Apr 1st, 8:00 AM

Advanced Beryllium Gyro Technology

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ADVANCED BERYLLIUM GYRO-MATERIALS TECHNOLOGY

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Summary

This paper describes the process developed for fabricating beryllium gyro components by hot isostatic pressing. Five different components, an inner gimbal, a gyro sleeve, an accelerometer sleeve, an inner cylinder, and an inner cylinder cover, were fabricated. Although the process varied somewhat for each type of specimen, it consisted primarily of vibratory packing, hydrostatic pressing, hot isostatic pressing, and leaching. Since the most challenging component to be fabricated was the inner gimbal, this paper is devoted primarily to the process development of this particular component.

Two key developments associated with the fabrication of the inner gimbal were the use of a deformable mandrel and the use of a new type of pressure-transmitting medium. The use of a porous copper mandrel allowed even deformation of the preform during cold hydropressing and, as a result, very accurate pressings could be made. A sodium chloride pressure-transmitting layer around the green compact allowed sealing of the irregular shape in a cylindrical pressing container.

A discussion of mechanical properties of the as-pressed material is included. Also, a brief discussion of equipment limitations, yields, material savings, and relative economics of this process are given. Adaptability of this process for fabricating other beryllium aerospace hardware components is covered.

Introduction and Background

Beryllium is considered for gyro applications because of its low specific weight (1.86 g/cc or 0.067 lb/in.^{3}) and relatively high microyield stress (MYS = 2,000-8,000 psi, depending upon the grade of material). This combination of properties allows the fabrication of lightweight gyro components for flight applications. The current state of the art does not allow casting of beryllium shapes because of excessive grain size in castings.[1] Therefore, only powder-metallurgical forms of beryllium can be used for these applications. The beryllium crystal is greatly anisotropic and wrought forms can show anisotropy of mechanical and physical properties.[2] Therefore, these forms of beryllium are generally unsatisfactory for precision applications.

Currently, the most common practice for forming beryllium gyro components is to machine them from vacuum-hot-pressed block. This form of beryllium is relatively isotropic (there is a slight preferred orientation perpendicular to the pressing direction) and is immediately available in most grades. However, this type of processing can be relatively expensive as a result of both the lengthy machining time and the high scrap losses. Beryllium is moderately difficult to machine, and the resultant machining times are relatively longer than those for more common structural materials. Since the parts are hogged from solid block, material utilization is poor and the overall cost is thus increased.

A second economic factor is associated with porosity and inclusions. The occurrence of either type of these microstructural defects in a super-finished surface will result in rejection of the component. Since super finishing is normally the final step of the operation, rejection at this point will result in loss of the full cost of the component. Inclusion content and size is a function of the metallurgical processing and can be controlled (or at least detected by radiographic techniques). On the other hand, porosity large enough to destroy an air-bearing surface cannot be readily detected by current nondestructive testing techniques.

Various approaches have been considered to lower the cost and increase the reliability of beryllium gyro components. Casting has been shown not to be feasible because of the relatively large grain size (and poor mechanical properties) and because of reaction with mold and core materials.[1] Both slip casting[3] and hydropressing[4] have been shown as feasible techniques to preform complex beryllium shapes for sintering. These methods provide for better material utilization by decreasing the amount of machining required on a complex configuration. Residual porosity in a sintered body however, would not allow super finishing of a bearing surface.

In an effort to lower the cost of beryllium components used in the Saturn guidance system, NASA-Marshall Space Flight Center sponsored a program at Battelle to investigate hot isostatic pressing (HIP) for fabricating such components. One of the major problems in producing air-bearing components for this package was rejection due to residual porosity in bearing surfaces. This is less of a problem with present beryllium because it is better understood by manufacturers and users. Since various grades of beryllium powder have been HIP to full theoretical density,[5] it was felt that rejection of finished parts, because of porosity, could be eliminated. HIP also could provide a means for pressing components to near-finished shape,[6] thus minimizing costs associated with machining and scrap loss. Further, beryllium consolidated by HIP has shown considerably higher strength (including MYS) than a comparable grade of vacuum-hot-pressed beryllium.[7] The isotropic nature of pressure application could possibly provide lower levels of residual stress and anisotropy.

The HIP process[8] uses a combination of gas pressure and high temperature to compact powders. The parts to be pressed are preformed by cold hydrostatic pressing. After preforming, the parts are assembled in thin-walled mild steel containers and hot dynamically outgassed prior to sealing. Then, the specimens are loaded into a cold-wall autoclave and densified under high temperature and gas pressure. After densification, the containers and internal mandrels are selectively leached from the finished part.

Fabrication of Gyro Components

During the course of this study, five different components were fabricated. Of these, four were relatively small and simple: a gyro sleeve, an accelerometer sleeve, an inner cylinder, and an inner-cylinder cover. These components have been discussed in a previous paper[6] but many of the principles used for fabricating the fifth, more complex component, an inner gimbal, were proven on these components. Although primary emphasis is placed on the inner gimbal, a brief discussion of the other components is in order for this presentation.

Inner Gimbal

The inner gimbal is the most complex of the components fabricated on this study both from the standpoint of size and geometry. The objective of this study was to make a minimum weight blank from which the specimen shown in Figure 1 could be machined. Development of the procedure to fabricate this component included hydropressing studies, mandrel development, and container studies. Principles proven on the smaller air-bearing components were applied.

The basic machining blank was designed to be approximately 19 lb, as compared with the 40-lb billet necessary for machining from hot-pressed block. Overall dimensions were designed to allow approximately 1/8-in. cleanup over the maximum point on all surfaces. Major cutouts which would have to be hogged out of the surface were integrally pressed. Also, five of the six internal cylindrical cavities were pressed into the finished blank. Much of the fine detail could be more economically reproduced by machining than by pressing.

Hydropressing Studies. The hydropressing approach considered required the development of unique techniques not previously employed. The basic approach consisted of preforming the rubber hydropressing bag into a fixed vacuum canister that defined the outer surface of the part. Internal cavities were formed by placing mandrels at predetermined points with respect to reference planes on the surfaces of the loading fixture. As the loading cavity was filled, additional mandrels were "laid up" in the beryllium-powder fill much as a sand-casting mold is constructed. Finally, the top closure was put in the hydropressing bag and the entire assembly was cold pressed.

The loading cavity was calculated from the final shape of the part. Since pressure is applied hydrostatically in both the cold- and hot-pressing steps, we assume that deformation of the powder compact occurs isotropically, or proportionally in all directions. The volume of the pressing at the start of pressing (either hot or cold isostatic) relative to the final volume is inversely proportional to the densities:

$$\frac{V_i}{V_f} = \frac{\rho_f}{\rho_i} \tag{1}$$

where

V_i = initial volume
V_f = final density
ρ_i = initial density
ρ_f = final density.

The volume is defined by three orthogonal axes, l, w, and t, so:

$$\frac{V_i}{V_f} = \frac{l_i w_i t_i}{l_f w_f t_f} \; . \tag{2}$$

If isotropic deformation does occur, the orthogonal axes, as well as any dimension (x), deform proportionally. Therefore,

$$\frac{l_i}{l_f} = \frac{w_i}{w_f} = \frac{t_i}{t_f} = \frac{x_i}{x_f} \; . \tag{3}$$

Substituting, we have

$$\frac{V_i}{V_f} = \frac{x_i^3}{x_f^3} = \frac{\rho_i}{\rho_f} \; , \tag{4}$$

or,

$$x_f = x_i \sqrt[3]{\rho_i/\rho_f} \; . \tag{5}$$

This formula can be used to predict the behavior of any powder compact densifying isotropically, and was shown to be accurate within 1 percent in the case under discussion.

After the basic machining blank for the inner gimbal was designed, the size of the loading cavity was calculated. Since the packing density of the beryllium powder was experimentally determined to be 57 percent of theoretical, the following empirical relationship was derived:

$$x_{fill} = x_{final} \sqrt[3]{100/57} = 1.20 \, x_{final} . \tag{6}$$

Based on this relationship, the loading fixture was fabricated from 1/8-in. cold-rolled mild steel sheet. Figure 2 shows the loading canister with the rubber hydropressing bag stretched into position by reducing the pressure between the bag and the form. This accurately fixed the shape of the bag.

Using the same relationship, the mandrels to form the cavities placed on the base plate were accurately placed as shown in Figure 2. Then, the cavity was partially filled with powder and additional mandrels were located as shown in Figure 3. Finally, the cavity was completely filled and the end closure inserted. After closure, the powder fill was de-aired. Then the assembly was removed from the loading fixture as shown in Figure 4 for hydropressing. Once the assembly has been de-aired air pressure holds the powder fill in its exact shape and the specimen can be safely handled with reasonable care. The part is then inserted directly into the hydropress for pressing.

Mandrel Development. As previously mentioned, copper mandrels were shown to be most satisfactory for fabricating these types of components because of the compatabiltiy of the thermal expansion differential. The first pressing was made using solid copper as the mandrel material. Because of the uneven deformation caused by these irregularly spaced mandrels, extremely uneven deformation of the part was experienced. Several large cracks were noted in the compacted powder, appraently caused by the inability of the beryllium powder to deform evenly because of the restriction of the mandrels. It should be noted at this point that the use of multiple solid mandrels is not impossible. Grids have been successfully fabricated in this manner by spacing the mandrels evenly so that uniform densification of the powder fill was not restricted.

In order to prevent the uneven deformation caused by the solid mandrels, it was decided to substitute a porous body of the same density as the vibratory packing of the part. The thought was to use a mandrel which would densify at approximately the same rate as the powder fill, thereby giving even densification of the compact. Several techniques to form these porous bodies were considered. The porous mandrels had to have sufficient strength to prevent any flaking of the copper which could mix with the beryllium during loading and contaminate the part. Green pressing and pressureless sintering were the methods considered. Green pressing alone was generally unsatisfactory because the green strength of the copper powders investigated was very poor in the 60-percent density range. As a result, pressureless sintering was used to form the mandrels.

Sintering at 1700 F for 3 hours produced the range of density required for these components. Pressureless sintering was chosen because the powder can be vibratory packed into the sintering molds and the mandrels sintered to near-finished shape. The sintered bodies were machined to finished size very readily and no contamination of the beryllium was experienced from loose copper particles.

Figure 5 shows a hydropressed preform made with porous copper mandrels. It can be noted that the part deformed very uniformly. The copper appeared to deform only slightly more than the beryllium during the cold-pressing step. This caused a slight dishing on the face of the mandrels. Regardless of this, the overall dimensions of the green pressing were within 1 percent of the predicted values. The technique as described thus provided a means for fabricating a sound green-pressed body of predictable dimensions.

Hot Isostatic Pressing. After cold hydropressing, the specimens were loaded into a mild steel hydropressing container, hot dynamically outgassed, and HIP. The container was stripped from the parts and the mandrels were selectively leached from the compact. Major problems associated with the HIP were in container design and fabrication.

Initially, it was felt that a container that would conform to the exterior surface of the pressing could be fabricated from sheet-metal components. However, attempts to make a leak-free container were unsuccessful. At about this time in the development schedule, the sodium chloride pressure-transmitting layer was shown to be a satisfactory technique for fabricating the smaller components. Since the form-fitting container appeared to be unfeasible, it was decided to apply the pressure-transmitter technique to the large inner-gimbal fabrication. If this was successful, the parts could be HIP in a cylindrical container, thereby decreasing the cost of processing by increasing reliability and decreasing the cost of container fabrication.

To provide even packing, the sodium chloride was hydropressed around the preformed beryllium part. This provided a high density in the sodium chloride so the container would undergo a minimum of deformation. Figure 6 illustrates an actual container which has undergone the compaction step. The dished end-plug configuration provides for ease of welding to the thin-gage container. The entire volume of the container not occupied by the specimen was filled with sodium chloride.

After the HIP operation, the container was mechanically stripped from the part and the sodium chloride was dissolved in cold water. The copper mandrels were removed by leaching in concentrated nitric acid. Figure 7 shows a fully dense inner-gimbal machining blank. From a blank of this type, the finished inner gimbal shown in Figure 1 was machined.

Air-Bearing Components

Mandrel Design. The inner cylinder is representative of a hollow, thin-walled component with a detailed inner geometry as shown in Figure 8. A later design used a hemispherical radius in the bottom of the cavity; the method for forming both designs was essentially the same. Since both nickel and copper are selectively leachable in nitric acid, each was considered as mandrel materials. Nickel, because of its smaller thermal-expansion coefficient, can cause cracking of larger shapes. Ultimately, copper was used because it has a larger thermal-expansion coefficient, which causes the part to draw away during cooling. The extensive diffusion reaction which occurs during pressing is leachable and is eliminated during mandrel removal.

Since the completion of this program, techniques have been developed for mechanical extraction of the mandrel. Hollow shapes have been pressed on austenitic stainless steel (both Types 304 and 316). The slightly higher thermal-expansion coefficient of the stainless steels allows separation of the mandrel after pressing. Alumina has been used as a layer to promote parting. A slight draft is required for mechanical removal in order that the mandrel will clear the part. Right circular cylinders approximately 12 in. in diameter by 3/8-in. wall by 12 in. long have been removed from a mandrel having only 1/2-degree draft.

Pressure-Transmitting Layer. Some of the components, such as the gyro sleeve shown in in Figure 9, had protrusions on the external surface which would have made fabrication of a container extremely difficult if not impossible. To simplify container design, a pressure-transmitting layer was used around the preformed part shown in Figure 10. The bore of the part was supported by a leachable copper mandrel.

Sodium chloride was selected as a pressure transmitter because of its compatibility with the beryllium, its plasticity at the HIP temperature, and its ease of removal. The sodium chloride was lightly pressed into place and the entire composite was loaded into a simple cylindrical container. After densification it was noted that there was no infiltration of the salt into the beryllium compact and no apparent reaction. Since it was shown that the use of sodium chloride as a pressure transmitter was feasible, the range of geometries which could be economically fabricated by HIP was increased.

Self-Bonding of Powder Compacts. The accelerometer sleeve shown in Figure 11 represents another problem associated with complex geometries. The trunnions protruding from the external surface of the basic cylinder were first green pressed independently and then simultaneously densified and bonded to the basic cylinder. The fully densified machining blank is shown in Figure 12. Metallographic examination of the joint revealed no trace of the original bond interface, which had parent material strength. This is further supported by tensile specimens prepared from two butt-bonded green-pressed rods which demonstrated parent-material strength. Not only does this allow building up complex shapes from simple geometries, but it also indicates that cracks in preforms will heal during the HIP operation.

Properties of HIP Beryllium

Improved machinability and increased yield were of primary concern for these particular components. Although not a prime concern for these components, mechanical properties of HIP beryllium are considerably higher than those of comparable chemical grades of vacuum-hot-pressed block. Both the micro and macro yield points are noticably higher.

Machining Characteristics. No actual measurements were made of the ease of machining these components. As a rule, however, the machinists doing the work commented that these components appeared to machine more easily than vacuum-hot-pressed block. Certainly, practical experience would dictate that beryllium processed in this manner would be at least as machinable as comparable grades of vacuum-hot-pressed block.

The most significant feature is the machining yield experienced with the various components machined. In one machining order for 12 air-bearing components, only one component was rejected for porosity on an air-bearing surface. The source of this porosity was not clear. Since none of the others displayed this microstructural porosity, it is possible that this was surface porosity from etching the copper mandrel. There were no other rejections of components due to porosity on bearing surfaces in earlier prototype specimens machined at MSFC. The yield is significantly better than that experienced with conventional vacuum-hot-pressed block.

Mechanical Properties. Mechanical properties were of only minor concern in this particular study since fabrication development was the primary objective. However, mechanical properties have been developed from other programs and are significant within the framework of this paper. In general, the mechanical properties of HIP beryllium are at least 40 percent greater than those of conventionally processed beryllium.

Table 1 lists typical properties achieved with HIP beryllium, and compares them with those of commercial grades of hot-pressed block beryllium. In all cases, it can be seen that HIP beryllium displays properties well above the minimum guaranteed level of the commercial material. Most significant from the standpoint of gyro and other stable elements is the fact that the MYS is significantly increased by HIP processing. This could allow a greater flexibility in design of components fabricated by HIP.

The exact mechanism of the increased strength in HIP beryllium is not fully understood. Certainly the fact that this material has a higher density and finer grain size than conventional material contributes to this strengthening. The lower temperature of compaction also contributes to a finer dispersion of microconstituents. As compaction temperature is raised, the properties tend toward the more conventional material. This mechanism is under further study. Full understanding of this mechanism would offer the potential of tailoring a material to a given strength requirement.

Potential Applications

This program demonstrated that high-reliability beryllium can be fabricated by HIP for making gyro components. Rejection rate was very low for components machined from this type of material. Pressing of complex configurations offers the potential of further savings by minimizing machining time and scrap losses. Indications are that high-strength materials can be produced by this technique, which could lead to lighter designs in flyable structures. The prospect for lower anistropy can offer more accuracy in instruments fabricated from this material.

In addition to the components described in this paper, many other components have been fabricated by this process. For example, blanks for mirrors have been pressed with the internal grid made integrally. Seamless bottles, rings, and cones have also been pressed from beryllium. The process appears directly applicable to beryllium-nozzle fabrication, although there have been no actual pressings from beryllium.

Size is somewhat of a problem with existing equipment. For example, in the experimental equipment at Battelle, beryllium pressings are made in a furnace 18 in. in diameter by 60 in. long. Slightly larger pieces of equipment are currently available. However, it is entirely feasible within current pressure-vessel technology to design and construct vessels in which pressings up to 10 ft in diameter could be made.

TABLE 1. MECHANICAL PROPERTIES OF VARIOUS GRADES OF BERYLLIUM

Grade	Process	Mechanical Properties MYS, offset 10^{-6}, in./in. ksi	TYS, offset 0.002 in./in. ksi	UTS, ksi	El, %
NP-50/P-8	HIP[(a)]		43	59	1.4
	VHP[(b)]		25	35	1
SP-100/P-12	HIP	4.2	54	64	1.3
	VHP		27	35	1
SP-200/P-20	HIP	6.4	60	70	1.4
	VHP	4	30	40	1
I-400/P-40	HIP	14.4	--	90	<1
	VHP	8		50	

(a) Hot isostatically pressed, typical properties
(b) Vacuum hot pressed, properties given are minimum guaranteed

Acknowledgements

The authors wish to acknowledge The National Aeronautics and Space Administration-Marshall Space Flight Center for their support of this program. The advice and encouragement of Mr. Richard H. Tuggle of the Astrionics Laboratory who monitored this program is especially appreciated.

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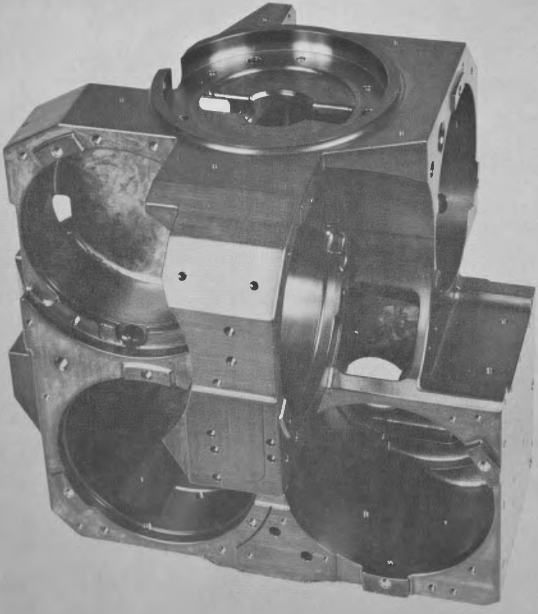

FIGURE 1. INNER GIMBAL AFTER FINAL MACHINING

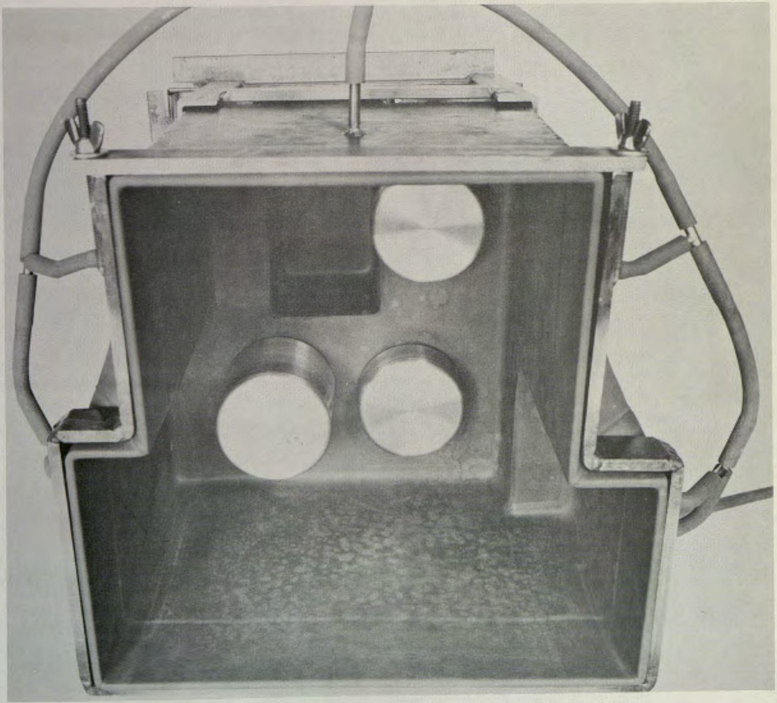

FIGURE 2. POWDER-LOADING FORM WITH RUBBER HYDROPRESSING BAG HELD IN PLACE BY VACUUM

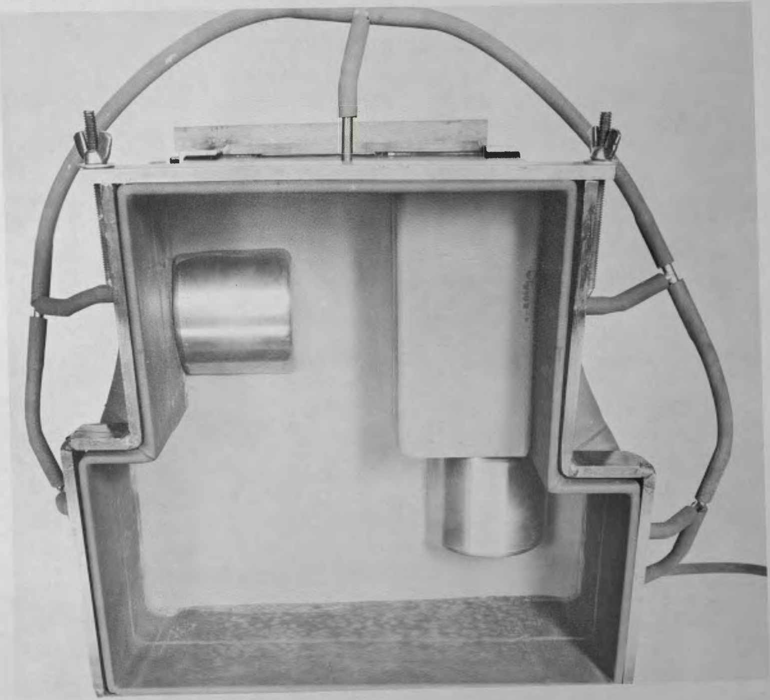

FIGURE 3. LOADING CAVITY PARTIALLY FILLED WITH POWDER

FIGURE 4. HYDROPRESSING SPECIMEN AFTER REMOVAL FROM THE STEEL BACKUP

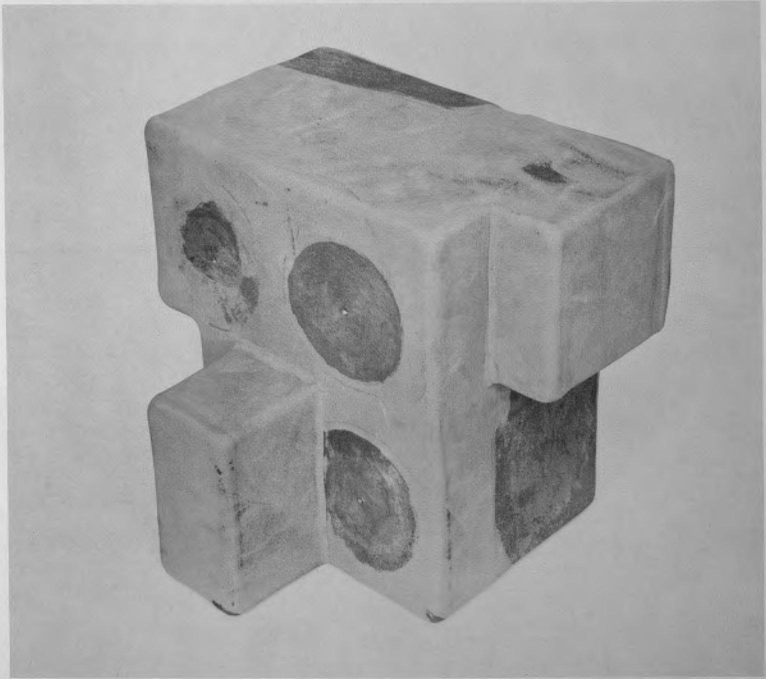

FIGURE 5. COLD-HYDROSTATICALLY PRESSED PREFORM USING POROUS COPPER MANDRELS

15.2-10

FIGURE 6. CYLINDRICAL CONTAINER USED FOR HOT ISOSTATICALLY PRESSED BERYLLIUM INNER GIMBAL

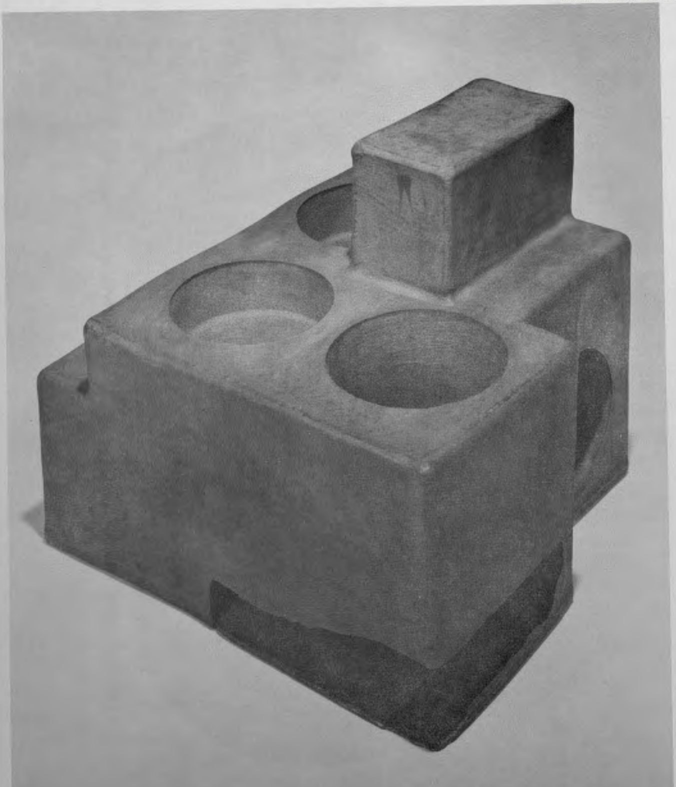

FIGURE 7. MACHINING BLANK OF THE INNER GIMBAL

FIGURE 8. MACROPHOTOGRAPH OF A SECTION THROUGH AN INNER GIMBAL PREFORM SHOWING PRESSED INTERNAL DETAIL

Specimen is shown in its metallographic mount.

FIGURE 9. GYRO SLEEVE AFTER FINISH MACHINING

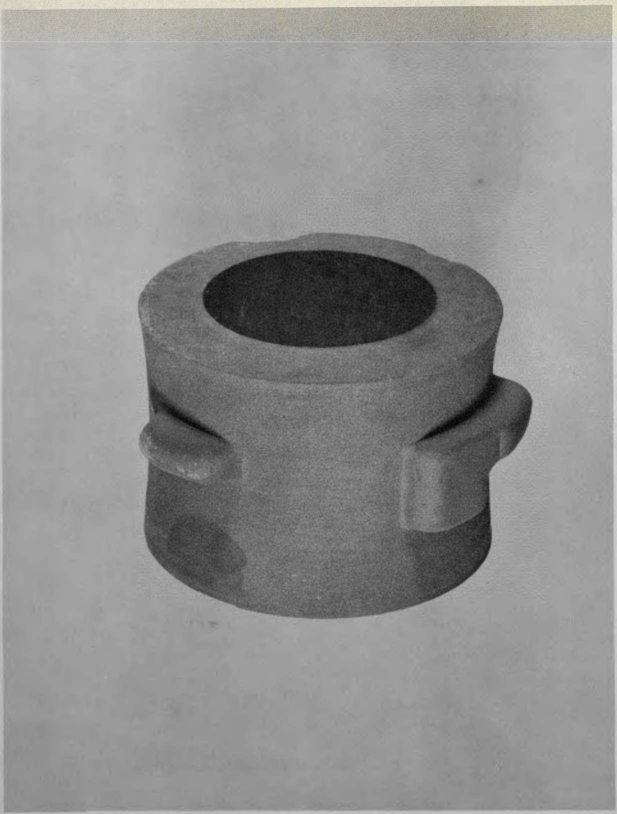

FIGURE 10. HOT ISOSTATICALLY PRESSED GYRO-SLEEVE MACHINING BLANK

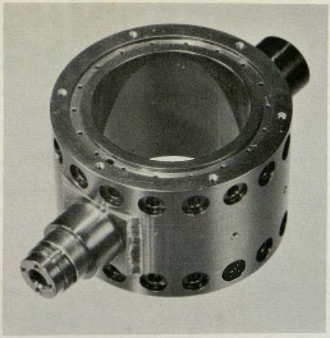

FIGURE 11. MACHINED ACCELEROMETER SLEEVE

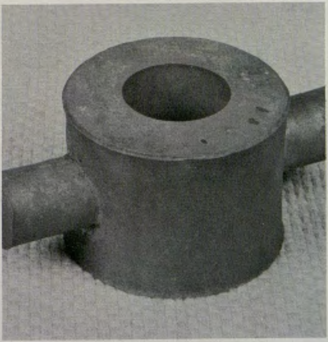

FIGURE 12. AS-PRESSED BLANK OF THE ACCELEROMETER SLEEVE