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GRAIN BOUNDARY STRUCTURE AND MECHANICAL PROPERTIES OF THE TiAl INTERMETALLIC COMPOUND

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Résumé - L'étude des propriétés mécaniques du composé intermétallique TiAl a été faite de la température ambiante à 1050°C. Ces propriétés dépendent fortement de la structure des joints de grain. En particulier, le comportement mécanique du composé intermétallique est relié à la capacité des joints à absorber les dislocations.

Abstract - An investigation of the TiAl intermetallic compound mechanical properties has been undertaken in the temperature interval of 20-1050°C. Its properties have been found to be considerably dependent on the structure of grain boundaries. Absorption properties of grain boundaries and mechanical behaviour of the intermetallic material are shown to be interrelated.

1 - INTRODUCTION

Presently, grain boundaries are undoubtedly recognized to be the most important component of a polycrystal structure exerting considerable influence on the mechanical properties of polycrystals /1-5/. At the same time, it is evident that these properties depend not only on the length of GB, but also on their structure /5-7/. This paper presents experimental data which prove that grain boundary structure and properties should be taken into account when predicting mechanical behaviour of polycrystals.

The TiAl intermetallic compound (superlattice L_{10}) was specially chosen as an object for investigation. This alloy is brittle and strain-resistant even at high temperatures /8, 9/. However, when converted to a fine-grained state, it can display superplasticity (SP) in certain temperature-rate conditions of deformation /10/. This material was chosen to enable a special kind of experiment with the end of comparing the alloy mechanical properties in states with close grain sizes, but considerably different in their GB structures /11, 12/.

2 - MATERIAL AND EXPERIMENTAL PROCEDURE

The Ti-36 wt% Al alloy (further denoted as TiAl) in the form of ingots and blanks obtained by the compaction of granules was used. The required structural states were created by means of special treatment whose modes are given in the Table.

Table. Modes of the TiAl Alloy Treatment.

State	Modes of Treatment
I	80% hot compression straining of the compacted alloy at 1000°C and at the strain rate of 10^{-3} s^{-1}
II	Same as in I + annealing at 1050°C for 2 hours
III	Same as in I, but for the cast alloy + 70% restraining under the same conditions and with a change of the direction of deformation to 90°
IV	Same as in III, but the restraining takes place at 1100°C
V	Same as in III + annealing at 1050°C for 2 hours

Mechanical tensile tests were conducted on the Instron machine in the temperature interval of 20-1050°C at the initial strain rate of $8.3 \times 10^{-4} \text{ s}^{-1}$. At 1025°C tests were conducted at the initial strain rates of $(1.6-8.3) \times 10^{-4} \text{ s}^{-1}$.

Tensile diagrams were used to define: maximal relative elongation to rupture, δ ; true flow stress at the relative elongation of 50%, σ_{50} ; conditional temporal resistance, σ_t . The strain rate sensitivity coefficient, m , was evaluated by the slope of $\lg \sigma_{50} - \lg \dot{\epsilon}$ curves. For mechanical tests flat specimens with the working portion dimensions of 10 x 5 x 2 mm were used.

These specimens were prepared by grinding with subsequent electropolishing.

To know the absorption properties of GB, the temperature of relaxation, t_r , i.e. "blurring" of electron microscopic contrast, of trapped lattice dislocations (TLD) in GB was measured. To do this, the alloy specimens in states IV and V after 2.5% deformation at room temperature were annealed for 15 minutes at various temperatures.

3 -RESULTS

3.1 Superplasticity of TiAl.

States I and II were studied.

Mechanical properties. The temperature dependence of the alloy mechanical properties in state I is as follows. With the rise of testing temperature the relative elongation to rupture, δ , first gradually grows, but after the maximum (250%) has been reached at 1025°C, it abruptly decreases. Flow stress decreases monotonously with the rise of temperature.

Flow stress, σ_{50} , largely depends on the strain rate at 1025°C (Fig. 1a), the strain rate sensitivity of σ_{50} in state I, contrary to state II, in a certain strain rate interval being increased.

Fig. 1 - The effect of strain rate on the TiAl mechanical properties: ● - state I; ○ - state II ($t=1025^\circ C$)

Thus, for state I the m values in the strain rate interval of $(0.83-1.6) \times 10^{-3} s^{-1}$ vary from 0.33 to 0.43 (Fig. 1b). Higher values of m are matched with the largest relative elongations to rupture (200-250%). For state II, m is constant throughout the considered strain rate interval and its value is 0.26 and relative elongation only slightly depends on strain rate ($\delta=130-160\%$).

Thus, in state I the alloy displays SP features while in state II SP behaviour is less pronounced.

Fig. 2 - The flow-stress-deformation curves of the TiAl alloy in states I (1) and II (2) ($t=1025^\circ C$, strain rate $8.3 \times 10^{-4} s^{-1}$)

Fig. 2 shows σ_s - ϵ curves during the tensile straining of the alloy specimens in states I and II at an optimal strain rate. The stage of steady state flow is preceded by a prolonged stage of strengthening. In state II at the initial stage, the σ_s peak is observed. With further deformation the flow stress monotonously decreases and approaches the σ_s level in state I.

Microstructure. When specimens are heated up to the optimal temperature of 1025°C their mean grain size d in state I increases from 5 to 8 μm . Subsequent soaking at this temperature for five hours causes no further growth of d . In state II, microstructure at 1025°C is stable with $\bar{d}=9.5 \mu\text{m}$.

Fig. 3 - Microstructure and histograms of grain size distribution of the TiAl alloy in the head of specimens 160% deformed at 1025°C and $\dot{\epsilon}=8.3 \times 10^{-4} \text{ s}^{-1}$: a - state I; b - state II; c: $\bullet$ - state I, $\circ$ - state II.

Fig. 3 shows the microstructure and histograms of the grain size distribution in both states in specimen heads. Besides the main γ -phase (TiAl) the alloy also contains about 3 vol.% of α_2 -phase (Ti₃Al - superlattice DO₁₉) in the form of particles sized 0.1-3 μm located mainly in GB. No difference in the amount, distribution, size, and shape of the α_2 -phase particles is observed. Comparison of the grain size distribution histograms of the alloy states shows that they are practically identical. Twin boundaries are observed in the microstructure of the alloy states. Their fraction in states I and II is 10 and 35% respectively of the total number of grains. No α_2 -particles are observed in twin boundaries. Since states I and II are characterized by close grain sizes, similar amount, shape, size, and distribution of α_2 -phase particles, the difference of the alloy properties in the said states are obviously due to the structure of GB, i.e. different number of twin boundaries in each state.

3.2 Tough-brittle transition in TiAl.

States III-V were studied.

Microstructure. Fig. 4 shows the microstructure and histograms of grain size distribution of the states. There are no differences in the amount, distribution, sizes, and shape of the α_2 -phase particles either. The mean grain size is 5 μm in state III, 9 μm in state IV, 11 μm in state V. The comparison of grain size distribution histograms in states III and IV has shown that they are practically identical. Annealing twins are observed in the microstructure of the states. Most of them are in state five making about 50% of boundaries while in states III and IV the fraction of twin boundaries does not exceed 5%. No α_2 -phase particles precipitate in twin boundaries.

Mechanical properties. Mechanical properties of the alloy in states III-V are shown in Fig. 5. The dependence of conditional temporal resistance, σ_t , on temperature for all the states is of an anomalous character. With the rise of temperature σ_t increases reaching the maximum at

Fig. 4 - Microstructures and histograms of the grain size distribution of the TiAl alloy: a - state III; b - state IV; c: Δ - state III, $\bullet$ - state IV, o - state V.

Fig. 5 - TiAl mechanical properties: Δ - state III, $\bullet$ - state IV, o - state V.

750°C, but with the further rise of temperature it decreases. In the same temperature interval where σ_y increases, the growth of δ takes place indicating that the tough brittle transition (TBT)^t is in progress.

The original microstructure influences the alloy properties which depend to a greater extent

on the GB structure than on the grain size. Thus, for example, states III and IV being considerably different in grain sizes, have practically identical properties. At the same time if we take states IV and V, the difference in their properties is connected with the difference in the GB structure since grain sizes in these states are quite close. States III and IV are characterized by higher values of σ and σ_t as compared to state V. Only at $t > 750^\circ\text{C}$, σ_t for state V is higher than in states III and IV.

Absorption properties of GB. The study of the relaxation of TLD in GB during annealing shows that in twin boundaries contrast due to TLD does not disappear even after the annealing at 1100°C (Fig. 6a). At 1000°C and more the TLD system in twin boundaries becomes ordered forming quasiperiodical rows and nets. Other boundaries which are obviously random are deprived of TLD already at 600°C (Fig. 6b).

Fig. 6 - The relaxation of TLD in GB: a - $t_{\text{ann}} = 1100^\circ\text{C}$, twin boundary; b - 600°C , 15 minutes.

Results obtained during the study of TLD relaxation in GB allow to define the fraction of twin and random boundaries in states IV and V of the alloy. It was established that the fraction of twin boundaries in these states constitutes 3 and 50% respectively, the rest being random boundaries. Hence, these results agree with those obtained metallographically.

4 - DISCUSSION

In the TBT interval and the SP conditions the TiAl mechanical properties depend to a great extent on the structure of GB. The growth of the fraction of twin boundaries leads to a considerable increase of the alloy plasticity above 600°C .

With the rise of temperature the ability of GB to absorb dislocations becomes very important for the growth of polycrystal plasticity [4, 5]. The study of the absorption properties of GB has shown that twin boundaries are less efficient as sinks for dislocations than random boundaries. That is why the growth of their fraction in the alloy leads to the decrease of its plasticity in the TBT interval above 600°C . Under the SP conditions, according to the model of grain boundary dislocation (GBD) motion kinetics, GB act not only as sinks for dislocations, but also as a "channel" along which plastic deformation is effectuated through the motion of GBD [13].

Since during the SP flow grain boundary sliding in twin boundaries is impeded due to a low mobility of GBD in these boundaries [4, 5], the increase of their fraction in the alloy leads to the decrease of the alloy plasticity under the given condition.

According to the experiment, the TLD relaxation in random boundaries occurs at temperatures which are lower than those of TBT. At the same time the process of TLD relaxation in GB is known [4, 5] to be indicative of the enhanced mobility of GBD in the boundaries. Hence, the growth of the TiAl plasticity in the polycrystalline state with the rise of temperature in the TBT interval is related to the enhancement of the GBD mobility in GB.

5 - CONCLUSIONS

1. Mechanical properties of the TiAl intermetallic compound are largely dependent on the structure of grain boundaries. The growth of the fraction of twin boundaries in the alloy considerably decreases its plasticity at temperatures above 600°C .
2. The relaxation of TLD in TiAl occurs at temperatures which are lower than those of TBT.

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