# RECENT DEVELOPMENTS IN HOT-DIE FORGING OF TITANIUM ALLOYS

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## Introduction

In recent years, considerable effort has been made on the manufacturing technology for hot-die forging of titanium alloys (1-4). The major contribution of the hot-die forging is to reduce or to eliminate the influence of die chilling and material strain-hardening. As a consequence, more refined shape, better utilization of costly input material, substantial reduction of machining cost, and reduced number of forging operations are achievable.

The main objective of this paper is to present the recent developments and advancements in the manufacturing technology for hot-die forging of titanium alloys. The general content of the paper includes the current technology for hot-die forging to near-net shapes, metallurgical fundamentals to hot-die technology, and economic and technological considerations for both ($\alpha$+$\beta$) and $\beta$-titanium alloys. Some of the current and potential manufacturing applications for the technology are also illustrated.

## Hot-Die Forging to Near-Net Shapes

In conventional forging, most of the forging operations employ die temperatures below 427C (800F) and ram rates above 4 mm/sec. (10 in./min.). At these die temperatures and ram rates, the influence of die chilling and strain hardening is very significant; the forgeability of the alloys at a given forge temperature is then appreciably reduced. The manufacture of hot-die forgings at relatively low ram rates appears to improve this situation; the forging of near-net shape to significantly decrease the traditional material allowance between the as-forged shape and the finish-machined shape becomes achievable.

From a broad sense, the hot-die forging process is defined as a deformation process during which the forging dies are maintained at the same or a temperature slightly below that of the alloy being deformed. For the case of Ti-6Al-4V alloy (designated as Ti-6-4), the forging temperature for ($\alpha$+$\beta$) forging is about 954C (1750F). As the die temperature approaches 954C (1750F), the metal flow can be closely controlled by the processing variables, and as the material allowance between the forging and the machined part approaches zero, it may become possible to forge a shape to the machine outline with only a small amount per surface allowed, which can be removed by chem-milling or very limited machining. Note that the terminology "hot-die forging" in this paper covers both isothermal and hot-die (near-isothermal) processes.

The forging design attainable in conventional forging is primarily a function of the alloy and its forging temperature, along with the number of forging sequences processed through separate tool impressions. Increased web thicknesses, large fillet radii, increased rib and flange widths, along with decreased depths are design features generally required for adequate filling of the die cavity using unit forge pressures of reasonable magnitudes. However, with a die system operating at increased temperatures, the decreased differential between the forging stock temperature and the tool temperature allows a more refined shape of the forged component to be produced in a given operation. Further control of the major process parameters such as the forge temperature, ram rate, preform microstructure, strain, strain rate, forge pressure, and dwell time shows that additional refinement is possible still maintaining reasonable forging forces at the tool temperature. Therefore, in hot-die forging, extensive metal flows are possible within one die cavity providing the preform shapes have previously distributed the necessary volume of material in localized zones from which the new shape is generated.

In the earlier development programs [2-4], the hot-die forging of ($\alpha$+$\beta$) titanium alloys concentrated on the concept of isothermal forging. In order to maintain truly isothermal forging, the technical efforts in these programs were primarily made to resolve the problems of designing, heating, and operating a tooling system above 927C (1700F). As a result, the IN-100 cast dies and induction heating tooling were developed for producing small and moderate size forgings. However, both structural and property stabilities of the IN-100 cast die alloys become serious problems at these operating temperatures, and the cost-effectiveness of the process to manufacturing applications becomes questionable. Based on the results of the experiments on forge temperature/die temperature/strain rate interactions, a more recent work demonstrated that by reducing the die temperature and increasing the ram rate, the hot-die (near-isothermal) approach is beneficial for increased die stability and strength so that a more dilute, less expensive Ni-base alloy could be used as die material (Figure 1). As a result, a tooling system using Astroloy die inserts and modular design concepts to accommodate a range of part sizes up to a maximum plan view of 3871 $cm^2$ (600 $in^2$) was developed. To further substantiate the hot-die technology to the manufacturing applications, very extensive effort was subsequently made to determine the forgeability, structure, and properties of various titanium alloys [5-15].

## Metallurgical Fundamentals to Hot-Die Technology

Major metallurgical factors to hot-die forging technology are deformation processes, structural characteristics, and mechanical properties. Since the manufacturing capability for hot-die processing to near-net shapes requires the knowledge of the material response to forging deformation and since the forging of titanium alloys is a structure-sensitive problem, the understanding of the nature of metallurgical response under hot-die conditions is of great importance to hot-die technology. It has been demonstrated that the near-net achievable of the forgings depends strongly on forge temperature, die temperature, strain rate, and preform microstructure [5-8]. Adequate control of these variables can maximize the forgeability of the alloy and optimize the resultant microstructure and properties of the forgings.

Figure 2 illustrates the basic flow stress versus strain rate and strain-rate-sensitivity (m) versus strain rate plots for a typical superplastic material such as titanium alloys. As can be seen, three types of forging deformation, namely creep deformation, superplastic deformation, and conventional hot-working can be closely exercised in hot-forming of titanium alloys. However, the selection of the deformation type in manufacturing applications often depend on the factors such as forge pressure required, production rate, and other metallurgical qualifications. Because of significant chilling-effect from the dies, the conventional forging cannot provide close control of the deformation processes.

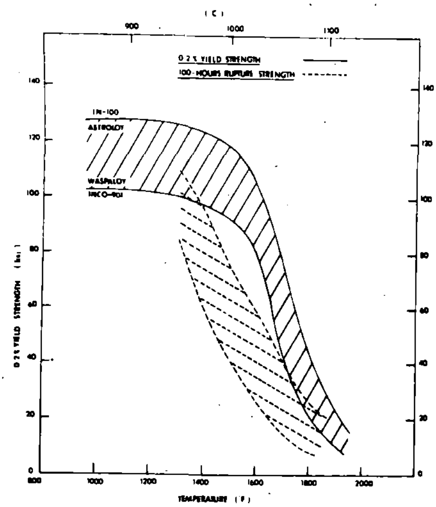



Figure 1 Effect of temperature on the yield strength and 100-hour rupture life of available nickel-base die alloys

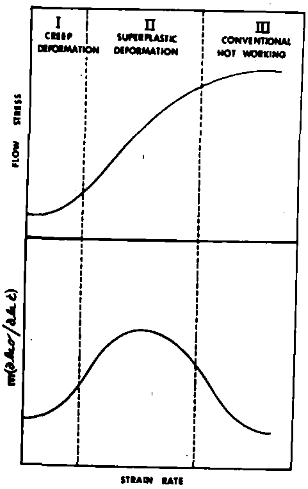



Figure 2 A schematic illustration of the deformation types for a superplastic material

The forging deformation properties under hot-die conditions were extensively investigated for various titanium alloys in recent years [5-8]. In particular, the effect of preform microstructure, forge temperature, and ram rate on the deformation behavior was emphasized (Figure 3). It was found that the deformation characteristics under forging could be quantitatively related to the hot deformation properties of the alloy, and the rate-controlling deformation process in ($\alpha$+$\beta$) forgings was attributed rather to the dynamic softening than to the more conventional rate-controlling mechanisms. For current commercial ($\alpha$+$\beta$) titanium alloys, the deformation of titanium alloys in the practical range of forge temperatures (871-982C or 1600$\sim$1800F) and ram rates (0.4$\sim$4 cm/s or 0.1$\sim$1.0 in/min.) was found to associate with high strain-rate-sensitivity and large strain softening; the deformation process is attributed to pseudo-superplastic behavior.

The structural characteristics of the forgings vary significantly with die temperature, strain rate, stock temperature, strain and preform microstructure. Figure 3 also presents examples of the as-forged microstructures at various forge conditions illustrating the influence of preform microstructure and forge temperature on structural characteristics of the hot-die forgings. It is seen that the microstructural response due to forge processing is extremely sensitive to the forge temperature for both ($\alpha$+$\beta$) and $\beta$ preforms. At 816 to 899C (1500 to 1650F) temperature range, forging results in a structure characterized by dynamic recrystallization, preferably occurring at and near the $\alpha$/$\beta$ interface boundaries.

The influence of die temperature and section thickness of the forgings on the as-forged microstructures of Ti-6-4 alloy is given in Figure 4. A significant difference in the nature of transformed-$\alpha$ regions can be clearly seen for both ($\alpha$+$\beta$) and $\beta$-forgings. Also, a martensitic transformed-$\alpha'$ for conventional forging and a Widmanstatten transformed-$\alpha$ for isothermal forging are seen for ($\alpha$+$\beta$) forgings. Note that the fracture toughness and ductility properties are generally degraded by the presence of martensitic-$\alpha'$ microstructure. For $\beta$-forgings, the hot-die approach to develop pseudo-$\beta$ microstructure can significantly improve the ductility of the forgings. It has

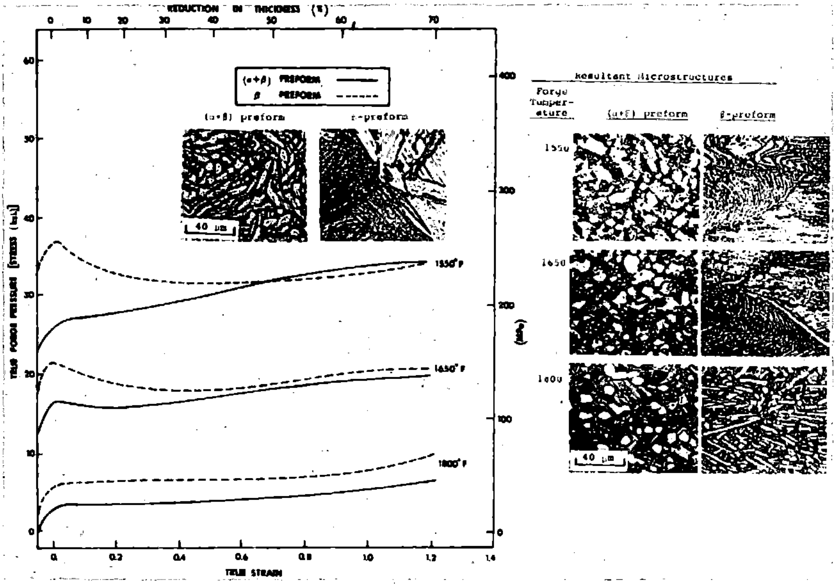



Figure 3 Examples of true stress-strain curves for isothermal forging of Ti-6Al-4V alloy pancakes using α+β and β-preforms at various forge-temperatures; $\dot{\varepsilon}=0.4$ min.$^{-1}$.

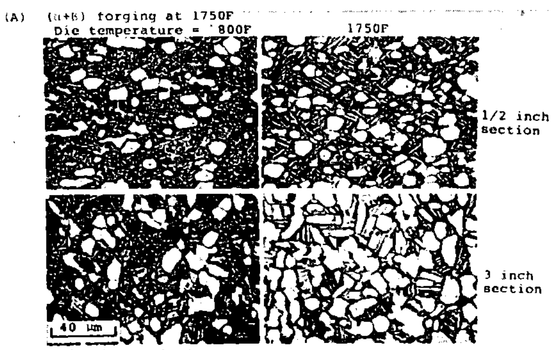
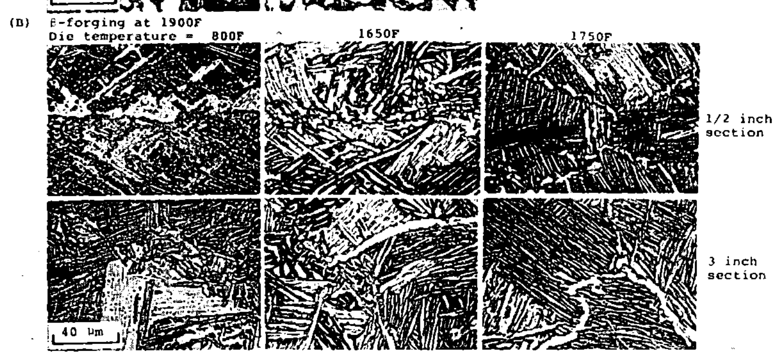



Figure 4

Effect of die temperatures and section thickness of the forgings on the as-forged microstructures of Ti-6Al-4V alloy



been previously shown that excellent uniformity of macrostructures is achievable for isothermal forgings. Very extended surface layers are observable for conventional forgings; the increased shear band and reduced metal flow due to die chill are very profound.

It can be generally stated that hot-die forgings result in a more uniform and improved mechanical properties of the forgings if proper forging variables are used [10-13]. The resultant properties depend critically on the forge temperature, die temperature, and preform microstructure. In general, fracture toughness, tensile ductility, and creep properties of the forgings can be significantly benefited by hot-die forging [11, 12]. The fracture toughness of the forgings generally increases, as the die temperatures increase (Figure 5). By controlling the die temperature slightly below the β-transus temperature, the relatively low ductility of the β-forgings can be significantly improved by hot-die approach (Figure 6). The creep resistance of Ti-6Al-2Sn-4Zr-2Mo∿0.1Si alloy (designated as Ti-6242Si) is seen to significantly increase by isothermal forgings (Figure 7). Metallurgically, such an improvement can be attributed to a more uniform, precise control of the nature and distribution of both globular-α and transformed products.

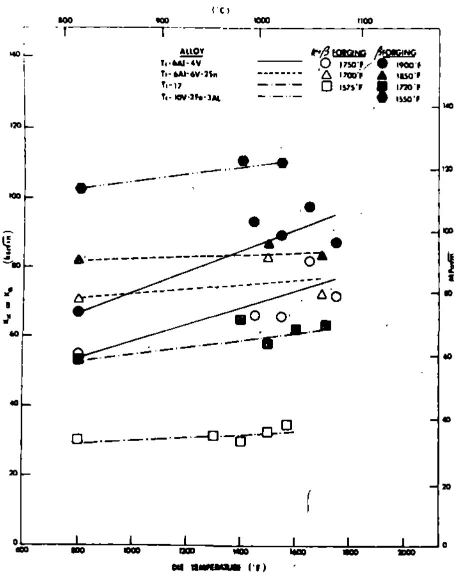


Figure 5 Variation of fracture toughness with die temperature for Ti-6Al-4V, Ti-6Al-6V-2Sn, Ti-17, and Ti-10V-2Fe-3Al alloys

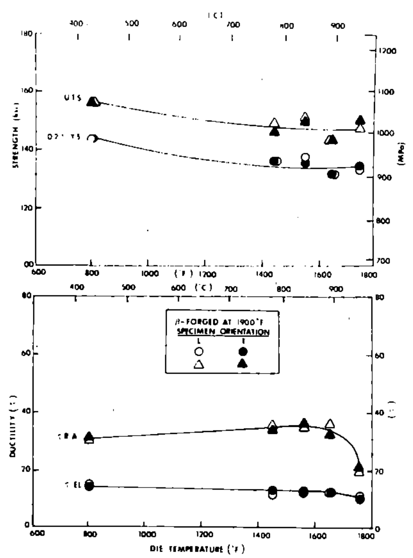


Figure 6 Room temperature tensile properties vs. die temperature for β-forged Ti-6Al-4V structural shape forgings

## Economic and Technological Considerations

The precise cost analysis for hot-die forging is difficult to provide because it varies with the particular forging selected; however, the major cost elements for hot-die forgings are associated with die material and operating die temperature, forging stock, forge temperature, and lubrication effectiveness.

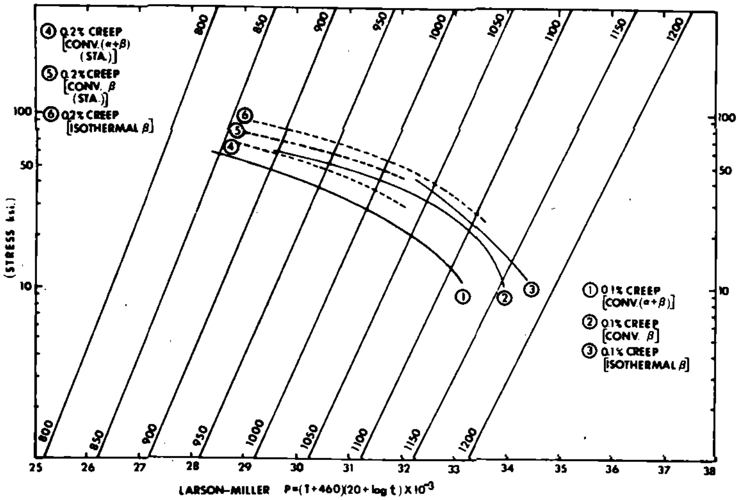



Figure 7 Comparison of creep strength of Ti-6Al-2Sn-4Zr-2Mo-0.1Si alloy forgings at 0.1% and 0.2% creep strain

Current cast IN-100 and wrought Astroloy for hot dies in air may permit satisfactory properties for (α+β) forging at die temperatures at or below 899C (1650F), but both structural and property stabilities of these alloys become serious problems at higher operating temperatures. The increase in die temperatures is necessary if one attempts to maximize the achievable near-nets and considers the potential die alloys for β-processing of (α+β) titanium alloys. This requires the upgrading of strength capability and high temperature stability of the die alloys.

The TZM-alloy is very satisfactory for strength and stability as a die material in service temperatures up to 1204C (2200F) and is being satisfactorily used in production applications as hot-die material. However, the alloy requires a protective atmosphere or vacuum around the die system to prevent oxidation of the dies. The costs for basic material and the required oxidation protection for using TZM dies equipment are very high. Furthermore, the press capacity is limited in the controlled atmosphere, and many elements need extremely precise control and integration during forging. It appears to be more practically and economically acceptable if other high oxidation resistant die alloy could be developed to satisfy technical requirements as hot-dies in air.

Unlike conventional forging for titanium alloys, a recent work on hot-die forging has demonstrated that the forge pressure required for hot-dies depends strongly on the flow stress of the alloys [6-8]; it means that, at a given temperature, the alloy having lower flow stress will require less energy for forging deformation. It was further demonstrated that the use of the β-titanium alloy lowers the flow stress required at 704 to 982C (1300 to 1800F) temperature range, as compared to the (α+β) alloy. For example, the yield stress of Ti-10V-2Fe-3Al alloy (designated as Ti-10-2-3) at 816C (1500F) is only about one-quarter of that for Ti-6-4 alloy [8].

Figure 8 gives a direct comparison of the forge pressure between Ti-10-2-3 and Ti-6-4 alloys for experimental structural shape forgings. It is seen that the forgeability of Ti-10-2-3 alloy under hot-die conditions at part/die temperatures of 843/760C (1550/1400F) are comparable to those for the Ti-6-4 alloy at part/die temperature of 954/899C (1750/1650F). In addition, the current hot-die technology can be employed for both (α+β) and β-forgings of β-titanium alloys. A direct comparison of the hot-die forgeability between the two alloys for two structural shape forgings is further presented in Figure 9; the forge temperature/die temperature/ram rate, unit pressure applied, and forging dimension are included. Also, it has been recently demonstrated that the newly developed metastable-β titanium alloys may offer significant improvement in strength-toughness combination of the forgings from that of (α+β) Ti-alloys and may result in improvement in structural efficiency of aircraft structural titanium forgings. The suitability of Ti-10-2-3 alloy forgings for structural applications at 1242 MPa (180 ksi) tensile strength level has been achieved for large production forgings [13, 14].

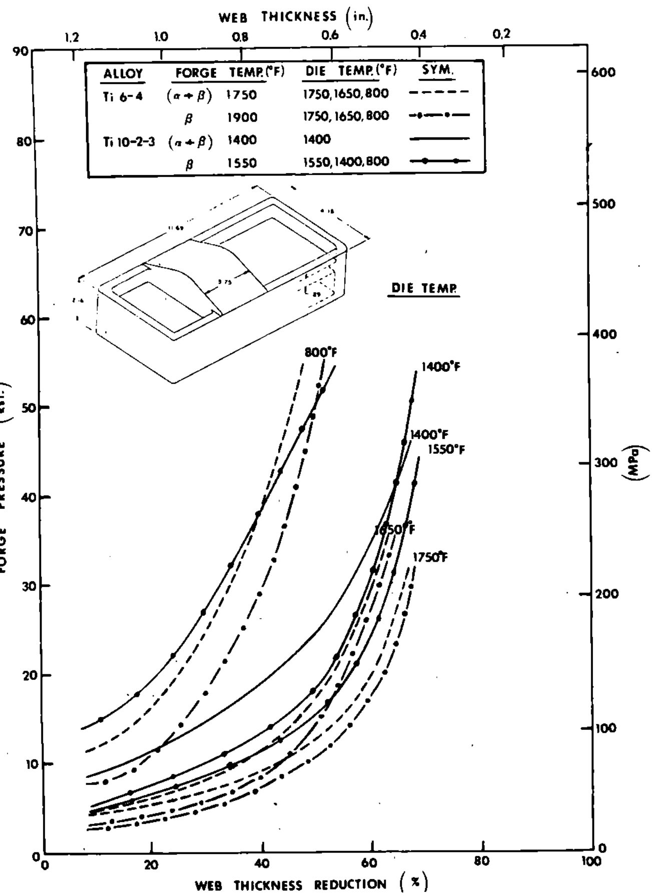



Figure 8 Variation of forge pressure with web thickness for Ti-6Al-4V and Ti-10V-2Fe-3Al experimental structural shape forgings

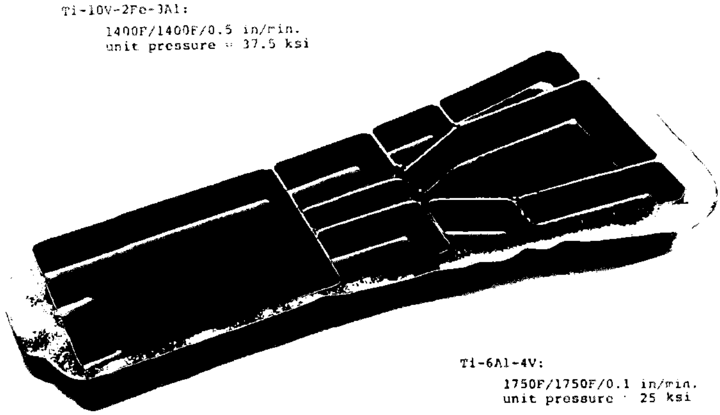



Figure 9a Isothermally forged F-15 bulkhead center body:

(~16 in. long x 5.5 in. wide x 1.5 in. deep)

Plan view 80 $in^2$ web 0.18 in.
Ship weight 5.5 lbs. rib 0.08 to 0.14 in.

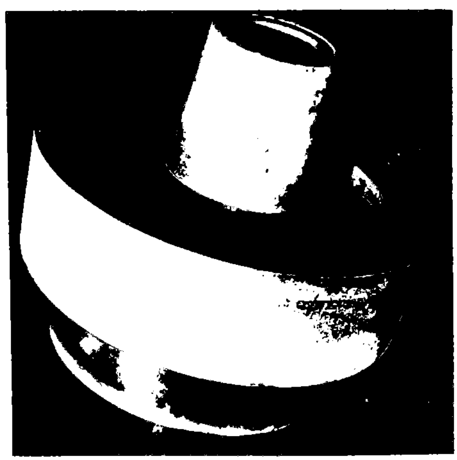


Figure 9b Isothermally forged F-100 1st stage compressor: Ti-6Al-2Sn-4Zr-6Mo

Diameter 14 in. Height (max.) 12 in.
Plan view 152 $in^2$

It has been very recently demonstrated [15] that none of the available lubricants for hot-die forging of ($\alpha$+$\beta$) titanium alloys could provide a satisfactory balance of the lubricity and adhesion properties for manufacturing applications, and there is a need for new lubricant formulations with improved lubrication effectiveness. Most of the commercial lubricants provided excellent anti-friction characteristics, but displayed unfavorable adhesion properties. From a production basis, any failure in removing the forgings under the extreme thermal environments encountered by hot-die systems in the forge shop will cost many times the amount that can be achieved by improving the anti-friction features. However, at the present state-of-technology, commercial lubricants with excellent combinations of lubricity, adhesion characteristics, and environmental inertness are available for hot-die forging applications in the 704-816C (1300-1500F) temperatures. Figure 10 gives a comparison of structural component forgings produced by hot-die forging using three most promising lubricants for each of ($\alpha$+$\beta$) and $\beta$-titanium alloys.

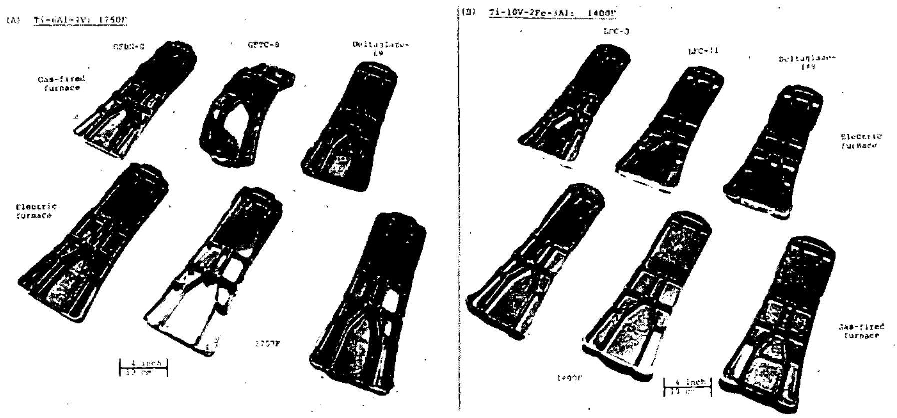



Figure 10 Comparison of structural component forgings produced by isothermal forging using three most promising lubricants for each of ($\alpha$+$\beta$) and $\beta$-titanium alloys; blast-cleaned condition.

Another major obstacle to the current hot-die technology for ($\alpha$+$\beta$) titanium alloys is the high energy consumption necessary for heating and tooling times at high die temperatures. Here the energy consumption for the processing depends not only on the heat-up to the temperature, but also on energy and time necessary to maintain the forge temperature after each forging operation. From a forger's standpoint, hot-die forging of Ti-10-2-3 alloy at lower die temperatures reduces the energy consumption, and consequently reduces heat-up times and temperature-maintaining costs. It also possesses practical optimization in forging operations at relatively low temperatures, reduces the handling difficulties and increases the operation safety in the forge shop.

## Manufacturing Applications

The application of hot-die processes to produce near-net forgings can be realized from two major areas: (1) economic justification of the process, and (2) improved structural efficiency of the forgings. Although the ability of hot-die process to produce cost-effective near-net shapes depends upon the die materials and their fabrication costs, the forgeability of the alloy, the die and forge temperatures used, and the effectiveness of the lubrication systems, it can be generally stated that the hot-die technology has been established as a reliable manufacturing method for the production of airframe and engine components. The technology can be cost-effective, depending on the size, shape, and quantity of a given alloy and forging, and has been demonstrated in producing moderate and large size forgings, as well as complex shape components.

Examples of current applications for hot-die technology to manufacture near-net shapes of titanium alloys at Wyman-Gordon Company are F-15 Bulkhead Center Body (Ti-6-4), CFM-56 engine Fan Disks (Ti-17), JT-8D first and second stage Compressors (Ti-6-4), and F-100 first stage Compressor (Ti-6Al-2Sn-4Zr-6Mo). It is believed that with recent increases in raw material costs and material availability problems for titanium alloys, the popularity of hot-die process to manufacture near-net shape forgings will continue to grow. In particular, the use of β-titanium alloys could be keys to further improvements of both cost-effectiveness and structural efficiency for hot-die forging of titanium near-net shapes.

As discussed earlier, the applications of hot-die technology should be very beneficial to forging technology where a precise control of processing variables and resultant microstructures of the forgings is required. Thus, the technology should have great potential in the manufacture of dual property titanium components for improved efficiency and economics of the forgings [11]. Furthermore, the press capacity can be maximized by hot-die forgings, and the tensile ductility, fracture toughness and creep properties of titanium alloy forgings can be significantly improved.

## Summary

Significant advancements in near-net shape technology by hot-die forgings have been made for titanium alloys in recent years. Although the cost-effectiveness of this technology for (α+β) titanium alloys depends on the particular forging selected, the hot-die forging has been generally demonstrated as a readily acceptable manufacturing process for producing structural and engine components. The improvement in the cost-effectiveness of the technology is continuously increasing with recent increases in titanium costs and titanium availability problems.

Current problems for hot-die forging of (α+β) alloys are: high costs of die material and their fabrication, poor die stability at high temperature, poor lubrication effectiveness of available lubricants, slow heating times and temperature-maintaining costs. However, the use of β-titanium alloys will significantly improve both economic and technological factors for hot-die forging. In addition to the improved and simplified forging process, excellent combinations of strength, toughness, and other properties for structural applications are achievable for β-titanium alloys.

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