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Application of Hot-Isostatic Pressing, Hydrostatic Extrusion, and Deformable-Die Tube Tapering Processes to Production of Titanium-6Al-4V Tapered Tubes

Battelle Columbus Laboratories

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APPLICATION OF HOT-ISOSTATIC PRESSING,
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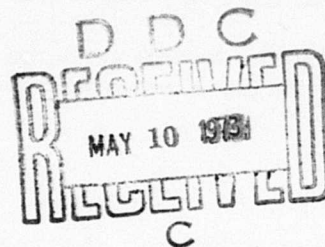
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February 1973

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

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13. ABSTRACT Small-scale tapered Ti-6A1-4V alloy tubes were to be processed by hot isostatic pressing (HIP), cold drawing, and hydrostatic extrusion. Tapered HIP tubes were successfully fabricated. The tensile, impact, and fracture toughness properties were comparable to or better than those of wrought material. However, fatigue properties of the HIP material were somewhat lower than those of wrought material. Tungsten and carbon impurities were found in the Ti-6A1-4V powder and may have served as crack initiation sites under loading, thereby, contributing to the lower fatigue life of the HIP preforms. This question was not resolved in this study. Wall tapering of a wrought tube preform was successfully accomplished by cold drawing, and the target of 50-percent wall thickness was obtained. A 10-percent taper on the diameter was produced on wrought tapered wall preforms, but efforts to increase the rate of taper were unsuccessful because of pointing problems. HIP material in the form of solid bar was successfully extruded at a 2.5:1 extrusion ratio by hydrostatic extrusion. Attempts to hydrostatically extrude the tubular HIP material were not successful due to circumferential cracking initiating on the OD of the extruded workpiece. Scanning-electron-microscope studies at NASA-Langley revealed the presence of small ID cracks at particle interfaces on as-HIP fatigue specimens. Such cracks may have been present on the ID surfaces of the as-HIP blanks prior to extrusion. Fatigue tests conducted on specimens from tubes manufactured by HIP and then cold drawn failed to show any improvement in fatigue resistance of the material as a result of cold working. Cost studies indicate that tapered spars 32 feet in length can potentially be fabricated at a cost of approximately \$3000 per spar using one or more of the processes studied in this program. This cost is approximately 15 percent of that which would be incurred if a thick-wall wrought extrusion was purchased and machined to produce the tapered spar.			

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This program was performed under Contract DAAJ02-71-C-0038 with Battelle Memorial Institute.

The report presents the results of an investigation to determine the potential of hot-isostatic pressing, hydrostatic extrusion, and deformable-die processes for the production of low-cost Ti-6Al-4V titanium helicopter rotor blade spars.

The report has been reviewed by the Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory and is considered to be technically sound. It is published for the exchange of information and the stimulation of future research.

This program was conducted under the technical management of Mr. I. E. Figge, Technology Applications Division.

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APPLICATION OF HOT-ISOSTATIC PRESSING,
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TUBE TAPERING PROCESSES TO PRODUCTION
OF TITANIUM-6Al-4V TAPERED TUBES

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U.S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

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SUMMARY

Small-scale tapered Ti-6Al-4V alloy tubes were to be processed by hot isostatic pressing (HIP), cold drawing, and hydrostatic extrusion. The results of this study are summarized as follows:

1. Tapered HIP tubes were successfully fabricated. The tensile, impact, and fracture toughness properties were comparable to or better than those of wrought material. Fatigue properties of the HIP material were somewhat lower than those of wrought material.
2. Tungsten and carbon impurities were found in the Ti-6Al-4V powder. These impurities in the Ti-6Al-4V matrix may have served as crack initiation sites under loading and, thereby, may have contributed to the lower fatigue life of the HIP preforms. However, this question was not resolved in this study.
3. Wall tapering of a wrought tube preform was successfully accomplished by cold drawing, and the target of 50-percent wall thickness was obtained.
4. Only limited success was achieved in tapering the OD with the deformable-die process. A 10-percent taper on the diameter was produced on wrought tapered wall preforms, but efforts to increase the rate of taper were unsuccessful because of tube pointing problems.
5. HIP material in the form of solid bar was successfully extruded at a 2.5:1 extrusion ratio by hydrostatic extrusion. Attempts to hydrostatically extrude the tubular HIP material were not successful due to circumferential cracking initiating on the ID of the extruded workpiece. However, cursory scanning-electron-microscope studies at NASA-Langley revealed the presence of small ID cracks at particle interfaces on as-HIP fatigue specimens. Such cracks (or weak zones) possibly may have been present on the ID surface of the as-HIP tube blanks prior to extrusion.
6. Fatigue tests conducted on specimens from tubes manufactured by HIP and then cold drawn failed to show any improvement in fatigue resistance of the material as a result of cold working.
7. Cost studies indicate that tapered spars 32 feet in length can potentially be fabricated at a cost of approximately \$3000 per spar using one or more of the processes studied in this program. This cost is approximately 15 percent of that which would be incurred if a thick-wall wrought extrusion was purchased and machined to produce the tapered spar.

FOREWORD

This report covers work performed under U.S. Army Contract DAAJ02-71 C-0038 (Task 1F162208A17002) from April 15, 1971, through May 31, 1972. It was administered under the direction of Mr. I. E. Figge, Structures Division, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia.

This program was conducted at Battelle's Columbus Laboratories, with overall responsibility for the program being carried out by the Metalworking Division, Mr. R. J. Fiorentino, Chief. Other divisions and personnel participating in the program are listed below.

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In addition, we wish to acknowledge the work done by Metals and Ceramics Division, Air Force Materials Laboratory, and Mr. R. F. Geisendorfer for conducting the fracture toughness tests reported in Appendix I. Acknowledgement also goes to Mr. Harvey Herring of NASA-Langley, Hampton, Virginia, for conducting scanning electron microscope studies on fatigue specimens.

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INTRODUCTION

The overall objective of this program was to investigate potentially lower cost manufacturing methods of producing Ti-6Al-4V tapered tubes for helicopter rotor spars. A typical rotor spar tube used in some advanced helicopter designs has a tapered wall and a tapered diameter. The usual method for producing these parts is to machine the tapers on a constant-diameter constant-wall hollow extrusion. This is obviously a very costly process due to the machining time involved and low yields since a large portion of the extrusion is converted into chips. Ultimately, titanium spar tubes approximately 32 feet long and 7 inches in diameter will be required in advanced helicopters now being designed.

The alternative manufacturing techniques studied in this program for forming tapered spar tubes were hot isostatic pressing (HIP) and two cold-forming techniques, hydrostatic extrusion and cold drawing. The latter techniques used starting billets of HIP material and commercial wrought materials. One of the primary questions to be resolved was the cold workability of HIP material and the effect of cold working on the mechanical properties of this material, in particular the effect on fatigue life. Another objective of this study was to determine the most cost-effective approach to manufacturing methods development.

Work on this program began on April 15, 1971, and ended on June 28, 1972.

PROGRAM APPROACH

As discussed previously, the tube tapering processes investigated in this program were hot isostatic pressing (HIP), hydrostatic extrusion, tube drawing using rigid dies and deformable-die techniques, and combinations of these processes. Prior work at Battelle had shown that each of these processes has unique features adaptable to making tapered Ti-6Al-4V tubes at potentially lower costs than competitive processes.

Small-scale specimens were fabricated by the processes discussed above with the following nominal dimensions:

Wall taper - 0.100 to 0.050 inch
OD taper - 1.360 inches to 0.954 inch
Length - 18 inches

After processing, test samples were cut from the various tubes to determine fatigue and mechanical properties. Commercial wrought titanium tubes were processed and evaluated with the HIP tubes to establish base-line data.

Each processing sequence was studied to determine which process or combination of processes offers the lowest cost approach to making full-size helicopter rotor spars with suitable fatigue properties.

Interrelationships between the tasks in this program are diagrammed in Figure 1. Using Task I as an example, billets were produced by HIP for subsequent deformation by hydrostatic extrusion, or by tube drawing with tapered mandrels or using deformable dies or for direct mechanical evaluation as indicated by the arrows. In the same way, all the other process sequences can be followed.

In addition to the experimental work conducted at Battelle, a hydrostatically extruded HIP billet was evaluated for fracture toughness by the Air Force Materials Laboratory. The results of this evaluation are presented in Appendix I. Also, cursory scanning-electron microscope (SEM) studies were performed on selected HIP fatigue specimens at NASA-Langley, Hampton, Virginia. These results are included in Appendix II.

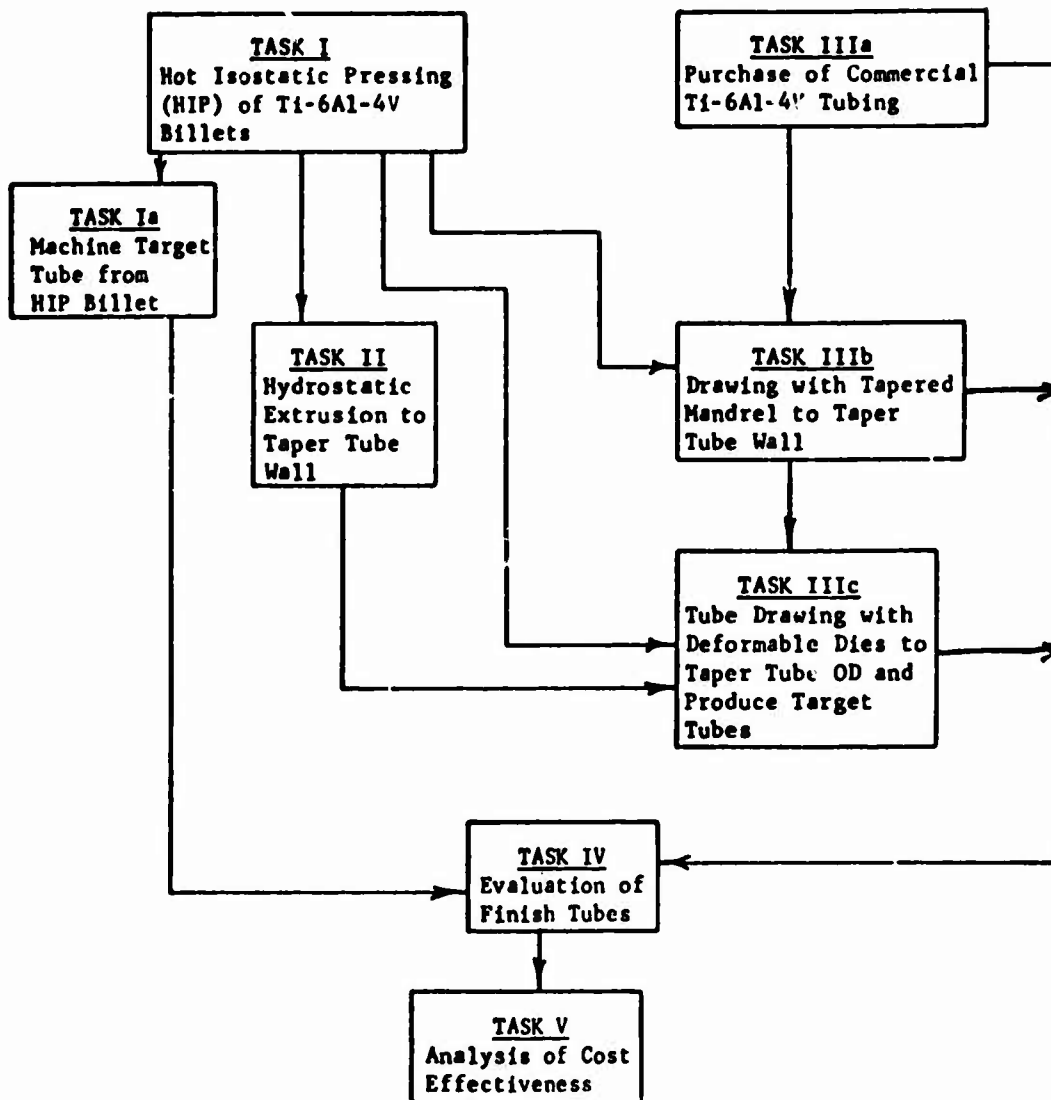


Figure 1. Interrelationships Between Various Tasks Performed in This Program.

HOT ISOSTATIC PRESSING (HIP)

OBJECTIVE

In this task, Ti-6Al-4V powder was consolidated into billets (preforms) suitable for direct mechanical testing and for subsequent deformation by either hydrostatic extrusion or tube drawing. The HIP process is described in Appendix III.

EXPERIMENTAL PROCEDURES AND RESULTS

Qualification of Ti-6Al-4V Powder Lot

A 92-pound lot of spherical Ti-6Al-4V powder was purchased from the Whittaker Corporation. The powder was produced by the rotating-electrode process. Sieve and chemical analyses of the as-received powder lot are given in Table I. The powder was vibrated through a U.S. Standard 40

TABLE I. SIEVE AND CHEMICAL ANALYSES OF AS-RECEIVED SPHERICAL Ti-6Al-4V POWDER												
<u>Sieve Analysis</u>												
Sieve, U.S.	Sieve	18	25	35	45	60	80	120	170	230	235	PAN
Percent Retained on Screen		--	--	--	22.1	23.9	22.0	8.4	2.8	0.4	0.2	0.2
<u>Chemical Analysis</u>												
Element	Al	C		H		N		O		V		Ti
Percent	6.30	84 ppn		28 ppn		215 ppn		1560 ppn		4.02		Bal

mesh sieve. Sixty pounds of -40 mesh powder was obtained from the screening operation. This powder size has been used in previous work to produce hot isostatically pressed tubing of 100 percent density with acceptable mechanical properties. The -40 mesh powder was used for all HIP tubing preforms in this program. The screening operation also eliminated large-size impurities (+40 mesh) in the powder, which would be detrimental to the fatigue properties of the fabricated Ti-6Al-4V tubes.

In order to qualify the powder lot received from Whittaker Corporation, small billets of Ti-6Al-4V powder were hot isostatically pressed and then evaluated for tensile and fatigue properties. The Ti-6Al-4V billets were prepared by vibratorily compacting -40 mesh powder in 304 stainless steel cans.

The billets were hot isostatically pressed at 1750°F with 10,000 psi pressure for 3 hours. The tensile properties of these billets were evaluated in the as-HIP, the 1400°F annealed, and the 1750°F annealed conditions. The tensile specimen design is given in Figure 2. The results of the tensile tests, summarized in Table II, indicate that increasing the annealing time and temperature increases the ductility of Ti-6Al-4V while decreasing the yield strength. The tensile properties for the as-HIP material are within the expected range of performance of annealed wrought Ti-6Al-4V.⁽¹⁾

To further qualify the powder lot received from Whittaker Corporation, billets of Ti-6Al-4V powder were HIP at 1750°F with 10,000 psi pressure for 3 hours and sent to the Air Force Materials Laboratory at Wright-Patterson Air Force Base for fracture toughness and impact testing. The as-HIP Ti-6Al-4V material had a stress intensity factor (K_{IC}) of 65 ksi 1/2 in. with a standard notched Charpy impact value of 19.21 foot-pounds. Both of these values for the as-HIP material are high within the expected range of performance of wrought Ti-6Al-4V.⁽²⁾

Particles of a contaminant were found in the microstructures of the as-HIP and the annealed Ti-6Al-4V billets. It was felt that these particles might have lowered the fatigue properties of the tubing preforms made in this program. The particles were identified as carbon and tungsten by electron microprobe analysis and metallography. The impurities are the result of contamination of the powder during production by the spinning electrode process. Limited attempts at eliminating all of these impurities from the powder were unsuccessful. Radiographs of the billets indicated that the distribution and the number of impurities were not significantly affected by either of the annealing treatments. A picture of a tungsten inclusion in a Ti-6Al-4V powder particle is shown in Figure 3. A micrograph of a tungsten inclusion in the as-HIP microstructure of a Ti-6Al-4V billet is shown in Figure 4.

In an attempt to estimate the effect of the contaminant particles in this program, the fatigue properties of solid billets were evaluated in the as-HIP and the 1750°F annealed conditions. The results of the fatigue tests are also included in Table II, and the fatigue specimen

TABLE II. RESULTS OF TENSILE AND FATIGUE TESTS
ON HIP Ti-6Al-4V SOLID BILLETS

Specimen Condition	Yield Strength, psi	Tensile Strength, psi	Ultimate Tensile Strength, psi	Elongation, percent	Reduction in Area, percent	Fatigue Life, Cycles to Failure*
As-HIP	130,000	137,000	137,000	13.5	28 to 29	31,600
Annealed 1400 °F - 2 hr	128,600	137,800	137,800	13.5 to 15.3	30 to 37	-
Annealed 1750 °F - 4-1/2 hr	126,500	135,300	135,300	15.4	38.5 to 40	18,300

* Axial load fatigue tests with 85 ksi maximum stress and R = -1.

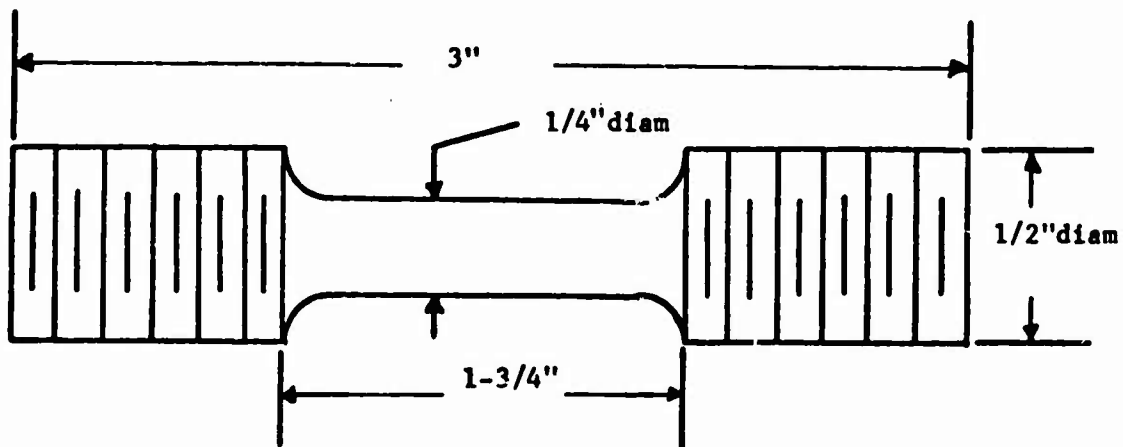
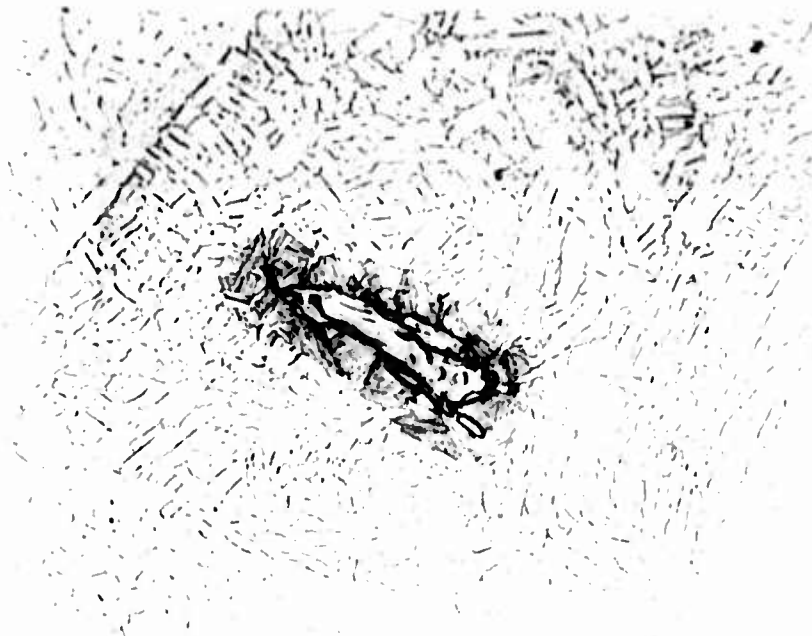


Figure 2. Tensile Test Specimen for HIP Ti-6Al-4V.



Figure 3. Tungsten Inclusion in a Ti-6Al-4V Powder Particle.



500 X

30 Percent Lactic Acid, 30 Percent HNO_3 ,
10 Percent HF

Figure 4. Tungsten Inclusion in As-HIP Microstructure
of Ti-6Al-4V Billet.

design is shown in Figure 5. With an axial load of 85 ksi maximum stress and with a stress range, R, of -1, the as-HIP Ti-6Al-4V failed at 31,600 cycles while the 1750°F annealed material failed at 18,300 cycles. These fatigue results are lower than the 9×10^4 to 10^5 cycles expected from handbook data for annealed wrought Ti-6Al-4V.(3)

It was not certain at that time if the powder on hand was typical of Whittaker Corporation REP powder, so a sample of a second powder lot was acquired from Whittaker Corporation.

The new powder lot had the same approximate impurity content as the original lot. The tensile and fatigue properties of as-HIP billets made from the second powder lot were also similar to the properties of billets made from the original lot, indicating that the first powder lot was apparently typical of Ti-6Al-4V powder made by Whittaker Corporation. The powder manufacturer was unable to identify the exact source of powder contamination and could not assure us of a capability of producing a new powder lot with a significantly lower impurity content in time for use in the tapered tubing research program. However, Whittaker reports that powder contamination can be eliminated in the near future. In any case, the original Ti-6Al-4V powder lot was used to make all the tubing preforms in this program.

Hot Isostatic Pressing

Two trial preforms for tube drawing and hydrostatic extrusion were initially hot isostatically pressed at 1750°F for 3 hours at 10,000 psi pressure. From the final dimensions of these HIP tubes, calculations were made to determine the tooling dimensions required for the additional as-HIP tubing preforms needed for the other tasks of this program. Three trial preforms for the tube drawing, hydrostatic extrusion, and HIP tasks of this program were then made with these calculated tooling dimensions and were hot isostatically pressed to ensure that the tooling designs were correct. The dimensions of these as-HIP tubes were within the specified tolerances for each preform type. Therefore, the remaining number of preforms required for this program were processed. These preforms were also hot isostatically pressed at 1750°F for 3 hours at 10,000 psi pressure. The general procedure for the production of the HIP Ti-6Al-4V preforms is given in Appendix IV.

Evaluation of as-HIP Preforms

The density of the as-HIP preforms was measured by the water-immersion method. All of the preforms produced in the final HIP cycles were found to be 100 percent dense. Transverse sections of all the preforms were examined metallographically. The general microstructure of the preforms was a basket-weave structure of alpha and beta phases as shown in Figure 6.

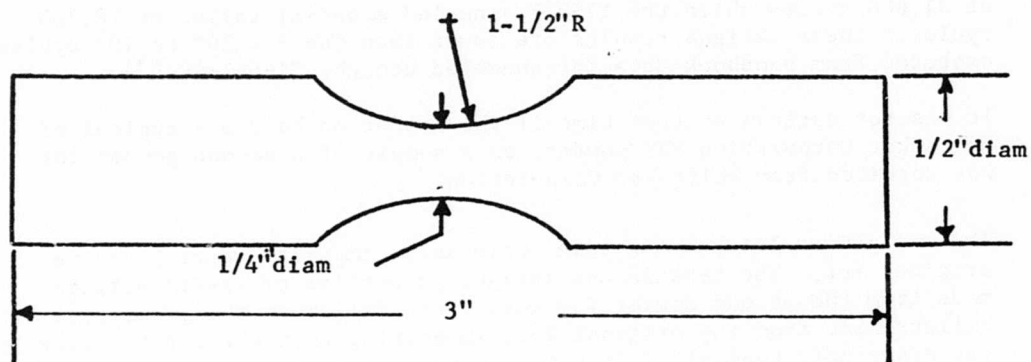
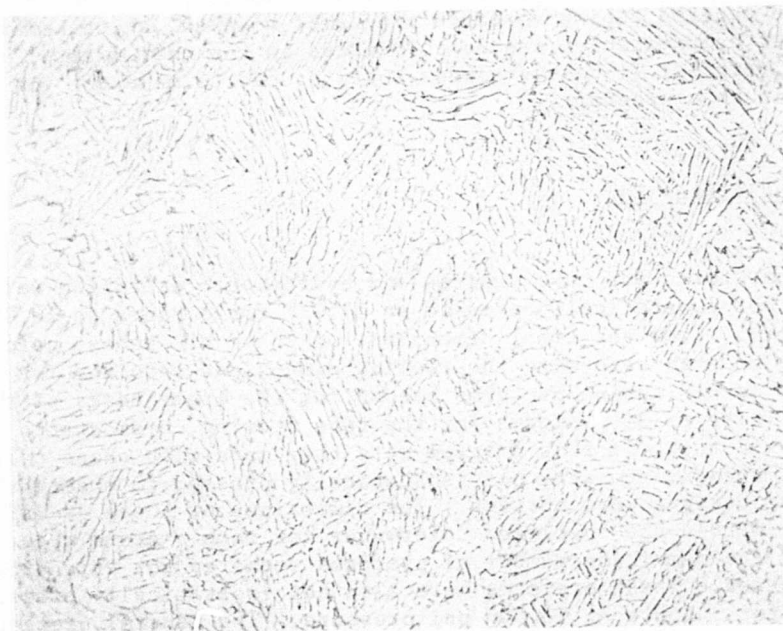


Figure 5. Fatigue Test Specimen for HIP Ti-6Al-4V.



250 X

3-1/2 Percent HNO_3 , 1-1/2 Percent HF

Figure 6. General Microstructure of As-HIP Ti-6Al-4V Preforms.

The grain size and microstructure were uniform throughout the wall thickness of the preforms. Tungsten inclusions were found to be randomly distributed throughout the Ti-6Al-4V matrix and were due to the contamination of the original powder lot, which was discussed in the powder qualification portion of this report. An unidentifiable thin layer was present on the ID surface of the as-HIP preform as shown in Figure 7. The layer thickness was considerably less than one powder particle diameter and could not be removed by pickling with hydrofluoric acid.

Machining of As-HIP Preforms

The short 12-inch-long preforms for the hydrostatic extrusion portion of the program were axially straight in the as-HIP pickled condition, but several of the longer as-HIP preforms to be used for direct mechanical testing (18 inches long) and for the tube drawing tasks (16.5 inches long) of this program were slightly bowed. An attempt was made to straighten the bowed preforms by three-point bending in a vertical hydraulic press. Although the as-HIP preforms for direct mechanical testing were satisfactorily straightened, the bow in some of the preforms for the tube-drawing tasks could not always be completely removed. Bowing of long preforms during the HIP cycle could occur as a result of the following possible causes:

1. Relief of nonuniform residual stresses in the HIP cans and core mandrels during the HIP cycle.
2. Misalignment of the core mandrel during vibratory compaction of the metal powder.
3. Nonuniform vibratory compaction of the powder during loading of the HIP can assembly, resulting in nonuniform consolidation of the preform during the HIP cycle.
4. Temperature gradients through the diameter of the preforms due to uneven heating in the HIP autoclave, which results in uneven expansion of the preform during heating and uneven contraction during cooling.

Bowing in long preforms might be controlled by the use of an external die which would serve as a rigid support for the preforms during the HIP cycle. The powder used for loading the parts might be sieved to a narrower particle size distribution than was used in this program to ensure a more uniform vibratory compaction of the powder during loading of the parts. The fact that several of the longer preforms did not bow when hot isostatically pressed in a large batch in the final HIP cycle of this program indicates that temperature gradients probably existed in and contributed to the bowing of several of the preforms during the HIP cycle.

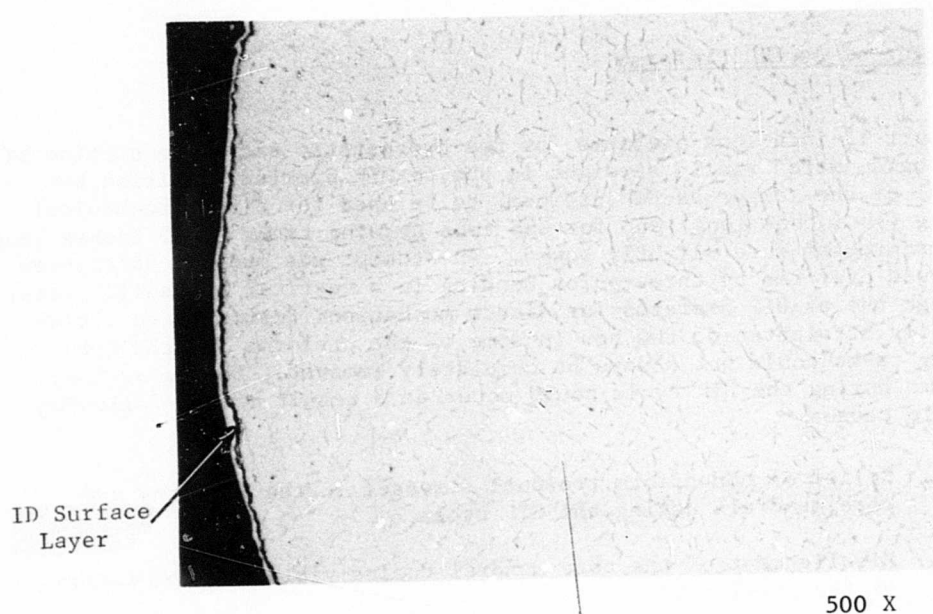


Figure 7. ID Surface of As-HIP Ti-6Al-4V Preforms.

The hot isostatic pressing of only a few preforms in a single HIP cycle would allow for more careful temperature control in the HIP autoclave. This small-batch approach is believed to be economically feasible when considering the HIP of 32-foot-long preforms. Bowing of the preforms may also be minimized by using an open-ended tube to form the ID surface of the preforms instead of using a solid-core mandrel. The open ends of the tube would permit gas flow through the interior of the preform during the HIP cycle and would result in more uniform compaction of the preform and smaller temperature gradients through the diameter of the part during HIP. The use of a tube instead of a solid mandrel would also perhaps minimize the problems of misalignment of the mandrel during loading of the can and nonuniform stress relief of the solid mandrel during the HIP cycle.

The pickled preforms were machined on the OD surface only to reduce the OD to the proper size. A picture and a diagram of the machined-tapered preforms, for direct mechanical testing, without further processing by tube drawing or hydrostatic extrusion, are shown in Figures 8 and 9. Machining of the bowed preforms made for the tube-drawing task of the program resulted in some preforms' being eccentric; that is, small variations in wall thickness existed around the circumference of the tube.

The machined preforms were vacuum annealed at 1500°F for 1 hour to remove hydrogen which may have been picked up during pickling of HIP and to relieve residual stresses from machining. Heat-treatment experiments showed that annealing the as-HIP preforms at higher temperatures resulted in significant grain growth in the Ti-6Al-4V matrix, a change which would have an adverse effect on fatigue properties of the preforms.

Discussion

Although the tensile properties, fracture toughness, and impact strength of the as-HIP Ti-6Al-4V were determined to be within or slightly better than the expected range of performance for wrought Ti-6Al-4V, the fatigue properties of the as-HIP material made in this program are appreciably below those of wrought and annealed Ti-6Al-4V. The as-HIP material has essentially a modified basket-weave microstructure. This structure is common in Ti-6Al-4V except that this modified structure does not exhibit grain-boundary alpha, which is known to cause embrittlement. Thus, this structure possesses the high fracture toughness of a material with a basket-weave structure typical of beta-forged material without suffering a loss in ductility.

The HIP temperature of 1750°F is above a standard mill-anneal temperature for wrought Ti-6Al-4V and consequently results in a coarse as-HIP grain size. Since it was not within the scope of this work to study the effect of HIP on physical properties, no effort was expended to try to optimize the HIP process. A refinement of the as-HIP grain size may result in an increase in the fatigue properties of the as-HIP Ti-6Al-4V and may also improve the fatigue properties of the Ti-6Al-4V preforms. Refinement of the as-HIP grain size may be achieved by determining the minimum temperature and time required in the HIP cycle for full consolidation of the Ti-6Al-4V powder to 100 percent density.

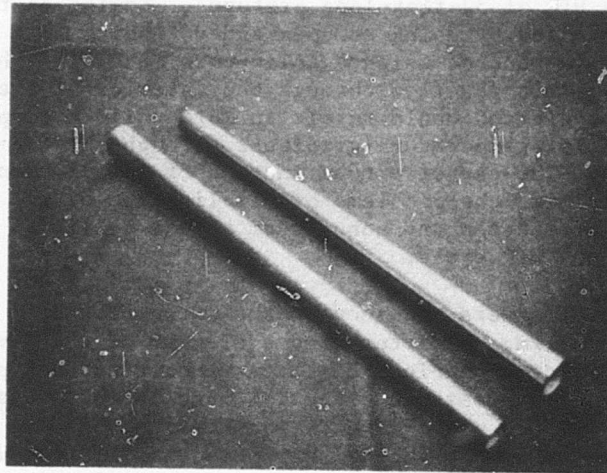


Figure 8. As-HIP and Machine-Tapered Ti-6Al-4V Preforms for Direct Mechanical Testing.

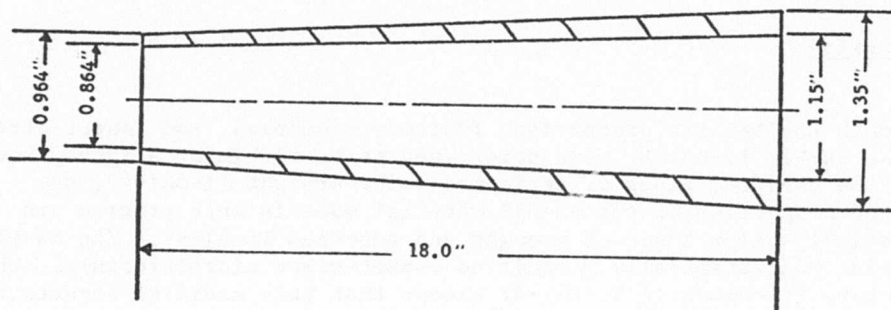


Figure 9. As-HIP and Machine-Tapered Ti-6Al-4V Preforms for Direct Mechanical Testing.

As was discussed in the powder-qualification portion of this report, there were tungsten and carbon impurities in the Ti-6Al-4V powder lot. These impurities and/or surface cracking indicated the SEC studies by NASA in the Ti-6Al-4V matrix may serve as crack initiation sites under loading and, therefore, lower the fatigue strength of the as-HIP Ti-6Al-4V. The fracture toughness and impact strength of as-HIP are high within the expected performance range of wrought Ti-6Al-4V, indicating that the resistance to crack propagation in the as-HIP Ti-6Al-4V is probably adequate. This would imply that the somewhat low fatigue strength of the as-HIP Ti-6Al-4V would be due to a relatively low resistance to crack initiation under loading, possibly as a result of the tungsten and carbon impurities in the as-HIP Ti-6Al-4V matrix.

HYDROSTATIC EXTRUSION

OBJECTIVE

The objective of this work was to hydrostatically extrude HIP Ti-6Al-4V tube preforms into constant-OD, tapered-wall tubes suitable for an ID tapering operation by deformable-die tube drawing. Tubes with tapered ID's and wall thickness were to be made by extruding hollow tube billets through a fixed opening using tapered mandrels. During extrusion, the mandrel moves through the die, increases the ID, and produces a progressively thinner tube wall.

The hydrostatic extrusion process and tooling arrangements used in this program are discussed in Appendix V.

EXPERIMENTAL DETAILS AND RESULTS

Billet Materials

The majority of hydrostatic extrusion trials were conducted on HIP-Ti-6Al-4V billets produced with a tapered ID and a uniform OD. The taper on the ID of these billets closely matched that of the mandrel. The straight portions on either end of the billet were intended to produce lengths of straight tubes which could be gripped in the subsequent tube drawing operation. The OD tapered on the billet nose was made to mismatch the die angle by 7-1/2 degrees when the 22-1/2-degree dies were used. This technique reduces static billet/die friction and minimizes the pressure breakthrough peak at the beginning of the extrusion operation.

Other billets used throughout the course of the program are as follows:

1. A solid HIP Ti-6Al-4V billet, 1-3/4 inches in diameter by 7 inches long.
2. Wrought Ti-6Al-4V tubes with 1.500-inch OD x 1.289-inch ID obtained from a commercial supplier.
3. An AISI 1018 steel billet machined to the same dimensions as the HIP billet shown in Figure 14.

Fluid and Lubricants

The fluid used in the course of these hydrostatic extrusion trials consisted exclusively of AA castor oil, which has been successfully used in the past for extruding many materials. Three billet lubricants were employed in the course of these trials. Two were used for titanium billets, and the third was used for the 1018 steel.

For the Ti-6Al-4V alloy billets, the following lubricants were used:

1. Fused TFE*
2. 'Tiodized' and anodized titanium layer coated with MoS_2 **

The 1018 steel was lubricated with a mixture of castor wax and MoS_2 and is described as L17 in Reference 4.

Results of Extrusion Trials

Seven hydrostatic extrusion trials were made to produce tapered-wall tubes and a solid Ti-6Al-4V rod. The rod was extruded without problems. Tubes were not extruded to the desired 30-inch lengths, because portions of the tubes either cracked or did not flow uniformly through the die. The hydrostatic extrusion trials conducted in this program are summarized in Table III.

In Trial 1, the solid Ti-6Al-4V HIP billet was extruded at a ratio of 2.5:1 to establish base-line extrusion data. This HIP billet was extruded under the same conditions successfully used in previous work to extrude wrought Ti-6Al-4V billets.⁴ The HIP billet extruded at about the same fluid pressure required for wrought material, and an excellent 1.110-inch-diameter rod was produced. The extruded rod subsequently was evaluated for fracture toughness by the Air Force Materials Laboratory. The results of this evaluation are presented in Appendix I.

In Trial 2, the first employing a HIP-tube billet, about 10 inches of tube was extruded. A 5-inch section of tube separated from the billet during the extrusion cycle. Subsequent examination of the extrusion and billet showed that (1) the OD of the first 5-inch extruded tube appeared to be sound and had a good surface, (2) the ID of the same piece exhibited some circumferential cracks, (3) the 5-inch tube section

* E. I. DuPont's Teflon 850 + 204 primer + 851-221 overcoat.

** Tiodize Inc., Burbank, California, Type II coating + Ti-O-Lub TAL-58.

TABLE III. HYDROSTATIC EXTRUSION DATA FOR Ti-6Al-4V ALLOY AND STEEL

FLUID: AA Castor Oil
 RAM SPEED: 6 ipm

TEMPERATURE: 70°F

Trial No.	Billet	Die		Extrusion Rat'o	Lubricant	Extrusion Pressure, (b)		Comments
		Diameter, in.	Included Angle, deg.			Break-through	Maximum Pressure	
1	HIP solid	1.110	45	2.5	Fused TFE	180	148 (c)	Smooth defect-free rod
2	HIP tube-1	1.360	54	1.8	Tiodized	144	138	5 inches of tube was produced followed by about 5 inches of tube with severe circumferential cracks. Unextruded billet upset.
3	HIP tube-7	1.360	60	1.8	Fused TFE	202	n.e. (d)	1-3/4 inches of extruded tube produced. Unextruded billet upset.
4	1018 steel tube	1.400	45	1.5	Castor Wax + MoS ₂	120	75 (c)	Close-fitting liner used to control billet upsetting. 8-1/2 inches of good tube produced when die failed. No billet upsetting.
5	HIP tube-6	1.400	45	1.5	Tiodized	135	n.e. (d)	Extrusion moved out of the die in a series of circumferential rings.

TABLE III. (Continued)

TABLE III. (Continued)									
Trial No.	Billet	Die Diameter, in.	Included Angle, deg.	Extrusion Ratio (a)	Lubricant	Break-through Runout Pressure	Extrusion Pressure, (b) Maximum Pressure	Comments	
6	Wrought tube-1	1.406	45	1.12 (e)	Fused TFE	77	77	153	6 inches of sound extrusion was produced.
7	Wrought tube-2	1.356	45	1.2	Fused TFE	n.e. (d)	n.3. (d)	255	About 1 inch of extrusion produced. Billet upset in die lead-in.
(a) Extrusion ratios are based on the starting dimensions of the billet and on the first portion of the extrusion produced.									
(b) Pressure reported is that applied to the end of the billet.									
(c) Same as breakthrough pressure.									
(d) Not established.									
(e) Final extrusion ratio was 1.53:1 in addition to an ID reduction of 1.6 percent.									

which remained attached to the billet was cracked in a spiral pattern which went completely through the wall, and (4) the unextruded portion of the billet showed some upsetting.

A 1-3/4-inch length of tube was produced in the next trial when the tube cracked in the die land, causing a fluid leak. This partially extruded tube had internal circumferential cracks in the area adjacent to the die land. Also, the unextruded section of the billet upset in a series of annual bulges.

Billet upsetting was controlled in all subsequent trials by the use of a sleeve in the extrusion liner which has an ID only 0.015 inch greater than the tube OD, thereby, limiting any upsetting of the billet. A steel tube billet was used to evaluate this liner arrangement, and about 8-1/2 inches of good tapered wall was produced. This indicates that this new tooling approach was sound.

In Trial 5, extrusion of a HIP-tube billet was unsuccessful as the tube broke in a series of discrete rings as it exited from the die. Wrought Ti-6Al-4V tubes were extruded next in an attempt to separate the effect of processing conditions from material property variations. The wrought tubes as-purchased had a uniform ID rather than one tapered to match the mandrel taper as did the as-HIP tube preforms. Consequently, the wrought tubes underwent some ID reduction as well as a maximum area reduction ratio of 1.53:1. Six inches of sound extrusion were produced with minimal evidence of ID defects. These results suggest that the extensive cracking obtained in the HIP tube extrusions may be related to mechanical property differences in the HIP preforms, particularly on the ID surface, as compared to the wrought tube material.

DISCUSSION

These hydrostatic extrusion trials demonstrated that the process can be used to extrude HIP billets into rounds. Also they have shown from the short lengths of defect-free tubes produced that it appears hydrostatic extrusion has potential for making tapered-wall tubes, but additional work is required to make such tubes defect-free. Optimization of the starting HIP billet properties and possible elimination of powder contamination may help to improve the room-temperature workability of this material. It is also possible that the unidentified layer on the ID of the HIP tubes (see page 14 and Figure 9) could contribute to tube surface failures if this layer is brittle in nature. In addition, the data presented in Appendix II indicates the presence of ID cracks in the fatigue specimens of the as-HIP tubes examined. Such cracks or weak zones, if present, in the as-HIP tube blanks, could also have contributed to the problems encountered in extrusion of HIP tubes.

It should be noted that conventional processing of wrought Ti-6Al-4V tubing has traditionally been plagued with problems of ID surface defects. However, very recent results on a Battelle program⁷ indicate that Ti-6Al-4V wrought tubing may be hydrostatically extruded free of harmful ID defects at warm (1400°F) temperatures and at an extrusion ratio of 5:1. It is recommended, therefore, that subsequent hydrostatic extrusion trials with HIP material be undertaken at warm temperatures to increase the potential for making defect-free tubes.

Earlier in this report, it was reported that cold working of HIP material did not improve fatigue life over that of as-HIP material. However, work by Peebles⁸ indicates that warm or hot working introduces sufficient shear deformation in a powder product such as HIP material to raise fatigue life to equal or exceed that of conventionally wrought materials. Peebles' work was done in hot forging P/M preforms of Ti-6Al-4V, and Figure 10 shows the improvement gained in fatigue life by 20 and 50 percent hot upsetting. Warm or hot shear deformation between powder particles promotes better bonding and thus better fatigue life. Thus, the use of warm working has potential advantages of improving fatigue life of the HIP material and enabling it to be successfully fabricated into a tapered tube product.

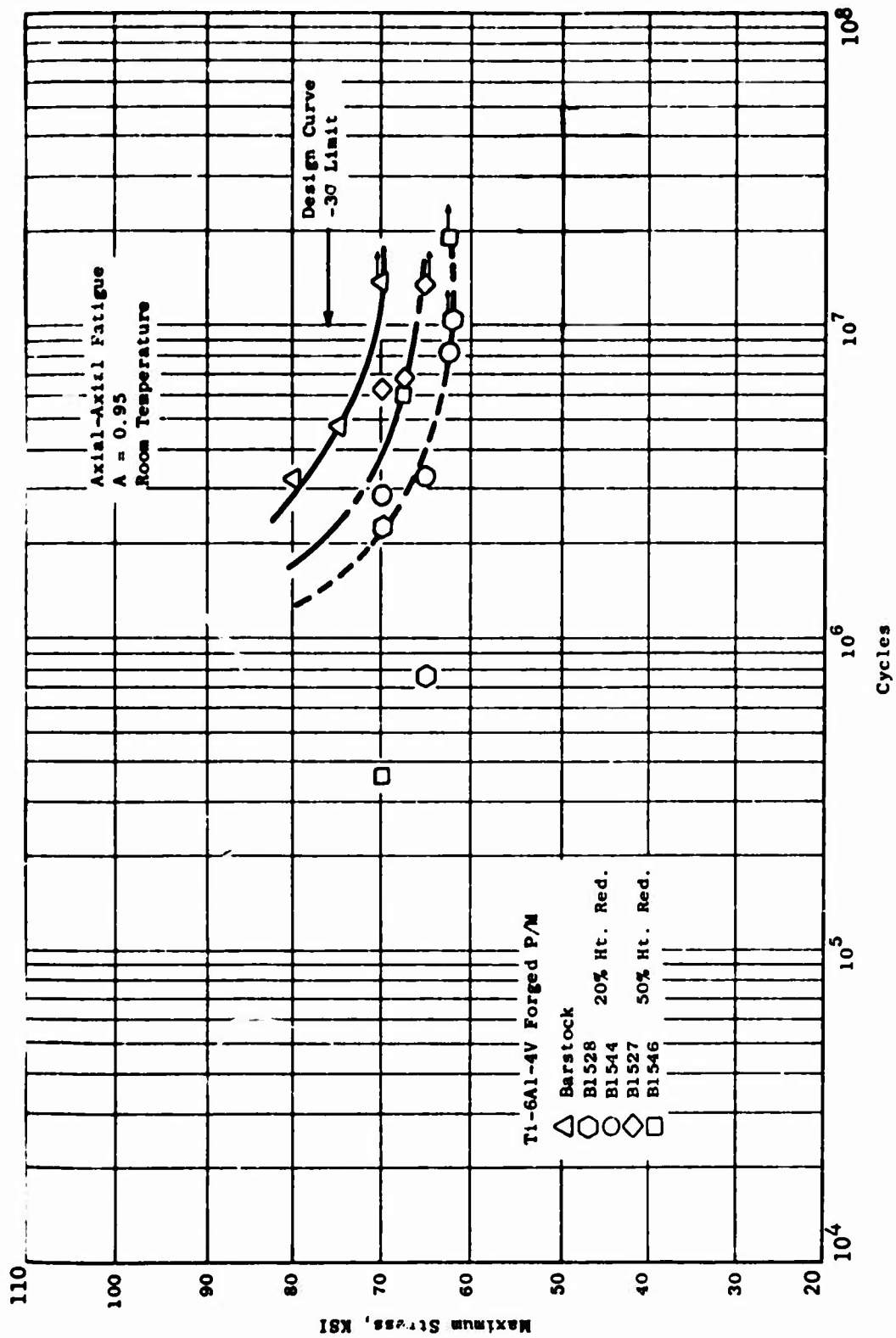


Figure 10. Fatigue Endurance Limit (10⁷ Cycles).

TUBE DRAWING

OBJECTIVE

The objectives of this work were:

1. Establish procedures to taper the wall and diameter of HIP and wrought Ti-6Al-4V alloy tubing by cold drawing.
2. Assess potential problems with tooling and lubrication, and determine number of interstage anneals required to form the finished part.
3. Establish drawing force data upon which tooling and equipment requirements can be estimated for producing full-scale spar tubes.
4. Prepare two tapered parts, each from commercial wrought and HIP tubing.
5. Taper the diameter of three tapered wall preforms produced by hydrostatic extrusion. The target tapered tube shape is shown in Figure 11.

Die tapering techniques are described in Appendix VI.



Figure 11. Target Tapered-Tube Shape.

EXPERIMENTAL PROCEDURES AND RESULTS

The processing sequence for producing the tapered titanium alloy parts can be broken down into three basic steps (outlined in Table IV): wall tapering with a rigid die, tube pointing, and diameter tapering with a deformable die. The procedures and results of these three cold-forming operations are discussed below.

Approach

Wrought commercial and HIP Ti-6Al-4V tubes with constant wall thicknesses were drawn through a rigid die and over a tapered mandrel to produce tubes with constant OD's and walls tapering from 0.100 inch to 0.050 inch. In this operation, the relative merits of pushing the tube-mandrel assembly through the die, which eliminates the need for a tube pointing step, were compared to those of the more common technique of pulling both through the die. The latter technique was found to be unsatisfactory because the transition areas in the tube points tended to shear off as the tubes were started through the drawing dies. Thus, wall tapering was accomplished by pushing the tube and mandrel assembly through the dies. After wall tapering, diameter tapering was accomplished by drawing the tapered wall preforms over a tapered mandrel with a deformable die.

Materials Investigated

The process for preparing the HIP tubes has been described elsewhere and needs no further comments here. Wrought Ti-6Al-4V tubes were obtained from two commercial sources and used to provide base data for a comparison with Ti-alloy parts made from HIP tubes.

A tube measuring 1.5 inches OD by 1.3 inches ID by 10 feet long was received from Wolverine Tube, Detroit, Michigan. Sixteen-inch-long sections of this material were ultrasonically inspected and prepared for subsequent cold drawing. Ultrasonic inspection indicated the as-received material to be sound and crack-free. The Wolverine tube was produced by tube reducing, which is a common tube-making process.

Another Ti-6Al-4V tube measuring 1.5 inches OD by 1.3 inches ID by 16 inches long, which was produced by a relatively new tube-making process called rotary ball swaging, was obtained from the Whittaker Corporation. It was anticipated that each tube-making process would produce tubes with slightly differing crystallographic textures and thereby with different deformation behavior. Tubes produced by both manufacturing processes were tapered to determine if either tube was preferable starting stock.

TABLE IV. FABRICATION SEQUENCE FOR TUBE TAPERING IN TASK III

Step	Operation
<u>Wall Tapering</u>	
1	Taper wall from 0.100 inch to 0.068 inch (4 passes in rigid dies)
2	Pickle and anneal
3	Finish wall taper from 0.068 inch to 0.050 inch
4	Pickle and anneal
<u>Pointing</u>	
5	Point end from 1.360 inches to 1.225 inches OD (1 pass)
6	Pickle and anneal
7	Finish pointing from 1.225 inches OD to 0.900 inches OD (3 passes)
<u>Diameter Tapering</u>	
8	Finish taper OD from 1.360 inches to 0.964 inch with deformable die

The as-received properties of the commercial titanium alloy tubes as reported by the suppliers are listed below:

<u>Source</u>	<u>Yield Point, psi</u>	<u>Ultimate Tensile Strength, psi</u>	<u>Elongation, percent</u>
Wolverine	129,000	143,000	28
Whittaker	129,750	143,450	15

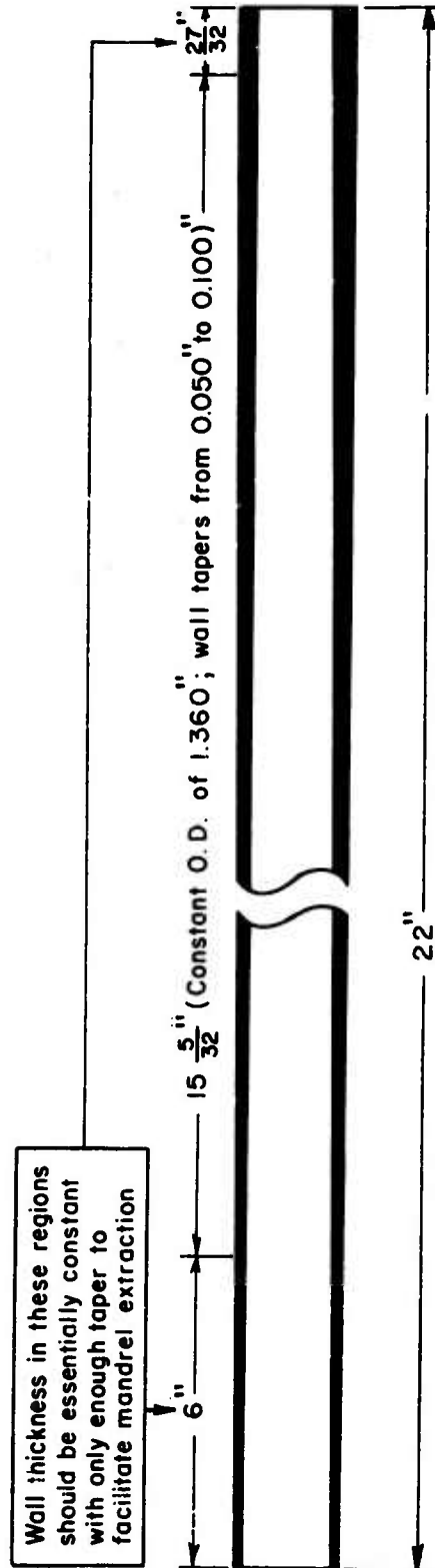
Wall Tapering

The target tapered-wall preform required for deformable die tapering to form the finished part is shown in Figure 12. The tapered ID is formed by pushing the tube and mandrel assembly through rigid dies. The mandrel surface is tapered and, as the tube moves through a constant die opening, the ID of the workpiece conforms to the taper on the mandrel surface.

Eight tapered-wall preforms were prepared by pushing the tubes through carbide dies in seven passes of approximately 10 percent reduction in area per pass. The tubes were annealed after a cumulative area reduction of about 35 percent. The finished tubular parts were 23 to 24 inches long, and the wall tapered from 0.100 inch to 0.050 inch. Seven of these workpieces were prepared from commercial Ti-6Al-4V tubing, and one was prepared by the HIP process at Battelle. The seven tubes prepared from wrought material were crack-free, with excellent OD and ID surface finishes. The Fel-Pro C300 lubricant and carbide die system performed satisfactorily. In fact, all seven wrought tubes were fabricated to final size without using any in-process surface conditioning other than recoating the workpiece with lubricants after each cold reduction. Results of the wall tapering experiments and the drawing loads required are shown in Table V.

The HIP-processed tube showed evidence of fine hairline cracks on the ID at two locations. These have been attributed to minor variations in density of the transverse cross section of the starting tube blanks along its longitudinal axis. A market fluctuation in the draw force was observed as this tube passed through the die which was presumably associated with these low-density areas.

Attempts were made to process seven additional HIP preforms. However, the wall thickness variations in these preforms (which resulted from machining of inadequately straightened HIP tube blanks) caused a severe ovality condition in the tubes during processing. This condition appears to have contributed to surface galling and, in some cases, wall fractures. As a result, work with these tubes had to be terminated.



The 6-inch length on the left end is for pointing. The 27/32-inch length on the right end is to assure sufficient length of the final part.

Figure 12. Half-Scale Drawing of Tapered-Wall Preform Required for Deformable Die Tapering.

TABLE V. DETAILS OF WALL TAPERING TRIALS

Tube Identification	R.A. Percent	Die Identification Number	Die Opening, in.	Draw Force, lb	
				Maximum	Steady
W-8	10 (29)	1	1.446	16,200	7,400
	10	2	1.428	14,200	-
	10 (29)*	3	1.412	12,500	6,400
	10	4	1.396	11,800	6,800
	10	5	1.382	12,200	6,000
	10	6	1.370	10,900	4,000
	10 (34)	7	1.360	9,200	2,400
W-9	10	1	1.446	16,400	7,800
	10	2	1.428	16,000	-
	10 (29)*	3	1.412	12,500	8,000
	10	4	1.396	14,800	7,000
	10	5	1.382	11,500	-
	10	6	1.370	11,000	-
	10 (34)	7	1.360	7,800	-
N-1	10	1	1.446	17,500	7,500
	10	2	1.428	14,500	-
	10 (29)*	3	1.412	11,800	8,250
	10	4	1.396	16,000	-
	10	5	1.382	12,400	-
	10	6	1.370	9,400	3,800
	10	7	1.360	7,600	3,900
W-11	10	1	1.446	15,500	7,500
	10	2	1.428	15,000	-
	10	3	1.412	14,000	-
	10 (34)*	4	1.396	13,200	-
	10	5	1.382	12,600	-
	10	6	1.370	12,000	-
	10	7	1.360	9,800	4,600
HIP-1	10	1	1.446	10,500	-
	10	2	1.428	13,250	-
	10 (29)**	3	1.412	13,300	-
	10	4	1.396	12,500	-
	10	5	1.382	12,000	-
	10	6	1.370	11,200	-
	10 (34)	7	1.360	9,250	-

Note: Numbers in parentheses indicate cumulative cold reduction in area between anneals.

* Tubes annealed at this point in processing.

** Hairline cracks visible on ID.

Tube Pointing

The workpiece must be pointed for a short distance to keep the tube from slipping over the mandrel during diameter tapering. Past experience on other materials had shown that pointing could be accomplished by simply pushing the workpiece into a die or series of dies. Since the target OD at the small end of the tapered tube was 0.964 inch, a tube slightly smaller than this was required to allow the end of the tube to start through the tapering die. It was planned to accomplish pointing in five passes of approximately 10 percent diametral reduction per pass as indicated below.

<u>Die No.</u>	<u>Die ID, in.</u>	<u>R.A., percent</u>	<u>Cumulative R.A., percent</u>
1	1.224	10	-
2	1.102	11	20
3	1.000	10	28
4	.900	10	-
5	.810	11	47

It was evident from the beginning that pointing was going to be a problem because of cracking of the tube. End cracks developed as the tube ends were pushed through the second pointing die (20 percent diametral reduction). The most common type of cracking observed is illustrated in Figure 13. This type of cracking was seen frequently in subsequent pointing attempts. In view of prior pointing experiences with other materials, this cracking was unexpected, especially at the relatively small reduction levels being used. When this cracking problem was first observed, various attempts were made to overcome it.

The approaches taken to alleviate the point-cracking problem are described below.

All tube ends were carefully faced in a lathe, and the edge making first contact with the die was rounded slightly. In addition, some of the tube samples were machined to various contours, including

- Slight bevel on OD
- Slight bevel on ID
- Bevel on both ID and OD

After machining, the tubes were honed on both the OD and ID and then chem-milled to remove any possible crack initiators.

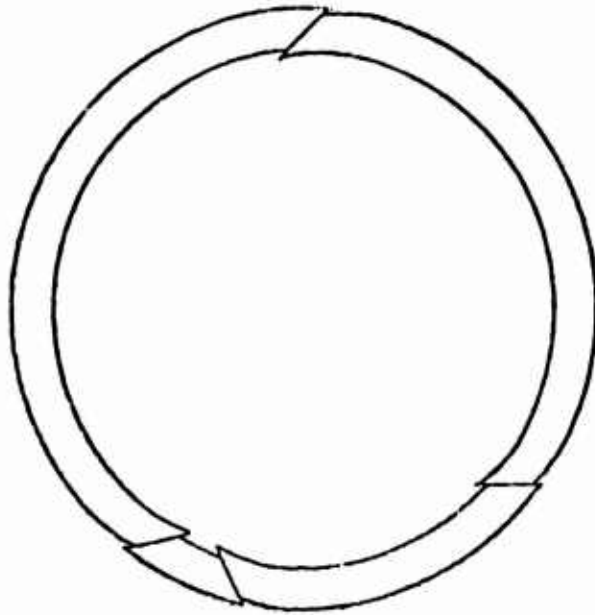


Figure 13. Sketch To Illustrate Type of Cracking Observed During Tube Pointing.

None of the measures described above were very effective in solving the cracking problem. At the 10-percent reduction level, pointing was nearly always successful. At the 20-percent level, successes outweighed failures by a fair margin. At 30-percent reduction, cracking always occurred. The practice of interstage annealing between passes did not show significant benefits.

The source of the pointing problem is not clear. The mechanical property data of these tubular materials indicates at least a 15-percent elongation in a tensile test. These data suggest that pointing to a 10-percent diametral reduction should be possible. Nonetheless, failures frequently occurred on a 10-percent reduction after annealing. The suggestion has been made that the tubing may have a pronounced texture, arising from its past processing history, such that the majority of individual grains are unfavorably oriented for the type plastic strain needed to reduce the tube diameter. This is a possibility, but at this point no attempt has been made to verify it. It should be noted that the two lots of wrought tubes were processed with two different deformation techniques, but the results of the pointing trials were essentially the same.

Diameter Tapering

The third stage of the tube tapering operation was to taper the diameter of the tapered wall preforms. However, due to the pointing problems discussed above, only a partial OD taper (1.350 to 1.220 inches) was actually

achieved. This was accomplished on three wrought tapered-wall preforms without difficulty and shows promise, provided the pointing problem can be solved. A tapered tube is shown in Figure 14.

CONCLUSIONS

This work has demonstrated that wall tapering of a wrought tube preform can be successfully achieved and a 50-percent reduction in wall thickness is obtainable. There is good reason to believe that these same procedures can be applied to the fabrication of full-scale parts provided that a draw bench or press with sufficient stroke and power is available. Some indications of the drawing force required to taper the wall of a full-scale part can be estimated from the measured loads required to form the small-scale parts. The estimated loads for drawing full-scale spars are compared with the actual measured loads for drawing the small-scale tubes in Table VII.

The problems in tapering the walls of the HIP tube preforms on this program are believed to be attributable at least partly to dimensional variations of the HIP preforms. Wall variation in the starting tube blanks resulted in nonuniform deformation in the workpiece, and this may have contributed to surface galling and, in some cases, wall cracking. Another possible factor may have been the presence of low-strength bond zones in the as-HIP tube preforms. However, more study would be required to establish whether this was the case and, if so, whether altering the HIP conditions could prevent this problem.

Tapering the diameter of the tapered-wall preforms with deformable dies met with only limited success due primarily to the pointing problems. Therefore, the amount of taper that could be accomplished in a single drawing pass was not determined. However, it is doubtful that 50-percent taper in the OD can be achieved in a single drawing pass. It would probably require multiple passes with interstage annealing to produce the full taper.

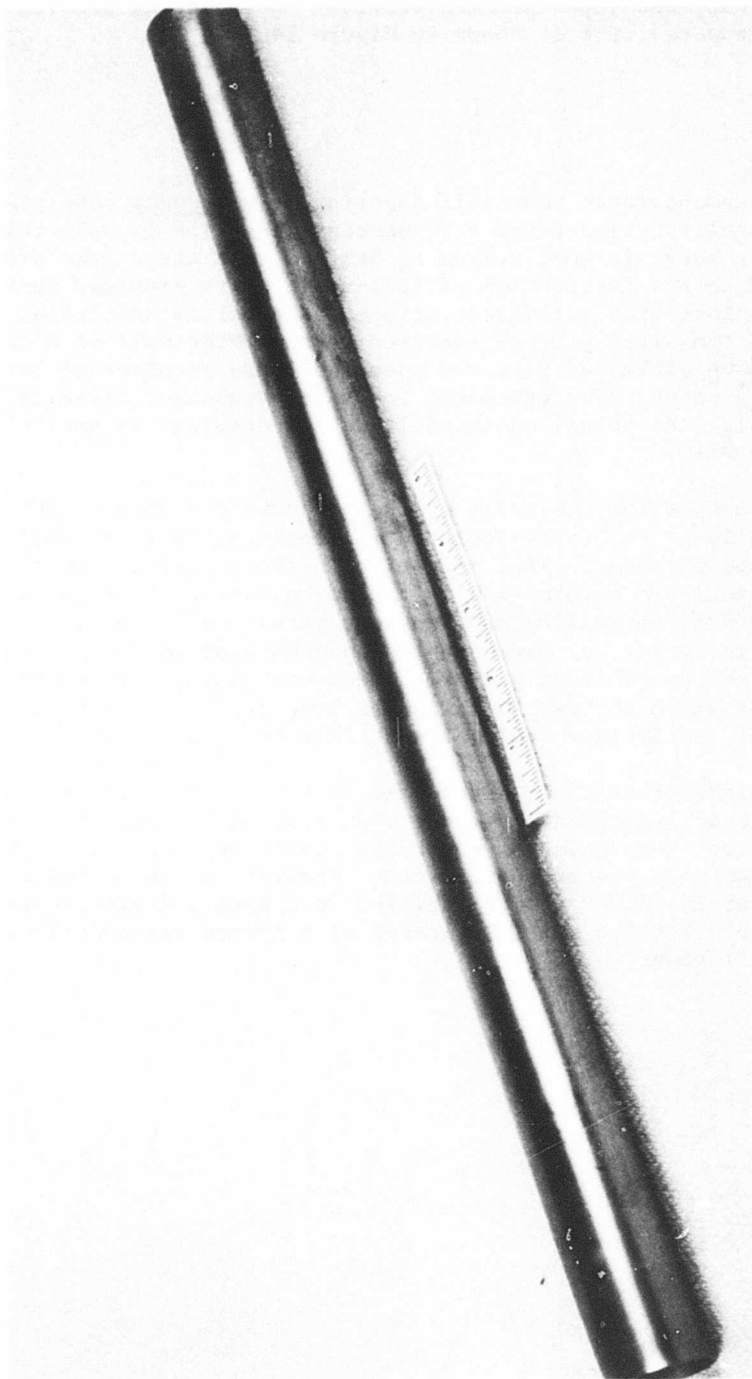


Figure 14. Subscale Spar Tube Tapered by Cold Drawing.

**TABLE VII. ESTIMATED LOADS REQUIRED TO TAPER WALL
OF FULL-SCALE T1-6A1-4V SPAR TUBE BY
COLD DRAWING**

Pass	R.A., Percent	Measured Max. Load in Drawing Small- Scale Tube, lb	Estimated Loads for Drawing Full- Scale Tube, lb
1	10	15,500	186,000
2	10	15,000	180,000
3	10	14,000	168,000
4	10	13,200*	158,000
5	10	12,600	151,000
6	10	12,000	144,000
7	10	9,800	117,000
* Tube annealed at this point in processing.			

EVALUATION OF FINISHED TUBES

OBJECTIVE

An experimental investigation was conducted to assess the fatigue resistance of titanium (Ti-6Al-4V) powder products. The test matrix was designed to compare the fatigue characteristics of (1) tapered titanium tubes produced by hot isostatic pressing (HIP) of a powder and (2) tapered tubes made of wrought (Wolverine) material.

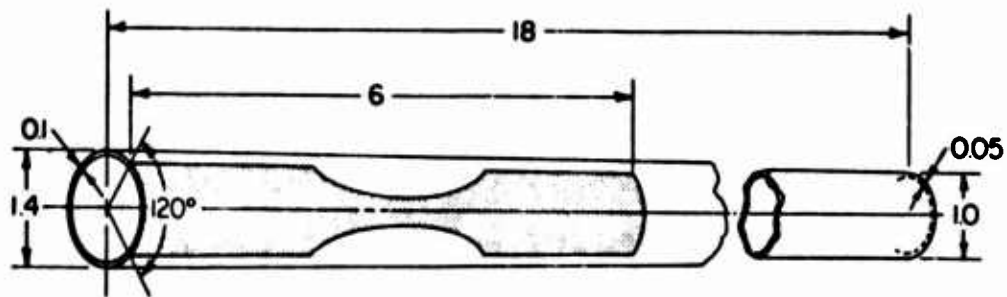
EXPERIMENTAL PROCEDURES AND RESULTS

Description of Test Specimens

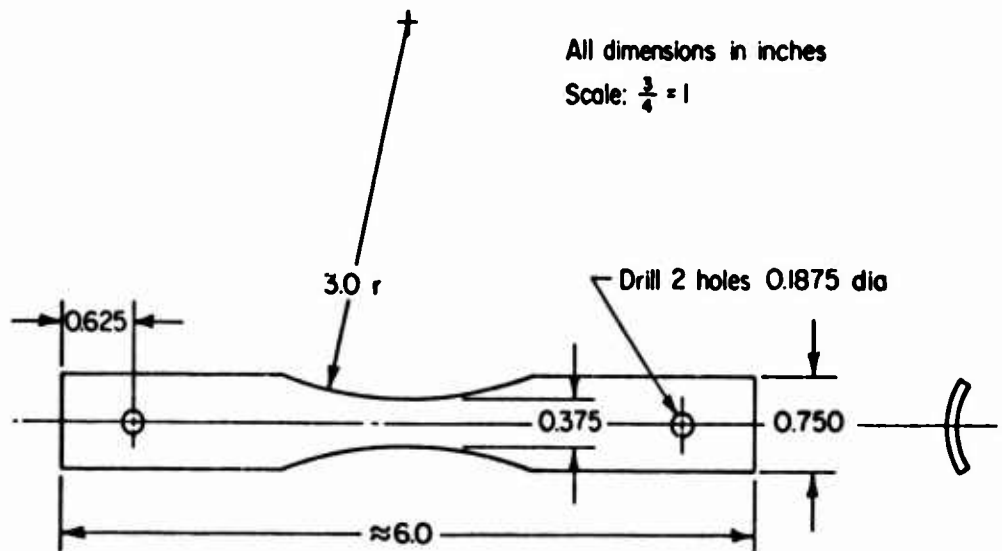
The specimens were machined from tapered tubes as shown in Figure 15a, to the configuration depicted in Figure 15b. The specimens were designed such that three blanks could be machined along the longitudinal axis (length) of each tube; i.e., specimens were taken from the thick end, middle section, and thin end. The titanium specimens were obtained from four tapered tubes (numbers 1, 15, 17, and SF8). Two of these tubes (numbers 15 and 17) were as-produced by hot isostatic pressing at 1750°F for 3 hours. The other two tapered titanium tubes (numbers 1 and SF8) were made by the HIP process, tapered by cold drawing, and then annealed at 1550°F for 1 hour. Six wrought Ti-6Al-4V specimens were obtained from a cold-drawn Wolverine tube (number W8) of a configuration similar to the HIP tubes. Three of the specimens machined from this tube were annealed at 1550°F for 1 hour, and the other three were heat treated at 1750°F for 3 hours. In the case of cold-drawn tubes, the specimen locations (thick, middle, and thin sections) correspond to areas of 25, 50, and 55 percent cold work, respectively.

Testing Procedures

The tests were conducted in a 5-kip-capacity machine (see Figure 16). With this machine, the load is applied to the specimen by means of a cam and lever arm arrangement. Constant-amplitude, load-controlled fatigue tests were conducted under tensile load cycling at $R = 0.10$ ($R = \text{minimum stress}/\text{maximum stress}$). Specimens were tested in air at a temperature of 70°F (room temperature) and at a frequency of 1725 cpm.



(a) Specimen orientation with respect to the tapered titanium tube.



(b) Configuration of fatigue specimen.

Figure 15. Titanium (Ti-6Al-4V) Fatigue Specimen as Used in This Program.

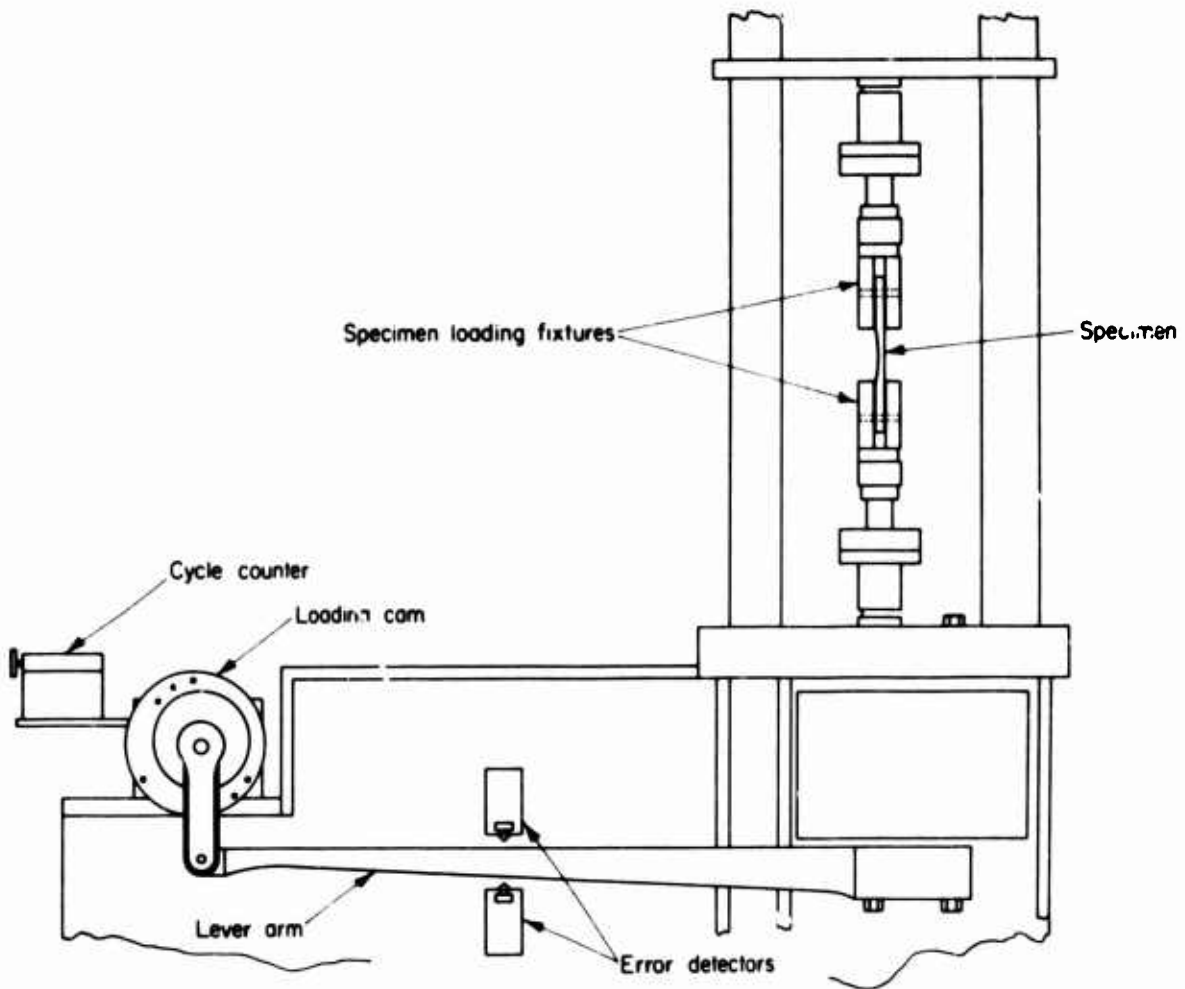


Figure 16. Experimental Apparatus, 5-Kip Capacity.

Each specimen was inspected for undesirable tool marks and processing flaws (such as voids, inclusions, and cracks); specimens which showed excessive amounts of these flaws were rejected. On specimens which were considered usable, the edges of their gage sections were hand polished, such that finishing marks were parallel to the longitudinal axis of the specimen. After the specimen preparation had been completed, the dimensions of the gage section (minimum width and thickness) were accurately measured. The specimens were loaded into the test system, taking care that the grips were properly aligned and the specimens correctly seated in the grips. The load required to achieve the desired axial stress (for a given test) was based upon the minimum cross-sectional area of the specimen. The calculated load was programmed into the test system by means of an eccentric cam arrangement (see Figure 16). The test was automatically terminated at failure, failure being defined as complete separation of the specimen.

Due to the configuration of the specimens tested, in this program, (see Figure 15), the centroid was slightly displaced from the line of applied force. This condition caused a slight bending stress to be superimposed on the axial stress. That is, the total stress imposed on the specimen can be approximated as the sum of the axial stress and the bending stress which was induced by the relative positions of the applied load and the centroid of the specimen. By making some simplifying assumptions, the bending stress was calculated to contribute approximately 5 percent to the total stress. This calculation was based on the target shape of the tube and a specimen which would be machined from such a tapered tube. However, due to manufacturing techniques and the machining process, there was considerable variation in the geometry of the specimens and this implies that there existed a variation in the induced bending stress component for each test. The stress tabulated in the data presentations is the axial stress as defined by the maximum load divided by the minimum cross-sectional area and does not include the bending stress. If the bending stress were calculated or measured for each specimen and the results analyzed on the basis of total stress instead of axial stress, the high degree of scatter in the results might be significantly reduced.

Results

The results of the fatigue tests on Ti-6Al-4V specimens are summarized in Table VIII and Figure 17. In the table, the results of the tests are grouped by maximum stress and ordered as to increasing fatigue life. Figure 17 is a plot of the data obtained during this program. The high degree of scatter in the results for the HIP material makes it difficult to draw a curve of mean life through these data. Therefore, a curve which is considered to be a lower bound has been drawn. The curves presented for the wrought materials are not intended to be representative, but instead are drawn only to help clarify the results. The specimens prepared from the thick, middle, and thin zones of the tube showed no trends in fatigue life; therefore, the specimen location has

TABLE VIII. SUMMARY OF FATIGUE RESULTS FOR Ti-6Al-4V TESTED AT ROOM TEMPERATURE

Specimen Number*	Specimen Type and Treatment	Maximum Axial Stress, ksi	Fatigue Life, cycles
15-T9	HIP at 1750°F - 3 hr	45	2,117,100**
15-M8	HIP at 1750°F - 3 hr	50	2,537,400
15-B7	HIP at 1750°F - 3 hr	50	5-7 x 10 ⁶ ***
1A-T1	HIP, cold drawn and annealed at 1550°F - 1 hr	65	45,800
1A-B3	HIP, cold drawn and annealed at 1550°F - 1 hr	65	70,000
15-M3	HIP at 1750°F - 3 hr	65	78,000
15-T1	HIP at 1750°F - 3 hr	65	90,000
15-B2	HIP at 1750°F - 3 hr	65	135,300
SF8A-T1	HIP, cold drawn and annealed at 1550°F - 1 hr	65	145,700
W8A-B3	Wolverine, cold drawn and annealed at 1550°F - 1 hr	65	931,200**
W8A-T4	Wolverine, cold drawn and heat treat 1750°F - 3 hr	65	5,126,600
W8A-T1	Wolverine, cold drawn and annealed at 1550°F - 1 hr	65	10 x 10 ⁶ D.N.F.
17-T1	HIP at 1750°F - 3 hr	80	12,100
W8A-M5	Wolverine, cold drawn and heat treat 1750°F - 3 hr	80	53,200
1A-M2	HIP, cold drawn and annealed at 1550°F - 1 hr	80	67,000
W8A-M2	Wolverine, cold drawn and annealed at 1550°F - 1 hr	80	140,200
15-B4	HIP at 1750°F - 3 hr	100	13,100
W8A-B6	Wolverine, cold drawn and heat treat 1750°F - 3 hr	100	15,100
15-M5	HIP at 1750°F - 3 hr	100	20,300
SF8A-T3	HIP, cold drawn and annealed at 1550°F - 1 hr	100	21,700
15-T6	HIP at 1750°F - 3 hr	100	90,300

* The portion of the specimen number before the dash designates the tube from which the specimen was taken. The letter immediately after the dash identifies the location on the tube; i.e., B = large section, M = middle section, and T = thin section.

** These specimens failed in the grips instead of in the gage section; therefore, their fatigue life is not representative and should be disregarded.

*** The test apparatus did not stop when the specimen failed, and thus continued to count false cycles. Therefore, the exact fatigue life is not known, and a range over which failure occurred is reported.

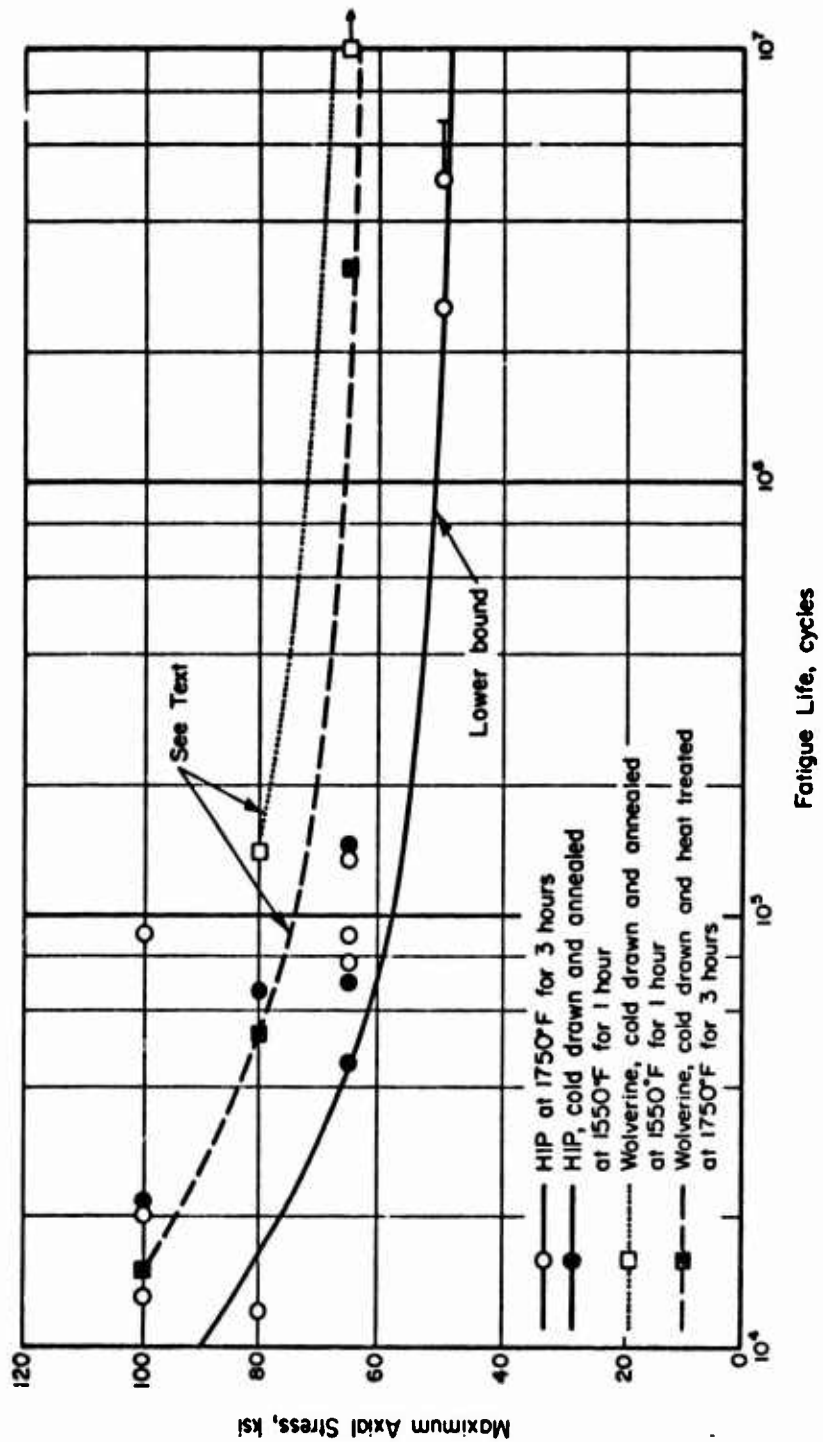


Figure 17. Fatigue Life as a Function of Maximum Axial Stress for HIP and Wrought (Wolverine) Titanium (Ti-6Al-4V) Tapered Tubes.

not been identified in Figure 17. However, the specimen identification number contains information regarding specimen location (see first footnote, Table VIII), so the section of the tube from which the specimen was machined can be determined from Table VIII.

Figure 17 clearly shows the superior fatigue behavior of the wrought materials. That is, in the lower stress ranges (below 70 ksi), the cold-drawn wrought material which was annealed at 1550°F for 1 hour has a fatigue strength, at 10^7 cycles, approximately 20 ksi greater than the HIP materials; and the wrought material which was heat treated at 1750°F for 3 hours has a fatigue strength 15 ksi greater than the HIP material at 10^7 cycles. In the higher stress ranges (above 70 ksi), it is difficult to distinguish the fatigue lives of the wrought material heat treated at 1750°F for 3 hours and the hot isostatically pressed material without more test data. This is due to the large amount of scatter encountered in the results. In the same stress range, however, the wrought material which was not heat treated appears to have a better resistance to cyclic loading.

The general trends in the data which are outlined above and summarized below can be considered to be consistent within the scope of this study. Since all the materials were tested under the same conditions and using the same specimen configuration the data points are directly comparable to one another. However, the data obtained from any one material should not be compared to data developed in the course of other experimental programs. The combined stresses (discussed previously) imposed on the material would, in general, make the fatigue strength of these materials appear reduced as compared to fatigue data developed under conditions of pure axial loading.

CONCLUSIONS

As a result of the experimental investigation conducted for this program, the following observations were made regarding the fatigue characteristics of hot isostatically pressed powder Ti-6Al-4V material:

- The tests conducted on specimens from tubes produced by hot isostatic pressing at 1750°F for 3 hours and tubes manufactured by the HIP process and then cold drawn to the desired taper show that the fatigue resistance of the material apparently is not improved by cold working.
- Specimens taken from the wrought (Wolverine) tubes show considerably better fatigue resistance than either of the powder titanium products.

ANALYSIS OF COST EFFECTIVENESS

The objective of this task was to assess potential process costs, using the techniques examined in this program, in making full-size helicopter rotor spars. The dimensions of a typical full-scale helicopter spar tube design are shown in Figure 18. These dimensions were used as a basis for estimating the various processing costs which are discussed here.

Presently, it requires a constant-wall tube shell weighing approximately 1950 pounds to produce the 200-pound part shown in Figure 19, using present methods of machining each tapered spar from an extruded shell. At a reported tube shell cost of \$11 per pound, this would amount to a starting billet cost of \$21,000 (finish machining costs would be added to this figure). Obviously, from an economic viewpoint, an alternate approach to machining is a worthwhile goal.

The following sections show cost estimates for making a finish tapered spar by the HIP process. Also shown are cost estimates for using hydrostatic extrusion and draw tapering techniques to fabricate a tapered spar from either a HIP preform or a conventionally-produced wrought tube shell. Data are presented in tabular form preceded by a simple listing of conditions used as a basis for the cost estimates.

ESTIMATED COSTS FOR PRODUCING Ti-6Al-4V ROTOR SPAR TUBES BY HOT ISOSTATIC PRESSING

The conditions used in calculating the costs presented in Table IX are given below.

Powder: Based upon projections by Whittaker Corporation, powder cost is quoted at \$8 per pound in large quantities.

Tooling: Expendable tooling - consists of low-carbon-steel material to be used as the deformable can material for each spar.

Nonexpendable tooling - consists of tooling which will be placed within the autoclave to support the spar during HIP and prevent bowing or distortion.

Equipment: Included is an autoclave vessel with heater and miscellaneous fittings and tooling required to hook the autoclave into powder, pressure, and cooling equipment. Installation is also included in this item of cost, as are leaching tanks and pumping equipment for acid leaching of the expendable HIP tooling.

Building Cost: Building cost at \$25/ft², assuming a 10,000 ft² area is required for HIP processing.

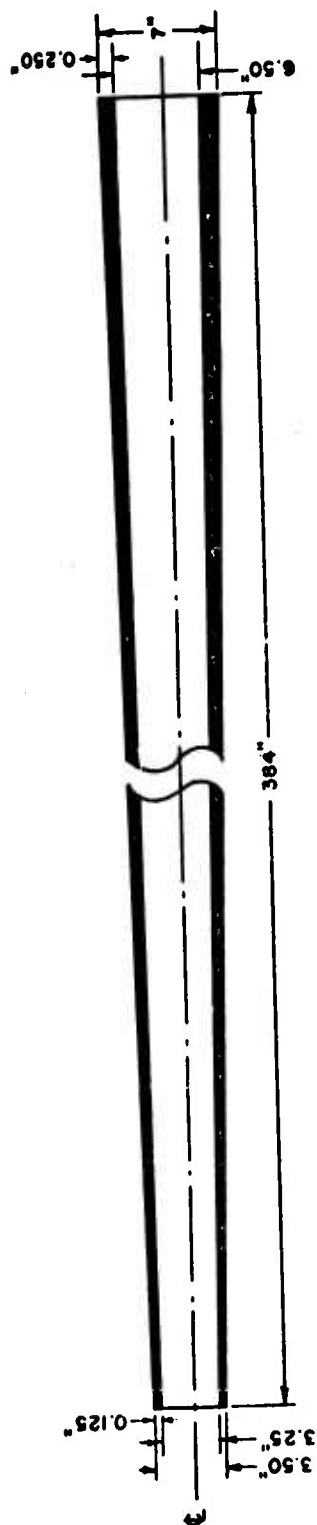


Figure 18. Approximate Dimensions of Full-Scale Spar Tube.

TABLE IX. ESTIMATED COSTS FOR PRODUCING Ti-6Al-4V ROTOR
SPAR TUBES BY HIP*

Item	1000 Spars**	5000 Spars**	10,000 Spars**
I. RAW MATERIAL			
Powder at \$8/lb =	\$8.00	\$8.00	\$8.00
Actual Powder Cost (based on 90 percent yield)	8.80	8.80	8.80
II. CONVERSION COSTS			
Tooling (expendable/spar)	2.10	1.84	1.71
Tooling (nonexpendable) at \$7000	0.04	<0.01	<0.01
Equipment (depreciation over total spars) at \$600,000 (including installation)	3.16	0.63	0.32
Building Cost at \$25/ft ² (10,000 ft ²)	1.32	0.26	0.13
Maintenance (5 percent of non-expendable tooling and equipment)	0.16	0.03	0.02
Labor (six laborers, one engineer, and one supervisor)***	0.57	0.57	0.57
Processing Costs (powder, water, acid, etc.)	0.53	0.53	0.53
Machining of OD of Part	<u>1.05</u>	<u>1.05</u>	<u>1.05</u>
III. TOTAL COSTS			
\$/pound	17.73	13.72	13.14
\$/spar	\$3,363	\$2,603	\$2,494

* All costs in dollars per pound.

** At 190 lb/spar (see Figure 2), production rate of 1.8 spars/hr

*** Laborer = \$12/hour with overhead. Engineer = \$25/hour with overhead. Supervisor = \$30/hr overhead (100 percent overhead).

Maintenance: Charge for equipment maintenance based upon 5 percent of the equipment cost item shown above.

Labor: Assumes that the HIP processing will require six laborers, one engineer, and one supervisor for the duration of the spar production.

Processing Costs: Cost for powder, water, acid, and other expendable items.

Machining: It is assumed that the OD of the spar will require final machining to produce acceptable surface finishes and tolerances. The ID of the spar will be left in the as-HIP condition.

ESTIMATED COSTS FOR PRODUCING Ti-6Al-4V ROTOR SPAR TUBES BY HYDROSTATIC EXTRUSION

The estimated conversion costs for producing Ti-6Al-4V tapered wall tubes by hydrostatic extrusion are summarized in Table X. These costs do not include conversion costs for diameter tapering which would be done by a process other than hydrostatic extrusion. Thus, hydrostatic extrusion is viewed at this point as a technique for producing a fixed-OD, tapered-wall tube which would then be OD tapered.

Since the experimental work done in this program did not define process conditions whereby HIP billets could be used, billet costs are based on the use of commercially available wrought tube shells.

Basic process conditions used for calculations in Table X are:

1. Availability of a 3000-ton production extrusion press equipped for hydrostatic extrusion.
2. Extrusion rate of 10 billets per hour.
3. Tooling costs including material and machining of dies and mandrels.
4. Miscellaneous costs including lubricants and seals.

ESTIMATED COSTS FOR PRODUCING Ti-6Al-4V ALLOY ROTOR SPAR TUBES BY COLD DRAWING

The estimated costs for producing the full-scale rotor spar tubes by cold drawing are based on the processing sequence outlined in Figure 19. This is basically the same fabrication sequence that was applied to the small-scale tubes prepared in this program, and the assumption has been made for the purpose of cost estimating that the same procedures can be

TABLE X. CONVERSION COSTS FOR HYDROSTATIC EXTRUSION OF
TAPERED Ti-6Al-4V TUBES*

I. RAW MATERIAL

Basic Billet Cost \$11/lb

Actual Billet Cost \$12/lb (Based on 90 percent tube yield)

II. CONVERSION COSTS

Cost per hour of operation for 3000-ton production hydrostatic
extrusion press (excluding dies and mandrel) \$400.00

At 10 extrusions per hour, cost per extrusion is \$40, cost/lb 0.21

Die Cost

Based on:

(a) cost of 10-inch-diameter x 5-inch starting material
with allowance for heat treatment = \$170

(b) 16 hours to machine at \$15/hour = \$240

(c) life - 100 extrusions cost/lb 0.02

Mandrel Cost

Based on:

(a) cost of 7-inch diameter x 144-inch starting
material with allowance for heat treatment = \$3000

(b) 40 hours to machine at \$15/hour = \$600

(c) life - 500 extrusions cost/lb 0.04

Miscellaneous Costs

0.03

fluids, lubricants, and seals

Total Cost \$/lb = \$12.40
\$/spar = 2,356

* Costs shown for producing fixed-OD, tapered-ID tube, which would later be OD tapered as a final step. Extruded tube would measure 32 feet in length by 7 inches in OD by 1/4 inch to 1/8 inch for tapered wall and would weigh 190 pounds.

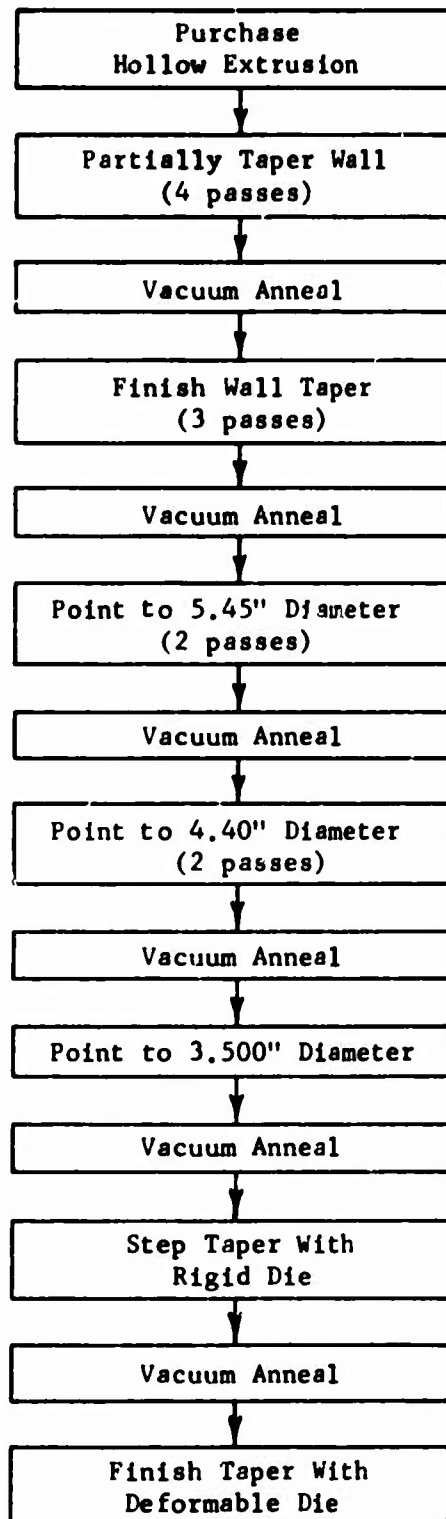


Figure 19. Process Chart for Cold Forming Full-Scale Rotor Spar Tubes.

applied to the manufacture of full-size rotor spar tubes. The approximate dimensions of a full-size spar tube used as a basis for cost estimating are shown in Figure 18.

Conditions used for calculating costs tabulated in Table XI are given below:

Billet Size - 7-inch OD x 0.250-inch wall x 237-inch length
Billet Weight - 200 pounds
Cost of Starting Billet - \$11/pound*

Tooling

1. Wall Tapering Mandrel: 3800 pounds at \$1.00/pound = \$3800.
Service life - 2000 tubes
2. Wall Tapering Dies: 7 dies at \$300/die = \$2100.
Service life - 30,000 tubes
3. Diameter Tapering Mandrel: 4200 pounds at \$1.00/pound = \$4200. Service life - 5000 tubes
4. Diameter Tapering Dies: 5 pounds at \$1.30/pound = \$6.50
Machining Costs = \$5.00
Total = \$11.50
5. Pointing Dies: 5 dies at \$300/die = \$1500.
Service life - 3000 tubes.

Labor

A. Wall Tapering

1. Production rate: 5 tubes/hour
2. Two men at \$15/hour per man or \$6/tube

B. Pointing

1. Production rate: 4 tubes/hour
2. Two men at \$15/hour per man or \$7.50/tube

C. Diameter Tapering

1. Production rate: 5 tubes/hour
2. Two men at \$15/hour per man or \$6/tube

* \$11 per pound is based on price quoted by Cameron Iron Works for a wrought hollow Ti-6Al-4V alloy extrusion.

TABLE XI. ESTIMATED COSTS FOR PRODUCING Ti-6Al-4V
ROTOR SPAR TUBES BY COLD DRAWING*

		Total Number Finished Spar Tubes		
		1000	5000	10,000
I.	RAW MATERIAL			
	Basic Billet Cost	\$11.00	\$11.00	\$11.00
	Actual Billet Cost (based on 90 percent tube yield)	12.10	12.10	12.10
II.	CONVERSION COSTS			
	A. Tooling	0.17	0.15	0.15
	B. Labor	0.15	0.15	0.15
	C. Vacuum Annealing	2.82	2.82	2.82
	D. Equipment	1.22	0.22	0.11
	E. Installation (25 percent)	0.28	0.05	0.03
	F. Building, \$25/ft ²	1.45	0.39	0.13
III.	TOTAL COSTS, \$/lb	18.17	15.88	15.49
	\$/spar	3,450	3,017	2,943
All costs in dollars per pound.				

D. Inspection and Finishing

1. Production Rate: 5 tubes/hour
2. Three men at \$15/hour per man or \$9/tube

Vacuum Annealing

According to the processing chart in Figure 19, six vacuum anneals are needed to complete processing of finished spars. Based upon cost information obtained from Wolverine Tube, the cost of one vacuum annealing run in their furnace, which has a capacity for three rotor spars, is \$280. The vacuum annealing cycle time is 8 hours.

Equipment

<u>Item</u>	<u>Cost, \$</u>
500-Ton Draw Bench	125,000
250-Ton Hydraulic Pointer	60,000
Handling equipment	15,000
Miscellaneous (pickling tanks, cutoff saws, etc.)	<u>20,000</u>
TOTAL	220,000

The cost data for manufacturing full-size rotor spar tubes by cold drawing are summarized in Table XI as a function of quantity.

SUMMARY OF ESTIMATED MANUFACTURING COSTS

Total estimated costs for producing the full-scale rotor spar tubes by the three processes studied in this program are summarized in Table XII. The costs are given in dollars/pound of finished spar tube and dollars/spar. From these cost estimates, it is apparent that all three techniques have potential for significantly reducing the cost of helicopter rotor spar fabrication. Costs per spar are on the order of \$2700 to \$3500 each, depending upon the process selected. The extrusion plus drawing technique, which is now projected to be slightly less expensive than the other processes, could be reduced even further in cost if a HIP billet could be supplied at a cost less than the current \$11/pound for wrought material.

As indicated earlier, starting with a thick-wall extruded tube to make a titanium spar costs approximately \$21,000 plus an additional \$3300 for machining. Costs projected in this program are on the order of

TABLE XII. SUMMARY OF PROJECTED MANUFACTURING COSTS
FOR PRODUCING Ti-6Al-4V SPAR TUBES BY
THE PROCESSES STUDIED IN THIS PROGRAM*

	HIP	Cold Drawing	Hydrostatic Extrusion and Deformable Die Tapering
\$/lb	17.73	18.17	14.24**
\$/spar	3,363	3,450	2,705

* Manufacturing estimated for producing 1000 spar tubes.

** Billet material and extrusion costs \$12.40/lb. The die tapering portion of the cold drawing costs is \$1.84/lb. Thus, extrusion and die tapering yield a cost of \$14.24.

15 percent of these costs. It is evident that additional work should be done with these processes to further define their specific applicability since (1) HIP material should provide better fatigue properties and (2) techniques examined in this program promise substantial cost savings over those currently used.

RECOMMENDATIONS

The findings of this program have opened up several new alternative routes to fabricating long, tapered spars for helicopter blades. Cost studies conducted on the three processes investigated on this program all suggest that tubes could be made by one or more of these alternative methods at a cost of about 15 percent of that of present methods proposed involving tapered machining of a thick-walled extruded tube.

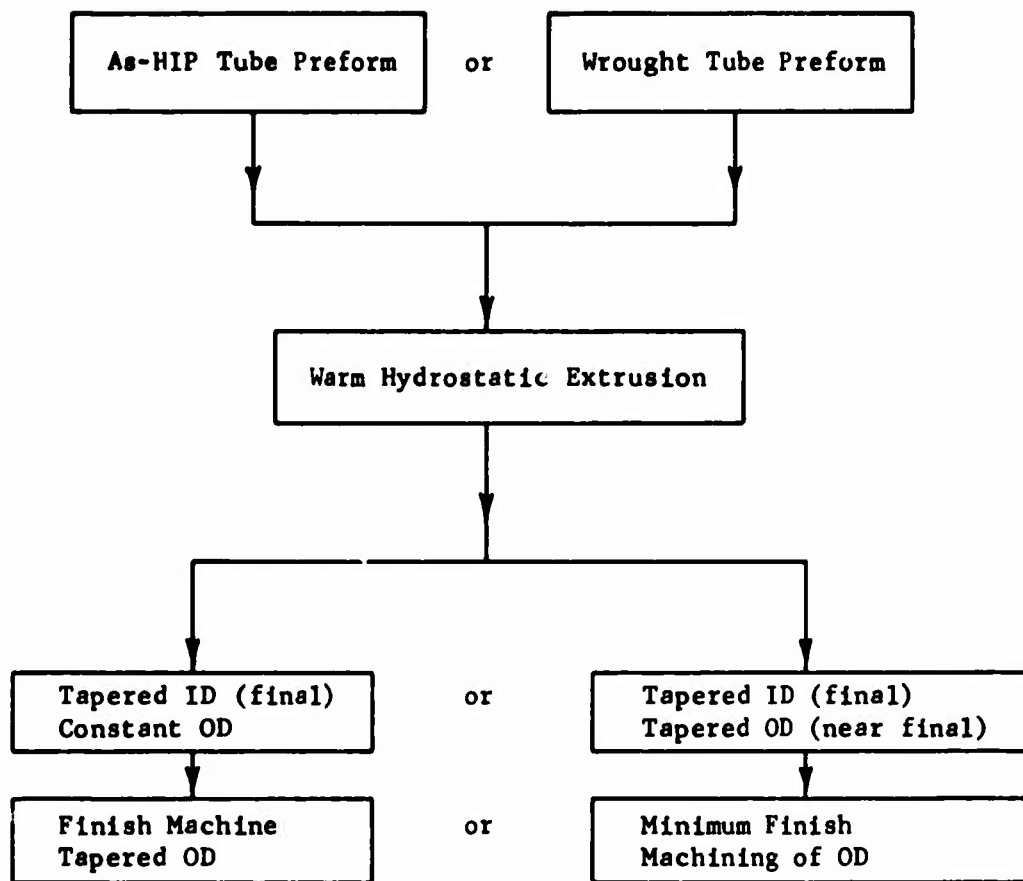
The cost studies done on this program suggest that a HIP tube 32 feet in length can be made at a cost of about \$3000 per spar. First, however, the contamination problem must be resolved and its relationship to fatigue strength fully defined. Also to be resolved is the matter of the ID surface layers and internal cracks which were discovered in the NASA-Langley investigation of fatigue specimens. It is not known whether the cracks found on the ID surface layers were the direct result of fatigue testing or were present beforehand; however, it is apparent that the cause of these cracks must be defined and eliminated if as-HIP material is to be used successfully in this application.

The approach involving hydrostatic extrusion of a tapered tube offers some interesting alternatives and may offer the greatest promise for producing acceptable products at a reasonable cost in a relatively short time period. Recent studies at Battelle on an Air Force-sponsored program have shown that the use of warm hydrostatic extrusion to produce a Ti-6Al-4V tube can be accomplished at an extrusion ratio of at least 4:1 without problems of cracking which have generally plagued cold forming of this particular alloy.

Outlined on the next page is a schematic representation of the processing which shows promise for fabricating either a HIP or a wrought-tube preform into the desired tapered tube.

One process would involve extruding a constant OD/tapered ID tube which would then be either finish machined to produce the tapered OD or deformable-die tapered as was examined in this program. The latter approach, however, seems less than desirable since indications are that this work would likely have to be done at warm temperatures, and its adaptability to a production operation seems questionable. The second approach would involve extruding a canned titanium billet where the OD and ID of the starting preform are tapered, and this taper would be maintained after extrusion. Here, only the minimum of finish machining may be required on the OD.

If a HIP preform were used, the hydrostatic extrusion step done at warm temperatures, perhaps up to about 1400°F, could introduce sufficient shear deformation between particles at an elevated temperature to assure adequate bonding and fatigue strength in the HIP material. Work



referenced elsewhere in this report on forging of powder preforms adds credence to this approach. As indicated earlier, reductions of 4:1 per pass have been obtained on titanium alloy tube extrusions which were done at temperatures of approximately 900°F. By using temperatures on the order of 1400°F, it may be possible to obtain an extrusion ratio of about 10:1. This approach is recommended over that of cold drawing or tube tapering by virtue of the larger single-pass reductions that can be obtained and the potential improvement in fatigue strength.

Hydrostatic warm extrusion is recommended over conventional extrusion because it will:

1. Minimize container and die friction
2. Minimize press tonnage requirements
3. Offer the potential of extruding closer to final dimensions and with better tolerances and surface finishes on the product, thereby minimizing finishing costs related to machining labor and material scrap.

Warm hydrostatic extrusion at the temperatures required is possible by means of Battelle's Hydrafil process. This approach allows the use of hydrostatic techniques on most existing press equipment with a minimum of modification.

Selection of billet material, whether HIP or wrought, would depend on relative mechanical property advantages (especially fatigue strength) and the relative costs of the starting blank. Further studies on HIP materials must be done to assess the relative importance of contaminant particles and the influence of subsequent warm working on fatigue strength and other properties.

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APPENDIX I
FRACTURE TOUGHNESS OF HIP AND HIP
PLUS COLD-WORKED Ti-6Al-4V

Fracture toughness tests were performed by personnel of Wright-Patterson Air Force Base Materials Laboratory on HIP and HIP plus cold-worked Ti-6Al-4V.

The data generated in the fracture toughness testing program are presented in Table XIII. These data were generated as a supplement to the main program to further define the characteristics of HIP Ti-6Al-4V material.

TABLE XIII. FRACTURE TOUGHNESS OF HIP AND HIP PLUS COLD-WORKED Ti-6Al-4V	
Material	Fracture Toughness, K_{Ic} (ksi/in.)
As-HIP Ti-6Al-4V	78-79*
As-HIP Ti-6Al-4V	65-70**
HIP plus cold hydrostatically extruded plus 1400°F - 2 hours annealed***	60-61**
Wrought Ti-6Al-4V	55****
* Compact tension specimens per ASTM requirements. ** Slow-bend Charpy tests per TMR Ronald in AFML-TR-70-311. *** Cold hydrostatically extruded bar stock with 2.5:1 reduction. **** The fracture toughness of wrought Ti-6Al-4V rarely exceeds 55 ksi per inch.	

The data in Table XIII indicate that HIP material has a fracture toughness that is at the high end of the range normally expected in wrought Ti-6Al-4V.

The cold-extruded and annealed HIP material has a lower fracture toughness than the as-HIP material, and this is probably due to a change in the metallurgical structure as compared to as-HIP stock. The "basket-weave" structure of the as-HIP material is well-known for its high fracture toughness. However, the fracture toughness of the cold-extruded and annealed HIP material apparently still compares favorably to that of conventional wrought Ti-6Al-4V stock.

APPENDIX II
SEM STUDY OF FATIGUE SPECIMENS

OBJECTIVE

Cursory scanning electron microscope (SEM) studies were performed on selected fatigue specimens in order to develop an understanding of the nature of the low fatigue life in the HIP product.

PROCEDURE

Four typical fatigue specimens were chosen for SEM study. The specimens are listed in Table XIV.

TABLE XIV. FATIGUE SPECIMENS FOR SEM STUDY			
Specimen Number	Stress Level	Condition	Number of Cycles to Failure
15-B-2	65 ksi	As-HIP at 1750 °F	135,300
15-M-5	100 ksi	As-HIP at 1750 °F	20,300
SF8-1	65 ksi	HIP + 20 percent reduction; annealed 1550 °F, 1 hour	145,700
SF8-3	100 ksi	HIP + 30 percent reduction; annealed 1550 °F, 1 hour	21,700

The fatigue fracture surface was examined with the SEM for the crack-initiation site and for chemical gradients within the specimen.

RESULTS

A tungsten inclusion which was typical of those previously described in this final report was found to be associated with the crack-initiation site in Specimen SF8-1 (see Figure 20). It is interesting to note that this particular specimen possessed the longest fatigue life at 65 ksi of any of the wrought HIP tubing. It is unclear from the limited data available whether the tungsten particle shortened the fatigue life appreciably.

Both as-HIP specimens exhibited crack-initiation sites on the former tubing ID surface. Figure 21 shows the former tubing ID surface of the fatigue specimens and its proximity to the initiation site. Figure 22 shows the former ID surface more clearly and also illustrates a typical crack of the type found on this surface.

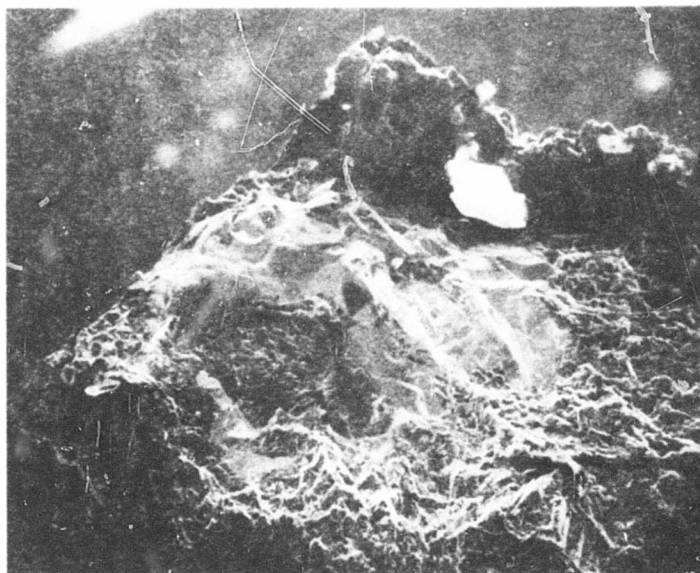
The dimple effect on the ID surface is produced by the spherical powder used to make the tube. The powder particles on the ID surface are forced into the steel ID HIP mandrel during the HIP cycle, and the contour of these particles is preserved during processing. The HIP mandrel is removed by acid leaching without disturbing the dimple pattern.

Several small cracks were found on the ID surface of the specimen. These cracks appeared in the region corresponding to the bond interface between powder particles (valleys). As shown in Figure 22, these cracks follow the valleys of particle interfaces, which suggests that this is a weak or brittle zone.

The SEM data indicated that the particle interfaces on the ID surface were enriched in aluminum and vanadium. Microprobe traces on the particle interfaces inside the ID surface did not yield evidence of abnormal alloy element segregation. This information suggests that the interface of particles near the low-carbon-steel mandrel are weak or brittle. Further, this interface problem may be associated with above-average concentrations of aluminum and/or vanadium. Further studies will be required to define the nature of the interface problem and to develop a processing sequence to eliminate this problem.

DISCUSSION

The impact of the ID cracks on fatigue life of HIP tubing is not readily discerned by analyzing the fatigue data generated in this program. Table XIV shows that the fatigue lives of HIP material containing the ID cracks are not significantly lower than HIP and worked material which does not appear to possess the ID surface cracks. It may be, however,



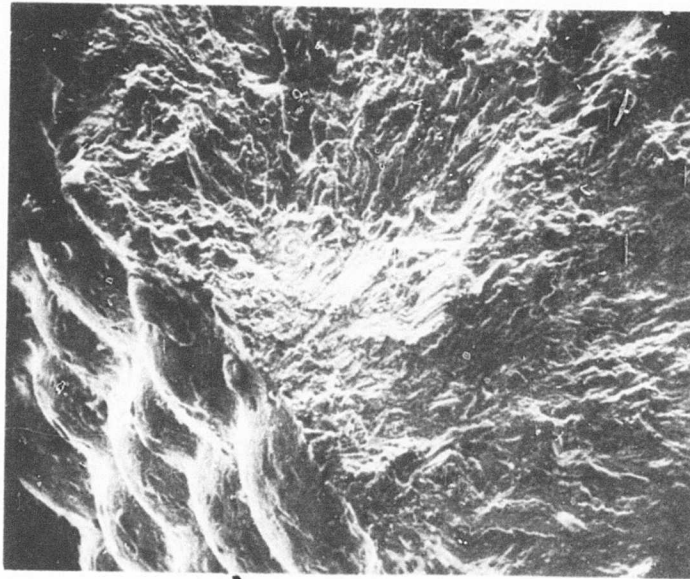
220X



1150X

Note the river marks on the inclusion
shown at 1150X.

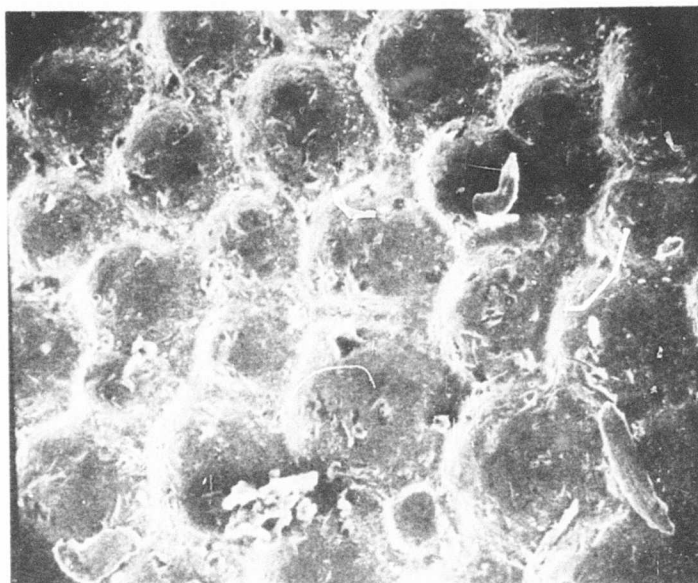
Figure 20. SEM Micrograph of a Tungsten Inclusion on
the Fatigue Surface of Specimen SF8-1.



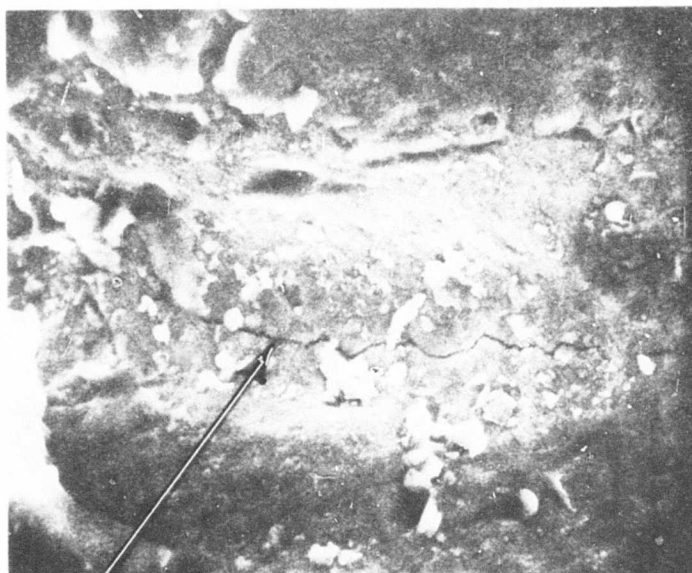
130X

The former ID surface of the tube is on the lower left-hand corner of the micrograph and is oriented almost perpendicular to the plane of the micrograph.

Figure 21. SEM Micrograph of the Fatigue-Initiation Site on Specimen 15M-5.



100X



1025X

Note the crack running along a valley in the surface of the specimen.

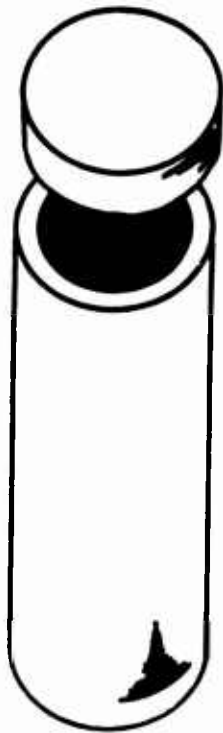
Figure 22. SEM Micrograph of the Former ID Surface of Specimen 15M-5.

that there were surface cracks on the ID of the worked material and that they were not as readily detected in this cursory SEM evaluation. These points will have to be evaluated in future experiments.

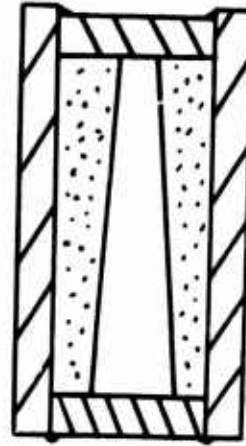
APPENDIX III
DESCRIPTION OF HOT ISOSTATIC PRESSING (HIP)

The hot isostatic pressing process uses isostatic gas pressure at high temperatures for the compaction of metal powders. Initially, the metal powder is vibratorily compacted in a thin-walled metallic container which may contain a core mandrel. The core mandrel and metallic container form the shape of the desired HIP part. After the powder is loaded, the container is evacuated, sealed, and placed in a gas-pressure vessel (autoclave). The autoclave is pressurized with an inert gas (helium) and heated to the desired temperature by either an external or an internal heater. The pressurized gas exerts an isostatic compressive force on all surfaces of the metallic container and its contents, resulting in a more uniform and controlled compaction of the metal powder than that achievable by any other method. The use of inert gas pressure at high temperature also promotes solid-state self-bonding of the metal powder. Consequently, metal powders may be consolidated by HIP into parts with 100 percent density and uniform mechanical properties throughout the part thickness and length.

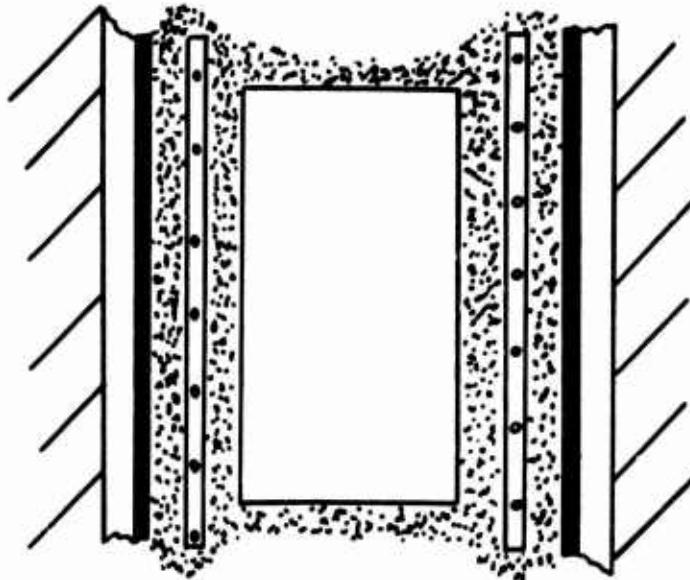
Figure 23 illustrates the basic steps involved in hot isostatic pressing.



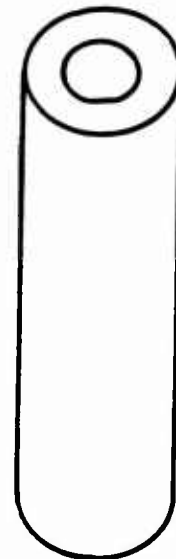
a. Metallic Container Fabricated To Fit Formed Parts



b. Sealed Container With Core Mandrel and Vibratorily Compacted Metal Powder



c. HIP in Gas-Pressure Vessel (Autoclave)



d. Consolidated Part With Container and Core Mandrel Removed

Figure 23. Sequence Used in Hot Isostatic Pressing Process.

APPENDIX IV
PROCEDURE FOR FABRICATING HIP TUBE PREFORMS

The general procedure for the production of the HIP Ti-6Al-4V preforms is as follows:

1. The mild-steel HIP tooling was vapor blasted and rinsed in 200 proof alcohol.
2. The bottom end plug was Tig welded to the HIP can.
3. The welded can was vacuum outgassed at 1750°F for 1 hour at 10^{-5} torr.
4. The OD surfaces of the core mandrels were carburized to retard diffusion of iron into the Ti-6Al-4V powder during the HIP cycle.
5. The mandrel was inserted in the can with the bottom of the mandrel resting in the counterbore of the bottom end plug. The HIP can and core mandrel together form the shape of the desired as-HIP preforms.
6. The -40 mesh Ti-6Al-4V powder was vibratorily compacted in the HIP can.
7. The loaded cans were sealed under vacuum by electron-beam welding.
8. The cans were helium leak checked at 400 psi pressure.
9. The sealed cans were hot isostatically pressed at 1750°F for 3 hours at 10,000 psi pressure.

The assembled tooling used for the production of the HIP preforms required for all of the tasks of this program is shown schematically in Figure 24. The cans and mandrels were removed from the as-HIP preforms by pickling in a solution of 20 percent nitric acid at 150°F. Passivated layers of steel which remained on the ID of the Ti-6Al-4V preforms were removed with a solution of 1.7 percent hydrofluoric acid and 40 percent nitric acid at 140°F. The ratio of HNO_3 to HF was maintained at 23:1 in order to minimize hydrogen pickup by the Ti-6Al-4V preforms during pickling.

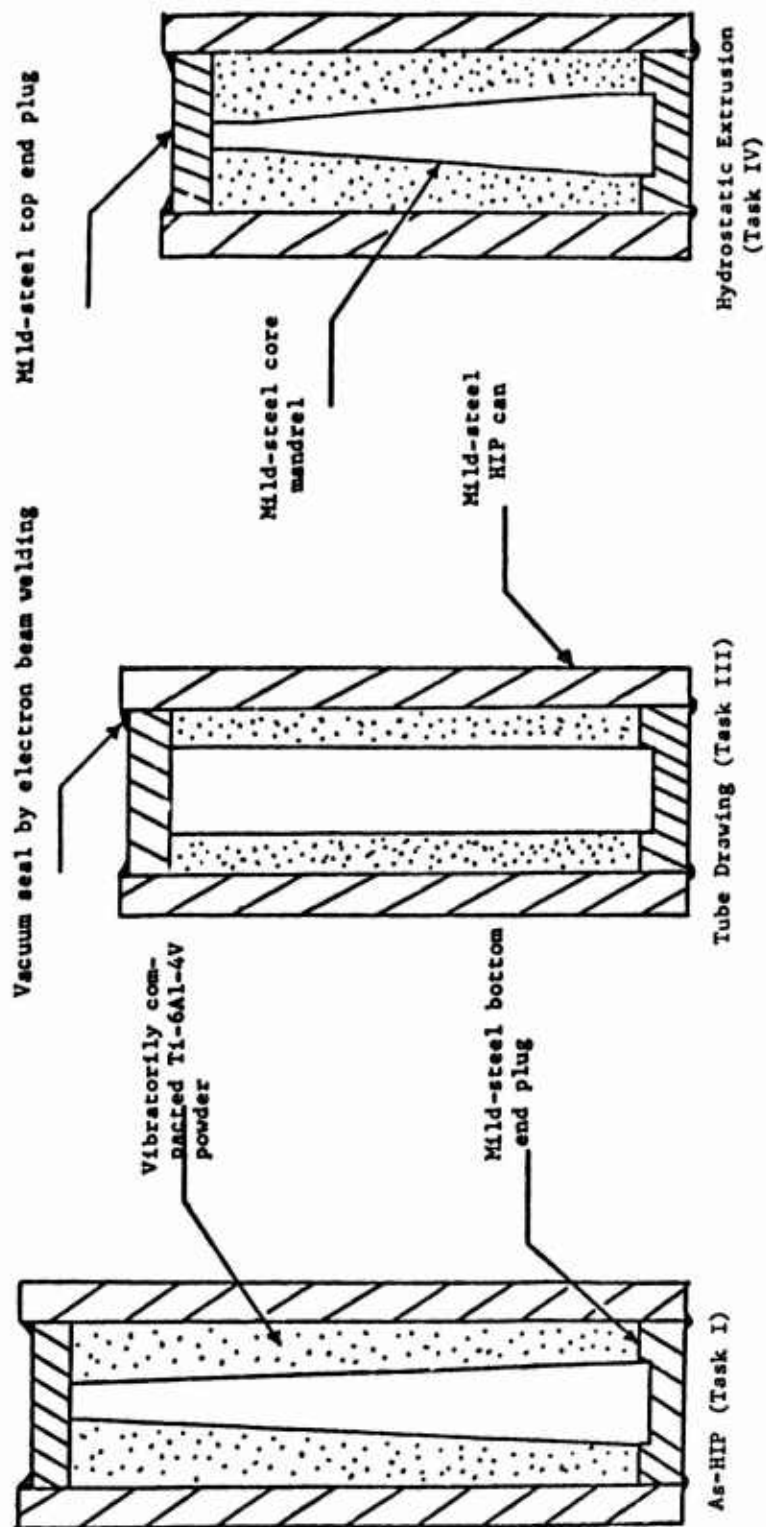


Figure 24. Assembled Tooling for the Production of HIP Ti-6Al-4V Preforms.

APPENDIX V

DESCRIPTION OF HYDROSTATIC EXTRUSION PROCESS

Hydrostatic extrusion differs from conventional forward extrusion in that a fluid surrounds the billet so there is no contact between the billet and container, nor between the billet and ram. The fluid which is pressurized for extrusion essentially eliminates friction between the billet and extrusion container by preventing billet upsetting against the container wall. This pressurized fluid also acts at the billet-die interface to reduce die friction. Reduced friction means that significant billet reductions can be taken at room temperature and all the benefits of cold working can be obtained. Further, improved lubrication at the die permits the use of relatively smaller angle dies, which, in turn, results in less redundant work (useless deformation that does not contribute to the final shape). Lower die friction and reduced redundant work result in less shear deformation at the surface of the extrusion, and thus the potential exists for greater deformation during extrusion than can be achieved by conventional cold extrusion. The features of the process are described in detail elsewhere.^{4,5,6}

EXTRUSION TOOLING

Experimental trials were conducted in a hydrostatic extrusion tooling which was designed and constructed at Battelle-Columbus on an Air Force Materials Laboratory program, Contract AF33(615)-1390. A cross section of the container and its associated tooling are shown in Figure 25. The container is of four-ring construction and has a 2-3/8-inch-diameter by 20-inch-long bore. It was designed for use at fluid pressures up to 250,000 psi at room temperature and up to 225,000 psi at 500°F. Complete design details of this tooling are given in Reference 4. This tooling was used in Battelle's 700-ton vertical hydraulic press.

MANDREL AND DIE ARRANGEMENT

The mandrel and die arrangement employed in this program is shown schematically in Figure 26. The mandrel collar or guide rests on the back of the billet and moves with the billet during extrusion. The fluid is free to flow past the mandrel guide to surround the billet OD, but the interface between the billet and mandrel collar acts as a seal

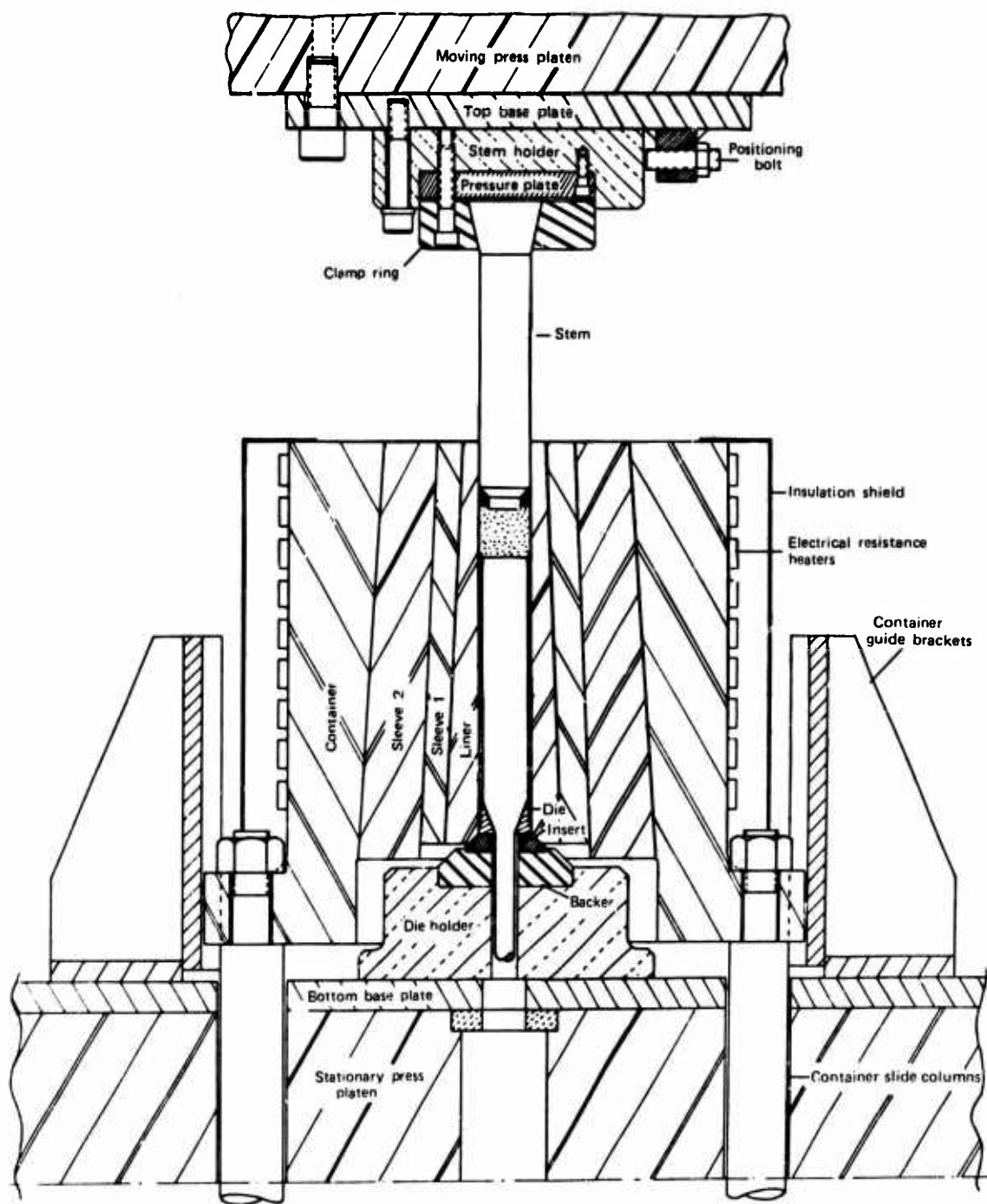


Figure 25. Hydrostatic Extrusion Tooling Used in This Program.

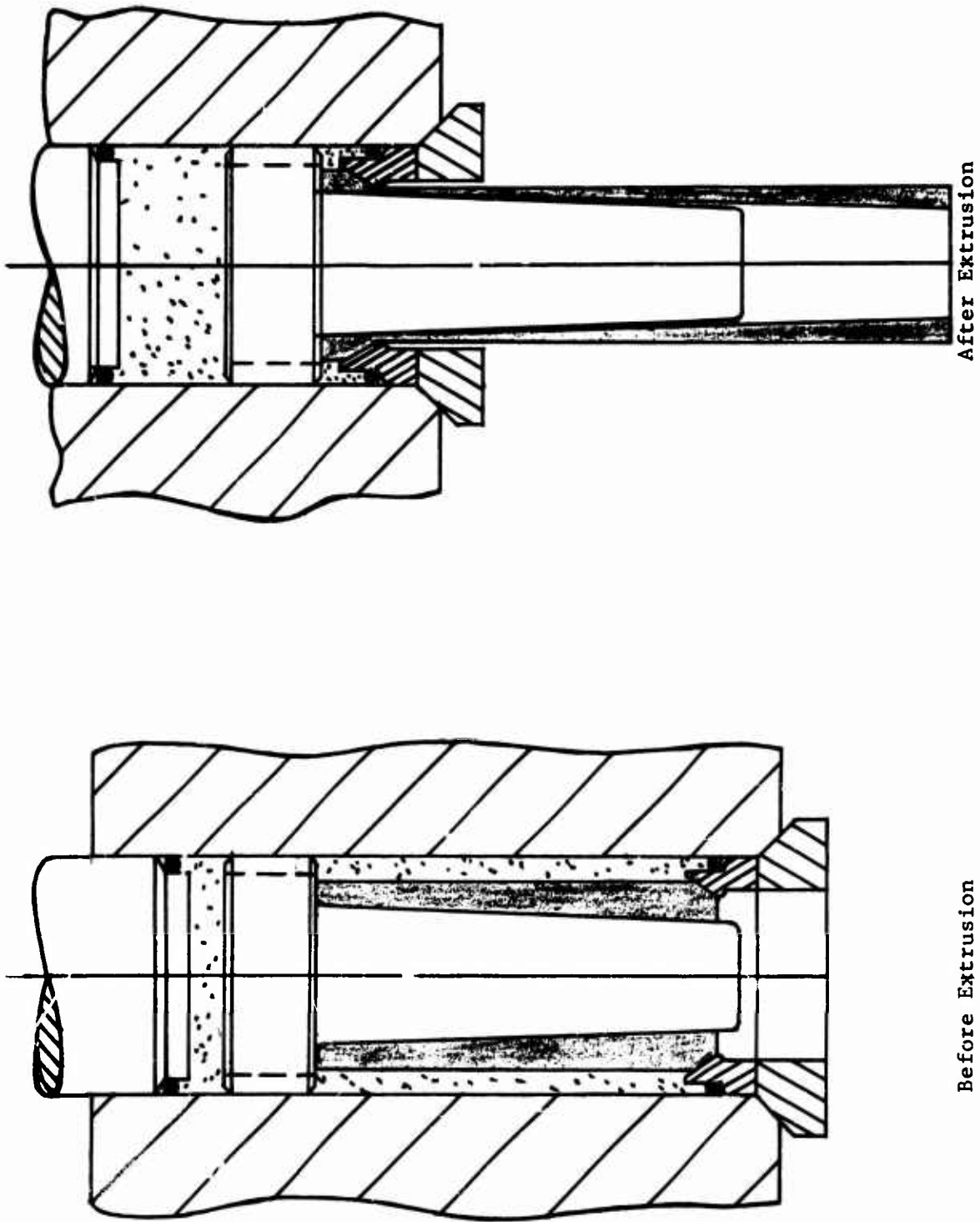


Figure 26. Technique for Hydrostatic Extrusion of Tapered-Wall Tubes.

to prevent fluid leaking past the mandrel. This floating mandrel design results in an end pressure on the billet greater than that of the fluid pressure. This augmentation effect occurs because of differences in surface area between the end of the mandrel and the tube billet. In this program, the augmentation factor was typically 3.4 for a given press load; that is, if the fluid pressure was 10,000 psi, the billet-end pressure would be 34,000 psi. This augmentation factor was relatively high and can cause the tube billet to upset ahead of the die.

With the tapered mandrel used in this program, the extrusion ratio is progressively increased as the billet passes through the die. This change in extrusion ratio (original/final area) was quite significant. In one case, the extrusion ratio was 1.8:1 at the beginning of extrusion and 2.5:1 near the end of the stroke.

The extrusion dies used in all of the trials were manufactured from AISI-A6 tool steel. The semiangle of each die was typically 22-1/2 degrees; although in one trial, a 30-degree semiangle die was used without a noticeable difference. The die-entry surfaces and bearings were polished to a 4- to 6-microinch finish.

APPENDIX VI

DIE TAPERING PROCESSES

Two die tapering techniques were used in tube drawing experiments. The first involved the use of a rigid draw die in combination with the tapered mandrel to produce a fixed-OD tube with varying wall thickness as shown in Figure 27. The second technique involved use of a deformable die, also with tapered mandrel to taper the OD of the tapered wall tubes produced with the rigid die.

The deformable-die process is basically simple and can be performed on a conventional tube draw bench. The deformable-die technique is shown schematically in Figure 28. The workpiece is pointed on one end, telescoped over a tapered mandrel, and then drawn through a soft deformable metal die. In this program, the titanium tubes were tapered with dies made of yellow brass. As the workpiece moves through the die, the tapered mandrel forces the die to enlarge as it moves up to taper. The circumferential pressure of the die forms the tube onto the mandrel. After tapering, the mandrel is removed from the tube by supporting the tube end with a stripping die. The mandrel is then gripped on one end and simply pulled out of the tube.

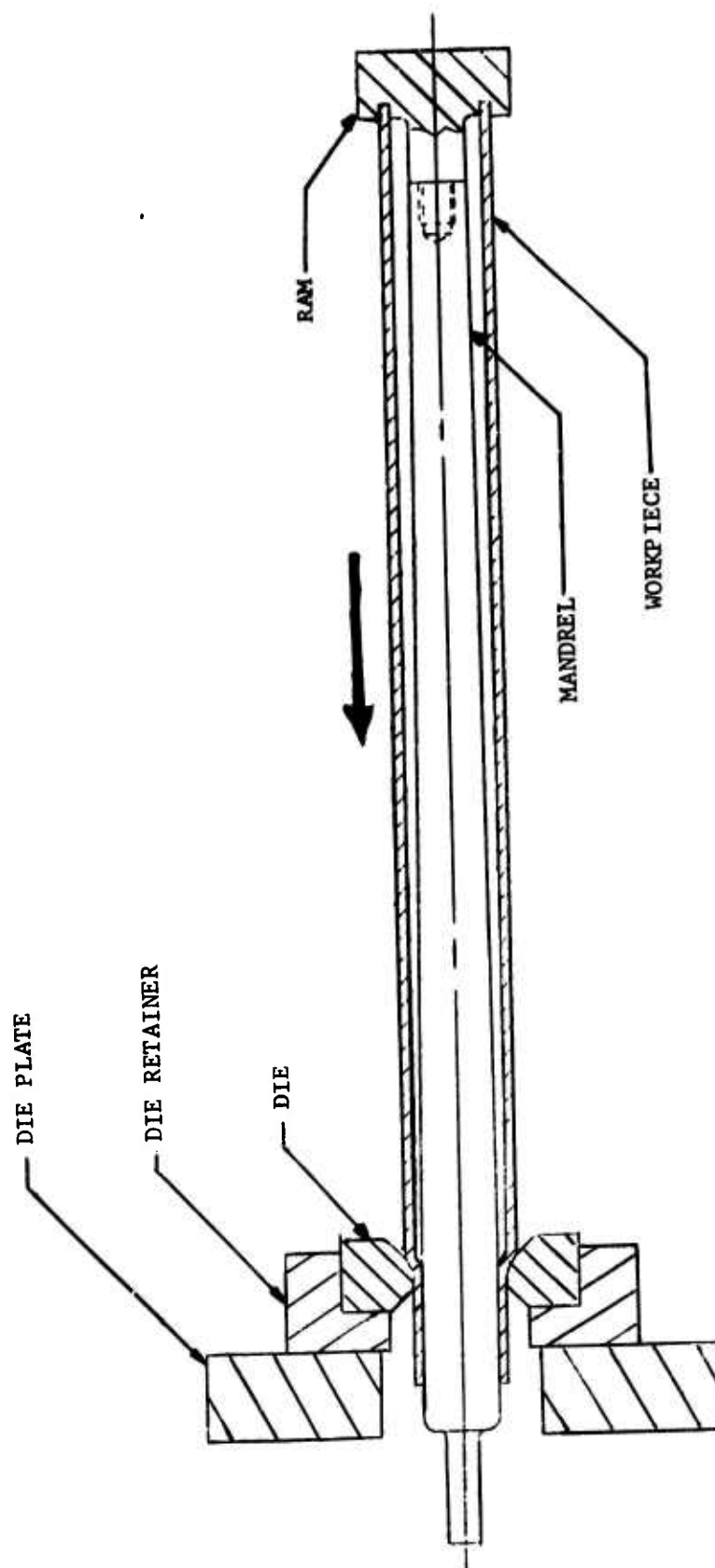


Figure 27. Tooling Arrangement for Wall Tapering With Rigid Die.

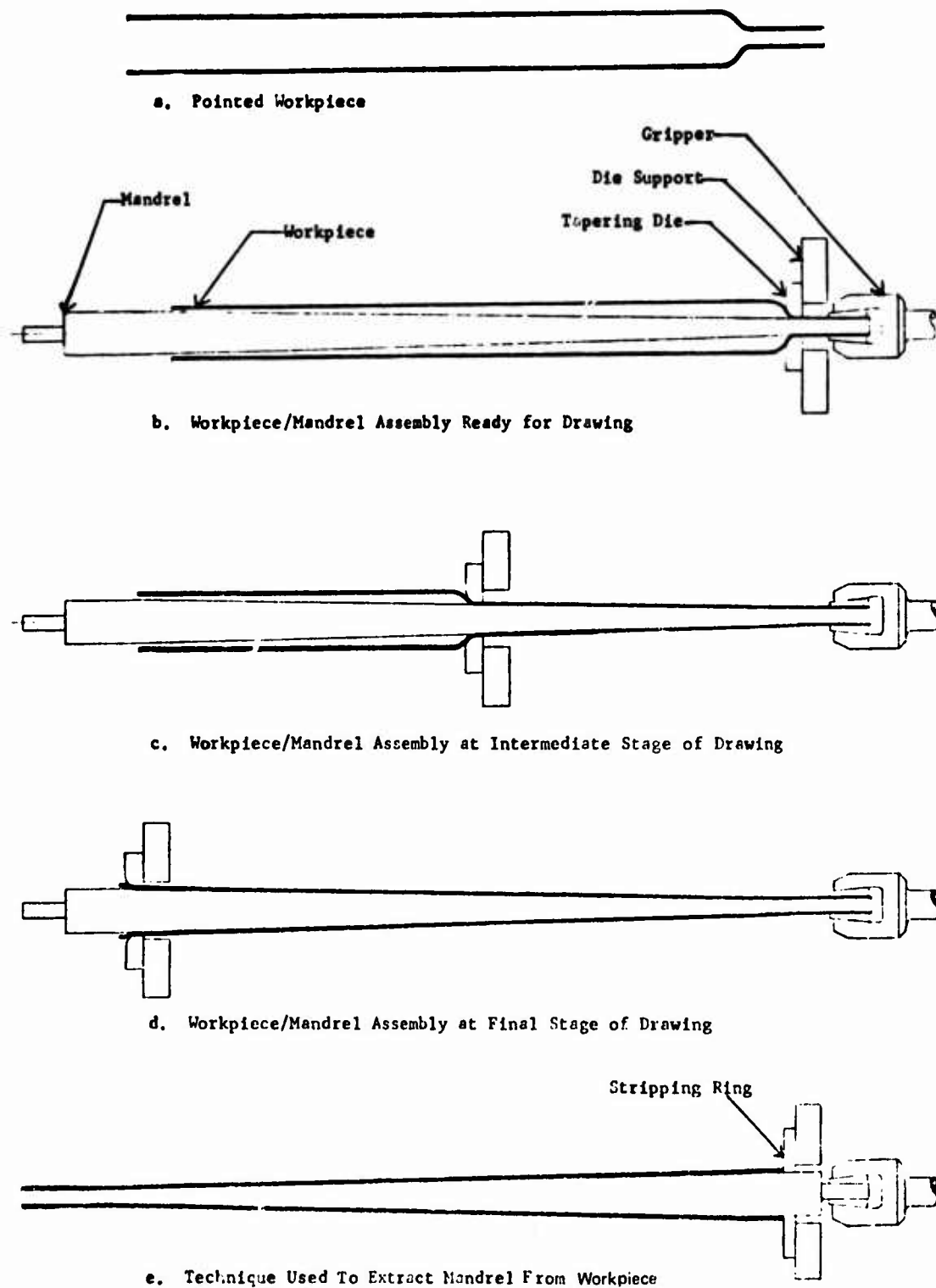


Figure 28. Deformable-Die Tapering Technique.