HIP OF NEAR-NET TURBINE DISKS

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ABSTRACT

A program was undertaken to evaluate the
relative shapemaking capabilities of metal
can plus HIP and Crucible's ceramic mold plus
HIP methods. Using a small but complex disk/
shaft assembly, it was shown that the ceramic
mold approach afforded the greatest potential
for very complex shapes. This process was
then scaled to produce a third stage turbine
disk for the F-102 engine. Properties of the
HIP plus heat-treated PA-101 alloy met or
exceeded the program goals and a weight
savings of 70 lb (32 kg) was demonstrated.

Introduction

The many desirable attributes of powder-processed superalloys have been much publicized. Various producers are making bar stock, forging preforms, and, more recently, as-pressed near-net shapes. The concept of producing a near-net shape with acceptable mechanical properties maximizes the payoff for PM. Specifically, input weight is reduced and, as a consequence, so is machining time and cost. In this paper, we shall discuss a portion of a current Air Force funded program (1) with the objective of hot-isostatic-pressing (HIP) of superalloy parts to near-net shape.

A variety of canning methods are being developed for the exploitation of HIP near-net shapes, i.e., those with buy-to-fly ratios less than 2:1. Two different containment schemes are addressed in this paper. One is Crucible's proprietary ceramic mold process and the other a more commonly used steel can approach. Both are being further established and refined on a current Air Force funded program with Avco-Lycoming to produce the first stage turbine shaft and disk for the F-102 engine.

In the Crucible Process, a low-cost, expendable ceramic mold is produced from a wax pattern. These molds, which can be extremely complex, are then filled with powder, sealed, and HIP.

The second canning process to be discussed is the more conventional metal can technique which is currently being used by numerous companies throughout the United States and Europe for the production of complex powder metallurgy forging preforms. The technique is more versatile than many realize. By using multi-component containers, the shapemaking capability is increased and costs are reduced by use of the most efficient forming process for each element of the container.

Processing Studies

The alloy involved in this program is PA-101, the chemistry of which is shown in Table I. Powder was produced by vacuum induction melting of vacuum melted candles, virgin charges, and revert material. In each case, the material was argon atomized. Analysis of material HIP from the various melt practices revealed that each was acceptable. The maximum strength variation in material produced via these three routes was one percent. A virgin plus revert practice was thus selected based upon economic considerations.

Gas atomization produces powder with a typical size distribution shown in Figure 1. From a cost viewpoint, it would be advantageous to use full-cut powder in HIP parts. To determine whether this was feasible, compacts were HIP from -30, -60, and -100 mesh powders. Test data showed somewhat inferior properties in billets HIP from -30 mesh material, whereas those produced from -60 and -100 mesh were quite comparable. Economics suggest the use of -60 mesh which offers an improved yield over the -100 mesh powder.

Shape Development - Small Disk

In classical powder metallurgy, powder is loaded into a die cavity and pressed. The part assumes the shape imparted by the die. This approach has many limitations, however. These include size and shape limitations, density gradients, and lack of full density. HIP affords an opportunity to go from loose powder to a fully dense shape in one operation. However, tooling must be designed to receive powder at 50 to 70 percent of theoretical density and reproducibly accommodate the shrinkage involved in going to full density. Although with some tooling concepts, a fixed reference surface or surfaces can be maintained, the more common case is for all surfaces to be "free", i.e., all will move in, hopefully, a controlled and predictable manner.

Table I

Chemistry Specification for PA-101

Element	Weight %
Chromium	12.2 to 13.0
Cobalt	8.5 to 9.5
Tungsten	3.85 to 4.05
Tantalum	3.85 to 4.05
Titanium	3.90 to 4.20
Aluminum	3.20 to 3.60
Molybdenum	1.85 to 2.05
Hafnium	0.75 to 1.25
Zirconium	0.08 to 0.14
Carbon	0.13 to 0.20*
Boron	0.01 to 0.02
Nickel	Balance

*A low carbon (0.02 - 0.05%) version of this alloy has
also been used on this program.

The first shape addressed on this program is shown in Figure 2. This is
a rather complex configuration consisting of a 6.1 inch (155 mm) diameter
disk with an undercut bolt flange and an attached shaft. The conventional
method of producing such a geometry would be to machine the disk from a pan-
cake forging and subsequently attach the shaft, e.g., by friction bonding.

The two methods described earlier were used to make this part. Each was
found to have advantages and limitations.

The metal can approach for this trial shape is shown in Figure 3. As can
be seen in the top photograph, the container for the disk consisted of shear-
spun top and bottom sections girth-welded together. A precisely sized spacer
ring fits inside the can to maintain the disk thickness. These components
were made from Crucible 26-1 stainless steel. The shaft portion of the can
was made using thick-walled seamless carbon steel tubing. The center cavity
was formed by an insert of cast CF3M steel (a cast equivalent to 316 L stain-
less). This is shown alongside the part in the lower photograph. Not shown
in the photograph is a spacer ring at the end of the shaft to maintain
correct alignment of the CF3M insert.

A number of parts were made using this same containment scheme. During
HIP, some were oriented vertically (both with the shaft up and with the shaft
down) and others horizontally. The part orientation in the autoclave appar-
ently has no effect on the shape dimensional control and reproducibility re-
sults. In Figure 4, we have compared the actual and target dimensions for
this part. These are both drawn to the same scale; note that the target di-
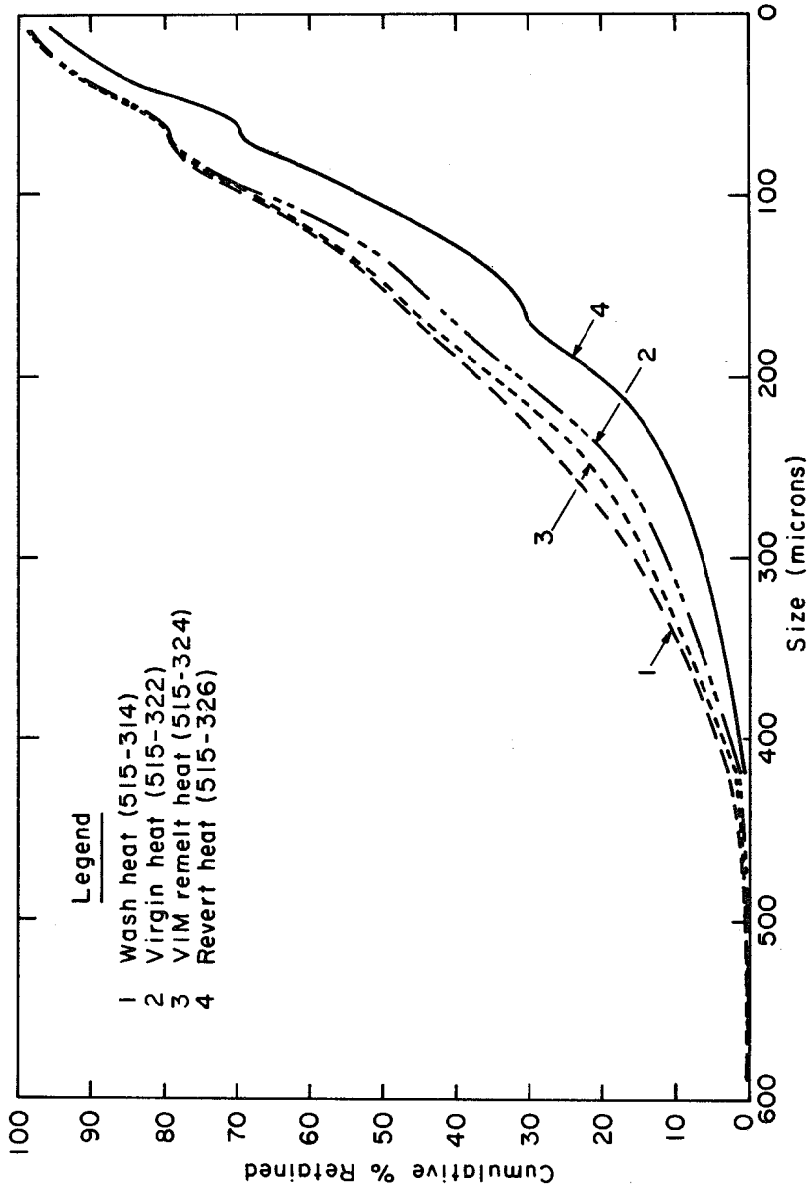mensions were shown earlier in Figure 2.
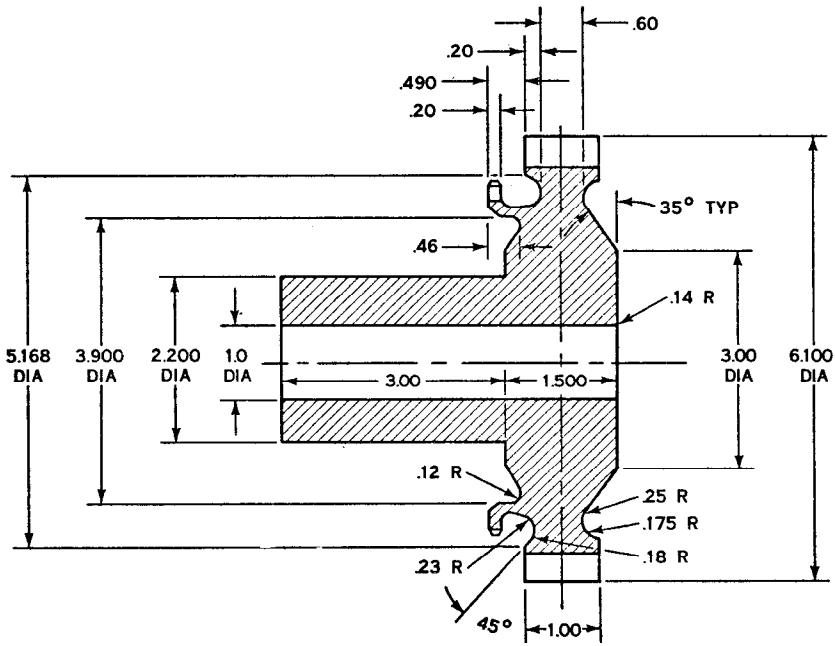
Figure 1. Size Distribution of PA-101 Powders.

Legend

1 — Wash heat (515-314)
2 — Virgin heat (515-322)
3 — VIM remelt heat (515-324)
4 — Revert heat (515-326)

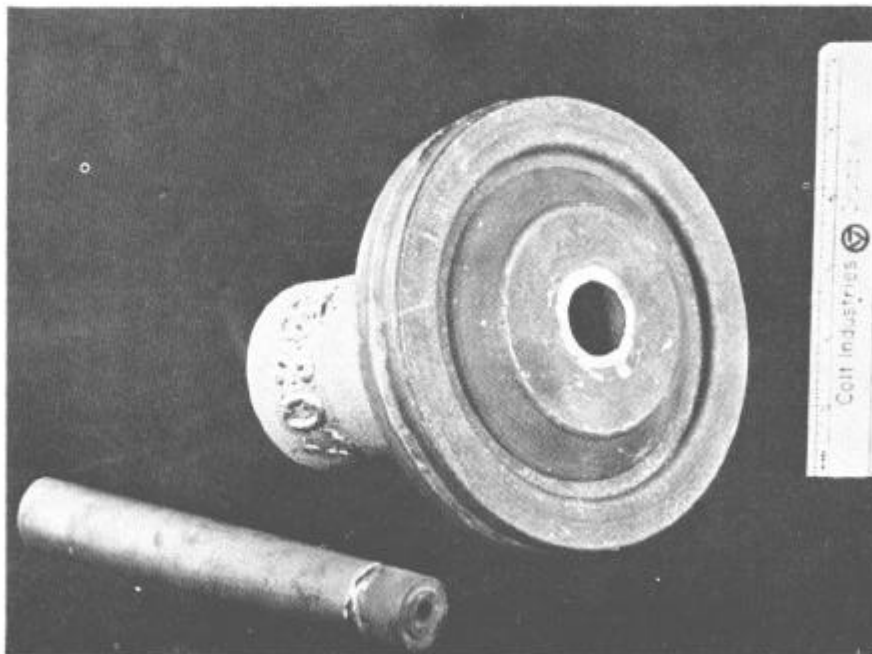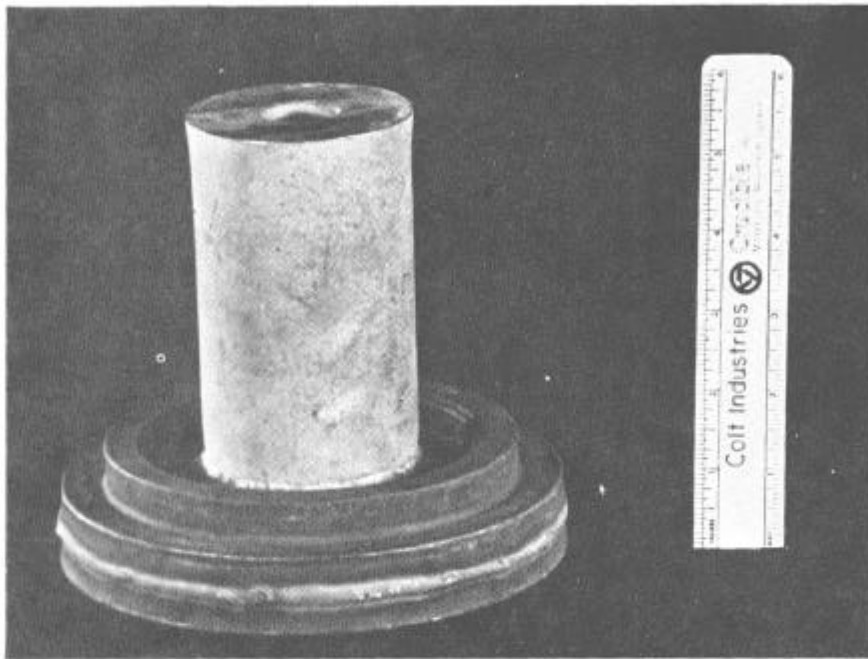Figure 2.   Target for initial shape development.
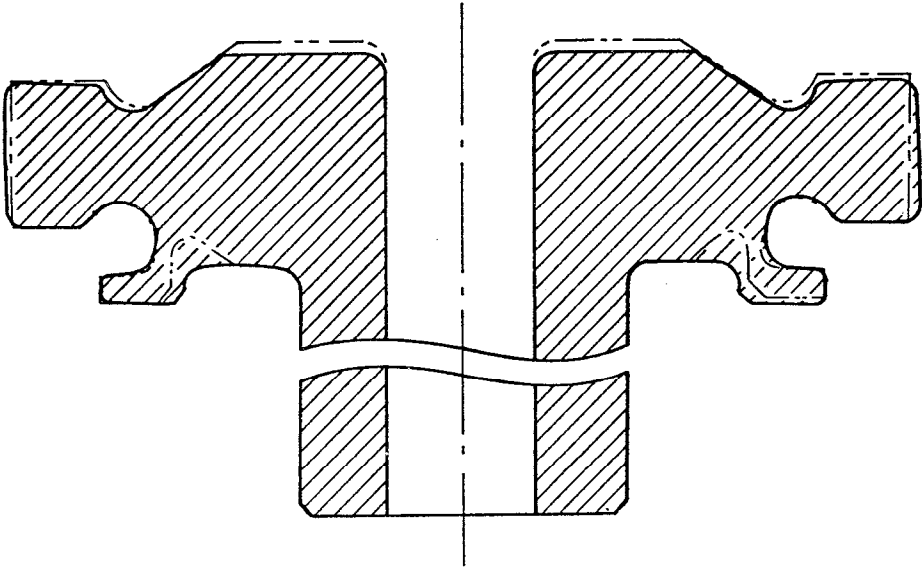
Figure 3. Metal can approach.

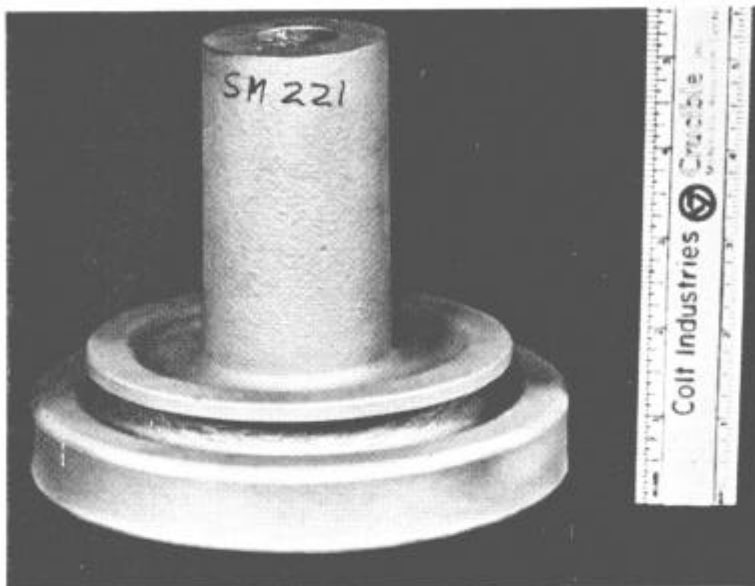Figure 4. Target versus actual dimensions
with metal can approach.

Actual Size

Figure 5. HIP shape produced
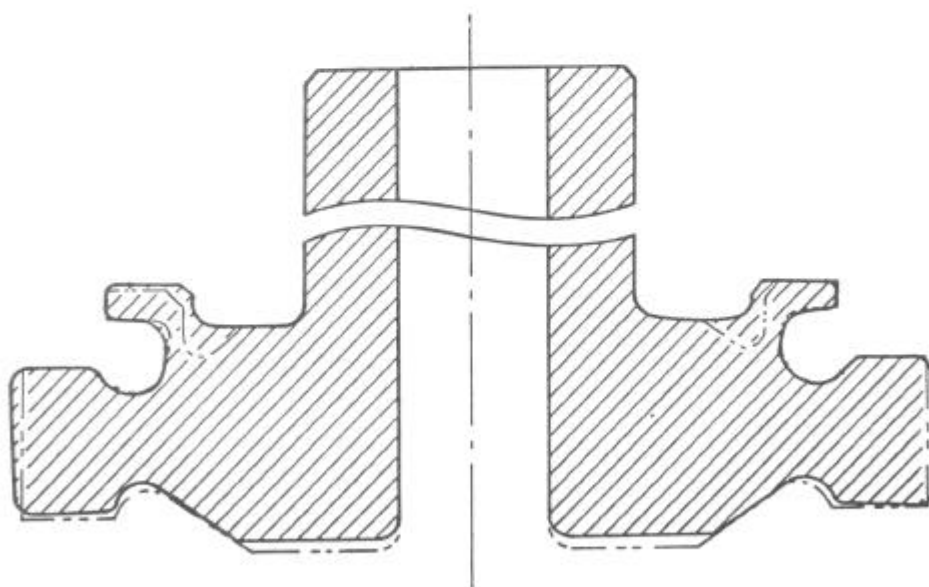in a ceramic mold.

Figure 6. Comparison of actual and target dimensions
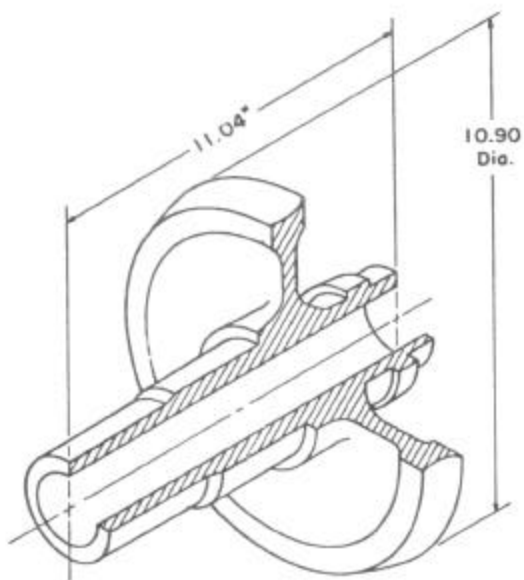of small disc HIP in ceramic mold.

Actual size

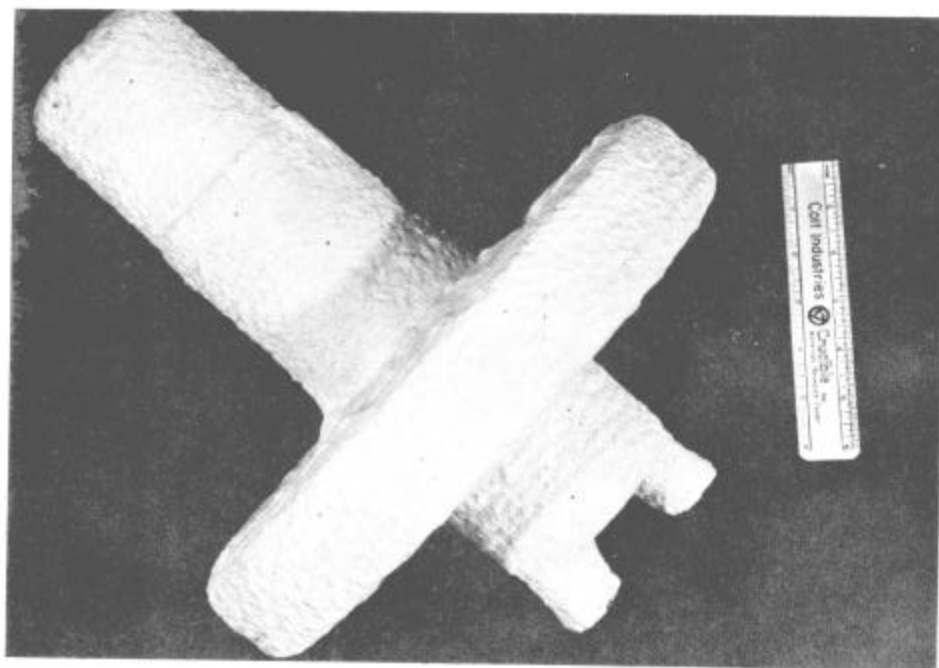Figure 7.   Schematic of F-102 disc.

Figure 8.   Ceramic mold for large disc.

A disadvantage of metal cans in general is the requirement for can stripping. This is usually accomplished either by machining or by selective acid leaching. Several ways to make these cans mechanically strippable were evaluated. One approach was to oxidize the internal surfaces of a stainless steel can. The tightly adherent oxide layer prevents the bonding which would otherwise occur between the powder and the can. This surface film, which probably involved both oxides and nitrides, was formed by heating in air.

Any surface film formed on carbon steel in this manner is not ᴜᴊ adherent, so the separating layer was applied by flame spraying with aluminum oxide.

PA-101 was HIP in containers processed by both techniques. In each case, the cans were stripped mechanically from the consolidated parts.

No further work was done with the metal can approach because of the success with the ceramic mold approach described earlier which was under concurrent evaluation.

A representative disk assembly HIP in a ceramic mold is shown in Figure 5. Obviously, this technique can provide much more shape definition than can economically be achieved with a fabricated metal can. Note, for example, the undercut bolt flange. In Figure 6, the actual and target dimensions of this part are compared on the same scale. Again, the target dimensions are those noted earlier in Figure 2.

As stated earlier, a large shrinkage (in this case, nearly 20%) occurs during consolidation. Therefore, in order to successfully produce shapes with close dimensional tolerance, it was necessary to gain a thorough understanding of the nature and degree of shrinkage which occurs. Thus, an iterative study of shrinkage factors was conducted and each successive mold was modified to compensate for shape corrections dictated by the previous trial. The part shown is the product of the third iteration. Based upon these limited data, it is believed that tolerances of $\pm$ 1 percent overall and $\pm$ 0.010 inch ($\pm$ 2 mm) on thickness may be achieved on a reproducible basis.

Shape Development - Large Disk

Based upon the success on the small disk, the ceramic mold approach was selected for scale-up to a larger disk. Specifically, the third stage turbine disk for the Avco-Lycoming F102-LD-100 engine was selected. This is shown schematically in Figure 7. As a conventional forging, the input weight is 103 lb (47 kg), and the finished part weighs 26 lb (12 kg)[2].

The required starting size and shape was determined, and the ceramic molds (shown in Figure 8) were prepared. These molds were filled with powder, sealed, and HIP in Battelle's sixty inch (1.5 m) autoclave. The required shape was not achieved on the first attempt, but, after a correction to compensate for an angular misalignment between the disk and shaft, the part shown in Figure 9 was made. The weight of this HIP near-net shape is 33 lb (15 kg), some 70 lb (32 kg) lower than that of the conventional forging!

Figure 10 shows the interaction zone between the mold and the PA-101 powder. This contamination zone is typically 0.005 inches (0.1 mm) or less in thickness and is quite uniform. Therefore, the potential exists for the production of still closer-to-net parts, some of which may require only a chemical cleaning operation rather than more expensive machining to meet dimensional requirements. The degree to which this can be achieved is not yet defined and much additional work must be accomplished to fully establish the capabilities and limitations of the process.
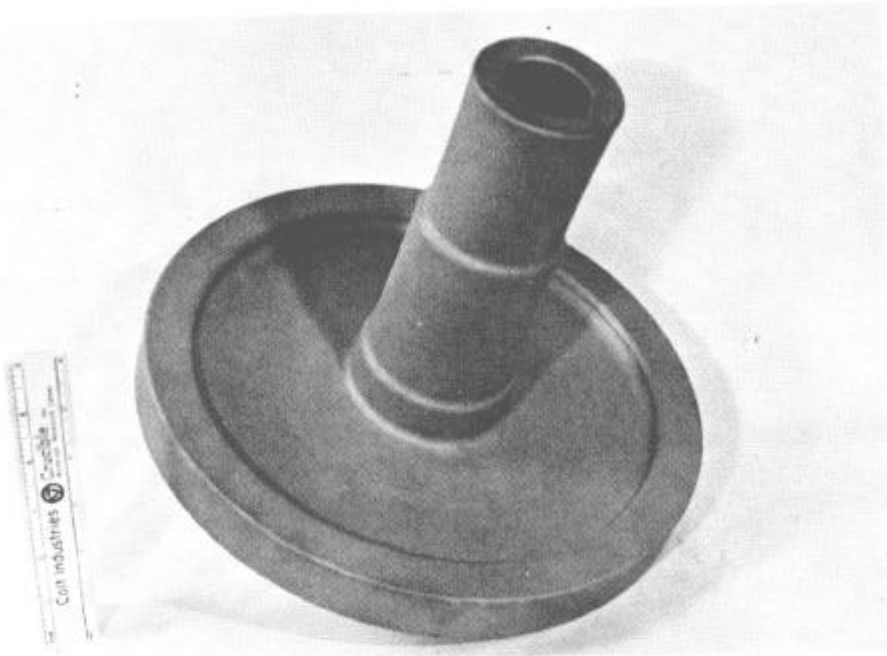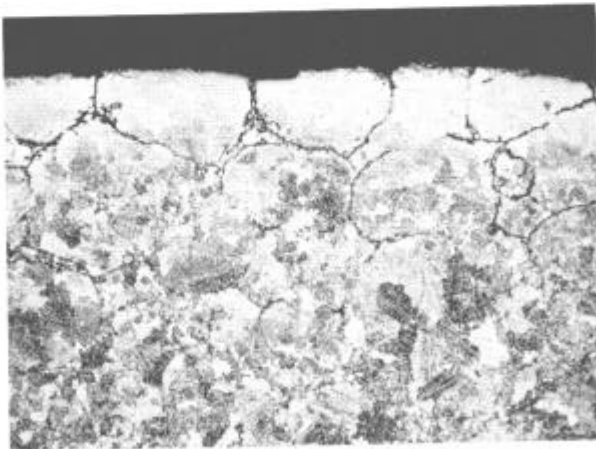
Figure 9.   As-HIP F-102 disk.

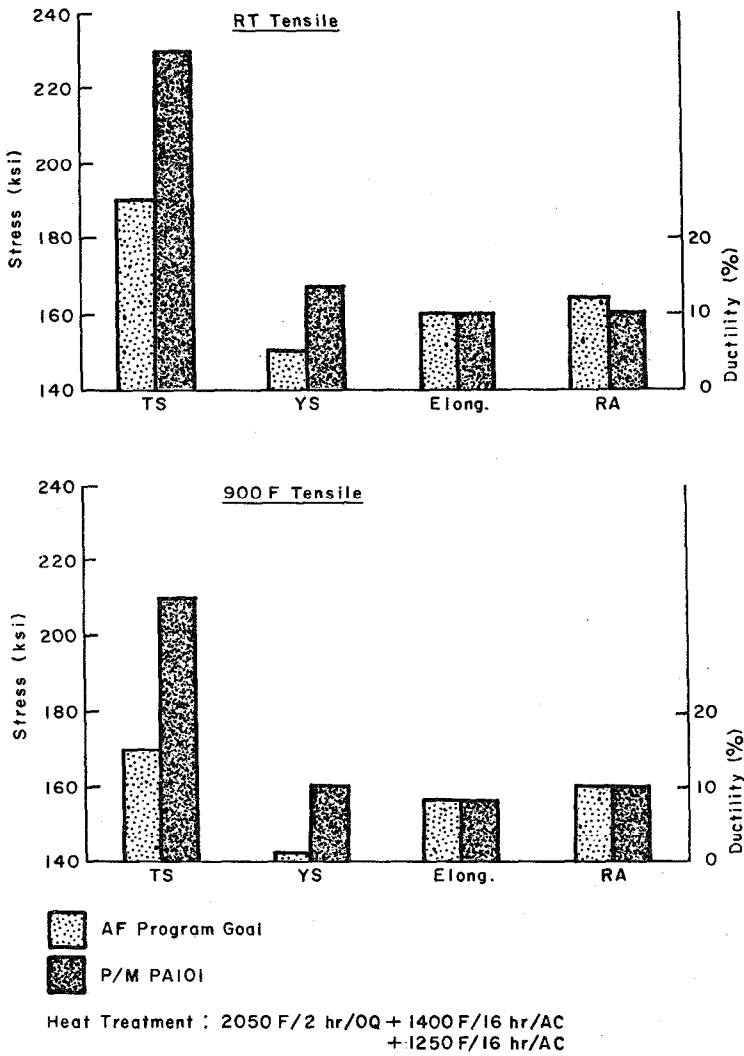Figure 10.   Typical mold-part interaction.
250X

RT Tensile

900 F Tensile

AF Program Goal

P/M PAIOI

Heat Treatment : 2050 F/2 hr/OQ + 1400 F/16 hr/AC
+ 1250 F/16 hr/AC

Figure 11.   Mechanical properties of HIP PA-101.

Mechanical Properties

At the outset of this program, mechanical property goals were established. The property levels achieved with HIP plus heat-treated PA-101 are compared with these goals in Figure 11. Although the properties are not equivalent to those of cast and wrought PA-101, the program goal, viz. equivalence or superiority to IN-718 and D979, was met.

Figure 12 shows the typical HIP plus heat-treated microstructure achieved. It is not the intent of this paper to discuss the physical metallurgy aspects of as-HIP PA-101 shapes. That will be discussed in a forthcoming paper by J. H. Moll etal.

Conclusion

In conclusion, we have demonstrated that both the metal and ceramic mold processes are technically viable. The metal can approach is economically viable only when applied to relatively uncomplicated shapes but offers the advantage of being able to withstand abusive handling and permit maximized autoclave loadings. The ceramic molds are, of course, more fragile and must be handled accordingly. However, they do provide tremendous flexibility in both size and complexity for a minimal cost. Therefore, the parts producers have the option of selecting that process which will best suit a given part and the associated "ground rules" such as cost, delivery time and part envelope.

References

1. Air Force Contract F33615-73-C-5040.

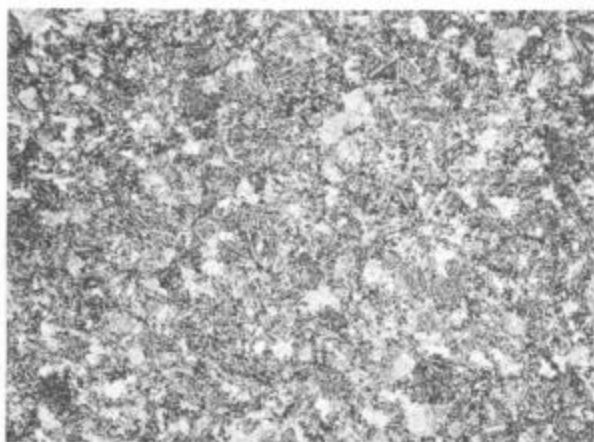2. Air Force News Release 76-56 (April 7, 1976).

Figure 12. Typical microstructure of HIP plus heat-treated PA-101.

250X