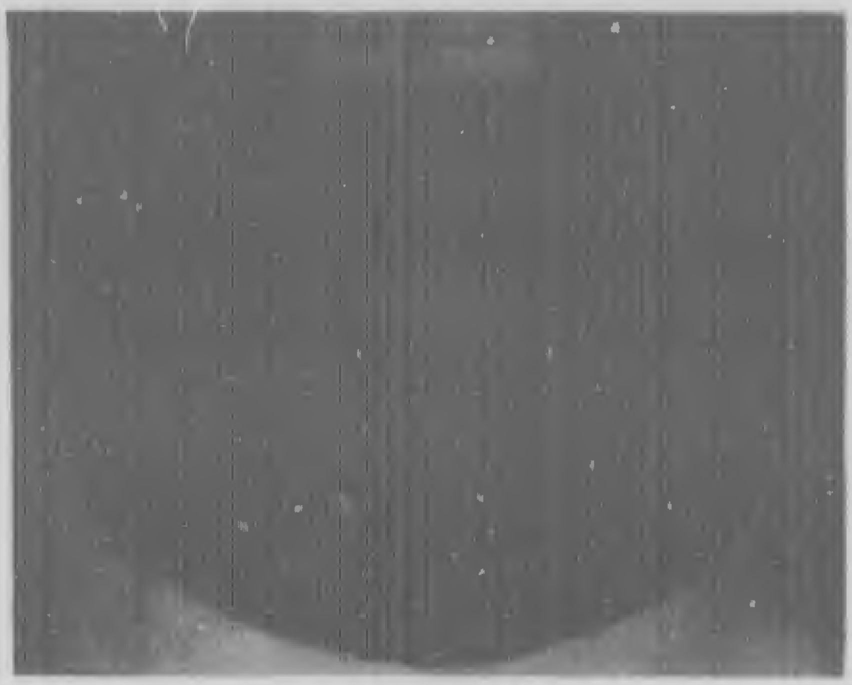


Figure 51
6061 Aluminum Forging after Trial 3

Figure 52
6061 Aluminum Forging after Trial 4

Forging No. 5 - The general preform dimensions were 11 1/4 in. OD, 6 1/4 in. ID by 2.8 in. thick with a 1 7/16 in. 45° chamfer on the bottom outer diameter. The preform weight was 15.0 lb. The forging load was 700 tons, and die and workpiece temperatures were 950°F. As shown in Figure 53, a good forging was obtained in one press operation with good fill around the outside diameter but some minor underfill near the internal diameter. The large chamfer on the lower outside diameter and the high tonnage and temperatures were noteworthy features of the reasonably successful trial.

Forging No. 6 - The preform for this trial was 11 in. OD, 6 1/2 in. ID by 3 in. thick with a 1.350 in. 45° chamfer on the lower outside diameter. The forging load was 700 tons, and the die/workpiece temperature was 950°F. Figure 54 shows the forging produced in this trial; there was underfill on the blades at the outside diameter with good fill on the castellated portion near the inside diameter. The flange on the inside diameter was completely formed, and some flash was generated in this area producing "die lock" which prevented full die closure from being achieved.

Some general observations can be made as a result of these few forging trials where aluminum was used as the preform material. The die set performed extremely well, and no problems were experienced with any of the die components. With aluminum a preform weight in the range of 15 to 16 lb appeared to be optimum for obtaining good overall die fill. The distribution of metal in the preform was critical. The outside diameter had to be around 11 3/8 in. to ensure that the blades on the outside diameter could be filled. The inside diameter of 6 1/4 to 6 1/2 in. appeared to be optimum. Preform thickness of approximately 2 3/4 in. gave the best overall die fill. It appeared that a chamfer on the lower outside diameter was absolutely essential to obtain good metal distribution during forging with consequent good die fill. A 45° chamfer having a side in the region of 1 3/8 to 1 7/16 in. seemed to give optimum die fill.

4.7.3 Forging Trials with Ti-6Al-4V Alloy

A series of forging trials utilizing ten Ti-6Al-4V alloy preforms was conducted, with the objective of producing impeller forgings having the minimum amount of machining. Details of die assembly and die heating were previously discussed. The preform dimensions which were to be employed for the titanium forging trials were influenced by the results obtained in the preceding aluminum forging trials. Table 7 is a summary of the forging trials conducted in this phase of the work.

Figure 53
6061 Aluminum Forging after Trial 5

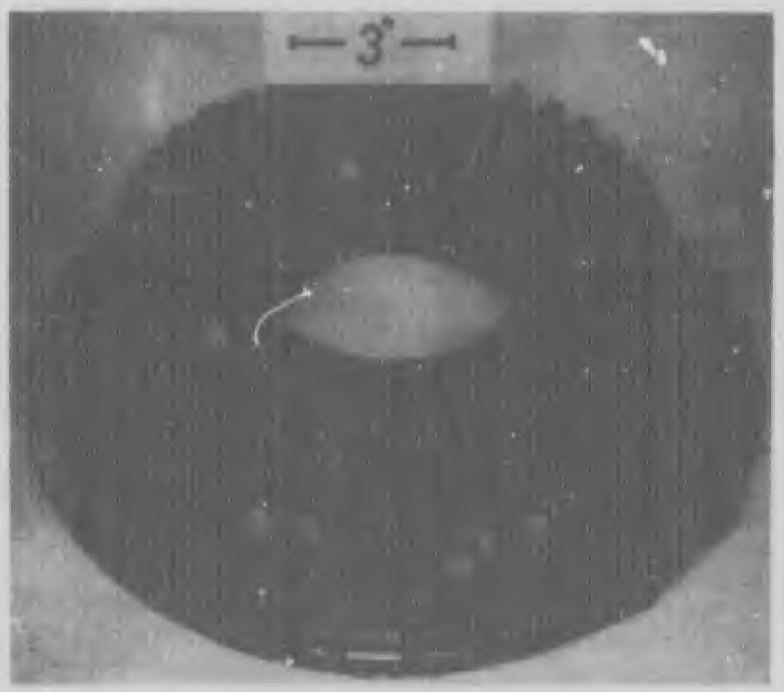


Figure 54
6061 Aluminum Forging after Trial 6

Table 7

SUMMARY OF Ti-6Al-4V FORGING TRIALS

Forging and Experiment No.	Preform Dimensions, in. OD	ID	Thickness	Chamfer	Preform Weight, lb	Tonnage, tons	Time, min	Die Temp., °F	Preform Temp., °F	Remarks
1	11.37	6.25	2.75	1.5 x 45°	25.0	725	5	1500	1800	Die not closed, insufficient tonnage.
1-1 (1 restruck)	OD reduced 0.5 in., ID increased 1.0 in.				24.32	1000	5	1600	1800	Good fill on blades, but laps due to improper indexing.
2	11.25	6.70	2.80	1.5 x 53°	24.30	1000	5	1600	1800	Minor lack of fill on blades at outside diameter.
3	11.25	6.65	2.72	1.13 x 45°	24.34	1000	4	1600	1800	Minor lack of fill on blades at outside diameter.
4	11.25	6.69	2.81	1.13 x 45°	25.05	1000	5	1600	1800	Excess volume, die lock on inside flange.
4-1 (4 restruck)	OD reduced 0.42 in., ID increased 1.0 in.				24.54	1000	3	1600	1760	Good fill.
5	11.25	6.69	2.82	0.90 x 37°	25.90	1000	5	1650	1760	Excess volume, die lock on inside flange.
5-1 (5 restruck)	OD reduced 0.50 in., ID increased 0.75 in.				25.01	1000	3	1600	1750	Good fill on blades and inside diameter.
6	11.25	6.70	2.73	0.97 x 38°	24.5	1000	3	1620	1750	Minor lack of volume on outside and inside diameter.
7	11.25	6.73	2.74	0.94 x 39°	24.92	1000	3	1610	1750	Lack of fill on outside diameter, die lock on inside diameter at flange.
7-1 (7 restruck)	OD reduced 0.50 in., ID increased 1.0 in.				24.30	1000	3	1650	1750	Good fill.
8	11.25	6.69	2.72	1.28 x 40°	25.33	1050	5	1610	1750	Lack of fill, die lock on ID.
8-1 (8 restruck)	OD reduced 0.50 in., ID increased 1.0 in.				24.60	1000	5	1600	1750	Good fill.
9	11.25	6.69	2.77	1.40 x 40°	25.62	1000	2	1600	1750	Lack of fill at OD, die lock
9-1 (9 restruck)	OD reduced 0.50 in., ID increased 1.0 in.				25.0	1000	3	1600	1750	Minor lack of fill on OD.
10	11.24	6.68	2.77	1.47 x 40°	25.6	1000	5	1630	1750	Lack of fill on OD, die lock on ID.
10-1 (10 restruck)	OD reduced 0.375 in., ID increased 1.0 in.				25.28	1000	3	1600	1750	Good fill.

The preforms were machined from the titanium stock previously described in Section 4.6. They were coated with Markal CRT-22 glass-based lubricant. Figure 55 is a typical coated preform ready for admission to the furnace. The preforms were heated in an electric furnace to the appropriate temperature (1750-1800°F) and held at temperature for approximately 1 hr. The dies were heated to the temperatures detailed in Table 7. The typical forging sequence was to admit heated preform to the heated die as quickly as possible, close the dies, build up tonnage as rapidly as possible, hold at the selected tonnage, and allow the metal to flow in the die cavity. Hold times ranged from 3 to 5 minutes. At the end of the hold period the upper die was retracted, the outside diameter of the forging was selectively cooled with compressed air for typically 30 seconds, and the ejection pin was activated to eject the forging from the die. The forging was stripped from the die by inserting a split collar under the lower center portion of the forging, retracting the ejection pin downwards and thereby freeing the forging and allowing the forging to be removed from the die by means of tongs. The forgings were air cooled to room temperature.

Several good forgings were obtained. Figure 56 shows two views of forging No. 4 with a typical preform. Figure 57 shows a general view of forging No. 5 after etching and a close view of the blade detail. Two views of forging No. 7, after etching, are shown in Figure 58. Two general views of the titanium forgings produced are shown in Figure 59.

Typical thickness of the blades at the outer extremity was 0.160 in., and the thickness of the forging at the outside diameter was typically 0.210 in. Titanium alloy forgings having such minimal section thicknesses could not be attempted by any method other than the isothermal forging technique.

With regard to forging technique and preform design a number of general comments can be made. It was originally anticipated that these complex forgings could be produced in one stroke of the press from the simple preform. For such an operation, preform dimensions and weight are extremely critical and excess material in either the outside or inside can produce die lock and prevent complete closure of the dies. This occurred in some instances in the forging trials where the inside flange was completely filled and flash generated between the ejection pin and the upper die before the blades at the outer edge were completely filled. When this occurred, the forging was stripped from the die and, as noted in Table 7, material was removed from the 4 3/4 in. diameter inner flange. The forgings were reheated and restruck, and usually sufficient metal flow occurred to fill both the blade extremities and the inner flange without any die lock occurring. This problem can be overcome by minor modification of the dies and preform dimensions. Die modification in

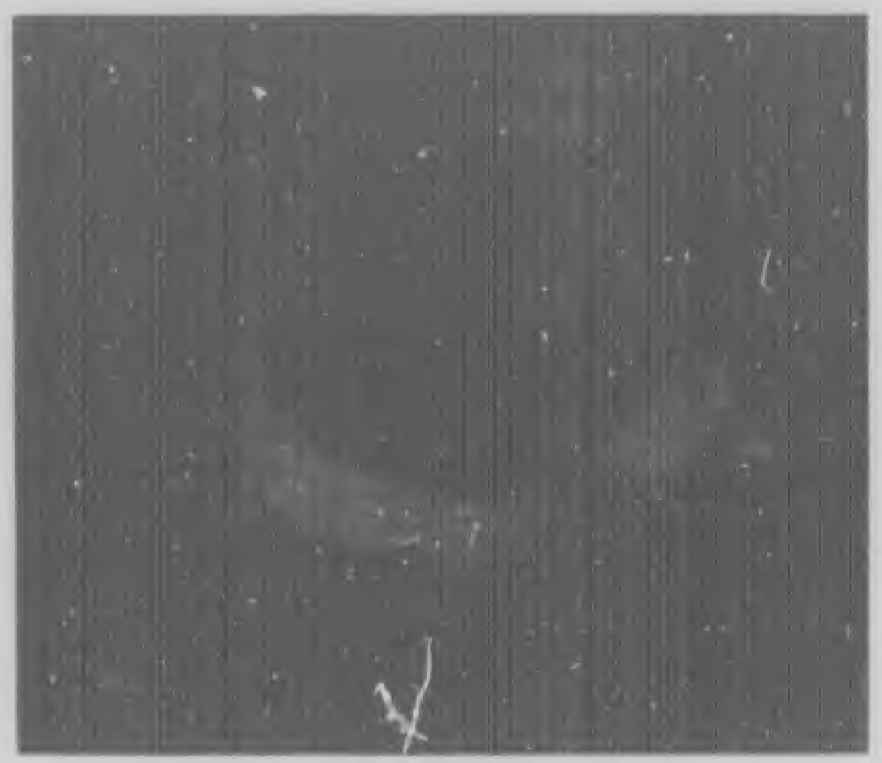
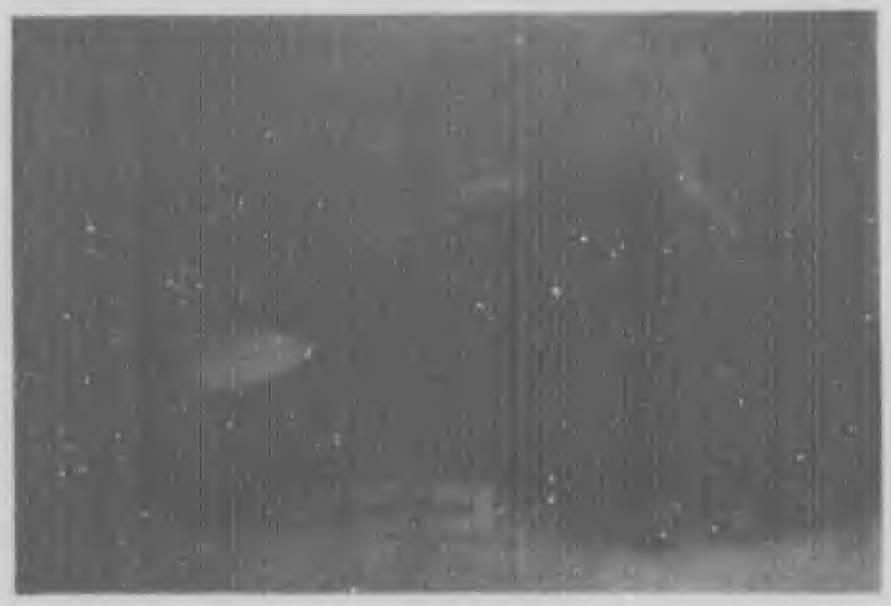


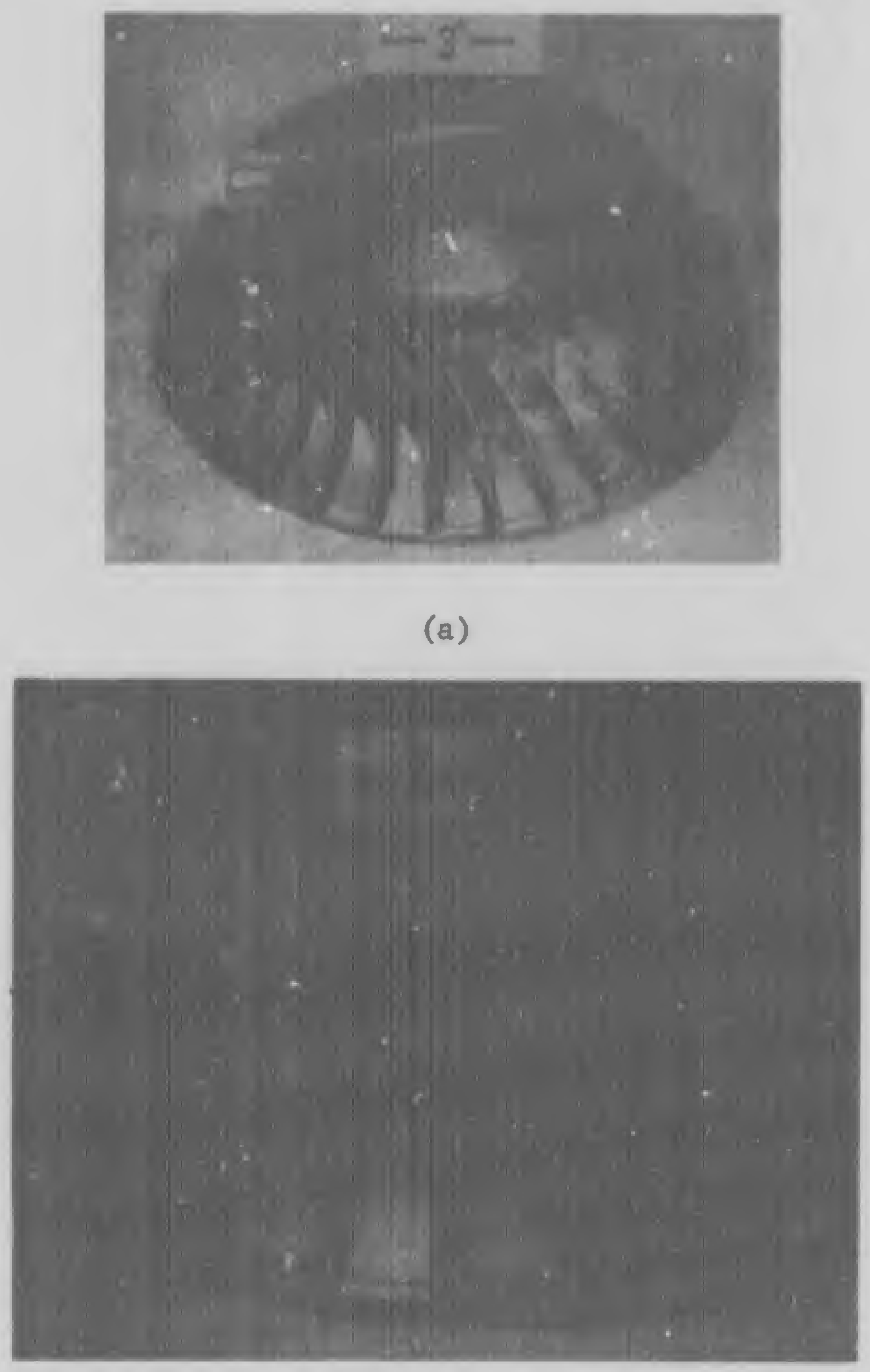
Figure 55
A Typical Ti-6Al-4V Preform Coated with Markal CRT-22



(a)

(b)

Figure 56
Two Views of Forging No. 4 with a Typical Preform



(a)

(b)

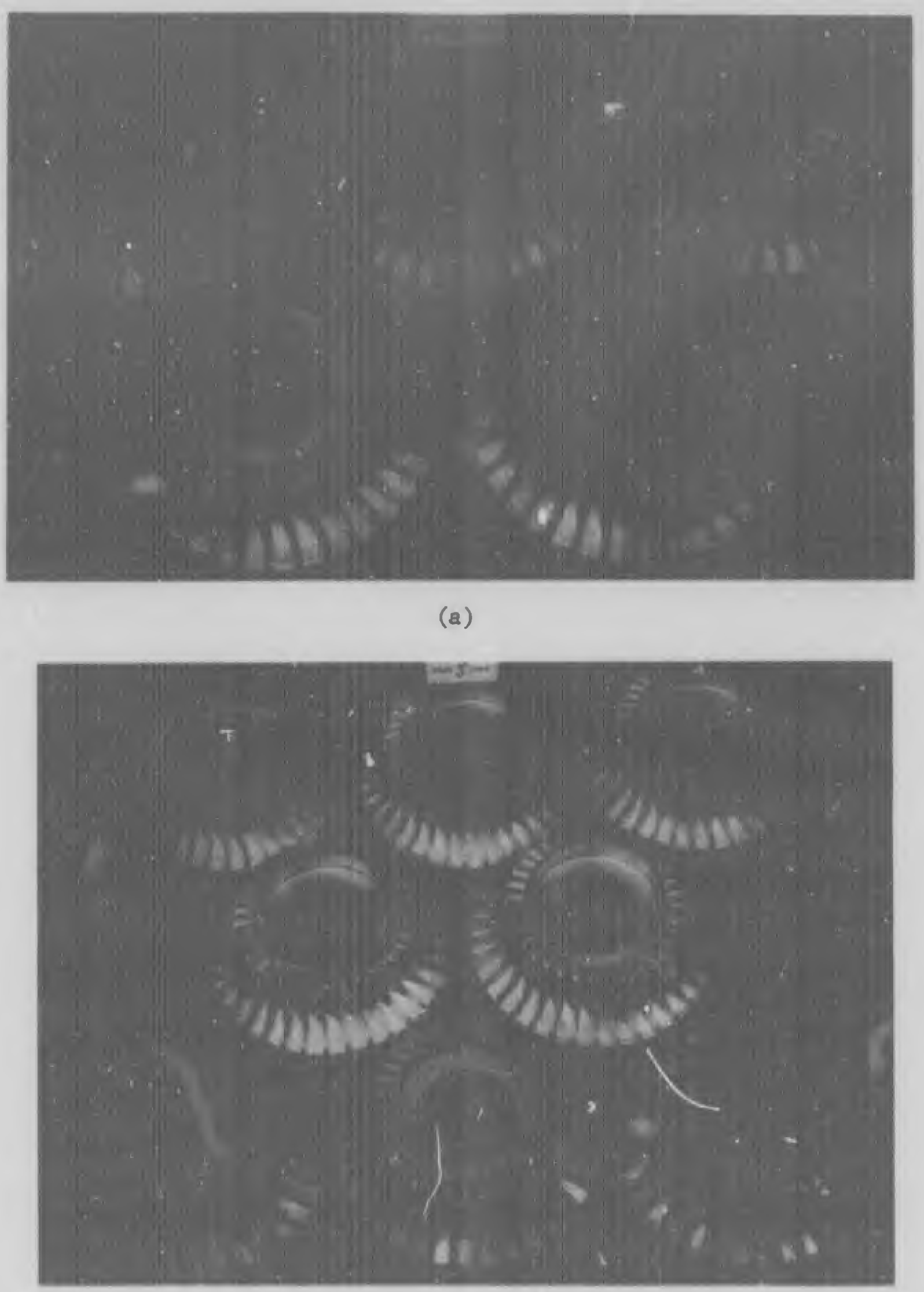
Figure 57

An Overall View of Forging No. 5
with a Closeup of the Blade Detail

(a)

(b)

Figure 58
Two Views of Forging No. 7



(a)

(b)

Figure 59

Two General Views of
Isothermally Forged Ti-6Al-4V Impeller Forgings

the inner flange area to prevent die lock, could consist of reducing the diameter of the flange or providing a flash gutter on either the ejection pin or the upper die where they mate. Additionally, it would be advisable to slightly extend and deepen the slots in the die at the outside diameter where the blades are formed on the outside diameter. Lack of die filling because of trapping of lubricant in this area would therefore be negated.

The preform weight is quite critical and must typically be in the range of 24 1/2 to 25 lb for the die configuration and forging technique used in the program. The outside diameter and thickness of the preform were essentially fixed because of the form of the forging stock obtained before forging trials were commenced. Consequently, adjustment of weight and metal distribution could only be achieved by changing the inside diameter of the preform and the necessary chamfer on the outside diameter. The results obtained indicate that a preform having an outside diameter of about 12 in., instead of the 11 1/4 in. employed, would probably have been somewhat better and ensured earlier fill of the blades at the extremity of the forging. The inside diameter, thickness, and chamfer would, of course, have to be optimized to produce a preform weight in the optimum range. These minor modifications of the die and the preform should allow the subject forgings to be repetitively produced in a single stroke of the press.

The forging loads required to produce the subject forging were usually 1000 tons. The plan area of the forging was calculated to be 114 sq in. Consequently, the forging pressure used was approximately 17 kpsi. This value is considerably lower than would be used in conventional titanium forging operations for parts with similar plan area but of much less complexity. Further, a 1000-ton press was employed for this work, and it is estimated that at least an 8000-ton press would be required for a component having this plan area if conventional forging techniques were used.

4.7.4 Mechanical Properties

Forging No. 2 was utilized for heat treatment studies and mechanical property determination of the forgings. Two 1 in. thick radial sections were removed from the forging and heat treated as follows:

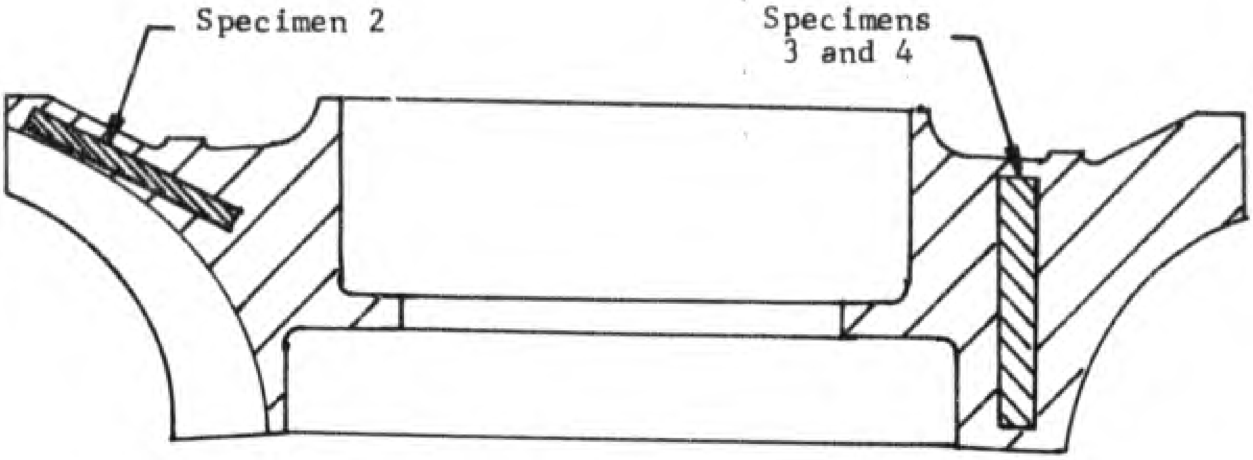
Heat to 1750°F, hold 1 hr, water quench

Heat to 1100°F, hold 4 hr, air cool

Tensile specimens were produced from these sections as shown in Table 8; these were tested and produced the data shown in Table 8. Flat tensile specimens were produced having gauge dimensions 0.198 in. thick by 0.29 in. wide. The gauge length

Table 8

TENSILE TEST DATA AND SITE OF TENSILE SPECIMEN



Specimen No.	Yield Strength, (0.1% Offset), kpsi	UTS, kpsi	Elongation, %
2	164	170	17
3	164	167	21
4	152	158	16

for specimen No. 2 was 1.5 in. and specimen Nos. 3 and 4, 0.750 in. The combinations of tensile strengths and ductilities obtained are extremely good and should be compared with the data shown in Table 5 for the initial forging stock.

5. SUMMARY AND CONCLUSIONS

The objective of this program was to utilize the isothermal forging process, developed at IITRI, for the production of Ti-6Al-4V alloy centrifugal compressor impeller forgings having the minimum of machining. A two-phase program was undertaken to secure this objective. The first phase involved the production of a simplified version of the impeller, drawing No. 1-100-078-03, to establish processing parameters, metal flow characteristics, and ability to meet specification requirements. The second phase required the production of a full-size impeller forging based on the findings in the first phase.

The concept of isothermal forging of titanium alloys in dies heated to the forging temperature holds many attractions especially for press forging work where the problem of extraction of heat from the workpiece by the dies would be eliminated and the sensitivity of titanium to strain rate could be accommodated. The operation requires heating the dies to the forging temperature range of 1600-1800°F.

In Phase I of the subject project a series of titanium alloy forgings of a simplified version of the impeller were produced. These forgings were 8 1/2 in. diameter, weighed approximately 8 lb, and incorporated 20 blades arranged in four clusters of five. The blades ranged in thickness from 0.100 to 0.200 in., were 3/4 in. in length, and had zero draft.

Preform temperatures of 1700°F and die temperatures of between 1700 and 1750°F were optimum for obtaining good die filling. Press forging pressures of 20 to 22 kpsi, at optimum die-preform temperatures, were adequate to obtain a good forging. This is in contrast to forging pressures of over 100 kpsi which are typically used in conventional titanium forging practice.

It was found that to obtain complete blades by isothermal forging a trapped die forging technique had to be used.

While a simple-shaped preform, having typical dimensions of 5 1/2 in. outside diameter, 1 3/4 in. inside diameter by 2 3/4 in. high, could be used to produce the forging, the mass, thickness and general shape of the blank were critical.

The several forgings were produced in a single stroke of the press, and such forgings would be impossible to make by conventional forging techniques.

The results obtained in Phase I for the scaled down simulated impeller allowed for the establishment of the influential factors associated with die design, die materials, die heating, preform design, and metal flow during the forging operation which could be used for isothermally forging the full-scale impeller forging in Phase II of the program.

A forging die set was designed which incorporated all the trapped die features developed in Phase I. The die set had four parts: an upper die which produced the upper or top face of the forging, a die insert in which the blades were formed, a die insert holder, and an ejection pin which also formed the detail on the inside diameter of the forging. The various components were precision cast in nickel-base superalloys, either IN-100, MAR-M 200, or Inconel 718. The blade detail in the die insert was produced by electro discharge machining. The total weight of the die set was approximately 2000 lb.

The forging to be produced was designed so that it could be extracted vertically from the lower die. The curvature and reentrant angles on the finish-machined impeller blades limited the blades being produced to net dimensions and still obtain vertical extraction from the die. Consequently, stock had to be added at certain undercut area.

A Plexiglas model of a section of the full-scale die was made to obtain data on the approximate size of the preform required and to study "metal" flow at different stages of die closure. Plasticine was used as the simulating forging material. These experiments indicated that the Ti-6Al-4V preforms should have approximate dimensions 11 in. OD, 6 1/2 in. ID by 3 in. thick. Full-scale forging trials were conducted in the 1000-ton HPM press, using 6061 aluminum for die tryout and optimization of preform design. Die-workpiece temperatures of 900°F were typically employed. The six trials showed that the dies performed satisfactorily and generally indicated the size of preform required to obtain good die filling.

Ten Ti-6Al-4V preforms having approximate dimensions 11 1/4 in. outside diameter, 6 1/2 in. inside diameter, and 2 3/4 in. thick were obtained. Chamfers approximately 1 1/4 to 1 1/2 in. by 45° were machined on the lower edge of the outside diameter to produce preforms having weights ranging from 25 1/2 to 26 1/2 lb.

A commercially available glass-based slurry, Markal CRT-22, was applied to the preforms for the purpose of protecting against excessive oxidation during heating to forging temperature and also as the forging lubricant. This material performed both functions satisfactorily.

The forging dies installed in the press were induction heated successfully to temperatures in the range of 1550-1650°F.

A series of forging trials, utilizing the ten titanium alloy preforms, was successfully conducted. Preform temperatures ranged from 1750 to 1800°F with the majority of the forging work being done with preform at 1750°F. Press tonnage of 1000 tons was employed for most of the forging trials. Several good forgings were produced in either a single stroke of the press or in two strokes of the press. The second forging sequence was employed after removal of excess material from the forging produced in the first trial. This excess material was invariably at the inside flange and produced die lock which prevented complete die closure. It is anticipated that the forgings can be made in a single stroke of press with some minor modification of the die set and preform geometry.

The ten Ti-6Al-4V forgings were 13 1/2 in. outside diameter, had a plan area of 114 sq in., weighed between 24 and 25 1/2 lb, and had 36 blades radially generated from the hub. These blades were 0.160 in. thick at the thinnest portion and had depths ranging from 3/4 to 1/2 in. depending upon location. The thickness of the hub portion of the forging of the 13 1/2 in. outside diameter was typically 0.210 in. Such complex titanium alloy forgings are impossible to produce by conventional forging techniques. The plan area of the forging was 114 sq in., and press forging load was usually 1000 tons. The 17 kpsi forging pressure is several times less than used in conventional practice for making titanium alloy forgings of much less complexity.

The finish-machined impeller weighs approximately 12 lb, the isothermally produced forging typically weighs 25 lb, and the forging conventionally produced for this impeller weighs approximately 60 lb. Significant savings in raw material and machining time would therefore accrue if isothermal titanium forgings are used for this part.

One forging was sectioned for heat treatment and tensile testing, and excellent tensile properties were obtained.

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