CREEP BEHAVIOUR OF A Ti-6Al-4V ALLOY IN DIFFERENT HEAT TREATING CONDITIONS

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The creep behaviour of a Ti-6Al-4V alloy in various heat treating conditions has been analysed. In the MA condition material exhibited the poorest creep behaviour. Fractographic examination revealed a small number of holes sited in the neighbourhood of the fracture surface suggesting that they are not really creep cavities but voids produced by plastic deformation and dislocation climb was the operating mechanism. Maximum creep lives were achieved in BA samples but with the drawback of a very low ductility. Operating failure mechanism was grain boundary sliding. 940/4 samples showed an intermediate creep behaviour and a dimpled fracture occurred by the nucleation, growth and coalescence of creep cavities formed at the alpha phase grain boundaries. Notched specimens exhibited longer creep lives than smooth ones indicating a very significant notch strengthening.

INTRODUCTION

Creep can be defined as the time dependent increase in strain in a solid which results under sustained load and eventually may lead to failure. Even if this deformation can occur at all temperatures above absolute zero it is only significant at temperatures above a certain limit. In components operating at elevated temperature this failure mechanism often becomes the determining factor for design.

Moreover, components operating at elevated temperatures are usually subjected to triaxial states of stress resulting from the mode of loading or from sharp changes in sections which cause marked local stress concentrations. In order to determine useful component lifetimes in such circumstances laws governing material behaviour under multiaxial stressing are needed. Of particular concern are states of triaxial tension since these inhibit deformation, enhance fracture processes, and can cause premature failure. Both notch strengthening and notch weakening have been observed, depending upon the notch dimensions and material examined (1).A uniform state of triaxial stress is difficult to produce in laboratory experiments. Notch testing evolved as a means of assessing the performance of materials subjected to a stress concentration equivalent to those typically found in engineering components. The most frequent method of introducing a three-dimensional state of stress into a specimen is to subject a circumferentially notched bar to an axial tensile load.

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As it has been previously indicated below a certain temperature it is widely accepted that the elastic-plastic behaviour of the metallic materials is time independent. However, many titanium alloys have been shown to exhibit appreciable amounts of creep at ambient temperatures at stresses far below the yield strength but work hardening and lack of recovery result in creep saturation and the creep curves appear to level off (2). A similar decrease in the stress rate to zero at elevated temperature is observed when the applied stress is below a threshold level (3). However, at even higher temperatures and/or stresses, both primary and secondary creep are found and the creep rate increases with temperature or stress level (3,4).

Relative to its melting point the creep resistance of titanium alloys is rather poor. A temperature in the range 600-650° C may represent a barrier for future developments in titanium alloys due to surface oxidation during prolonged exposures to temperature (5).

Ti-6Al-4V was developed during the fifties and rated up to about 350° C. Since its introduction it has become the universal workhorse in the aerospace industry and has widespread to other applications. Moreover, the mechanical properties of this alloy can be significantly modified by thermomechanical treating.

The objective of this paper is to investigate the influence of heat treatment on the creep behaviour of both smooth and notched specimens of a Ti-6Al-4V alloy.

EXPERIMENTAL PROCEDURE

The material chosen for the present study was a 17 mm thick plate of a Ti-6Al-4V alloy whose chemical composition was given in a previous paper (6). In the as received condition this plate was in the mill annealed (MA) condition, that is a short maintenance at 720° C followed by air cooling as the final step of its thermomechanical process.

Various coupons obtained from this plate were heat treated in a small laboratory furnace under argon protection. BA samples were annealed in the beta field at 1030° C for 1/2 hour, air cooled and aged 2 hours at 730° C. Those samples marked as 940/4 were treated in the alpha-beta field at 940° C for 4 hours, furnace cooled to 700° C and air cooled to obtain a good combination of ductility and toughness.

Smooth creep specimens were machined from these heat treated coupons in the longitudinal or transverse directions. Moreover, Bridgman semi-circular notched specimens were obtained in the longitudinal direction of the plate. Creep tests were performed at 455° C in air at two stress levels. Following failure a fractographic examination of the broken specimens was performed to determine the operating mechanism.

RESULTS AND DISCUSSION

Table 1 exhibits the creep lives (t_r) for various smooth, longitudinal (L) and transverse (T), or notched (N) specimens together with the steady state creep strain rate.

TABLE 1 - Results obtained in the creep tests .

Ref.	Or.	σ(MPa)	ε' (h^{-1})	t_r (h)	Ref.	Or.	σ(MPa)	ε' (h^{-1})	t_r (h)
MA	L	489	0.349	36	BA	T	489	0.044	178
MA	L	345	0.017	714	BA	N	489	0.0007	2377
MA	T	489	0.163	61	940/4	L	489	0.057	107
MA	N	489	0.0012	828	940/4	L	379	0.0033	1619
BA	L	489	0.037	209	940/4	T	489	0.101	58
BA	L	379	0.0046	1744	940/4	N	489	0.0018	828

Minimum creep lives are recorded in tests carried out on specimens in the as-received (MA) condition. Scanning electron microscope observation of the broken specimens revealed that their fracture surfaces are covered with ductile dimples pointing towards a microvoid coalescence mechanism. Moreover, metallographic analysis of longitudinal sections of these specimens revealed that a reduced number of holes, just sited in the neighbourhood of the fracture surface. This suggests that these holes are not really creep cavities but voids generated by the plastic deformation of the material and dislocation climb activated by the testing temperature was responsible of the failure. Figure 1 shows one example of these voids near the fracture surface.

No clear explanation has been found for the observed differences between longitudinal and transverse specimens as the microstructure of the alloy in both orientations is very similar and the failure operating mechanism identical. The opposite trend was found in the fracture toughness tests where higher values in the L-T specimens were obtained (6). A plausible explanation for this behaviour could be based on the basal type texture of the plate although a larger number of data and in-depth research will be needed before a conclusion is reached.

BA samples exhibited the maximum creep lives in both longitudinal and transverse directions and in smooth or notched specimens. A very great isotropy of properties was found and the life recorded in the specimen machined in the longitudinal direction was only a 15% longer than that in the transverse one. Once again fractographic examination of the broken specimens revealed the operating failure mechanisms. As it is seen in the figure 2 cracks were formed at the former beta grain boundaries and preferentially at the triple-point corners indicating that the operating mechanism was grain boundary sliding.

The most salient observation is nevertheless the strongly marked increase in creep life, about 11 times longer, of the notched specimens with respect to the smooth ones. It must be kept in mind however that although the notched specimen may have a higher net section stress it requires lower load for fracture (7). Moreover, it has been pointed out that the ratio of rupture strength between notched and smooth specimens for a given life initially increases with the notch sharpness but reaches a peak and then decreases with increasing sharpness. That seems to indicate that there is a limit to the amount of notch strengthening that a material may exhibit.

The fractographic analysis of this notched specimen revealed a near complete similitude in the facets with those observed in the smooth ones. The only significant difference that was found is based on the distribution of the cracks along the specimens. In the smooth specimens cracks were observed relatively far-away from the fracture surface while in the notched ones they were confined to the notched section where a stress concentration is introduced.

Moreover, material in this condition possesses the maximum fracture toughness in both orientations that was associated with the microstructure constituted by relatively fine needles of alpha phase with a basket-weave appearance (6). Due to this microstructure fracture propagates along a tortuous path surrounding individual needles. However, as a consequence of this acicular microstructure, BA specimens presents the drawback of a very poor ductility, not only in the tensile tests but also in the creep ones, which could lead to an unexpected failure.

A very strong directionality is observed in the alpha-beta annealed and furnace cooled (940/4) samples. Both smooth and notched specimens machined in the longitudinal direction showed clearly longer creep lives than those in the as-received MA condition for the two stress levels that have been considered. Time to failure for the 940/4 sample tested at the lowest stress level is even just slightly below than that recorded in the BA specimen. On the other hand, MA and 940/4 specimens machined in the transverse orientation showed nearly identical failure times which were clearly lower than those in the BA sample. This anisotropy was not observed in tensile or fracture toughness tests where near identical values were measured in both orientations.

The metallographic and fractographic studies carried out on these broken specimens helped to understand these differences in behaviour. The failure operating mechanism was one of diffusional creep even if the Norton´s law exponent (11.25) much higher than the linear relationship between strain rate and stress proposed in the models seems to contradict this hypothesis. It will be necessary to have a larger number of data before a definitive conclusion could be reached. Dimpled fracture occurred by the nucleation, growth and coalescence of the creep cavities formed at the alpha phase grain boundaries Directionality in creep lives could be attributed to the longer mean free path and the presence of a certain number of needles in the longitudinal specimens that were not observed in the transverse one. These differences in microstructure are easily seen when the micrographs of the figures 3 and 4 are compared.

This point deserves further analysis as if the operation of diffusional creep is confirmed, according to the proposed models, a decrease of the secondary creep strain rate with the square or the cube of the grain size can be expected. Moreover, this larger grain size of the alloy also produces an improvement in fracture toughness with no significant effect on the mechanical strength or the ductility (6).

Material in the MA or 940/4 conditions also exhibits a certain notch strengthening as the creep lives recorded in tests performed on the notched specimens were markedly higher than those in the smooth ones. Nevertheless, these differences were not so high as those found in the BA condition.

CONCLUSIONS

a.- Maximum creep lives were obtained in beta annealed BA specimens in any direction and in both smooth and notched ones. However, this microstructure that also possesses the highest fracture toughness presents the drawback of poor ductility. Operating failure mechanism on these samples was grain boundary sliding.

b.- 940/4 samples exhibit a strong directionality with lives in the longitudinal direction clearly higher than that of the transverse specimen. Diffusional creep seems to be the operating mechanism although an in-depth research is recommended in order to improve the creep resistance.

c.- MA specimens possessed the shortest creep lives and fractographic analysis suggests that failure is produced by dislocation climb and holes found near the fracture surfaces are not creep cavities but voids produced by the plastic deformation of the material.

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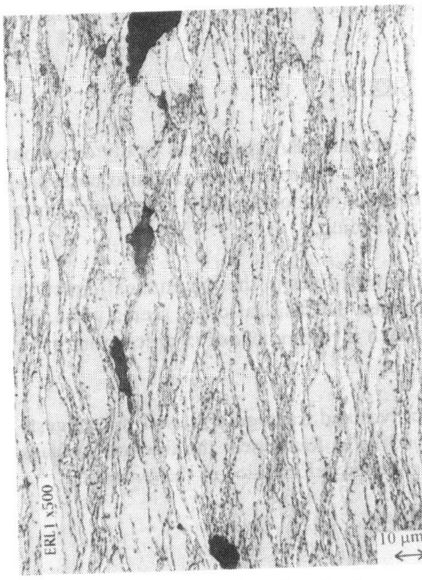

Figure 1. Voids created by the plastic deformation MA specimen

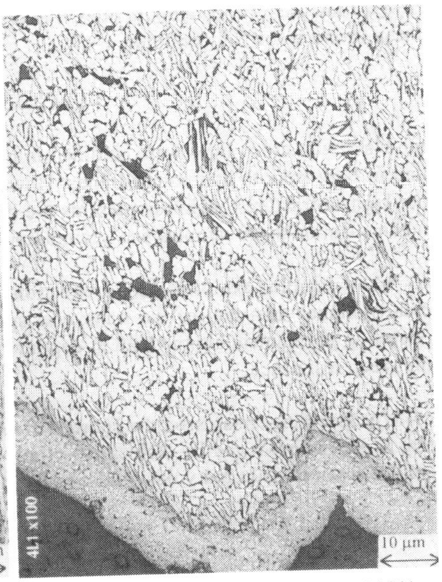

Figure 3. Creep cavities in a 940/4 longitudinal specimen

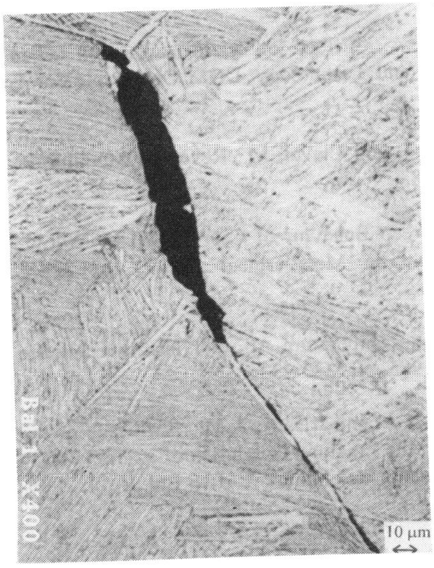

Figure 2. Grain boundary sliding BA specimen

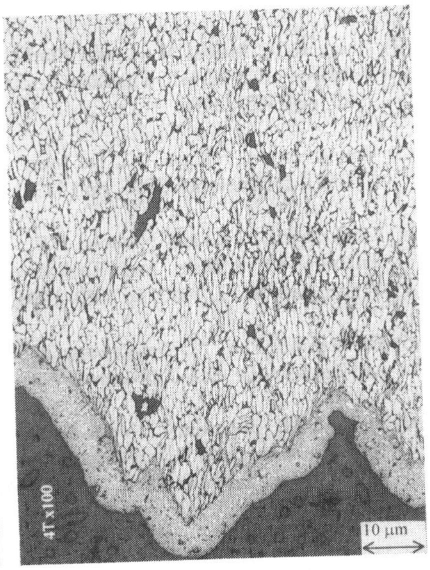

Figure 4. Creep cavities in a 940/4 transverse specimen