Competition between Powder Metallurgy and Other Near Net Shape Processes:
Case Studies in the Automotive and Aerospace Industries

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Introduction
With increasing industry competition, development of new alloys, stiffer price competition, and rising energy and material costs, there has been a distinct trend to diverge from conventional forming technologies. The need to produce the final product in fewer processing steps with minimal material wastage has led engineers and component designers to develop and critically evaluate alternative processing routes which would be more cost effective, while maintaining the same high level of performance. Several techniques for manufacture to "net shape" or "near net shape" are being developed to meet present and future demands.

The fundamental incentive for the development of alternative fabrication processes is economic. The reduction and, at times, elimination of a large number of machining steps provides sufficient cost savings on a per part basis to warrant the use of net shape processes, even though they may entail extra capital equipment and/or special handling equipment 

An indication of the significance of net shape processes can be found in automobile industry statistics: approximately fifty pounds of precision formed parts are used in a typical American or European automobile, and about three times that amount in a Japanese automobile

The material selection problem faced by present day designers is also a problem of choosing the optimal processing route, especially since the choice of a particular material is tied to the manufacturing process employed. For example, a switch to steel from nodular iron for connecting rod also implies a change in processing from casting to forging.

Driven by the need to reduce the costs of fabrication, and enhance material utilization rates, net shape and near net shape processes have been gaining in importance. These encompass not only the traditional casting and forging, but also exotic powder techniques such as hot isostatic pressing, and powder forging.

One of the key forces driving the shift towards near net shape production is the reduction of secondary machining or metal removal operations. The annual economic value of material removed, measured in terms of labor and overhead, is estimated at over $125 billion in the U.S. alone. Considering the enormous economic value, it is apparent that any reduction in metal cutting operations will provide substantial economic savings for the manufacturing industry. To this end, there have been sizable efforts focused on improving the machining operation and in developing means to reduce, if not eliminate, the amount of machining required. Further, the field of machining has been aided by the development of a host of empirical relations relating the various cutting parameters in order to choose the optimum cutting conditions

There have been a large number of changes in the field of machining itself, spurred by the evolution of new materials, difficult to machine alloys, etc., and also by the need for higher precision. To meet these requirements there have been numerous advances in the cutting tool industry, such as the emergence of new material cutting systems and surface coatings aimed at enhancing tool life. Global competition, in conjunction with the difficulty associated with machining some high-temperature alloys and some composite materials, provides a constant incentive for the development of new tool materials and tool surface treatments aimed at extending metal removal rates. These advances serve to aid shifts in technology towards net shape. Figure 1 highlights the chron-
ological order of advances in the cutting speed capabilities of tool materials. The improvements in cutting speeds progressively achieved over the years have been both through the introduction of new tool materials (solid line), and the use of coatings on existing tool materials (dashed line).

![Graph showing chronological development of tools with their cutting speed capability](image)

**Fig. 1** Chronological development of tools with their cutting speed capability

The technologies summarized above are just a tip of the iceberg as far as the whole range of possible fabrication routes available for metals processing are concerned. There is an interdependence between the technologies themselves, to a limited extent, and between the primary fabrication routes and secondary routes, such as machining, to a larger extent. Although part of this shift towards near net shape technologies is material driven, a large fraction still stems from the economic advantages to be reaped by a shift in technology. The advent of these new technologies warrants active markets where possible applications can be found. The range of applicability depends on the level of economic savings offered by near net shape technologies, and on the performance characteristics obtainable. Further, a particular application may, at times, warrant the use of a high performance material due to performance requirements. A change in material may also be associated with a change in processing route. Thus competition between technologies may arise out of pure performance considerations based on the limitations of the current material/process.

The scenario outlined above is quite prevalent in the automotive industry where continual changes in engine designs place stringent requirements on the possible materials which may be used for their manufacture. The automotive industry, where large production volumes are typical, has been an optimal environment for the penetration of these technologies. The automotive industry is one of the largest users of formed parts, either cast, forged or stamped. In 1988, the automotive industry consumed a total of $16.9 billion worth of steel stampings, 1.6 million tons of nodular iron castings, and approximately 21 lbs/auto of metal powder. Thus, from the point of view of introducing new net shape processing routes which may require high initial capital investments, it is preferable to have high production volume runs to obtain economies of scale, which are typical of the automotive industry. In the case of P/M, almost 70% of the end of metal powder can be traced to the automotive industry. Further, as mentioned above, the automotive industry is under continuous pressure to innovate and use lighter, stronger materials for its components. Figure 2 presents the trend of iron powder shipments used solely for P/M parts. The increasing trend clearly shows the enhanced use of P/M parts in automobiles. In fact, General Motors recently announced their intention to use at least 18-20 lbs of powder parts per automobile in the next few years.

The advent of new materials and near net technologies is not limited to the automotive industry alone. Table 1 tabulates the projected growth rate for RS materials in the U.S. The growth of these exotic materials is tied into the growth of the near net technologies associated with their processing.

From the foregoing discussion it is apparent that there is currently a great deal of interest in the advent of near net shape technologies. The prime motivation for a shift in technology towards net shape is economic, though performance considerations are also of importance. The above discussion also suggests that there is a dual nature to the materials selection problem. Designers need to lay emphasis not only on the level of performance delivered by the component, but also on the costs of manufacture.

The drive towards more powerful, fuel efficient aerospace engines has been such that,
since the establishment of civil jet transport in the mid 1950's, specific fuel consumption has been halved, thrust has increased fifty fold, and engine thrust to weight ratios have been increased by a factor of ten. In addition to the proliferation of new materials, many of these improvements have been achieved by the exploitation of cost-effective near net shape manufacturing technology and by an increased understanding of the dependence of performance on manufacturing\textsuperscript{12}.

The use of nickel based superalloys for aircraft engine components has been on the rise. The successful application of these “superalloys” is due to their creep strength and stability at elevated temperatures over long times. Nickel base superalloys owe their high temperature mechanical properties to the presence of gamma-prime precipitates, which are coherent and remain stable at high temperatures\textsuperscript{13}.

Aircraft turbine engines are manufactured worldwide by some 35 companies and consortia. A recent study by the Gorham Advanced Materials Institute predicts U.S. domination of this industry for the next ten years\textsuperscript{14}. However, the next decade will show an increasing competitiveness among consortia as designers, builders, and marketeers of engines.

Currently, about 91% of the weight of an advanced gas turbine engine consists of either superalloys (41.5%), steel (26.5%), or titanium (23.5%), with the balance being made up of aluminum and small amounts of magnesium, polymers/polymer matrix composites, and refractory materials. Superalloys are expected to maintain their superiority in this market, and by 1998 the mix of materials used is expected to become 43% superalloys, 23.5% steel, and 22.5% titanium\textsuperscript{15}. A breakdown of the overall materials consumption is presented in Table 3, and in Fig. 3.

This attractive market potential for superalloy materials makes it an active area of research, especially when considering the proliferation of gas turbine applications. The attractive high temperature properties offered by this class of materials makes it the obvious choice for certain applications. The traditional processing routes, casting and forging, are being replaced by powder metallurgical routes. This trend has been driven by the more stringent performance requirements needed in hostile engine environments. Currently, the two main near net shape processing routes, hot isostatic pressing and isothermal forging, have their roots in powder metallurgy.

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\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Global materials consumption in aircraft gas turbine engines (1988-1998)}
\end{figure}

The low cycle fatigue (LCF) capability of current superalloys for disk applications is...
largely limited by the presence of defects in the alloy. The defects in a typical René 95 alloy are determined by the processing route undertaken. As shown in Table 2, the largest defects in the as-hipped product are large reactive prior particle boundary defects. The inclusion of small ceramic particles during the melting and atomization stage of the cycle limits the fatigue capability of the thermomechanically processed disk. As evidenced by the data in Table 2, a shift in technology from hot isostatic pressing to isothermal forging from extruded bar has potential for improvements in LCF properties.

The mechanical properties of extruded compacts were higher than their hipped counterparts due to the fine grain size of extrusions. Because of heavy deformation occurring in the extrusion process, the size of the original powder particle did not significantly affect final grain size. Coarser particle size distribution results in larger grained compacts having lower tensile properties and increased stress rupture problems. Compaction by extrusion minimizes differences caused by original powder particle size distribution. It is this phenomenon that leads to an enhancement of final disk properties.

The problems associated with the larger scatter of low cycle fatigue properties in as-HIP consolidated René 95 have increased the use of isothermal forging techniques for final fabrication. This, in turn, has encouraged shear deformation methods such as extrusion for the forging stock in order to break up ceramic inclusions and to reduce overall defect size. The large particle size variation for the hipped product has deleterious results on mechanical and fatigue properties. As opposed to this, isothermal forging from an extruded bar results in a more uniform grain structure, because the extrusion process breaks down the individual grains to a fine structure. This leads to an enhancement of properties. Of course, it is possible to use a starting powder stock for hot isostatic pressing with a very close size distribution and cleanliness. This will result in enhanced properties of the isostatically pressed turbine disk. However, a close powder particle size distribution will result in low yields at the screening stage of the isostatic pressing operation, resulting in poor material utilization. This will lead to an escalation of the amount of raw material required to process each component, thereby leading to enhanced cost.

It is evident from the foregoing discussion that while powder metallurgical processes, viz., hot isostatic pressing and isothermal forging, are being preferred over conventional wrought techniques for this application, the exact choice depends not only on the economics of fabrication, but also on the technical ramifications of certain processing variables. This study was focused towards understanding the economic and technical forces underlying the use of these technologies. The automotive connecting rod and the aerospace turbine disk were used as cases to test the applicability of materials systems analysis at looking at material competitiveness.

| Temp (°F) | Total strain % | Defect type* | HIP Avg. | Max | Extruded + iso forge Avg. | Max |
|-----------|----------------|--------------|---------|-----|-------------------------|-----|
| 1000 <0.75 | 1              | 6.7          | 36      | 4.8 | 9.8                     |     |
|           | 2              | 9.5          | 50      | 8.9 | 12.1                    |     |
|           | 3              | 18.7         | 242     | None| None                    |     |
|           | 4              | 6.3          | 10.3    | None| None                    |     |
| 1000 >0.75 | 1              | 11.2         | 50      | 4.8 | 8.1                     |     |
|           | 2              | 13.1         | 111     | 7.1 | 16.0                    |     |
|           | 3              | 19.3         | 83.6    | None| None                    |     |
|           | 4              | 5.3          | 6.8     | 1.0 | 1.5                     |     |
| 750 0.75  | 1              | 7.5          | 9.1     | 4.1 | 8.7                     |     |
|           | 2              | 8.6          | 13.1    | 5.2 | 10.2                    |     |
|           | 3              | 6.4          | 6.4     | None| None                    |     |
|           | 4              | None         | 0.5     | 0.7 |                         |     |

* 1 - Ceramics, 2 - Ceramic clusters, 3 - Prior particle boundaries, 4 - Voids

| Material                      | Millions of pounds |
|-------------------------------|--------------------|
| Superalloys                   | 600.00             |
| Steel                         | 356.00             |
| Titanium                      | 321.00             |
| Aluminum                      | 75.00              |
| Magnesium                     | 10.00              |
| Polymer/Polymer composites    | 13.00              |
| Rubber/Elastomers             | 0.15               |
| Total                         | 1,375.15           |

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The use of nickel base superalloys in engine disks has created widespread research interest, especially in the area of processing. Powder metallurgy (P/M), has increasingly become the process of choice, due to the flexibility it provides to tailor properties according to need. Further, P/M has been aided by advances in the field of rapid solidification, now capable of delivering fine uniformly sized powder with exotic non-equilibrium microstructures. The mechanical and fatigue properties are often tied closely to the size and size distribution of the raw powder used. This has led to research into the production of fine powder. A controlled inert gas P/M process has proven successful for producing fine grain, segregation-free material. Inert gas atomization requires the use of special controls, especially the control of oxygen and nitrogen content which degrade mechanical properties if present in quantities larger than a few hundred ppm. Further, the presence of certain tramp elements may be detrimental to processing, especially elements such as Cr, Al, and Ti which form oxides that are difficult to reduce. Likewise, the nitrides of Ti and Zr are detrimental as they do not dissociate in a vacuum melting furnace.

Conventional powder consolidation techniques are not readily applicable to superalloy powders because the powders are incompressible. Additionally, these powders do not sinter easily because they contain aluminum, chromium, and titanium, which oxidize easily at the sintering temperatures. Consequently, other techniques for powder consolidation which can apply high pressures at sintering temperatures, without triggering material problems, are required.

The superplastic behavior of superalloys was discovered at Pratt & Whitney, and led to the development of the gatorizing process. However, it was found that gatorizing could not eliminate macrosegregation in as-forged alloys. Thus, gatorizing, more commonly known as isothermal forging, was applied to dense PM preforms. On an industrial scale, it has been applied to extruded PM billets. The superplastic deformation helps achieve forgings close to net shape, minimizing the amount of machining required and scrap losses. In order to obtain a fine grain size (1-10 μm) stable at temperatures above half the melting point, the powder compacts are extruded at temperatures slightly below the recrystallization temperature of the alloys.

Hot isostatic pressing (HIP) is a technique used to consolidate powders to full density. HIP is a process by which an isostatic pressure is applied at high temperature, to metal powder placed within a container or die. The compact is compressed in a pressure vessel using argon gas. Pressures range from 20 to 300 MPa, and temperatures from 480°C for aluminum alloy powders to approximately 1700°C for tungsten powder. Processing temperatures are within the plastic range of the material being formed — high enough for diffusion bonding to occur, yet low enough to prevent undesirable microstructural changes. Heat transfer during isostatic pressing is highly efficient. At high pressures argon gas is denser than water. To ensure uniform heating, molybdenum resistance heating elements are located throughout the work zone.

The first use of HIP was in the 1960's for diffusion bonding of clad nuclear fuel elements. Consolidation of beryllium metal powder to shape followed shortly thereafter. Since then, the size of units and use of the process has extended greatly. Uses now include the production of titanium and superalloys for the aerospace industry, net shapes in PM beryllium and niobium alloys and other refractory metals.

Isothermal forging and hot isostatic pressing have evolved into the dominant processes for this application over the past few years. An investigation geared towards understanding the key forces underlying the choice of either of these technologies would be invaluable, due to the fact that they form a class of emerging near net shape processes. As such, a competitive analysis based on cost was carried out in this study. The study used the technique of “Technical Cost Modeling” to estimate the manufacturing costs based on the given fabrication routes. Performance also plays an important role in the final choice of the processing route. Therefore, the ramifications of performance considerations on cost was also assessed.

Technical Cost Modeling

The importance of a systematic evaluation
of the costs of manufacturing cannot be over-emphasized. The approach used in technical cost modeling is to separate the different cost elements and estimate each one separately. This applies basic engineering principles, the physics of the manufacturing process, and clearly defined and verifiable economic and accounting principles. The models themselves are developed using a spreadsheet methodology. The use of a spreadsheet methodology to simulate the fabrication process is very helpful, because it provides a flexible environment for estimating the costs of manufacture using exotic materials and processes that are currently not in production, and because it is easy to use and offers visible parametrizing of the model.

A detailed account of the various cost elements are presented elsewhere. Interested readers may review the following references23), 24).

**Hot Isostatic Pressing**

Based on the premise that isostatic pressing and isothermal forging have emerged as viable alternatives for the turbine disk application, it stands to reason that a detailed construct aimed at understanding the economic competitiveness of the above processes would be very helpful in making strategic decisions about the processes in the future. This paper undertakes such an evaluation using the technique mentioned above. Further, the economic implication of technical changes is also highlighted in this paper. A competitive assessment of a typical T700 turbine disk was carried out as a part of this study.

The T700 Turboshaft engine design includes four cooling plates and two isostatically pressed P/M René 95 disks. This engine is characterized by improved fuel consumption, extended operating life and simplified maintenance. As used in the U.S. Army Blackhawk helicopter, the T700 engine has accumulated well over 200,000 operating hours. The composition of René 95 used for turbine disk applications is presented below25):

| Element   | Composition    |
|-----------|----------------|
| Carbon    | 0.04-0.09%     |
| Manganese | 0.15% Max      |
| Silicon   | 0.20% Max      |
| Sulfur    | 0.015% Max     |
| Phosphorus| 0.015% Max     |
| Chromium  | 12.0-14.0%     |
| Cobalt    | 7.0-9.0%       |
| Iron      | 0.50% Max      |
| Tantalum  | 0.20% Max      |
| Columbium | 3.30-3.70%     |
| Zirconium | 0.03-0.07%     |
| Titanium  | 2.30-2.70%     |
| Aluminum  | 3.30-3.70%     |
| Boron     | 0.006-0.015%   |
| Tungsten  | 3.30-3.70%     |
| Oxygen    | 0.015% Max     |
| Nitrogen  | 0.005% Max     |
| Hydrogen  | 0.001% Max     |
| Nickel    | Remainder      |

The powder required for the isostatic pressing process is first screened to a-150 mesh size was (the size assumed in this study). Based upon the requirements of the turbine disk, the screened powder size distribution may need to be finer (around-270 mesh). The screening step of the operation is typified by low yields, especially if there are stringent controls on cleanliness and the final powder size distribution. The screened powder is then blended to homogenize different batches of atomized grades and loaded into a clean, evacuated container. This stem also serves as a vent for outgassing. The container is usually made of mild steel. The stem is joined to the container by gas tungsten arc welding.

The loaded container is outgassed by heating under vacuum up to about 700°F. The containers are placed in the HIP unit. The isostatic pressing was done at 2050°F, under a pressure of 30,000 psi for a minimum of 2 hours. Under this pressure, the heated container collapses, compacting the metal powder. At 2050°F the powder particles become plastic and coalesce to form a solid alloy. After pressing, the fully dense parts are heat treated as follows:

1. 2090°F, 1 hour, salt quench
2. Aged at 1600°F, 1 hour, air cooled
3. Aged at 1200°F, 16 hours, air cooled26).

Age hardening strengthens the material through precipitation of the gamma prime (Ni₃Al, Ti) and the heat treatment develops resistance to low cycle fatigue27). Mechanical properties of René 95 are influenced by the rate of cooling from the solutioning temperature. If quenched too rapidly, there is a danger of cracking the disk. If quenched too slowly, it
It will not obtain the desired property level. It is for this reason that a salt bath solution and quench was used.

A hot isostatic pressing model was constructed to estimate the manufacturing costs based on the sequence of operations shown in Fig. 4. The set of assumptions used in the cost estimates is outlined below:

**HIP - Assumptions**

- Finished Weight of Disk: 4.5 lbs
- Annual Production Volume: 125 parts/year
- Raw Material: René 95
- Raw Material Cost: $22/lb
- Labor Cost: $16/hr
- Labor Overhead: 40%
- Labor Productivity: 85%
- Working Period: 240 days/year

![Fig. 4 Operation sequence for hot isostatic pressing of turbine disks](image)

It was assumed that components other than turbine disk were made using the same equipment used to fabricate the disk. In other words the isostatic pressing facility was run in a non-dedicated fashion primarily due to the low production volumes. The powder yield during the screening operation is a very critical determinant of the total cost of the finished component. Figure 5 shows the breakdown of cost by processing step as estimated by the model, assuming a screening yield of 40%. Material cost is the most cost intensive factor in the total cost of the component. The high cost of container loading is a consequence of the high labor content. The breakdown of cost by factor and process is tabulated in Table 4.

**Isothermal Forging**

The alternative to hot isostatic pressing is isothermal forging of turbine disks. This process is also called gatorizing (as patented by Pratt & Whitney). The disks are forged from an extruded bar of René 95. The extrusion process

![Fig. 5 Breakdown of cost by processing step for the hot isostatically pressed turbine disk](image)

| Table 4 Breakdown of cost for hot isostatically pressed turbine disk |
|------------------------|-----------------|
| By Factor              | $/part | Percent  |
| Raw material           | $1,045.00 | 36.28%  |
| Process material       | $27.39   | 0.95%   |
| Labor                  | $857.03  | 29.76%  |
| Energy                 | $12.70   | 0.44%   |
| Scrap credit           | ($3.21)  | -0.11%  |
| Equipment              | $461.45  | 16.02%  |
| Tooling                | $214.05  | 7.43%   |
| Aux. equipment         | $18.03   | 0.63%   |
| Maintenance            | $69.22   | 2.40%   |
| Taxes                  | $9.23    | 0.32%   |
| Insurance              | $6.92    | 0.24%   |
| Building               | $162.47  | 5.64%   |
| **Total**              | $2,880.29| 100.00% |

| By Process              | $/part | Percent  |
| Raw material            | $1,045.00 | 36.28%  |
| Screening               | $247.32  | 8.59%   |
| Blending                | $53.74   | 1.87%   |
| Container loading       | $205.22  | 7.12%   |
| Hipping                 | $401.65  | 13.94%  |
| Heat treating           | $69.36   | 2.41%   |
| Tumblasting             | $3.49    | 0.12%   |
| Machining               | $436.78  | 15.16%  |
| Inspection              | $9.71    | 0.34%   |
| Testing                 | $245.55  | 8.53%   |
| Building                | $162.47  | 5.64%   |
| **Total**               | $2,880.29| 100.00% |

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results in a more uniform, fine grain structure. The implications of this fine grain structure will be explained later in this paper.

The process involves heating stock to a temperature of about 2050°F and forging at a very controlled strain rate in dies heated to the same temperature. The best available die material is TZM molybdenum, an alloy that is very strong at the required forging temperature, but also one that oxidizes rapidly when exposed to air. Consequently, the isothermal forging press requires a vacuum chamber for the actual operation and sensitive temperature controls to ensure that the material being forged remains at the temperature where it is superplastic. Other system features unique to the isothermal forging press include a special vacuum furnace to bring the stock to forging temperature, transfer units for moving the forge multis from the furnace to the dies, and press controls that allow the programming of slow cross-head movements.

The sequence of processing steps is graphically shown in Fig. 6.

![Flowchart of operations for the case of the isothermally forged turbine disk](image)

The billet operations mainly consist of cutting and grinding the billet down to the required size. The boron nitride coating prior to isothermal forging serves both as a lubricant and as a parting agent that prevents the adhesion of the forged disk to the die. Isothermal forging is achieved in two stages, the initial forge yielding a rough disk shape. After the forging, the component is etched using an etchant called "Heppenstal." The purpose of the etchant is to reveal surface flaws. This is actually a two bath etching process. Their compositions are listed below:

- **Bath 1**: HCl + HF + HNO₃
- **Bath 2**: HCl + HNO₃ + Ferric Solution

It should be noted that the cost of disposing the etchant is a significant fraction of the total cost of the etchant. While the actual etchant is priced at $1.25/gallon, it costs $1.30/gallon to dispose of it.

The isothermal forging operation is accomplished using a pair of TZM Molybdenum dies. Under the assumed manufacturing scenario, the dies cost $175,000/set and are replaced after 600 forcings.

The heat treating and testing operations were assumed to be similar to those in the case of hot isostatic pressing. Each forging was assumed to be individually tested for room temperature strength, high temperature strength, and stress rupture properties. The final inspection operations included Brinell hardness testing, surface etching to reveal surface flaws, and dimensional tolerance measurements.

The assumptions used in the model are listed below:

**Isothermal Forging - Assumptions**

- **Finished Weight of Disk**: 4.5 lbs
- **Annual Production Volume**: 125 parts/year
- **Raw Material**: Extruded René 95 Bar
- **Raw Material Cost**: $31/lb
- **Labor Cost**: $16/hr
- **Labor Overhead**: 40%
- **Labor Productivity**: 85%
- **Working Period**: 240 days/year

The breakdown of cost by processing step, as estimated by the model, is graphically presented in Fig. 7. Isothermal forging accounts for almost half of the total cost of the finished component, because of the high cost of the equipment and the TZM dies. Table 5 presents a breakdown of total cost by factor and process. Unlike the case of hot isostatic pressing, material costs were a far smaller fraction of total cost. This reduction is a consequence of the material yield increase associated with the process.

**Competitive Analysis**

Figure 8 presents a breakdown of cost by factor for the two competing processes. In the
Table 5  Breakdown of cost for isothermally forged turbine disk

| By Factor           | $/part  | Percent |
|---------------------|---------|---------|
| Raw material        | $589.00 | 14.05%  |
| Process material    | $11.86  | 0.28%   |
| Labor               | $705.67 | 16.83%  |
| Energy              | $9.80   | 0.23%   |
| Scrap credit        | ($1.24) | -0.03%  |
| Equipment           | $1,127.45 | 26.89% |
| Tooling             | $1,356.84 | 32.36% |
| Aux. equipment      | $1.33   | 0.03%   |
| Maintenance         | $169.12 | 4.03%   |
| Taxes               | $22.55  | 0.54%   |
| Insurance           | $16.91  | 0.40%   |
| Building            | $183.49 | 4.38%   |
| **Total**           | $4,192.78 | 100.00%|

By Process

| $/part  | Percent |
|---------|---------|
| Raw material        | $589.00 | 14.05%  |
| Billet operations   | $133.76 | 3.19%   |
| BN coating          | $11.51  | 0.27%   |
| Isothermal forging  | $2,033.89 | 48.51% |
| Etching             | $23.86  | 0.57%   |
| Heat treating       | $86.88  | 2.07%   |
| Tumblasting         | $15.44  | 0.37%   |
| Machining           | $715.37 | 17.06%  |
| Inspection          | $11.79  | 0.28%   |
| Testing             | $387.78 | 9.25%   |
| Building            | $183.49 | 4.38%   |
| **Total**           | $4,192.78 | 100.00%|

In Figure 7, the breakdown is presented for the isothermally forged turbine disk.

In other words, at low screening yields (say 10%) the hipped turbine disk is less expensive at volumes below 50 parts/year. At all volumes above this, changing to isothermal forging is economically advantageous. As opposed to this, if the yield were to increase to 15% at the screening stage of the hot isostatic pressing operation, the break-even point would shift to 110 parts/year. Thus, while low screening yields result in a closer control in the powder size distribution leading to a concomitant enhancement of fatigue and mechanical properties, it also results in highly elevated costs. The original motivation for resorting to a powder process was to reduce final costs by minimizing material input. This is defeated because a coarse particle size distribution leads to poor LCF properties.

Figure 8 presents a graphical representation of the sensitivity of cost to annual production volume. The HIP costs are presented for three different screening yields. The results show economies of scale because the fixed costs are distributed over higher volumes leading to a smaller contribution on a per piece basis. The spike in the curve at a volume of around 500 parts/year is due to the requirement of an additional set of tools. As can be seen, the break-even point shifts to higher production volumes with increasing HIP screening yields.
Figure 10 presents the variation of the cost of the isostatically pressed turbine disk with screening yield. The base case isothermal forging cost refers to the cost as estimated by the isothermal forging model using the set of assumptions listed above. It can be seen that at screening yields below about 16%, isothermal forging presents cost benefits over hot isostatic pressing. As screening yields increase, isostatic pressing becomes progressively less expensive. However, there is an adverse effect on properties at high screening yields. This leads to the conclusion that although isostatic pressing does present a feasible alternative and has been used in the past, production with adequate performance is not a feasible solution, especially when isothermal forging presents an attractive cost effective alternative.

Based on the premise that isothermal forging is the most feasible alternative for this application, it stands to reason that efforts be directed to reduce the cost of fabrication. Referring to Fig. 6, it can be seen that tooling is a sizable chunk of the final total cost of the component. Thus, any reduction in the cost of the TZM die set would aid in reducing the total fabrication cost.

Figure 11 presents a set of scenarios presenting the sensitivity of cost to production volume at different die set costs. The figure shows that a reduction in the cost of the TZM dies from $175,000 to $25,000 results in a 30% reduction of total cost at volumes around 100 parts/year.

Case Study: Material Alternatives for Automotive Connecting Rod

Conventional forging has traditionally been the processing route of choice for this application. Of late, powder forging has emerged as a key process for this application. Powder forging yields a high density component with properties akin to those of conventional hot forging. Although this technology emerged in the early seventies, it has not been exploited as completely as one would have expected. However, Ford Motor Company has been using powder forged connecting rods ever since 1987, and production recently crossed the 1.0 million mark.

Further, in the case of conventional forging, the rods and caps have been forged and machined separately. Powder forging, on the other hand, undertakes a single piece forging operation. There seems to be no real technical reason as to why the rods and caps cannot be forged as a single piece by conventional forging as well.

Based upon these considerations, the three
processing routes for the manufacture of the automotive connecting rod and cap were evaluated: steel forging a one piece rod, forging the rod and cap separately, and powder forging a one piece rod.

**Fig. 12** Breakdown of cost by factor for the connecting rod & cap

The costs of production and their breakdown by factor are presented graphically in Fig. 12. There are several critical features to note:

| Table 6 Breakup of cost by factor for the connecting rod & cap |
|---------------------------------------------------------------|
| **Fully machined cost**                                       |
| Combined forging | Separate forging | Powder forging |
|------------------|------------------|----------------|
| Variable costs   | $2.49            | $2.48          | $2.10          |
| Fixed costs      | $2.91            | $3.02          | $2.96          |
| Total costs      | $5.40            | $5.50          | $5.06          |

| **Fully machined cost**                                       |
|---------------------------------------------------------------|
| Combined forging | Separate forging | Powder forging |
|------------------|------------------|----------------|
| Processing cost  | $2.06            | $2.16          | $2.94          |
| Machining cost   | $3.34            | $3.34          | $2.12          |
| Total costs      | $5.40            | $5.50          | $5.06          |

| **Material** | **Labor** | **Tooling** | **Capital** | **Maintenance** | **Other** | **Total** |
|--------------|-----------|-------------|-------------|-----------------|----------|----------|
| $0.89        | $1.48     | $1.31       | $1.21       | $0.24           | $0.26    | $5.40    |
| $0.87        | $1.49     | $1.37       | $1.25       | $0.24           | $0.27    | $5.50    |
| $0.96        | $1.06     | $1.57       | $1.06       | $0.21           | $0.21    | $5.06    |

○ The breakdown clearly depicts the cost advantages of powder forged connecting rods over the competing processes, in spite of the high material costs.

○ Forging the rod and cap as one single piece offered a cost savings over a two piece forging.

○ The high cost of forging can be attributed not only to the amount of machining required, but also to the fact that expensive, dedicated equipment is required.

The fabrication costs estimated by the different models for the four cases are presented in Table 6. Powder forging is clearly less expensive than the other alternatives. Combined forging offers cost savings over separate forging due to lower fixed costs because of the elimination of a separate line to forge them separately.

Although these are point estimates, it is possible to use the cost model to evaluate the sensitivity of these costs to critical assumptions. Sensitivity with respect to volume was evaluated and is graphically presented in Figs. 13 and 14. The sensitivity of the unmachined component cost to production volume is of particular importance when evaluating a high capital, near net shape alternative to a low capital, machining intensive process. In particular, the perception of cost effectiveness can be adversely affected if the consumer of a semi-finished part is not familiar with machining differences between alternatives and their cost consequences. For example, a process which may look cost effective to a consumer who buys less expensive as-formed parts may actually entail enough in-house machining that the final part cost exceeds that which would be incurred using a
more expensive, but nearer to net shape part.

At the base case production volume of 3,000,000 parts/year, powder forging yields the most cost effective component. Figure 13 clearly shows that, in the unmachined state, the powder forged rod and cap are more expensive than the conventional rod and cap. This is attributed to the high capital cost and the cost per pound of raw powder, which is almost double the cost of bar stock. Further, it is also evident that forging the rod and cap as one piece offers savings at all volumes considered up to 5,000,000 parts/year over the other two cases.

As opposed to this, as seen in Fig. 14, powder forging offers cost savings over conventional forging at all volumes up to 5,000,000 parts/year. Powder forging offers a near net shape product, unlike the conventionally forged rod and cap. This is clearly evidence by the cost savings accrued in the machining step of the operation. Thus, while powder forging was more expensive that the conventionally forged rod and cap in the unmachined state, it offers significant savings over the conventional rod and cap in the fully machined state. This is a classic example of the cost savings accrued by a shift towards a near net shape technology.

The cost difference between a two-piece and one-piece conventional forging is about 9 cents/part, which is too small to detect within the scale of the graph in Fig. 14. A primary factor influencing materials choice in this application is the issue of tooling requirements for machining of these rods. It became apparent that, once a commitment to tool a line for machining a rod and cap of a given material had been made, it was virtually impossible to reverse the choice of material for the rod and cap, even though an alternative might offer some attractive features. Further, increases in tensile and fatigue strength served only to improve the design margin of safety in the engine. An interesting feature was the fact that, although a stiffer rod may be beneficial up to a certain limit by reducing vibration, further increases may actually be detrimental, since they can lead to increases in crank loading.

Based upon the preceding cost analyses, the powder forged rod seems to be well positioned to substitute for conventionally forged rods. However, there is considerable skepticism as to the cost effectiveness of these rods and caps. As was pointed out in the section on cost analysis of connecting rods and caps, as-forged rods are cheaper than as-forged powder rods, while in the finished state the reverse is true. At present, the machinability of powder forged rods is an issue of some concern and there seems to be a lack of comprehensive information in this area. Since it is the machining step which provides the cost benefit of powder forged rods, uncertainty in this area is almost guaranteed to slow introduction of this material technology.

Further, there is the issue of tooling expenditures on existing facilities to be considered when deciding a possible shift from conventional forging to powder forging. In the event of setting up of a new facility for connecting rods, it is quite apparent that opting for a powder forging route as opposed to conventional forging offers substantial cost savings.

The possibility of a combined forging as opposed to a two-piece forging was analyzed in the preceding sections. Stemming from the cost minimizing drive in decision making, it follows that a shift to a one piece forging would improve cost effectiveness. In fact, this practice is being followed for some V-8 connecting rods and caps.

Cold forging of caps also offers the possibility of forging closer to net shape and better forging detail, reducing cost by reducing the number of machining steps. In situations where the rod and cap are forged separately, cold forging could improve cost effectiveness.

This outlines the major issues of concern for connecting rods and caps. While powder forging does not seem to be a potent threat to exist-
ing facilities, it should be borne in mind that the industry is becoming more aware of the cost effectiveness of this processing route. Thus, for the case of green field facilities, it is likely that powder forging will be seriously considered, provided that both forging and machining be conducted by the same source (since the major cost advantages come about only in the machining stage of the operation).

Discussions indicated that powder forging is the only commercially acceptable alternative to forged connecting rods in higher performance engine applications. While more exotic material alternatives do exist and are in use, they are restricted to specialty platforms or long term development programs.

To restate the primary conclusions of the utility analysis of connecting rods and caps:

1. The automotive industry is giving increased consideration to powder forged rods and caps.
2. The critical limitation to P/M competitiveness in this application is the lack of comprehensive, reliable process information, especially machining information.
3. The economic advantages of powder forging can be best exploited by fabricators who both forge and machine the component.
4. Manufacturers who are currently tooled to handle conventionally forged rods and caps can more cost effectively manufacture connecting rods from one piece forgings, rather than forging the rod and the cap separately.
5. Steel forging shops must enhance forging detail, reduce trim scrap, and move toward increased use of forging presses. Better dimensional control and the reduction of process scrap can go far to improve the economics of forging.

Conclusions

This paper has highlighted the growing importance of near net shape processes in metals fabrication. The economics of near net forming has been treated using the very useful tool of cost modeling.

The connecting rod and cap offers a classic example of the cost savings to be accrued from opting for a near net shape production route. The cost of powder forged rods and caps is high in the unmachined state, due to the high cost of powder and capital equipment. However, they offer significant cost savings over the conventional forged rod and cap in the fully machined state, due to the fact that powder forging results in a near net shape component, which does not require extensive machining. Thus, the savings are accrued in the machining stage of the operation. While powder forging has the highest degree of acceptability at the moment due to its low cost, it is evident that redesign of the component resulting in weight savings would further enhance this acceptable rating due to cost savings.

The case of the turbine disk presents an interesting situation of competition between alternate net shape technologies. While isostatic pressing can potentially provide low cost turbine disks, it requires high material yields in the screening stage of the operation, which in turn leads to wide range of particle size distribution and degraded mechanical and fatigue properties. On the other hand, isothermal forging offers an alternative route to fabricate the component having acceptable performance. An isostatically pressed disk with performance characteristics equivalent to that of an isothermally forged disk, requires low screening yields, increasing cost dramatically. Thus, isothermal forging or gatorizing offers an optimal set of characteristics for commercial use in this market. Efforts to reduce the cost of the isothermally forged disk should be focused towards reducing the cost of the TZM dies. The underlying assumption in the above analysis is that the level of testing required is the same in both cases.

Isothermal forging has a promising future if one could exploit the tremendous savings in material utilization possible. In the aerospace industry, this accounts for a significant fraction of the total cost of fabrication. Parts with pronounced circular geometry are particularly well suited for isothermal forging due to the fact that the symmetry of the component aids in prolonging the die life. Smaller size and lower complexity makes it easier to forge the surfaces to net shape. In large forgings over about 150 sq.in. plane area, net surface forging becomes increasingly difficult because of the manufacturing tolerances on die dimensions, variability in material properties, and varia-
tion and non-uniformity of die temperatures\textsuperscript{29}). Research geared towards reducing the high cost of TZM tooling or using alternate tool materials would also help enhance the economic position of this process.

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