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FORGEABILITY OF β-TITANIUM ALLOYS UNDER ISOTHERMAL FORGING CONDITIONS

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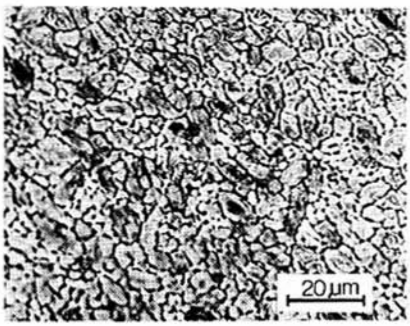
Introduction

Several types of compressor impellers are being made from Ti-6Al-4V due to the alloy's high strength to weight ratio in the 20-300°C degree range. Although Ti-6Al-4V exhibits excellent superplastic properties under isothermal forging conditions, the forging temperatures are at or beyond the capabilities of nickel base isothermal forging dies. Thus the alloy is usually isothermal forged in molybdenum dies, which tend to be expensive both due to the high raw material costs of molybdenum and because the dies cannot be exposed to air at elevated temperatures. Such considerations have led to the present investigation aimed at evaluating the possibility of replacing Ti-6-4 with an alloy from the so-called β-Ti class of alloys which are reportedly more forgeable than the $\alpha + \beta$ class of alloys of which Ti-6-4 is a member. Beta alloys are a relatively new type of titanium alloy in which the β-phase is sufficiently stabilized by additions of Fe, Cr, V, and/or Mo so that the martensitic $\beta \rightarrow \alpha''$ reaction is suppressed when the alloy is quenched from the β-phase field. Such alloys have recently become of great interest to the aircraft industries (1 - 4) partly due to their increased hot formabilities, but more so because of their higher specific strengths, toughnesses, and their exceptional deep hardenabilities.

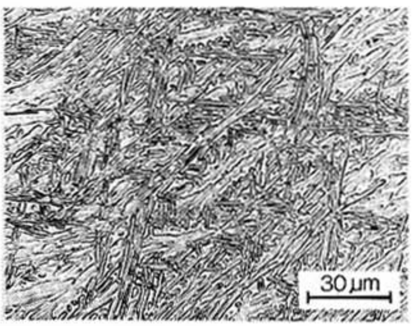
Four alloys were studied in this particular program: Ti-10V-2Fe-3Al, Transage 134 (Ti-12V-2Al-6Zr-2Sn), β-c (Ti-8V-6Cr-4Mo-4Zr-3.5Al) and Ti-6Al-4V.

Results and Discussion

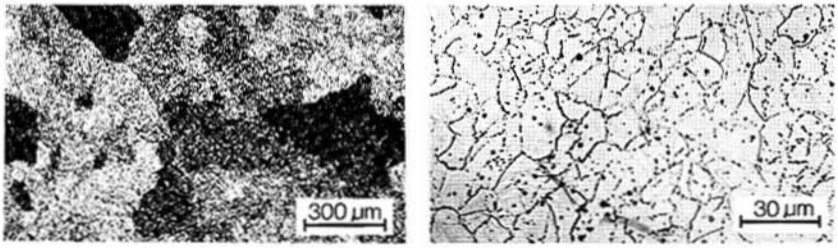
Figure 1 shows optical micrographs depicting the starting microstructures of all four alloys.



Ti-6Al-4V



Ti-10V-2Fe-3Al



Transage 134 β-c

Fig. 1: Optical micrographs of the four alloys used before forging.

Ti-6Al-4V: is considered to be the "workhorse" of the titanium alloys due to its relatively low price and excellent compromise of properties. The alloy was included in this study as a reference. Although the alloy can be forged with quite small press loads above its β-transus, the ensuing rapid grain growth and accicular microstructure leads to unacceptably poor ductilities. Thus the alloy is generally forged in the 900-950°C temperature range, by either conventional hot-die or isothermal techniques. The source material used in this particular study was mill annealed 8.6 mm diameter rod from RMI, "mill annealing" in this case, is defined as a two hour anneal at 700°C.

Ti-10V-2Fe-3Al: Ti-10-2-3 is a β (or near β) alloy developed by TIMET. The alloy exhibits an excellent deep hardening response, and is thus used in the solution treated, quenched and aged condition. Such a treatment typically consists of an α + β solution treatment (765°C for 2 hours followed by water quench), and a subsequent age (typically at 500°C for 8 hours). The β-transus temperature of the alloy is 800°C, some 160°C lower than Ti-6-4. The as-quenched structure optically appears to be β, but there is evidence of both an α'' and an ω_{ath} decomposition (5). The alloy can be easily forged above its β-transus temperature, but the properties are optimized by forging just below. This leads to a more spherical, or equiaxed, primary alpha distribution which tends to provide better ductilities. This temperature requirement is not as rigid as in the case of Ti-6-4, the alloy can be forged above its transus temperature when a maximum toughness condition is desired (6). The Ti-10-2-3 used in this particular study was a commercial ingot from RMI; no ingot breakdown beyond that routinely done by RMI was done prior to testing.

Transage 134: Transage 134 is an invention of Lockheed (2, 7, 8, 9) and was developed for very similar reasons and applications to those pertaining to Ti-10-2-3. The alloy is interesting scientifically because its β-transus temperature is notably lower than that of Ti-10-2-3 (765°C), but at the same time it can decompose martensitically during quenching from the β-phase field (10). In any case, the alloy should not, accurately speaking, be classified as a β- alloy, but as a very stable α + β-alloy, since a martensitic decomposition does occur during quenching. The optimum heat treatment of this alloy has probably not yet been established, but the recommended heat treatment is a 790°C solution treatment for 2 hours, oil quench, an aging at 650°C for one hour, oil quench, and finally, a 4 hour aging at 480°C. As a final comment on this alloy, one should note that it is the newest, and least tested of these alloys. The Transage used in this study was a laboratory sized ingot, melted and conditioned by Krupp (BRD).

Beta-c: The so-called β-c alloy, Ti-8V-6Cr-4Mo-4Zr-3.5Al, is the oldest of the β-alloys studied, and is the most stable in the sense that the decomposition of the β-phase tends to be quite slow. The β-transus temperature of the alloy is 790°C. The alloy is generally used in the ST'ed and aged condition, with the ST consisting of a 15 minute treatment at 820°C, and the aging a 565°C treatment for 6 hours. Although the alloy is said to have excellent cold working characteristics, relatively little is known about its hot workability. The β-c used in this study was taken from a 10 mm diameter cold drawn rod commercially available from RMI.

The flow stresses of the candidate alloys were determined at two strain rates by cylindrical upset compression tests in an instrumented 1000 kN hydraulic press. Specimens were 10 mm in diameter, 15 mm high, and were lubricated prior to testing with a boron-nitride-glass based lubricant. TZM dies (a molybdenum based alloy), were heated in argon using a 40 kW induction heating generator. Temperatures were measured continuously during forging via thermocouples within the TZM dies. Specimens were forged to a height of 5 mm (a 66% reduction), at fixed ram speeds of 0.1 and 4.0 mm per second. Temperature increases due to deformation were calculated in the worst case (assuming adiabatic conditions) to be 25°C.

The flow stresses of all four alloys were recorded as a function of strain. For all but the lowest temperatures, steady state material flow was observed almost immediately. Testing at the lowest temperatures, however, was characterized by a rather strong work softening. The flow stresses of the four materials were then plotted as a function of test temperature by taking the flow stresses at strains of $\varepsilon_1 = 0.5$. The results for $\dot{\varepsilon} = 1.1 \cdot 10^{-2}\ s^{-1}$ and $\dot{\varepsilon} = 4{,}4 \cdot 10^{-1}\ s^{-1}$ are shown in Fig. 2. At both strain rates, Ti-10-2-3 was proven to be the most forgeable alloy and Ti-6-4 the most difficult to forge. In fact, all the β-alloys were more forgeable than Ti-6-4, and given any specific stress level, one concludes that forging temperatures are between 100° and 120°C lower with 10-2-3 than with Ti-6-4.

It is common in such work to try to fit the flow characteristics of a material to the expression:

$$\dot{\varepsilon} = k\ \sigma^n \exp(-Q/RT) \qquad \text{Equ. 1}$$

To see if this equation can properly express the flow characteristics of our alloys, it is convenient to rearrange the equation into the form:

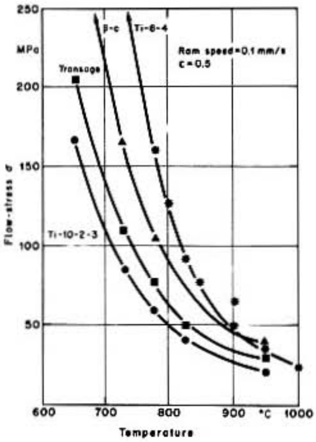


Fig. 2a: Flow stresses of the four Ti alloys at a ram speed of 0.1 mm/s ($\dot{\varepsilon} = 1.1 \cdot 10^{-2}\ s^{-1}$) for $\varepsilon = 0.5$.

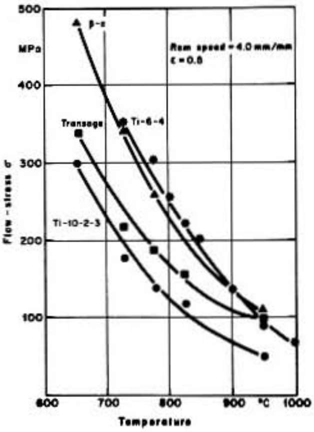


Fig. 2b: Flow stresses of the four Ti alloys at a ram speed of 4 mm/s ($\dot{\varepsilon} = 4.4 \cdot 10^{-1}\ s^{-1}$) for $\varepsilon = 0.5$.

$$\ln \sigma = \left[\frac{\ln(\dot{\varepsilon}/k)}{n} \right] + \left[{}^{Q}/_{R \cdot n} \right] \frac{1}{T} \qquad \text{Equ. 2}$$

Thus for any given strain rate, the quantities (1/T) and (ln σ) can be plotted as a straight line. This is done in Fig. 3. Such an exercise is quite successful in bringing all the data for given strain rate onto a straight line, but is unsuccessful in the respect that the slopes for the two strain rates differ. Thus one must conclude that either 'Q' or 'n' is not constant, but dependent upon either strain rate or stress.

From a practical point of view, one should relate the flow stress of the forging material normalized with the yield stress of the die material. Such a ratio gives some indication of the die lifetime. Figure 4 shows the flow stresses of the four candidate materials normalized with respect to the die material yield stresses. Note that the die material selected to normalize Ti-6-4 is TZM, while the material selected to normalize the beta alloys is IN 100; such a choice is logical since it is the basic premise of this work that switching alloys would permit one to switch die materials. As can be seen by this figure, the flow stress difference between Ti-10-2-3 at 850°C and Ti-6-4 at 950°C is not negatively affected by the normalization, and that in general, the advantages of 10-2-3 are exaggerated.

Since Ti-10-2-3 was found to be the most interesting of the candidate alloys from a forgeability point of view, it was decided to expand upon the upset forging program for this alloy by testing over a wider range of strain rates. Four new strain

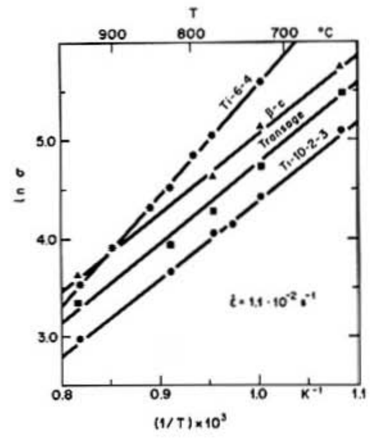


Fig. 3: The same data as shown in Fig. 2a, drawn as (1/T) versus (lnσ) with σ in MPa and T in K.

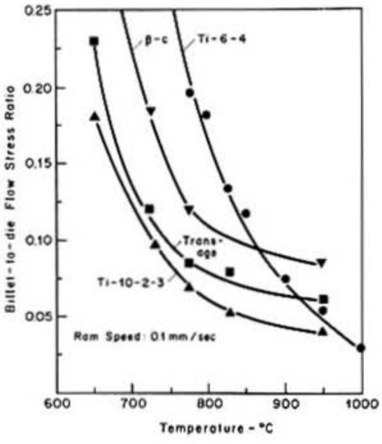


Fig. 4: Flow stress ratios with $\dot{\varepsilon} = 1.1 \cdot 10^{-2}\ s^{-1}$. All materials are normalized to the yield stress as function of temperature of IN 100 except Ti-6-4, which was normalized with TZM.

rates were tested, all at 815°C. For these tests a mechanical screw Instron machine was used, with ceramic dies and convective heating of the specimen. Loads, in this case, were measured directly with a load cell. Again taking the stresses at $\varepsilon = 0.5$, a plot was made of $\ln \sigma$ against $\ln \dot{\varepsilon}$. If the relationship expressed by equation (1) is correct, a straight line should result, with a slope of $m = 1/n$. Figure 5 shows the results of this effort, along with some similar results from other investigations. One should note that the slope may become a bit flatter at higher strain rates, but basically 'm' does seem to be a constant between $\dot{\varepsilon} = (6 \cdot 10^{-6} - 3.6 \cdot 10^{-1})\ s^{-1}$, with the best value for m being 0.33. This has two implications. First, 10-2-3 seems to behave quite differently from Ti-6-4, which is known to exhibit a distinct maximum in 'm' (11). Further, this observation seems quite similar to observations in Transage 129 (12), where a nearly constant strain exponent was measured over a wide range of strain rates, but somewhat at odds with previous observations in Ti-10-2-3 where m was reported to vary with strain rate (13). Secondly, the slope variations would not appear to be attributable to a non-linearity in 'm', but seem instead to be better described by a dependence in 'Q', similar to that reported by Martorell (14).

An attempt was made to refine the grain size of the Ti-10-2-3 alloy to see how grain size affected the flow stress of the alloy. The resulting grain size was found to be about 10 microns,

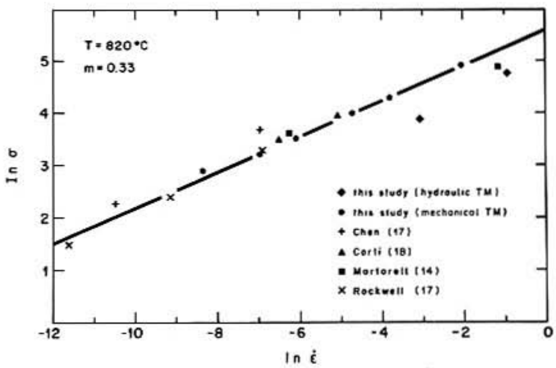


Fig. 5: Plot of ($\ln\dot{\varepsilon}$) vs ($\ln\sigma$) values for Ti-10-2-3 with σ in MPa and $\dot{\varepsilon}$ in s^{-1}.

compared to an original grain size of several hundred microns. Upset forging tests were conducted at 725°, 775° and 825°C. No difference in flow curves was found between the coarse and fine grain sizes. This is in agreement with Martorell (14), who found only very slight differences between grain sizes of 250 and 8 microns.

As a final comment on forgeability, it is possible to compare the forging response of this alloy with some other β-Ti alloys reported in the literature. Accordingly, we can conclude that both Ti-10-2-3 and Transage 134 are more forgeable than Ti-11.5Mo-6Zr-4.5Sn (β-III) (15), Ti-10Mo-6Cr-2.5Al (16), and Ti-10Mo-8V-2.5Al (16), which are, in turn, all more forgeable than Ti-6-4.

Pilot Phase Testing

Model impellers were made from the two most promising alloys, Ti-10-2-3 and Transage. The scaled wheels were 160 mm diameter, and of a complex shape requiring flow into rather long and narrow ribs (3 mm wide by 12 mm deep), Fig. 6. The dies used in these tests were IN 100, and the lubricant again a BN-glass mixture. The tests were done in a 3000 kN hydraulic press, and temperatures were measured at several points in both the bottom and top dies. Both the dies and the preform were heated by induction heating, and forging was done in vacuum. Due to the complex shape of the forging and the dies, heating was not very uniform; temperature differences of up to 60°C were detected during forging.

Two finished forging are shown in Fig. 6, along with the preform geometry used. For a given holding temperature, time, and load, Ti-10-2-3 had a flowability superior to that of Transage, but both alloys were indeed forgeable at 850°C. The surface quality, in all cases was excellent, and in no cases were cracks observed.

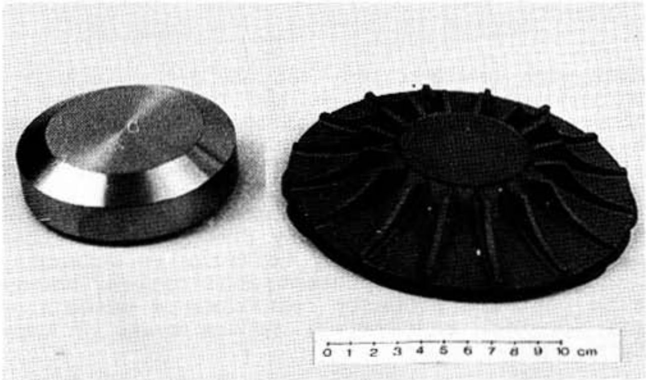


Fig. 6: Pilot phase (a) preform shape, (b) finished Ti-10-2-3 forging. Forgings were held for 20 minutes at 850°C under a load of 2200 kN.

<u>Tensile Properties</u>

After slowly cooling, the forged wheels were sectioned and properties measured. Although a detailed accounting of the results is too lengthy to be presented here, it is useful to summarize:

1. Tensile strength and ductility in the circumferential direction were found to be superior in solution treated and aged Ti-10-2-3 than in mill annelaed Ti-6-4 wheels. This strength advantage was reduced by correcting for density differences, but not eliminated. The advantage was maintained over the full range of test temperatures, from 20 to 300°C.

2. Since the above strength advantage could not be utilized without redesigning the entire turbocharger, a less expensive heat treatment route for the Ti-10-2-3 was attempted: directly ageing the as-forged condition. Direct ageing at 500°C for 8 hours was found to result in reduced strength and ductility when compared to Ti-10-2-3, but results that were quite comparable to Ti-6-4 on a density normalized basis.

3. Both smooth and notched bar rotating-bending fatigue tests were conducted. Although the scatter was significantly greater in Ti-10-2-3 than in the mill annealed Ti-6-4, the minimum lifetime envelopes for the two materials coincided almost perfectly once the stresses were normalized with density. (The Ti-10-2-3 was tested in the directly aged condition described

above.)

Summary

The present work demonstrates that the β-Ti class of alloys are more easily forged than Ti-6-4, and that Ti-10-2-3 is the most easily forged commercially available β alloy. Similar flow stresses and flow into complex shapes can be achieved with Ti-10-2-3 at temperatures some 100-125°C lower than those used for Ti-6-4. Such lower temperatures allow one to change to less expensive die materials. Super-transus forging of Ti-10-2-3 is uncommon in the aircraft industry due to the delicate thermomechanical conditions necessary to optimize strength, ductility, and toughness; in the present application, however, it was possible to meet the property requirements using super-transus isothermal forging, and thereby reduce costs by improving the proximity to net shape.

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