WRDC-TR-90-4140

FEASIBILITY STUDY FOR THE QUALIFICATION OF AN ECONOMICALLY ADVANTAGEOUS Ti-6Al-4V BEARING HOUSING FOR GAS TURBINE ENGINE APPLICATION BY POWDER METAL MANUFACTURING TECHNOLOGY

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Final Report for Period Nov 88 - Apr 89

Approved for public release; distribution unlimited

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Feasibility Study for the Qualification of an Economically Advantageous Ti-6Al-4V Bearing Housing for Gas Turbine Engine Application by Powder Metal Manufacturing Technology

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SBIR Phase I Final Report

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This Small Business Innovative Research (SBIR) Phase I program has demonstrated that titanium alloy aircraft engine components can be manufactured to near-net shape by an economical advanced powder metallurgy (P/M) process without compromising the structural performance and reliability of the component.

In the program Ti-6Al-4V alloys test bar materials were made by the Dynamet CHIP process. Two types of alloy test material were evaluated, one utilizing standard low cost titanium powder containing 1500 ppm of chloride impurity and a second premium priced titanium powder with extra low levels of chloride. Tensile properties of the former material were near specified minimums for the forgings currently used in turbine engine components. For the extra low chloride material, however tensile strength and ductility were far in excess of the specified minimums.

Prototype preforms for bearing housing manufacture were fabricated by the CHIP process using the two grades of titanium powders.

Titanium, Powder Metal, Processing

21

Unclassified | Unclassified | Unclassified | UL

CONTENTS

PROGRAM SUMMARY

This Small Business Innovative Research (SBIR) Phase I program has demonstrated that titanium alloy aircraft engine components can be manufactured to near-net shape by an economical advanced powder metallurgy (P/M) process without compromising the structural performance and reliability of the component.

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Prototype preforms for bearing housing manufacture were fabricated by the CHIP process using the two grades of titanium powders. Tensile properties of material taken from the preforms were the same as for the test bars and the properties of material taken from several locations in the preforms appeared to be uniform.

For the specific gas turbine engine bearing housing which was the subject of this Phase I program, the CHIP produced preforms weighed about 9 pounds compared to a minimum of 16 pounds for the ring forging currently purchased by the engine manufacturer. This 70% weight reduction would be improved by an additional 10-25% (1-1 1/2 lbs) by further refinement of the preform design and the tooling for its manufacture.

Economic analyses conducted by value engineering indicate that cost savings up to 60% could be achieved utilizing this technology as opposed to the current production techniques of machining from a forging. Furthermore, with completion of the proposed Phase II, this economic advantage could be applied to many comparable titanium alloy components.

INTRODUCTION

This is the final report of the Small Business Innovative Research Phase I Contract entitled "Feasibility Study for the Qualification of an Economically Advantageous Ti-6Al-4V Bearing Housing for Gas Turbine Engine Application by Powder Metal Manufacturing Technology".

The goal of this SBIR program was to prove significant cost savings in the production of a titanium alloy support bearing housing currently manufactured by Textron Lycoming Division for its 502 Gas Turbine Engine. Dynamet has proposed to reduce the cost of this propulsion system component by manufacturing it to a "near net" shape via its unique powder metallurgy (P/M) technology. The specific bearing housing was chosen as a representative engine component to demonstrate the potential benefits of the technology. Just as many other propulsion system components could have been chosen, any advantages realized in the manufacture of the bearing housing would also apply to these other components.

Dynamet's P/M approach involves cold isostatic pressing (CIP) of blends of inexpensive, commercially available elemental powder followed by vacuum sintering, hot isostatic pressing (HIP) and heat treatment. Overall the Dynamet process, which has come to be known as the CHIP process, enables expensive alloys to be produced with lower material input and lower machining costs. Technically, the structural properties of the P/M processed materials are superior to castings and comparable to wrought materials.

A drawing of the turbine support bearing housing is shown in Figure 1. With a maximum outside diameter (OD) flange dimension of just under 7 inches and a minimum inside diameter (ID) of more than 4 inches, it is a relatively complex shape with a wall thickness of about 1/2-inch over most of its 3-inch length.

This component is currently made by machining from a 16 pound ring forging of Ti-6Al-4V* which utilizes a substantial amount of excess material and requires additional costly machining to obtain final dimensions. The material must meet the requirements specified by AMS4928, Titanium 6Al-4V Alloy Bars, Forgings, and Rings in the solution annealed and aged condition with yield strength of 120,000 psi minimum. The minimum tensile properties called for in large diameter (4.00 inch to 6.00 inch diameter) components are as follows:

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* Specified dimensions of the ring forging are 7.34 inches minimum OD x 3.82 inches maximum ID x 3.20 inches minimum length.

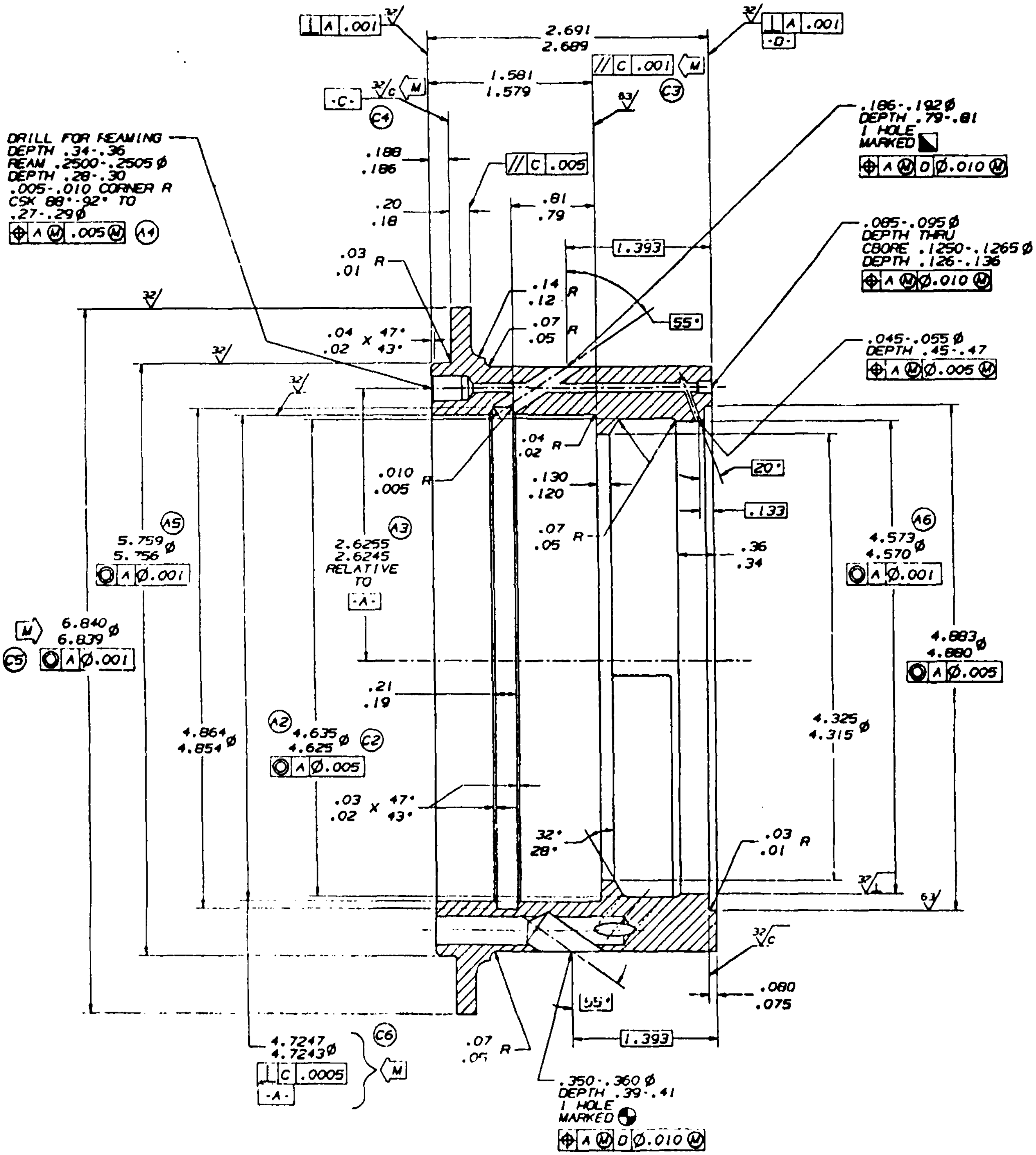


Figure 1. TEXTRON LYCOMING TURBINE SUPPORT BEARING HOUSING CURRENTLY MACHINED FROM FORGED RING.

CURRENT COMPONENT SPECIFICATONS

Tensile Strength	130,000 psi
Yield Strength at 0.2% Offset	120,000 psi
Elongation in 2 inch or 4 x D	10 %
Reduction in Area	20 %

In order to apply the Dynamet CHIP process to the economical manufacture of the bearing housing, several technical and economic issues must first be addressed. From the point of view of economics there is a choice in the titanium powder starting material which has a significant cost impact on the final component. So-called elemental titanium "sponge-fines" are the least expensive commercially available powder material and the standard material used in titanium alloy P/M. Unfortunately, this material has a relatively high concentrations of a chloride contaminant (about 1500 ppm) which has an adverse effect on some of the structural properties. Alternatively, an extra low chloride grade of titanium powder with less than 10 ppm chloride can be employed but at additional cost. However, it has been demonstrated that use of this starting material results in structural properties of the P/M components equivalent to wrought products.

This Phase I program was designed to provide preliminary answers to some of the basic questions. The program consisted of a preliminary evaluation of P/M processed Ti-6Al-4V test bars made from the two alternative titanium starting materials to determine if the required mechanical properties could be achieved in CHIP processed material. In addition, a prototype P/M preform was designed, and several demonstration units were manufactured and evaluated. The goals were to establish that the necessary mechanical properties could also be achieved in the full size bearing housing, to demonstrate the feasibility of P/M near-net shape manufacturing and to provide baseline cost data for comparison to the costs of bearing housings currently manufactured from ring forgings.

REVIEW OF PROGRAM

The program consisted of the following four major tasks:

1. Titanium Alloy and P/M Process Development
2. Manufacture and Evaluation of Initial Bearing Housing Preforms
3. Manufacture and Evaluation of Prototype Preforms
4. Economic Considerations

The work performed is summarized in the following sections.

Titanium Alloy and P/M Process Development

For this part of the program two powder blends of Ti-6Al-4V were prepared; one containing titanium powder (-100 mesh) with the standard level of chloride contaminant (designated StCl) and the second containing titanium powder (-180 mesh) with extra low chloride (designated ELCl). The titanium powders were V-blended with a 10% addition of 60%Al-40%V master alloy powder (-100 mesh) in two 25 pound blends identified as B-1553 (StCl) and B-1554 (ELCl).

Test bars about 5/8 inch in diameter x 5 inches long were pressed, vacuum sintered and HIPed following the standard procedures of Dynamet's CHIP process. Specific process conditions were as follows:

1. Cold isostatic press at 55,000 psi
2. Vacuum sinter for 2 hours at 2200°F at a pressure of 10^{-6} Torr.
3. HIP in argon at 1650°F for 2 hours at a pressure of 15,000 psi.

Ten test bars of each material were manufactured for evaluation purposes. Measurements of density were made after sintering and after HIPing and these data are shown in Table I.

The test bars were heat treated (solution annealed, water quenched and aged) according to the relevant material specification, AMS4928K. Solution annealing was at 1750°F for 1 hour, aging temperatures were in the range 900°F - 1450°F and all aging treatments were for 4 hours. The test bars were machined into standard tensile specimens (0.252 inch diameter x 1 inch gage length) and tensile tested at room temperature. The results are shown in Table II.

According to these data only the materials aged at 1450°F exceed the minimum ductility requirements of AMS4928K. Both the StCl and ELCl materials show adequate ductility at all aging temperatures and both meet the requirements for strength. However, the strength level for the StCl material is only slightly above specified levels at best.

Table I

Density Measurements (gm/cc) of Test Bars
Comparing Values as Sintered and HIPed

Sample No.	Blend 1553 (StCl) Sintered	Blend 1553 (StCl) HIPed	Blend 1554 (ELCl) Sintered	Blend 1554 (ELCl) HIPed
1	4.20	4.41	4.19	4.45
2	4.22	4.41	4.19	4.52
3	4.25	4.44	4.19	4.49
4	4.21	4.43	4.19	4.48
5	4.21	4.42	4.19	4.50
6	4.22	4.43	4.19	4.47
7	4.24	4.40	4.17	4.47
8	4.21	4.38	4.20	4.47
9	4.21	4.37	4.15	4.44
10	4.20	4.44	4.18	4.46
Average	4.22	4.41	4.18	4.48

Our preliminary analysis conjectures that the higher tensile and yield strength values of the ELCl alloy are due to two strengthening characteristics. First, the higher oxygen content of the starting ELCl titanium powder (0.159%) compared to that of the StCl titanium powder (0.080%) and secondly, the iron content of the ELCl blend compared to the standard blend is about 35% higher or 0.279% and 0.201%, respectively. The higher ductility of the ELCl alloy could be attributed to the combined effects of low chloride content and slightly higher density (see Table I).

Manufacture and Evaluation of Initial Bearing Housing Preforms

To demonstrate the feasibility of manufacturing the bearing housings via Dynamet's CHIP process within the scope of a Phase I program, the simple P/M preform shown in Figure 2 was designed. This preform, which includes a closed-end web to minimize distortion in sintering, allows for finishing to the finish dimensions of Figure 1 without risking the difficulties that might arise with a design to nearer net-shape. A more refined preform design could have been sought, but not logically within the limited scope of a Phase I program.

Table II.

Summary of Results of Heat Treated* Test Bars of Ti-6Al-4V StCl and Ti-6Al-4V ELCl

Alloy Material	Aging Temp °F	Density % Theoretical	Tensile Strength, psi	0.2% Yield Strength, psi	% Elongation	% Reduction in Area
StCl #1	70	99.6	138,300	113,000	4.7	15.6
#2	900	99.6	149,800	126,800	6.5	11.4
#3	1050	100.2	141,500	123,400	7.2	20.0
#4	1150	99.9	138,300	125,100	6.6	16.8
#5	1300	99.7	131,900	115,500	7.7	18.0
#6	1450	100.3	131,300	113,900	10.6	19.8
ELCl #1	70	100.3	155,100	138,200	7.5	11.1
#2	900	102.0	152,500	131,800	10.7	17.6
#3	1050	101.4	154,900	137,400	9.5	16.2
#4	1150	101.1	-	-	-	-
#5	1300	101.5	146,500	132,900	8.9	20.8
#6	1450	100.7	139,000	122,400	10.3	29.4
Specified (AMS 4928K)	MIN.	-	130,000	120,000	10.0	20.0

* Heat treatment consisted of solution annealing for 1 hour at 1750°F followed by water quenching and aging for 4 hours at the designated temperatures.

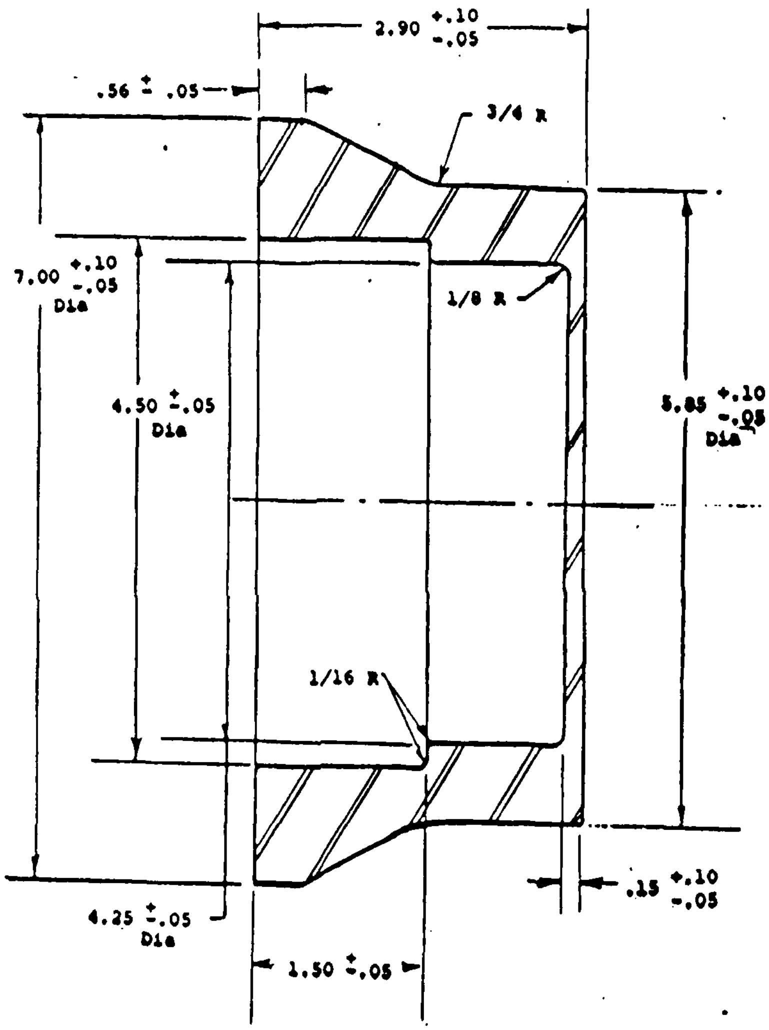


Figure 2. PRELIMINARY DESIGN OF P/M PREFORM FOR MANUFACTURE OF TURBINE ENGINE SUPPORT BEARING HOUSING SHOWN IN FIGURE 1.

Simultaneous with the manufacture of test bars of the two experimental alloy materials, an even more simplified bearing housing preform design was used to manufacture component-sized test material to be evaluated by Textron along with the test bars. The preform design incorporated all the features of Figure 2 except that the enlarged 7.00-inch outside diameter at the flange end was reduced to 5.85 inches resulting in a uniform outside diameter along the total 2.90 inch length of the preform.

Two of these initial preforms, one of StCl and one of ELCl material, were manufactured using the same powder blends and following the same processing as described for the test bars; cold pressing at 55,000 psi in elastomeric tooling, vacuum sintering for 2 hours at 2200°F with background vacuum pressure of 10^{-6} Torr., and HIPing in argon at 1650°F for 2 hours at a pressure of 15,000 psi. The initial preforms are shown in Figure 3.

Figure 3. FULLY DENSE INITIAL BEARING HOUSING PREFORMS WITH STCl AND ELCl PREFORMS SHOWN ON THE LEFT AND RIGHT, RESPECTIVELY

Density measurements of the complete preforms at Dynamet indicated values in excess of 99% of theoretical density for both the StCl and ELCl materials.

These preforms were shipped to Textron in the as-HIPed condition. Based on the tensile test results obtained with test bars (Table II) and prior experience at Dynamet, it was decided not to heat treat these initial preforms but to evaluate them in the as-HIPed condition. Machining blanks were cut from the wall of the HIPed preforms and tensile specimens were machined from the blanks. Because of the size of the preforms, the tensile specimens were sub-size with a 0.200-inch diameter and 0.7-inch gage length.

Test results, which are shown in Table III, are similar to results of the heat treated test bars (Table II). The tensile properties of the ELCl material exceed specified minimums for strength and ductility whereas the StCl specimens are only slightly deficient with respect to ductility. Nevertheless, both preforms exhibit repeatable mechanical properties as an indication of the metallurgical uniformity of CHIP processed materials.

Table III

Tensile Properties of Specimens from the StCl and ELCl Preforms

Specimen No.	Tensile Strength (psi)	0.2% Offset Yield Strength(psi)	% Elongation	%Reduction in Area
StCl - 6a	129,000	117,300	6.2	19.0
StCl - 7a	132,000	120,200	7.6	18.4
StCl - 8a	132,400	121,500	10.5	22.7
StCl - 9a	134,000	122,800	8.9	22.5
ELCl - 7a	143,400	132,400	12.0	31.0
ELCl - 8a	144,100	133,400	8.4	23.9

Manufacture and Evaluation of Prototype Preforms

Based on the initial tensile results obtained with test bars (Table II), it was decided to make the three final preforms all from ELCl material. Three bearing housing preforms were manufactured to the dimensions of Figure 2 for delivery to the Air Force. For this purpose a new 30 pound powder blend (No. B-1597), consisting of ELCl titanium powder (-80 mesh) and Al-V master alloy powder (-100 mesh), was made up. Because of the size limitations of the Dynamet cold isostatic press, the preforms were pressed in two steps; first, to a uniform 5.85-inch outside diameter component as with the initial preforms and then, after modifying the elastomeric tooling, to the dimensions of Figure 2 in a second cold isostatic pressing step. The latter pressing was done at an outside facility with a larger capacity press but at the same 55,000 psi pressure employed at Dynamet.

Thereafter, the pressed compacts were vacuum sintered and HIPed following the processing procedures already described. Figure 4 shows the three Ti-6Al-4V ELCl preforms after HIPing.

Figure 5 shows dimensional measurements and the weights of the three preforms. These data illustrate the excellent product uniformity and repeatability that can be expected of CHIP manufactured preforms.

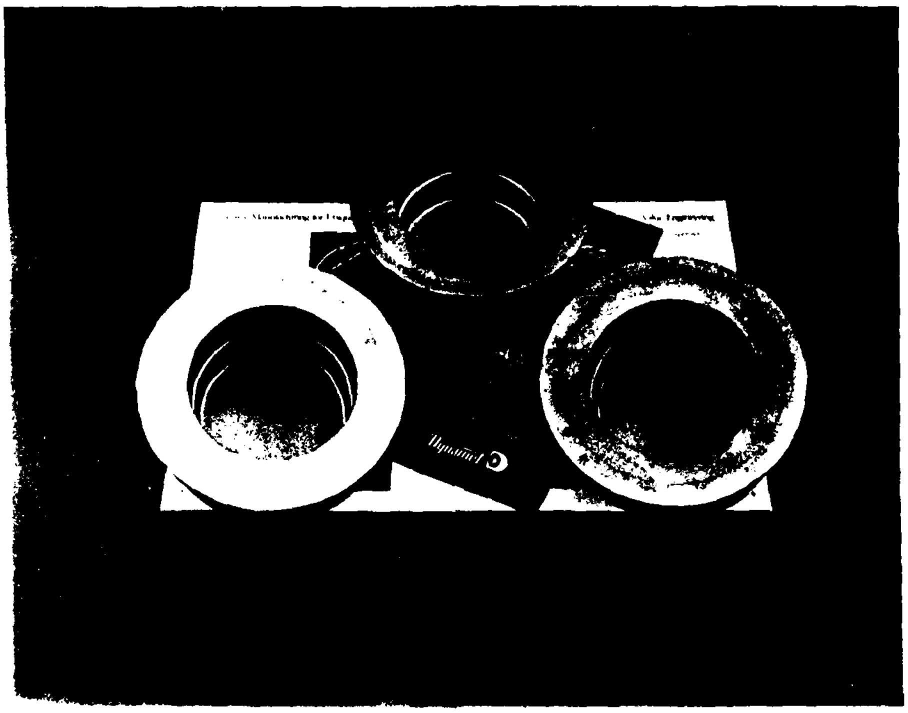
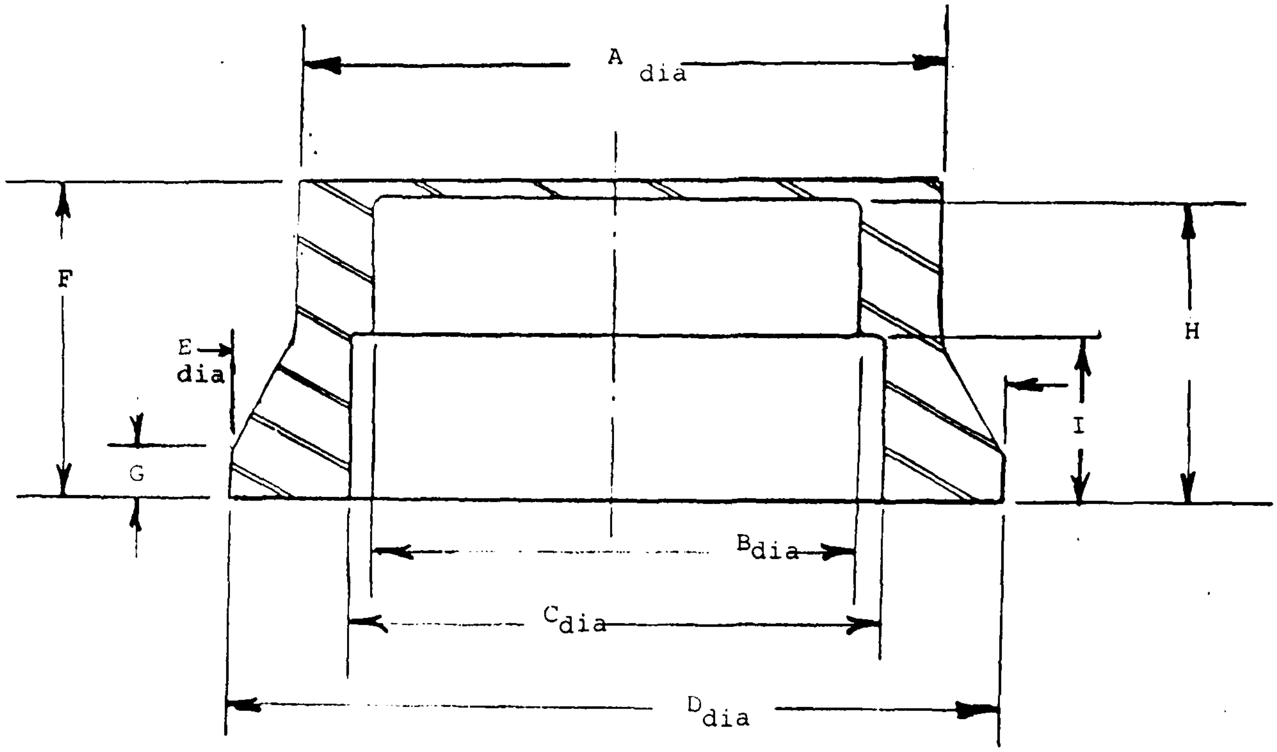


Figure 4. FULLY DENSE CHIP PROCESSED Ti-6Al-4V (ELC1) PREFORMS DELIVERED TO THE AIR FORCE.

The three preforms of Figure 4 were not heat treated. They were delivered to the Air Force in the as-HIPed condition. Prior to shipment densities were measured with results shown in Table IV. Also shown in Table IV are density and tensile test results of as HIPed witness bars (5/8-inch diameter x 5-inches long) made at the same time as the bearing housing preforms from the same alloy blend. The tensile properties of the witness bars are typical of ELC1 material as HIPed and exceed the specified minimums. These results also suggest that the preforms will have similar properties as-HIPed and should also be heat treatable to achieve even higher strength properties, comparable to best heat treated values for the ELC1 material of Table II.



1597-1	
A dia	6.15
B dia	4.22
C dia	4.45
D dia	7.075
E dia	6.85
F	2.935
G	.75
H	2.675
I	1.485
WEIGHT	9.1#

1597-2	
A dia	6.15
B dia	4.215
C dia	4.40
D dia	7.15
E dia	6.92
F	2.93
G	.75
H	2.685
I	1.475
WEIGHT	9.2#

1597-3	
A dia	6.12
B dia	4.22
C dia	4.40
D dia	7.195
E dia	6.85
F	2.937
G	.76
H	2.677
I	1.48
WEIGHT	9.1#

Figure 5. DIMENSIONAL MEASUREMENTS AND WEIGHTS OF THREE PROTOTYPE PREFORMS DELIVERED TO AIR FORCE

Table IV

Densities and Tensile Properties of Alloy B-1597 Witness Bars and Densities of Preforms Made from the Same Blend, Sintered and HIPed together

Sample No.	Density, % of Theoretical	Tensile Strength, psi	0.2% Yield Strength, psi	% Elongation	% Reduction in Area
B1597-1	100.4	140,000	123,300	13.8	42.2
B1597-2	100.3	142,000	125,000	17.9	44.0
Preform #1	100.1				
Preform #2	100.7				
Preform #3	100.4				

Table IVa

Chemical Analysis of Alloy B-1597

Element	Percent
Titanium	REM
Aluminum	5.81
Vanadium	4.38
Iron	0.35
Yttrium	ND<0.0003
Carbon	0.02
Hydrogen	0.0015
Nitrogen	0.0266
Oxygen	0.2094
Silicon	0.05
Chromium	0.02

ECONOMIC CONSIDERATIONS

The specific bearing housing component studied in this Phase I investigation is currently manufactured as a forging and finish machined to final configuration. The forging is produced as a 16 lb. ring forging and must then be finish machined to the final dimensions of the housing. The P/M prototype preform shaped components produced in this program had target shape configuration and weighed 9.1 lbs. This represented a first iteration preform design (intentionally designed oversized to insure sufficient material for final machining). Based upon past experience a conservative final preform design of 7.6 lbs is anticipated to result from the Phase II program.

Dynamet has furnished budgetary cost estimates to Lycoming based on supply of this component as a Ti-6Al-4V alloy preform using standard chloride as well as extra low chloride titanium.

Lycoming's value engineering staff have analyzed this Dynamet pricing data and has conducted comparisons with existing production fabrication costs and have reported the following:

1. With the utilization of this innovative powder metal technology cost reductions of 40-60% could be achieved with this component when manufactured using the standard chloride level as compared to the current practice of machining from a forging. Test results thus far indicate that mechanical properties achieved would readily meet the requirements of the component.

2. Even with the use of the higher price ELCl (extra-low chloride) powder raw material the manufacture of this bearing housing by this powder metal technology results in 20 to 30% cost reduction. Thus even the most critical titanium alloy components from mechanical properties requirements would benefit from the technology.

3. Depending on the specific mechanical property requirements of the components an optimum blend of the standard and ELCl titanium powder could yield a potential cost advantage of 20 to 60% over current manufacturing technology. In addition this technology and the mechanical property data generated would be applicable to other titanium base alloys and to a wide variety of component configurations.

CONCLUSIONS

This SBIR Phase I program has achieved all of its proposed objectives. The work performed and the results obtained lead to the following conclusions:

1. Ti-6Al-4V alloy test bars produced by the Dynamet CHIP process, whether from extra low chloride or standard chloride grades of titanium powder, achieve full density and display tensile strength and ductility properties meeting requirements specified for forgings.

2. The tensile properties of material taken from the full size, CHIP produced component preforms are comparable to those of test bars. Furthermore, these properties appear to be uniform and reproducible throughout the component preform.

3. The CHIP process provides a means of economically manufacturing relatively complex components to near-net shape with substantial reductions in the amount of input material used and in the extent of costly machining needed to achieve finish dimensions. Estimated cost savings of bearing housings produced by this method could amount to as much as 60% of current manufacturing costs.

RECOMMENDATIONS

With the goals of the proposed Phase I program fully realized and the feasibility of manufacturing the turbine engine bearing housing by the P/M route clearly demonstrated, additional work is needed to bring this technology to production status for the purpose of manufacturing turbine engine bearing housings and other propulsion components. The following recommended tasks and related innovations will be further amplified in Dynamet's forthcoming Phase II proposal.

1. The three (3) Ti-6Al-4V (ELCl) bearing housing preforms which were delivered to the Air Force as part of the Phase I effort should be evaluated. One bearing housing preform should be used for additional mechanical property testing to include tensile, impact and preliminary low cycle fatigue testing. The other two preforms should be finish machined to final component configuration and tested, as such. Acceptance testing would consist of non-destructive testing (radiography and ultrasonic examination), leak testing (to confirm the integrity of the oil-carrying channels in the machined housing) and simulation testing in an engine test stand.

2. The major effort of the Phase II program would focus on finding an optimized level of the chloride impurity so as to minimize raw material costs while maximizing the mechanical performance of the component. Alloying studies involving various blends of ELCl and StCl titanium powders would be pursued. Besides the need for acceptable tensile properties the alloy test materials also would be evaluated for resistance to high cycle fatigue, since the component must withstand the vibration of the engine environment, and for fracture toughness, since resistance to unstable crack growth is required to prevent engine failure due to loss of bearing lubrication. Because of the large number of process variables and the need to optimize processing with respect to a large number of properties, it is contemplated that a statistically designed experimental plan would be developed and followed.

3. The substantial (44%) weight reduction provided by the Phase I P/M prototype preform could be further increased by an estimated 15-20% (1-1 1/2 pounds). This could be accomplished by eliminating the end-closure (or reducing its thickness) and reducing wall thickness consistent

with minimizing distortion. This weight reduction along with new refinements to the preform design would further eliminate some machining and thus contribute to the total cost reduction. An iterative process study involving further refinements in tooling and testing of more refined preform designs is needed to fully realize these improvements.

4. Once the optimum bearing housing alloy composition and optimum configuration have been developed, the evaluation of prototype preforms described in (1) would be repeated as a preliminary to transferring current production requirements to the new economically advantageous process.

5. Having established the functional relationship between chloride content and critical mechanical properties this data would be applied to several other engine propulsion components currently manufactured by Textron Lycoming. With this data and the manufacturing experience generated in Phase II. Several of these additional components could then readily be placed in production permitting multi-component cost savings. Textron Lycoming has agreed to continue their participation and contribute to the evaluation portions of the follow-on program.

We feel the Air Force has achieved one of the finest of all Phase I SBIR programs with the combined technical effort by Lycoming and Dynamet. We believe that a Phase II program has high probability of success and will result in significant cost savings compared to current manufacturing technology for many comparable Air Force components.