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Superplastic properties of a TiAl based alloy with a duplex microstructure

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The superplastic properties of a engineering TiAl based alloy with a duplex microstructure were investigated with respect to the effect of testing temperatures ranging from 950°C to 1075°C and strain rates ranging from 8×10^{-5} s^{-1} to 2×10^{-3} s^{-1}. A maximum elongation of 467% was achieved at 1050°C and at a strain rate of 8×10^{-5} s^{-1}. The apparent activation energy was calculated to be 345 kJ/mol. Also, the dependence of the strain rate sensitivity values on strain during superplastic deformation was examined through the jump strain rate tests, and microstructural analysis was performed after superplastic deformation. It is concluded that superplasticity of the alloy at relatively low temperature and relatively high strain rate results from dynamic recrystallization, and grain boundary sliding and associated accommodation mechanism is related to superplasticity at higher temperature and lower strain rate.

1. Introduction

Ordered intermetallic alloys have considerable potential for advanced structural applications at high temperatures, due to their attractive elevated temperature strength, low density and good oxidation resistance. However, ordered intermetallic alloys normally exhibit low ductility at intermediate and room temperatures. Much research has been focused on the improvement of the low ductility of these intermetallics by alloying and control of microstructure through thermomechanical processing [1–2]. Recently, superplasticity in the intermetallic alloys, such as nickel aluminides, titanium aluminides, and so on, has been demonstrated [3–6], which makes it possible to utilize superplasticity of these intermetallic alloys for shaping into structural components.

Titanium aluminide, one of the most important ordered intermetallic alloys, has become the subject of extensive investigation during the past decade. It was pointed out that duplex TiAl based alloys consisting of equaixed gamma and lamellar $\gamma + \alpha_2$ grains have reasonably high mechanical properties [7]. Further more, superplasticity of the TiAl based alloys with a duplex microstructure was also reported [8–10]. Cheng *et al*. demonstrated superplasticity with an elongation of 275% in a duplex Ti-43 at% Al alloy at 1050°C and at an initial strain rate of 2.4×10^{-4} s^{-1} [9]. Lee *et al*. systematically studied superplasticity of a practical engineering TiAl based alloy which had a duplex microstructure at relatively high temperatures above the eutectoid temperature and the tensile elongation of 470% was achieved at 1280°C and at 8×10^{-5} s^{-1} [10]. From the application viewpoint, such high deforming temperatures cause both tooling and oxidation problems. Therefore, a reduced forming temperature and a high superplasticity for the TiAl alloys are desirable. It is the aim of the present work to investigate superplastic properties of a technological Ti-46.8Al-2.2Cr-0.2Mo (at%) alloy with a duplex microstructure, with respect to the effects of testing temperatures below the eutectoid temperature and of strain rates. The microstructural evolution after superplastic deformation is also examined and correlated to the mechanical properties. Finally, possible mechanisms of the superplastic deformation of the duplex TiAl based alloys are discussed.

2. Experimental procedure

The alloy with a composition of Ti-46.8Al-2.2Cr-0.2Mo (at%) was prepared by arc-melting with a consumable electrode in an argon atmosphere. The ingots of 7 kg were given a hot isostatic pressing treatment at 1250°C for 4 hrs under a pressure of 170 MPa to remove porosity, and were homogenized at 1040°C for 48 hrs in an flowing argon atmosphere. Then, the ingots were forged isothermally at 1040°C with a compression strain of about 80% and subsequently heat-treated at 1250°C for 4 hrs. The initial microstructure of the alloy is presented in Fig. 1, which shows a typical duplex microstructure consisting of equaixed gamma and lamellar $\gamma + \alpha_2$ grains. Measurement of the volume fraction of α_2 phase was not attempted due to the difficulty to distinguish them by optical microscopy. The mean grain size of gamma and lamellar grains was measured to be 16 μm by the linear intercept methods.

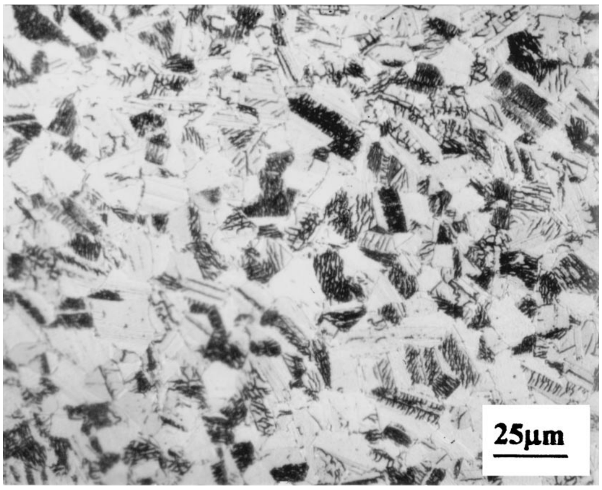

Figure 1 The initial microstructure of a duplex TiAl based alloy.

Specimens for mechanical tests were wire-cut from the treated materials with a gauge section of $2 \times 3 \times 6$ mm. The tensile axis of the specimens was perpendicular to the forging direction of the alloy. Tensile tests were conducted in air on a Shimaduz test machine equipped with a split and three zone high temperature furnace. Test temperatures ranged from 950°C to 1075°C in $\gamma + \alpha_2$ areas and approximately constant strain rates ranging from 8×10^{-5} s^{-1} to 2×10^{-3} s^{-1} were obtained through increasing of the crosshead speed of the machine. The gauge length of the specimens was coated with a thin special glass layer in order to prevent the specimen from early damage or failure due to oxidation in the processing of high temperature deformation in air. Incremental strain rate tests were performed to determine the flow stress and the strain rate sensitivity value as a function of strain rate. Specimens were initially deformed at an intermediate strain rate of 2×10^{-4} s^{-1} for all the incremental tests. Also, the dependence of the strain rate sensitivity values on true strain during superplastic deformation was examined through the jump strain rate tests.

The initial microstructure and microstructure after superplastic deformation of the specimens were observed by optical microscopy. The Kroll's agent (10% HF + 5% HNO_3 + 85% H_2O) was used to etch the specimens.

3. Results and discussion

The tensile true stress-strain curves of the duplex Ti-46.8Al-2.2Cr-0.2Mo (at%) alloy loaded at different temperatures are shown in Fig. 2a. At a strain rate of 2×10^{-4} s^{-1} (when $T = 1075$°C, strain rate was 8×10^{-5} s^{-1}), a prolonged stage of steady flow after an immediate hardening stage was observed at 1000°C and above, and a peak of flow stress at a certain strain followed by strain softening occurred at 950°C for the alloy. At a fixed temperature of 1050°C, the effect of strain rates on the stress-strain curves of the alloy is presented in Fig. 2b. The alloy exhibits almost a steady flow after an immediate stage of hardening at relatively low strain rates of 2×10^{-4} s^{-1} and below. At a strain rate of 8×10^{-4} s^{-1}, the alloy softens continuously after an early hardening stage. All of the specimens deformed quite uniformly. Table I summarizes the results of superplastic elongation of the alloy with respect to the testing temperatures and strain rates, which shows that the duplex TiAl based alloy is of a high superplasticity deformed at temperatures below the eutectoid temperature. At temperature of 950°C and a strain rate of 2×10^{-4} s^{-1}, the tensile elongation of the alloy was 263%. A maximum elongation of 467% was achieved at 1050°C and at a strain rate of 8×10^{-5} s^{-1}. This value is the same as that reported in literature [10]. However, the superplastic deformation temperature in the present work is lower than the temperature adopted in the literature by more than 200°C.

The flow stress and strain-rate sensitivity of the duplex TiAl alloy, which were determined from incremental strain-rate tests, plotted against strain rate at

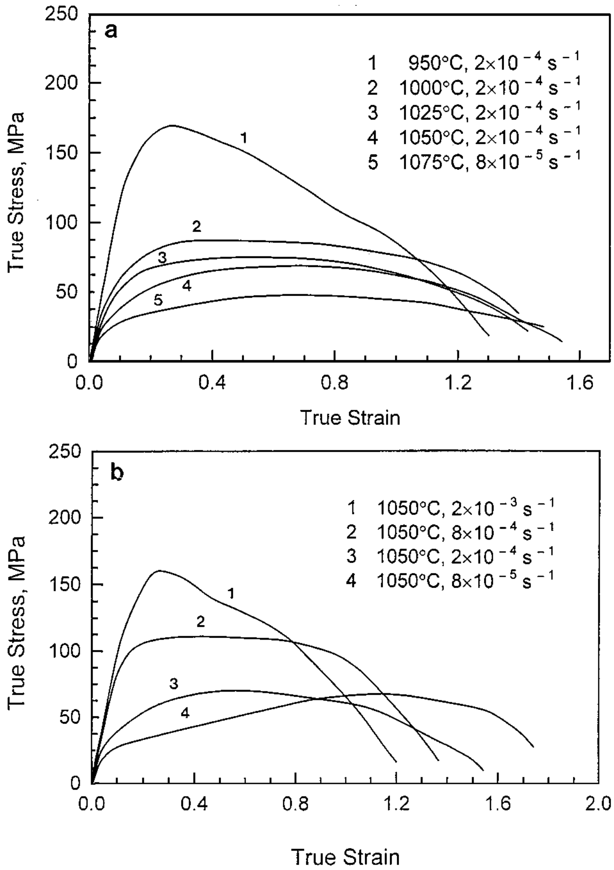

Figure 2 Effect of temperatures (a) and strain rates (b) on the true stress-strain curves of the duplex TiAl alloy.

TABLE I Elongations of a duplex TiAl based alloy deformed at different testing conditions

Temperature, °C	950	1000	1025	1050	1075	1050	1050	1050
Strain rate, s^{-1}	2×10^{-4}	2×10^{-4}	2×10^{-4}	2×10^{-4}	8×10^{-5}	2×10^{-3}	8×10^{-4}	8×10^{-5}
Elongation, %	263	310	317	360	333	233	290	467

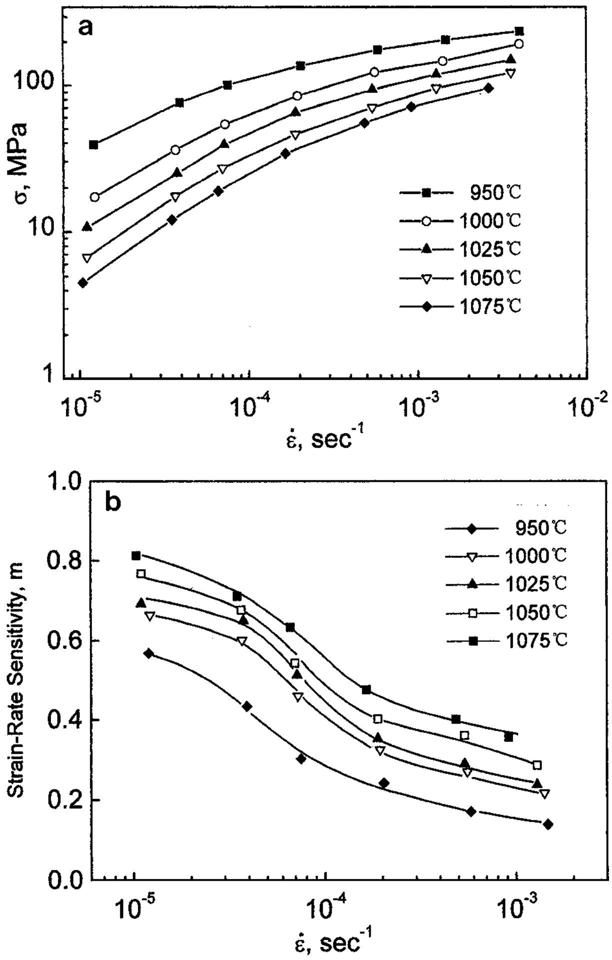

Figure 3 Plots of the flow stress (a) and strain-rate sensitivity (b) vs. strain rate of the duplex TiAl alloy.

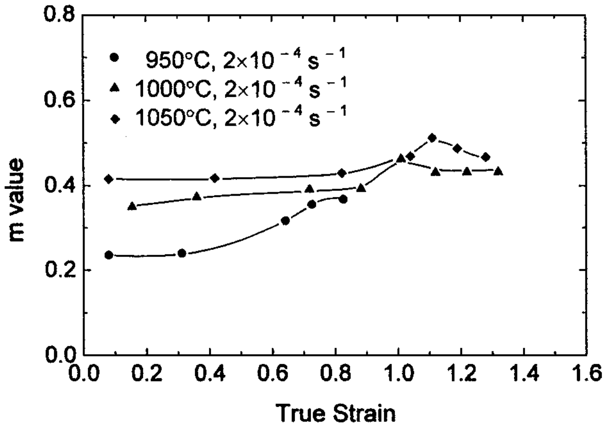

Figure 4 Variation of the *m* values as a function of the true strain of the duplex TiAl alloy during superplastic deformation.

temperatures ranging from 950°C to 1075°C are shown in Fig. 3a and b. The strain rate sensitive values, m, were calculated from strain rate step test plots, not derived from the slopes of curves in Fig. 3a. It can be seen that the m values of the alloy are about 0.5 and above at 1000°C and strain rates lower than $7 \times 10^{-5}\ s^{-1}$, and drop to 0.33 above $2 \times 10^{-4}\ s^{-1}$, which suggests the change of the rate controlling mechanism at higher strain rates. At higher temperatures, the transition in m from a higher value at intermediate strain rate to a low value at higher strain rate is shifted to higher strain rates (in Fig. 3b).

By using the flow stress data as a function of strain rates obtained from the step strain rate tests in Fig. 3a and the usual power law creep relationship:

$$\frac{d\varepsilon}{dt} = A\sigma^n \exp\left(-\frac{Q}{RT}\right),$$

the apparent activation energy, Q, for the superplastic deformation of the TiAl alloy can be calculated at stress level of 20–60 MPa. The apparent activation energy of the alloy is 345 kJ/mol. This value is comparable to the activation energies in the TiAl based alloys with a typical duplex microstructure obtained by Cheng *et al.* and Lee *et al.* respectively [9, 10].

Variation of the strain rate sensitivity values, m, as a function of strain in the process of superplastic deformation at temperatures of 950°C, 1000°C and 1050°C and at a strain rate of $2 \times 10^{-4}\ s^{-1}$ is shown in Fig. 4. The initial m value of 0.235 was low and with increasing strain the m value increased gradually to 0.367 at 950°C. When the alloy tested at 1000°C and above, the m values nearly kept the level of about 0.4 with the true strain to a value of about 0.9 Subsequently, the m values increased slightly until the maximum value and then decreased slowly. It is noted that the variation of the m value during superplastic deformation was not large and the maximum value of m at 1050°C reached 0.512.

In order to explain the mechanical properties, microstructural analysis of the TiAl alloy after superplastic deformation was performed. The microstructures of the alloy deformed at different temperatures are shown in Fig. 5. By comparing with the initial microstrusture, it is seen that the grain size of the alloy tested at 950°C decreased and new fine grains were also observed in the alloy after superplastic deformation. It is assumed that dynamic recrystallization took place in the process of deformation. At 1000°C and above, the grain size of the alloy did not change apparently after superplastic deformation. Therefore, the peak of flow stress in the very early stage of deformation and subsequent continuous softening on the true stress- strain curves of the alloy tested at 950°C can be related to dynamic recrystallization during deformation. An increase of m value results from the refining of the microstructure in the process of deformation. Also, dynamic recrystallization is considered to accounted for the continuous softening on the curve of true stress-strain at 1050°C and relatively high strain rate of $2 \times 10^{-3}\ s^{-1}$. When the alloy tested at 1000°C and above, the prolonged stage of steady flow stress can be explained by the quite stable grain size of the alloy during superplastic deformation. It can be also found from Fig. 5 that the grain shape of the alloy became equiaxed and rounded after superplastic deformation, especially at higher temperatures. The more and more equiaxed microstructure with increasing strain results in easier grain boundary sliding and also a higher m value during superplastic deformation. However, detailed microstructural investigation by transmission electron microscopy is needed to better understand microstructural evolution

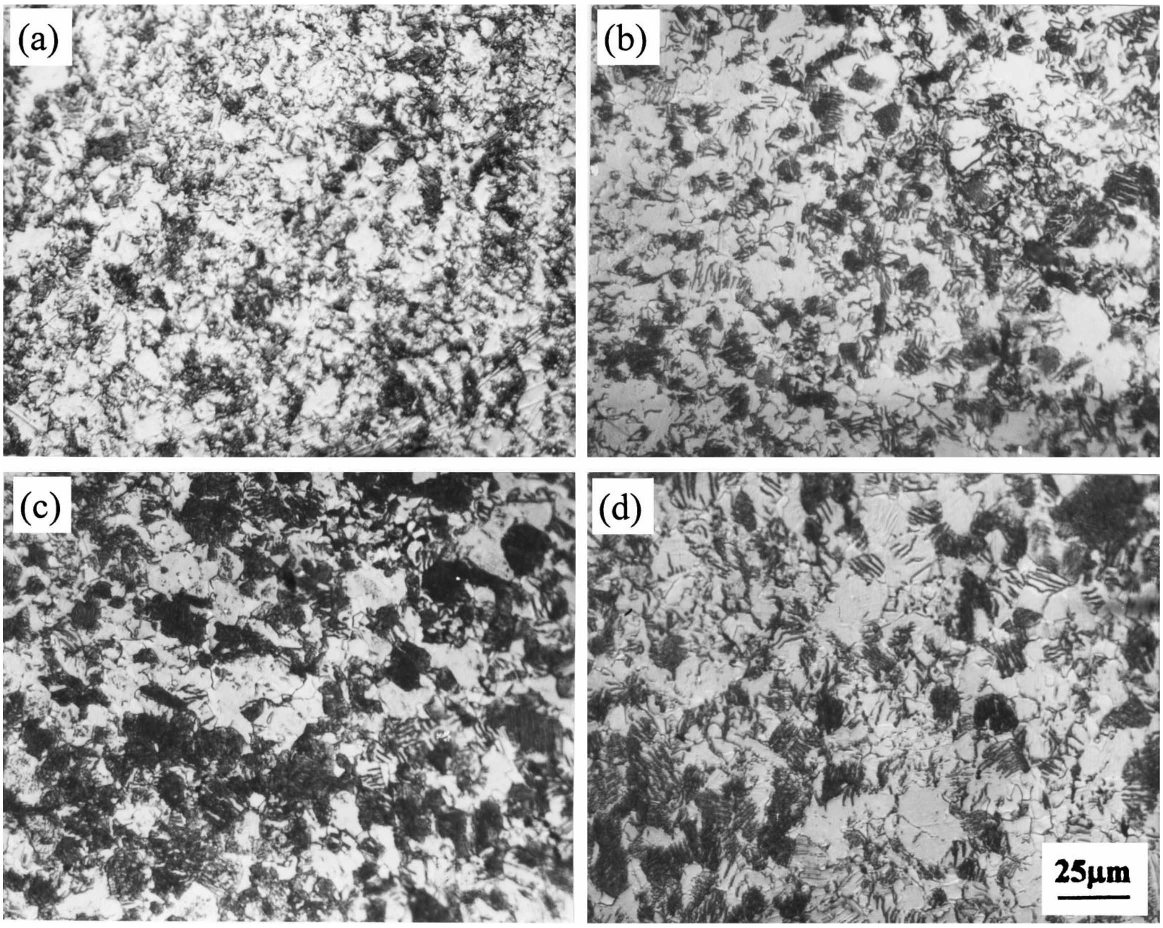

Figure 5 Microstructural evolution of the duplex TiAl alloy after superplastic deformation at (a) 950°C, (b) 1000°C, (c) 1050°C and (d) 1075°C.

after superplastic deformation and correlate to the mechanical properties.

Concerning the mechanism of superplastic behavior of TiAl based alloys, it was suggested that grain boundary sliding and associated accommodation play a dominate role in superplastic deformation at intermediate strain rates and the deformation mechanism is governed by the viscous glide of dislocations at higher strain rates [9–11]. Based on the stress-strain curves of superplastic deformation, variation of the *m* values during deformation and the microstructural evolution of the duplex TiAl alloy in the present work, superplasticity of the duplex TiAl alloy at relatively low temperature and relatively high strain rate results from dynamic recrystallization, and superplasticity at higher temperatures and lower strain rates is attributed to grain boundary sliding and associated accommodation mechanism.

4. Conclusions

1. The duplex TiAl based alloy is of high superplastic properties at temperatures ranging from 950°C to 1075°C and strain rates ranging from 8×10^{-5} s^{-1} to 2×10^{-3} s^{-1}. A maximum elongation reached 467% at 1050°C and at a strain rate of 8×10^{-5} s^{-1}.

2. The apparent activation energy of the duplex TiAl based alloy was calculated to be 345 kJ/mol, which is comparable to the apparent activation energies in literature.

3. Superplasticity of the duplex TiAl alloy is believed to result from dynamic recrystallization at relatively low temperature and relatively high strain rate. At higher temperatures and lower strain rates, the grain boundary sliding and associated accommodation mechanism is related to superplastic deformation of the alloy.

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