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LOW TEMPERATURE MECHANICAL PROPERTIES AND FAILURE PECULIARITIES OF THE Ti-6Al-4V ELI ULTRA-FINE GRAINED ALLOY

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Abstract. Mechanical properties of the ultra-fine grained Ti-6Al-4V ELI alloy processed by the equal channel angular pressing (ECAP) have been studied under the uniaxial tension with ~ $4\cdot 10^{-4}$ s^{-1} constant strain-rate at 300 and 77K. Yield stress, ultimate stress, and ultimate plastic strain values have been compared for different ultra-fine grained states of Ti-6Al-4V ELI, distinguished by the average grain size and phases microstructure. Obtained microstructures, mechanical behavior and failure peculiarities of the ultra-fine grained (UFG) Ti-6Al-4V ELI alloy are discussed.

1. INTRODUCTION

Study of the cryogenic mechanical characteristics of the UFG Ti-6Al-4V alloy, carried out under uniaxial compression [1] had shown that reducing of the grain size through ECAP results in the ~25% strength increasing (with conserving an essential plasticity in the 300-4.2K temperature interval). However, there is no sufficiently detailed study of the influence of UFG Ti-6Al-4V alloy structure upon cryogenic mechanical characteristics. In this connection, the aim of this paper was to study the influence of UFG Ti-6Al-4V ELI alloy of various structures upon its cryogenic mechanical properties under tension and microstructured features of failure.

2. EXPERIMENTAL MATERIALS AND PROCEDURES

Experimental investigation of mechanical characteristics and failure regularities of the ultra-fine grained Ti-6Al-4V ELI alloy, produced by ECA pressing, have been carried out under the uniaxial tension of the specimens (5.5×0.75×2.4 mm) with $4\cdot 10^{-4}$ s^{-1} strain-rate at 300 and 77K. These characteristics have been compared for three different structural states of the Ti-6Al-4V ELI alloy, distinguished by the average grain size and by the morphology of α and β phases. In initial polycrystalline state 1 the average grain size (d) of α phase is 10–25 μm. Ultra-fine grained state 2, produced by ECA pressing of the state 1, has d~0.5–1 μm (billets 40 mm in diameter and 150 mm long were processed at 600 °C by 4 ECAP passes with the 90° rotation around the billet axis in a die-set with a channel intersection angle of 120°, ECAP rate was equal to 6 mm/s). UFG state 3 had been produced by thermal treatment, ECAP, and extrusion of the initial state 1, and the average size of α grains is 200–400 nm (billets 40 mm in diameter and 150 mm long of Ti-6Al-4V ELI initial alloy were heated to 950 °C, quenched to water, and further aged; then,

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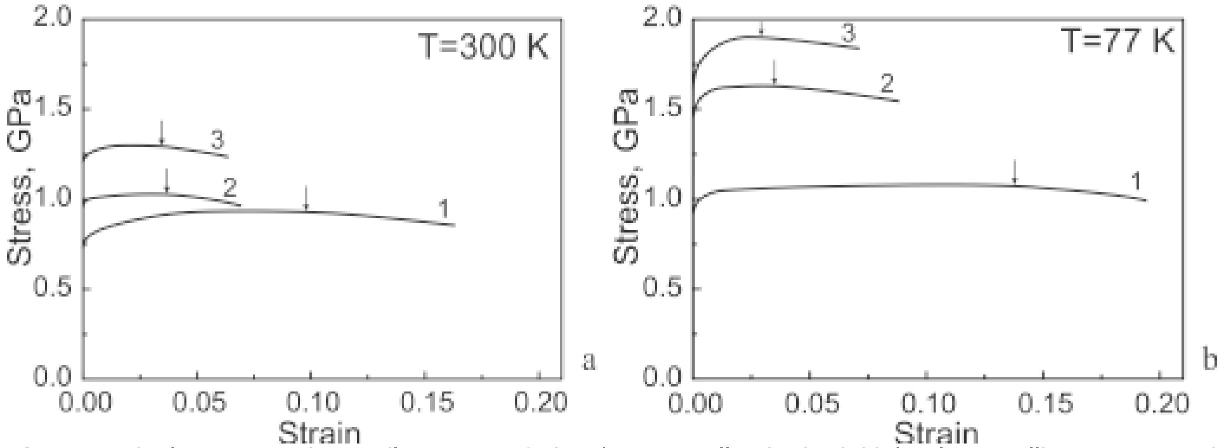

Fig. 1. Typical stress-strain tensile curves of Ti-6Al-4V ELI alloy in the initial polycrystalline state 1 and ultra-fine grained states 2 and 3 at 300K (a) and 77K (b). Arrows indicate the end of the uniform plastic strain (ε_{unif}).

the billet was processed at 600 °C by 4 ECAP passes, which was followed by multi-cycle extrusion at 300 °C). The β phase forms an interlayer between the grains of α phase for all these structural states and its volume part is 5–12% [2]. Mechanical characteristics (yeld stress $\sigma_{0.2}$, ultimate stress σ_u, and ultimate uniform plastic strain ε_{unif} (plastic strain to a neck formation beginning)) values have been measured. Activation volume *V* of plastic deformation has been calculated by deforming stress relaxation method [3] at 300 and 77K. The type of failure has been specified, and the fracture surface morphology has been studied with the TESLA BS-300 scanning electron microscope (SEM).

3. EXPERIMENTAL RESULTS

Fig. 1 shows stress-strain curves at 300K and 77K under tension of all three structural states of Ti-6Al-4V ELI specimens investigated.

As one can see, the grain structure modification and decreasing of grain sizes by ECAP processing leads to considerable increase of the alloy's yield stress $\sigma_{0.2}$ and ultimate stress σ_u in the nanostructured state 2, comparing to the initial coarse-grained state 1 (20% at 300K and 50% at 77K). The heat treatment of the initial alloy before ECAP and the extrusion stimulate further dispersing of Ti-6Al-4V ELI grains (state 3). It results in the additional yield stress $\sigma_{0.2}$ and ultimate stress σ_u increment in comparison with the state 2 (22.5% at 300K and 18% at 77K).

Change of the structural state from 1 to 2 has led to decreasing of the ultimate uniform plastic deformation ε_{unif} from 10% to 4% at 300K, and from 15% to 3% at 77K as it is shown by Figs. 2a and 2b. In state 3, the ultimate uniform plastic deformation ε_{unif} practically coincides with the ε_{unif} for state 2 at 300K and 77K.

Values of activation volume *V*, obtained from stress relaxation data, nearly coincide for all investigated structural states of Ti-6Al-4V ELI alloy. Thus, measurements at the yield limit give $V \approx 3.5 \cdot 10^{-28}$ m^3 at 300K and $V \approx 0.9 \cdot 10^{-28}$ m^3 at 77K.

Fracture surfaces of specimens in states 1 and 2, which had been tested at 300 and 77K, are oriented at the angle of 45° (shear failure), as well as 90° (normal failure) with respect to the tension axis. In state 3, failure of specimens at 300 and 77K took place along the different shear planes, oriented at the angle of 45° to the tension axis.

Only a ductile failure with typical dimples rupture morphology under the uniaxial tension have been observed for all structural states of the specimens, which were deformed at 300 and 77K. Typical morphology of the failure surfaces is shown in Figs. 2a and 2b. As one can see, failure surfaces oriented at the angle of 45° to tension axis have the dimple pattern that is elongated in the direction of the shear crack propagation (Fig. 2a), while sur-

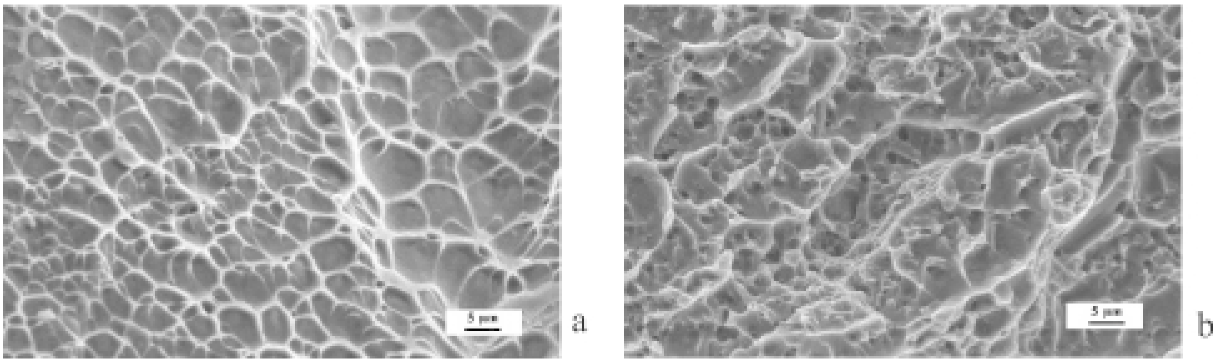

Fig. 2. Failure surfaces of Ti-6Al-4V ELI, tension, 77K, state 2: the “shear failure” (a), the “normal failure” (b); SEM.

faces of a “normal failure” have no elongation of a dimple pattern (Fig. 2b).

4. DISCUSSION OF RESULTS

UFG state 2, produced by ECAP of the initial polycrystalline alloy, has equiaxed microstructure with average grain sizes approximately 500 nm. Yet, UFG state 3, produced by ECAP of the coarse-grained alloy with the Widmanstatten structure, which was followed by the multi-cycle extrusion, have more dispersed microstructure with average grain sizes ~350 nm. The differences in mechanical characteristics and failure features of specimens in various structural states, confirm the essential dependency of these characteristics on the initial structure of material (before ECAP) and give the possibility to estimate the effectiveness of different methods of alloy’s UFG state production.

Observed $\sigma_{0.2}$ increasing and ε_{unif} decreasing in the state 2 comparing with the state 1 of the Ti-6Al-4V ELI are explained by presence of the additional strong barriers for the dislocations slip in the form of grain boundaries and twin colonies in the ultra-fine grained state.

Further 20% increasing of the $\sigma_{0.2}$ in the state 3 in comparison with the state 2, is apparently determined by additional barriers for the dislocation motion in the form of crushed into pieces (after ECAP and the extrusion) plate-like lamellas of Widmanstatten structure, which are effective barriers for dislocations.

It is interesting to note that uniform plastic deformation values for states 2 and 3 practically coincide at 300K, as well as at 77K. Such behavior can be explained by the rather similar lamellar character of microstructures: colonies of twins in the state 2 and colonies of a phase lamellas in state 3. Boundaries of colonies of twins and of α phase lamellas can be considered as strong barriers for dislocation slip. This may give an explanation of the small plastic deformation values in states 2 and 3 at 300 and 77K.

Observed absence of activation volume dependency on the structural state of the alloy can mean that thermally activated overcoming of impurity atoms by dislocations is the mechanism that controls the sliding of dislocations in grains.

5. SUMMARY

The strength and the plasticity of the Ti-6Al-4V ELI alloy depend essentially on the alloy’s structure, which can be changed by the appropriate treatment of the material both before and after ECAP. It has been established that the grain structure dispersion of the Ti-6Al-4V ELI alloy by ECAP leads to a considerable increase of the alloy’s strength in comparison with the initial alloy (20% at 300K and 50% at 77K). The dispersing heat treatment of the initial alloy before ECAP and following extrusion stimulate further grain sizes reduction in the Ti-6Al-4V ELI alloy (state 3) and results in the high strength (1.3 GPa at 300K and 1.9 GPa at 77K) and rather enough plasticity at 300 and 77K. Only ductile failure was observed at 300 and 77K for all investigated structural states of the Ti-6Al-4V ELI alloy. The fracture surface consists of regions failed under normal and shear stresses for samples in states

1 and 2. For specimens is state 3 failure occurred only in shear planes.

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