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ULTRAFINE-GRAINED Ti-6Al-4V-ALLOY USED FOR PRODUCTION OF COMPLEX-SHAPED ARTICLES WITH ENHANCED SERVICE PROPERTIES

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Abstract. This work presents the results of investigation of microstructure and mechanical properties of gas-turbine engine (GTE) blades made from Ti-6Al-4V alloy with an ultrafine-grained (UFG) structure fabricated by means of severe plastic deformation. A possibility of efficient shaping of a blade out of the UFG alloy by means of isothermal stamping at lowered temperatures with retention of the UFG structure in a blade-item was demonstrated. Comparative fatigue tests of blades manufactured by conventional and pilot technologies were conducted, which demonstrated increase of the fatigue endurance in blades with the UFG structure by almost 30%. The V- and T-notch impact strength of pilot blades retained the increased values (no less than 320 and 210 KJ/m^2, respectively).

1. INTRODUCTION

Titanium and its alloys are widely used in medicine, mechanical engineering and aviation due to their high strength-to-weight ratio, corrosion resistance and biocompatibility. However, development of modern industry sets increasingly high requirements to service properties of structural materials applied to produce highly-loaded items, such as parts for electric power stations, gas-compressor stations and aircraft engineering. Conventionally titanium alloys are strengthened by alloying, thermomechanical treatment via control over their chemical composition change and phase-structure transformations. Creation of ultrafine-grained (UFG) structures in them with the help of severe plastic deformation (SPD) techniques is a new efficient way to enhance physical and mechanical properties of commercial metals and alloys, which allow reaching very high plastic strains at considerably low temperatures (usually 0.3…0.4 T, K) under the conditions of high applied pressures [1,2].

As it is known, UFG materials processed by SPD techniques exhibit low-temperature and/or high-rate superplasticity at room temperature alongside with enhanced strength and fatigue properties [3-6]. For example, conventional titanium alloys demonstrate superplastic (SP) behavior in the range of temperatures of 850…950 °C and strain rates of $10^{-3}…10^{-5}$ s^{-1} [7]. Ti-6Al-4V alloy in the UFG state displays superplastic features already at a temperature of 600 °C, which are characterized by high tensile elongations and increased sensitivity to flow stress [8,9,10]. This approach can be promising for fabrication of complex-shaped items with enhanced level of mechanical properties due to retention of the UFG structure in the item. Alongside with that

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full-scale studies of service properties at the stage of fabrication of semi-products and products is rather topical under the conditions of transition from fundamental investigations to commercial exploitations of UFG materials. Gas-turbine engine (GTE) blades operate under difficult working conditions with high static and dynamic loads, erosion, corrosion and temperature effects. If the operating temperature in the GTE compressor and outlet straightener does not exceed 450 °C, then blades made from Ti alloys are given preference due to their higher strength-to-weight ratio and corrosion stability as compared to heat-resistant steels and nickel-based alloys [11].

Therefore, the objective of the present work is to study the influence of deformation and thermal treatment conditions applied to UFG Ti-6Al-4V alloy at comparatively low temperatures on the evolution of the UFG structure and mechanical properties and to evaluate the fatigue properties of GTE blades produced from the UFG Ti-6Al-4V alloy by means of isothermal stamping.

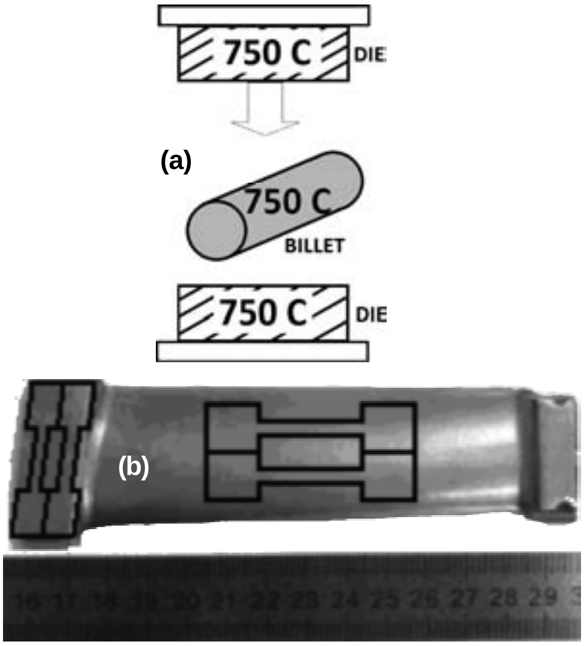

Fig. 1. Conditions of isothermal stamping of UFG Ti-6Al-4V alloy billets (à); general view of a pilot GTE blade after stamping (b).

2. EXPERIMENTAL PROCEDURE

In order to carry out investigations Ti-6Al-4V alloy was used (Ti-basis, Al – 6.6%; V – 4.9%; Zr – 0.02%; Si – 0.033%; Fe – 0.18%; C – 0.007%; O_2 – 0.17%; N_2 – 0.01%; H_2 – 0.002%). The β-transus temperature (T_{PT}) in the alloy makes 975±5 °C. A Ti-6Al-4V alloy billet with a diameter of 20 mm and a length of 135 mm was preliminary processed by equal-channel angular pressing (ECAP) technique on a die-set with the channels' intersection angle of φ = 120° and at a temperature of 700 °C and subsequent extrusion at 300 °C [12].

In order to produce GTE blades, the billets processed by SPD after mechanical machining were subjected to isothermal stamping on an industrial press with preliminary heating at T = 750±10 °C, the strain degree was no less than 70 % (Fig. 1a). The strain rate made 10^{-2} s^{-1} on the average. The isothermal stamping regime (temperature, rate and strain degree) was chosen on the basis of computer simulation and implementability of this process on the existing equipment [13]. Blade-stamped ingots from conventional alloys were produced by means of the conventional technology at a temperature of 920±10 °C. A general view of pilot blades is shown in Fig. 1b.

The microstructure was investigated with the help of optical microscopy and transmission electron microscopy (TEM) on the JEM-200CX device with an accelerating voltage of 200 kV. Thin foils for TEM were prepared with the help of electrospark cutting of plates with a thickness of 0.8…1.0 mm, mechanical thinning with subsequent electrolytic polishing at subzero temperatures. The X-ray phase structure analysis was performed on a diffractometer DRON-4 with application of monochromated Cu-K_α irradiation in the range of angles of 2θ = 20°-100°. In order to eliminate the texture influence, the samples were rotated perpendicularly to the irradiation axis. The diffraction patterns were subjected to standard processing (smoothing, background subtraction). Then diffraction peaks were determined and corresponding interplanar distances were calculated. The phase analysis of samples was performed on the basis of standard data library. Mechanical tensile tests of cylindrical samples with a gauge length of 15 mm and a diameter of 3 mm cut from the blade foot were performed on the tensile-testing machine Instron at room temperature with a strain rate of $\dot{\varepsilon} = 10^{-3}$ s^{-1}. Flat samples with the cross section of 2×4 mm were cut from the wing part of a blade. At least 3 samples were tested for each state.

The impact strength of the samples with V-,U- and T–notch was determined in accordance with the Russian standard GOST 9454-78 on model samples manufactured by standard and pilot regimes of isothermal stamping of blades. The tests were performed on an impact testing machine 2121 KM-0.05 with an impact velocity of 3.8±0.05 m/s and a nominal potential pendulum energy of 50 J at room temperature. The fatigue tests of blades (see

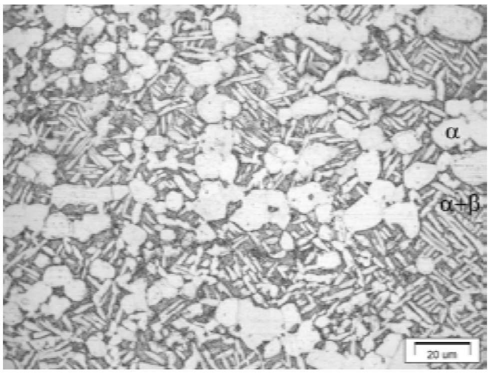

Fig. 2. Microstructure of the initial Ti-6Al-4V billet. Optical microscopy.

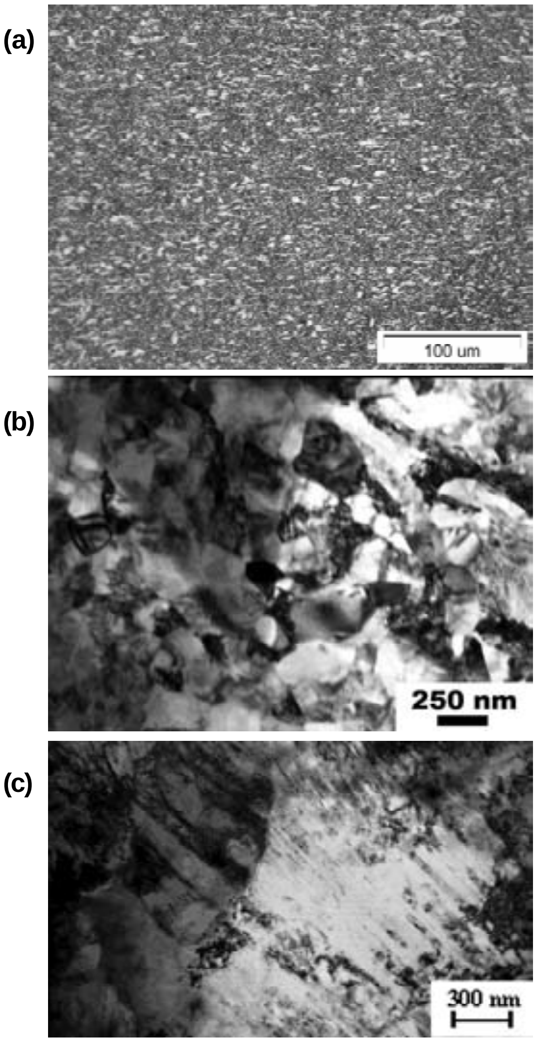

Fig. 3. Microstructure of the Ti-6Al-4V alloy after SPD-processing: (a) – optical microscopy; (b) (α+β) structure area; (c) fragmented grains of primary a-phase – transmission electron microscopy.

Fig. 1c) were performed on a special vibration testing machine VEDS – 400A at room temperature and the symmetric loading cycle *R* = -1, the number of cycles 2×10^7, frequency *f* = 500 Hz.

3. INVESTIGATION RESULTS AND DISCUSSION

3.1. Microstructure of the Ti-6Al-4V alloy processed by SPD

Fig. 2 presents the Ti-6Al-4V alloy microstructure in the as-received state (Fig.2). The structure of an initial billet consists of (α+β) regions with lamellar morphology and primary α-phase grains of 15±5 mm typical of hot-rolled rods. The volume fraction of the primary α-phase was about 65 %. The volume fraction of the β-phase did not exceed 12 % in accordance with the X-ray phase analysis.

Severe plastic deformation of the billet led to fragmentation of primary α-phase grains down to 5 μm and formation of new subgrains in them (Figs. 3a and 3c). A UFG structure was formed in the (α+β) areas, which was characterized by high dislocation density (up to 1.7×10^{15} m^{-2}), high internal stresses due to strong crystal lattice distortions, which is typical of various metals processed by SPD (Fig. 3b) [1,2]. The average size of α-phase grains/subgrains taken from the dark-field microstructure images was about 240±60 nm. The volume fraction of the β-phase decreased to 6% due to its partial dissolution and decomposition $\beta_m \rightarrow \alpha + \beta$ induced by SPD [8].

3.2. Microstructure and mechanical properties of a blade produced by isothermal stamping at lowered temperatures

The microstructure of blades processed by conventional isothermal stamping technology is shown in Fig. 4. The blade-stamped ingot has a bimodal microstructure typical of (α+β)-titanium alloys. The microstructure forms during stamping in the range of temperatures, which are 40…60 °C lower than the beta-transus temperature. Primary α-phase grains with the size of from 3 to 10 μm and (α+β) areas were observed in the microstructure. The α-phase has a shape of thin lamellas with a thickness from 1.2 to 0.8 μm, and the β-phase is in the form of interphase regions (Fig. 4b). Judging by the X-ray phase analysis, the volume fraction of the β-phase in the as-received state and after press stamping was similar and made about 13%.

Optical images of the microstructure of blades made from the UFG Ti-6Al-4V alloy display uniform distribution of structure elements, the sizes of which were almost undetectable (Fig. 5a). The microstructure after pilot stamping was characterized by both recrystallized and deformed grains of the α-phase

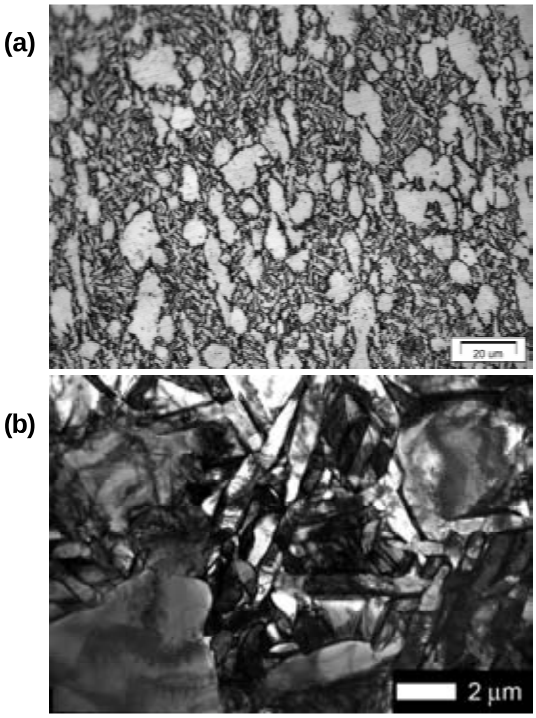

Fig. 4. Microscopy of the blade after conventional isothermal stamping 910 °C. (a) Optical metallography; (b) TEM.

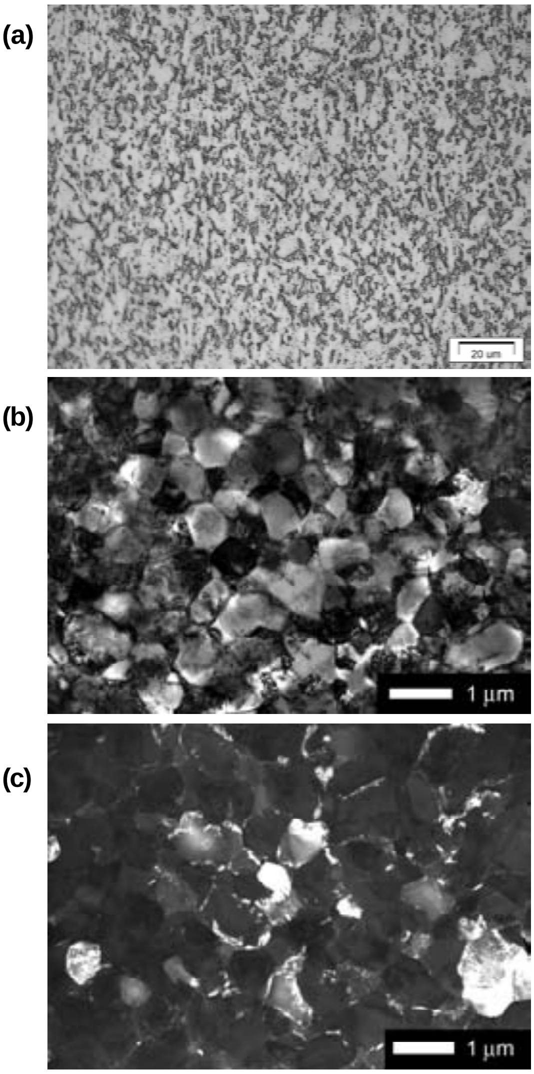

Fig. 5. Microstructure of the blade wing produced by isothermal stamping at T = 750 °C out of the UFG billet. a,b – bright-field images; c) dark-field image. TEM.

of predominantly equiaxed shape with a high-angle misorientation. Their average size was 0.8 μm according to the dark-field images (Fig. 5b). On the basis of the X-ray phase analysis, the volume fraction of the β-phase in comparison with the state after SPD increased from 6 to 10% as a result of deformation temperature increase to 750 °C.

The mechanical properties of samples cut from the blade footing and blade wing are shown in Table 1.

Table 1 shows that the alloy in the as-received state demonstrates rather low strength (UTS about 965 MPa) and good ductility (El. =19%). Subsequent isothermal stamping led to some strengthening of the alloy (up to 1060 MPa), which can be connected with slight structure refinement as a result of phase transformations and dynamic recrystallization processes. The alloy strengthening was accompanied by a certain decrease of the relative and uniform elongation of a sample to 14 and 5.7%, correspondingly, which was predetermined by formation of lamellar-like morphology of the α-phase (states 1 and 2 in Table 1). The samples were cut from pilot blades manufactured by isothermal stamping of UFG billets. A decrease of strength to 1220 MPa was observed in the samples in comparison with the initial deformed state (1450 MPa) (Table 1, states 4 and 3). The ductility considerably increases, in particular the relative and uniform elongations grow up to 16 and 9% correspondingly. This can be related to structure changes that take place as a result of isothermal deformation of a UFG billet under the conditions close to those necessary to achieve superplasticity. The TEM images of the blade-stamped ingot microstructure demonstrate that the grain-subgrain structure after SPD processing transformed into an equiaxed grain structure, which is testified by a more clear-cut boundary contrast (Figs. 3b and 5b). However, the size of α-phase grains increased from 0.3 to 0.8 μm as a result of processes of recovery and recrystallization during forging. Such processing results in a significant increase of ductility, in particular, of relative and uniform elongation with retention of high strength at room temperature. Such mechanical behavior of UFG titanium

Table 1. Mechanical properties of Ti-6Al-4V alloy samples at room temperature, after isothermal stamping from CG and UFG billets.

	State	UTS, MPa	0.2 YS, MPa	Elong., %	Uniform elong., %
1	As-received	965 ± 10	900 ± 20	19 ± 1	8.5 ± 0.2
2	Blade produced by conventional technique	1060 ± 15	1015 ± 15	14 ± 1	5.7 ± 0.1
3	UFG alloy	1450±15	1400±15	8±1	1.5±0.5
4	Blade produced by pilot technique	1220 ± 5	1180 ± 10	16.0 ± 0.3	9.0 ± 0.2

Table 2. Impact strength of the notched samples cut out from blades produced by conventional and pilot technologies.

	State	U-notch,KJ/m^2	V-notch,KJ/m^2	T-notch,KJ/m^2
2	Blade produced by conventional technology	500	400	230
3	Blade produced by pilot technology	420	320	210

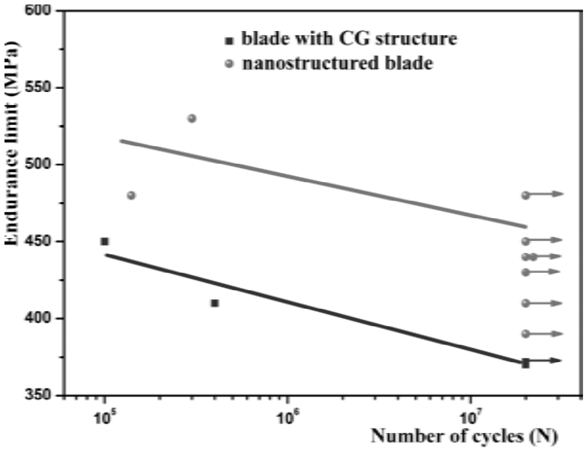

Fig. 6. Results of fatigue tests of conventional and pilot blades.

can be related to grain boundary structure change and also to increase of the volume fraction of high-angle boundaries, which, as it is known, contribute to grain boundary sliding of ultrafine grains during plastic deformation [2]. Decrease of strength in the UFG alloy after warm deformation can be explained by grain size increase (from 0.3 to 0.8 μm) in the course of isothermal forging due to simultaneous processes of recovery and recrystallization. Increase of the β-phase volume fraction in the alloy microstructure, apparently, also contributes to the ductility enhancement.

Impact strength of GTE blades is one of the main requirements imposed on the material's service properties. It is seen from Table 2 that the lamellar with primary α-phase structure of a blade manufactured according to the conventional isothermal forging regime provides quite high values of U-notch impact strength (500 KJ/m^2). Alongside with that some decrease in the U-notch impact strength to 420 KJ/m^2 in a pilot blade with the equiaxed UFG structure was observed. The T-notch impact strength values in a sample with a T-notch and guided fatigue crack are close for both blades manufactured via conventional and pilot technologies (230 and 210 KJ/m^2, respectively).

It is known that combination of high strength and enhanced ductility in UFG metals allows increasing a fatigue strength. In particular, such approach was described for UFG Ti and Ti-6Al-4V alloy in recent publications [14-17]. In the present work the fatigue tests were carried out on blades manufactured by means of conventional and pilot technologies (Fig. 6). On the basis of the test results it was established that the type of the blade microstructure has a considerable influence on the fatigue strength. While the fatigue endurance limit of blades with the bimodal structure (conventional technology) made 370 MPa, the blades with the UFG structure demonstrated the fatigue endurance limit of about 470 MPa, which is almost 30% higher.

Thus, this work demonstrated a possibility to increase the service properties in complex-shaped items by means of formation of the ultrafine-grained structure and, consequently, increased mechanical properties as a result of low-temperature isothermal stamping of a billet preliminary subjected to SPD. On the example of a GTE blade made from Ti-6Al-4V alloy it was shown that achievement of enhanced strength and ductility by means of formation of the UFG structure in it allowed increasing the fatigue endurance limit by 30%.

4. CONCLUSIONS

Thus, on the basis of the performed investigations the following conclusions can be made:

1. The UFG Ti-6Al-4V alloy processed by SPD exhibits an enhanced strength (up to 1450 MPa) at room temperature.
2. The possibility of the effective forming of complex-shaped articles – gas-turbine blades from UFG alloy using stamping at lower temperatures was demonstrated.
3. It is established that achievement of enhanced strength and ductility in pilot blades with the UFG structure allowed increasing the fatigue endurance limit by 30% and retaining the enhanced impact strength.

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