A METALLOGRAPHIC STUDY OF CAVITATION IN Ti-6A1-4V ALLOY

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ABSTRACT

Metallographic evidence is presented to show that cavities nucleate and grow in Ti-6Al-4V alloy below 850°C. Cavities are not observed in specimens deformed above this temperature due to the presence of larger volume fraction of β phase. Cavities seem to nucleate at α/α, α/β interfaces, at grain boundary triple points and at hard particles located at grain boundary. During growth, the cavities become elongated and align themselves in the direction of tensile axis, suggesting the operation of plasticity-controlled hole growth process.

KEYWORDS

Cavity nucleation and growth, superplasticity, Ti-6Al-4V.

INTRODUCTION

Superplastic forming has been demonstrated to be a very viable forming process for airframes and for gas turbine engines using the new generation of alloys. Sometimes however, the limiting conditions for superplastic forming are set not by maximum attainable ductility but by the onset of superplastic cavitation and cavity interlinkages, leading to failure. Contrary to earlier reports, cavitation at grain boundary is now known to be a fairly common phenomenon during superplastic deformation.

Many titanium alloys exhibit superplasticity in the temperature range where the α and β phases coexist. The Ti-6Al-4V alloy displays optimum superplastic properties near 925°C (Paton et. al., 1979), the temperature often used for superplastic forming of full scale components with this alloy. However, a lower forming temperature would be of significant help in reducing die wear, shorten forming cycle times and also would minimize problems associated with oxidation. Unfortunately, such lowering of forming temperature also enhances the ease of cavity nucleation and growth. The present work describes the result of decreasing the temperature of superplastic deformation on the cavitation process in Ti-6Al-4V alloy.

EXPERIMENTAL

All mechanical tests were conducted using a MTS servohydraulic machine interfaced with a PDP/11 computer and digital data acquisition system. This enabled us to use the computer as a controller in order to conduct either constant strain rate or differential strain rate tensile tests. In the latter test, a single specimen is strained at constant temperature at various strain rates in either an incremental or decremental mode. The "Quad Elliptical Radiant" heating furnace provided a heating rate of 200°C/min. The "Phaser" power controller gave excellent temperature control capability (±1°C). The tests were conducted in an atmosphere of purified argon gas. At the conclusion of the tests, specimens were quenched in pre-chilled argon, under load, in order to preserve the deformed microstructure for subsequent metallographic observation at room temperature.

The Ti-6Al-4V alloy was vacuum cast and then forged in "β" phase field and subsequently hot rolled at 925°C to give a total reduction of 97 percent. This thermomechanical processing produced a fine grained (~10 microns diameter) equiaxed microstructure of α and β phases. In order to establish the relationship between the flow stress and the strain rate, tests were conducted over a range of strain rates (5×10^{-6} to 2×10^{-4} s^{-1}) and temperatures (750°, 800°, 850° and 900°C). The plot of log (stress) vs log (strain rate) delineated the range of manifestation of region II of superplasticity in this alloy.

The deformed specimens were investigated in a Phillips EM400 electron microscope operating at 120 KV. The specimens were jet polished and finally thinned electrolytically using an electrolyte consisting of 30 ml perchloric acid, 75 ml butylalcohol, 300 ml methanol at 35 volt and at -35°C. For scanning electron microscopy, the specimens were lightly etched using an etchant consisting of 10 percent HF, 5 percent HNO_3, and 85 percent H_2O and investigated using a Hitachi SEM operated at 30 KV.

RESULTS

The temperature and strain rates selected for deformation in this investigation were such that the specimens deformed in region II of superplasticity. As a general rule above 900°C, no cavities were detected in the present work. Cavities were observed in Ti-6Al-4V in the temperature range of 750-850°C and at a strain rate $\dot{\varepsilon} = 10^{-5}$ to 10^{-4} s^{-1}. The higher the temperature, the more difficult is the task of revealing the cavities, particularly while using TEM because of transformed martensile in the microstructure. Fig. 1 (SEM micrograph) shows cavities formed at 800°C at a strain rate of 10^{-4} s^{-1} and the cavities are aligned along the tensile axis. Fig. 2 (TEM) shows the presence of cavity at α/α grain boundary after deformation at 750°C at $\dot{\varepsilon} = 10^{-4}$ s^{-1} to a true strain of 1.0. Fig. 3 (SEM) shows similar cavity at 850°C at a true strain of 1.4 for a specimen tested at the same strain rate as that for Fig. 2. Fig. 4 (SEM) shows the presence of cavity at α/β grain boundary after deformation at 850°C and at $\dot{\varepsilon} = 10^{-4}$ s^{-1}. Fig. 5 (TEM) shows a cavity formed at grain boundary triple point and observed at an early stage of deformation (true strain 0.2). Often the cavity can be clearly associated with particle located at grain boundary. Fig. 6 (TEM) reveals such a cavity presumably formed by decohesion of particle and matrix in the grain boundary region. Fig. 7 (TEM) depicts a cavity situated at the interface of a second phase particle and α matrix close to a triple point region. Fig. 8 (SEM) shows the coalescence of cavities that are located between two beta and three alpha grains.

DISCUSSION

One of the main microstructural aspect of superplastic deformation is the dominant role played by grain boundary sliding (GBS). This sliding process gives rise to stress concentration at grain boundary triple points or at hard particles located at the grain boundary. Most of the theoretical models for superplasticity have to deal with appropriate accomodation process in order to relieve this stress concentration. Such accomodation process however, can be inadequate under some microstructural and test situations, leading to opening up of cavities.

Cavities are not easily seen in specimens deformed above 850°C. Earlier workers (Ito and Hasegawa, 1980; Cope, 1982) have also confirmed this observation. The reason for the absence of cavitation above 850°C is very likely due to the larger amount of highly deformable β phase present in the microstructure at higher temperatures. The β phase is seen to coat the α/α phase boundaries, often in a continuous fashion. This observation supports the conjecture that the soft β phase helps to accomodate the grain boundary sliding process.

Both TEM and SEM micrographs showed that cavities are nucleated preferentially at α/α and α/β boundaries. However, no cavities were seen in β/β boundaries. The diffusivity of Ti in the β-phase is two orders of magnitude greater (Leclaire, 1964) than that in α-phase. Hence, cavities presumably do not form in β/β boundary because of the ease of diffusional accomodation at such an interface.

Cavities can also nucleate in this alloy due to stress concentration at grain boundary triple points (Fig. 5) or by decohesion of hard particles located at the grain boundary (Fig. 6). We have observed both dynamic recrystallization (at lower temperatures, higher strain rate) and grain growth (at higher temperatures and/or lower strain rates) in this alloy as a result of superplastic deformation. These processes signify alterations in grain boundary positions (i.e., migration, etc.). Hence, it was possible to occasionally observe cavity associated with particle that was not located at a grain boundary. Presumably the particle was at the grain boundary to begin with and the grain boundary subsequently migrated to another position.

The cavities seem to grow by a process of interlinking in a direction parallel to the tensile axis (Fig. 1). As a consequence of such cavity coalescence and growth, a larger cavity can often be seen between two β grains (Fig. 8) even though they are never seen to nucleate at β/β grain boundary. The elongated shape of the cavities and their alignment along the tensile axis, suggests a plasticity-controlled cavity growth

(Hancock, 1976) rather than diffusion-controlled growth (Beere', 1978). The present observation on cavitation in Ti-6Al-4V is very similar to an earlier investigation on α/β brasses (Patterson and Ridley, 1981). In that work, low volume fraction of β phase (achieved by having lower zinc content in the alloy) was associated with maximum cavitation. This was explained in terms of the inadequate volume fraction of the highly accomodating (deformable) β phase in that alloy. These results compare with those obtained in the present work as well as that obtained by Cope (Cope, 1982) on Ti-6Al-4V, where the phase proportions were varied by changing the temperature rather than the alloy content.

CONCLUSIONS

Nucleation and growth of cavities are observed in fine grained Ti-6Al-4V alloy superplastically deformed below 850°C. Above this temperature, no cavities can be detected in the α/β titanium alloy. The lack of cavitation at higher temperatures is very likely due to the presence of larger volume fraction of soft, deformable β phase. At temperatures below 850°C, cavities are seen to nucleate at α/α, α/β interfaces, at grain boundary triple points and at hard particles located at the grain boundary. The elongated shape of the growing cavities and their alignment along tensile axis suggest a plasticity-controlled cavity growth process.

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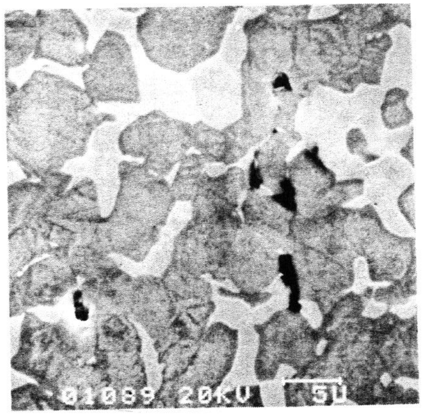

Fig. 1. Cavities aligned along the tensile axis, specimen deformed at 800°C, $\dot{\varepsilon} = 10^{-4}$ s^{-1}, $\varepsilon = 1.35$. (SEM, X 1000)

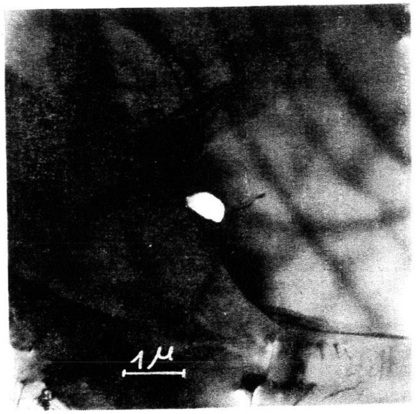

Fig. 2. Cavity at α/α grain boundary, 750°C, $\dot{\varepsilon} = 10^{-4}$ s^{-1}, $\varepsilon = 1.0$. (TEM, X 12,550)

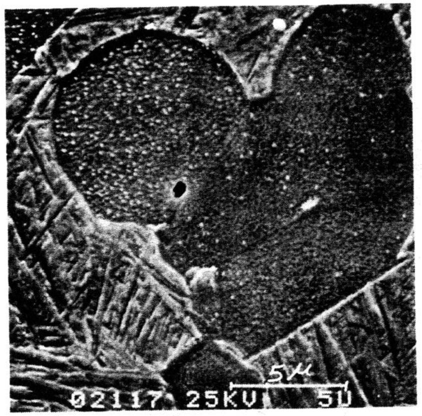

Fig. 3. Cavity at α/α grain boundary, 850°C, $\dot{\varepsilon} = 10^{-4}$s^{-1}, $\varepsilon = 1.0$. (SEM, X 5,000)

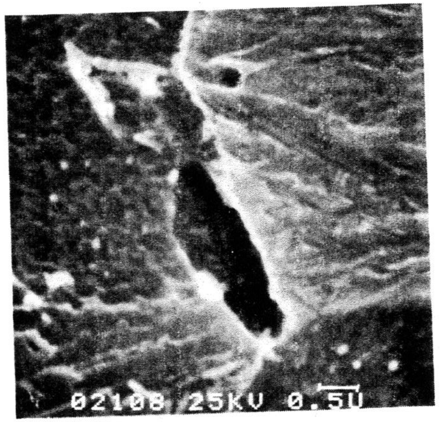

Fig. 4. Cavity at α/β grain boundary, 850°C, $\dot{\varepsilon} = 10^{-4}$ s^{-1}, $\varepsilon = 1.4$. (SEM, X 10,000)

Fig. 5. Cavity at grain boundary triple point, at early strain, 800°C, 10^{-4} s^{-1}, $\varepsilon = 0.2$.
(TEM, X 60,000)

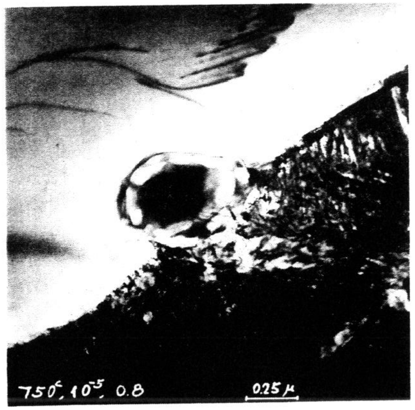

Fig. 6. Cavity formed by decohesion of particle/grain boundary interface. 750°C, $\dot{\varepsilon} = 10^{-5}$ s^{-1}, $\varepsilon = 0.8$.
(TEM, X 27,000)

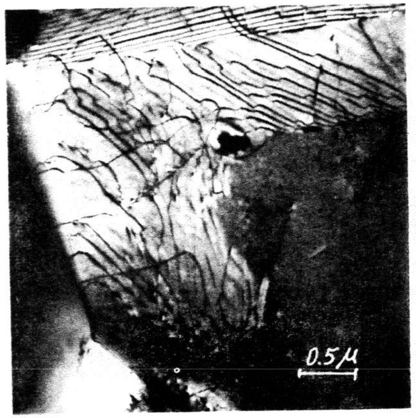

Fig. 7. Cavity at interface of particle and α matrix, close to a triple-point region.
(TEM X 27,500)

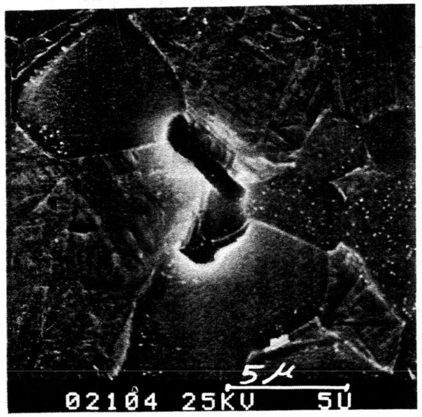

Fig. 8. Cavity coalescence between two beta and three alpha grains. 850°C, $\dot{\varepsilon} = 10^{-4}$ s^{-1}, $\varepsilon = 1.4$.
(SEM, X 10,000)