Effect of high pressure torsion technical parameters on grain refinement in Ti-6Al-4V alloy

Roman R Valiev¹, Ivan V Smirnov²

¹ Junior Researcher. Institute of Physics of Advanced Materials, USATU, Ufa, Russia
² Junior Researcher. Saint Petersburg State University, St. Petersburg, Russia
E-mail rovaliev@gmail.com

Abstract. Cycling of the compression pressure during high pressure torsion (HPT) of the titanium Ti-6Al-4V alloy significantly improves the grain refinement process, and also results in a more uniform microstructure along the sample diameter.

It is known that methods of severe plastic deformation (SPD) can substantially increase the strength of metals and alloys due to grain refinement to nanoscale dimensions. High pressure torsion (HPT) is of particular interest for producing ultrafine-grained (UFG) materials [1,2]. HPT is implemented on the anvils with a specific compression pressure of 3-6 GPa and subsequent rotation of a moving anvil around its axis with a speed of 0.2-1.5 rev/min.

It was demonstrated that HPT applied to coarse-grained disk-shaped workpieces of different metals and alloys resulted in strong refinement of the grain structure to the size of about 100 nm and less [1,3]. HPT also results in a formation of high-angle grain boundaries in combination with high internal stresses.

But there are certain problems in the HPT process, such as heterogeneity of a microstructure across sample thickness and diameter, as well as insufficient grain refinement, especially for hard-to-deform metals and alloys [2,4].

In order to solve these problems, it is important to choose various technical parameters, namely temperature, pressure, strain rate and degree. [1,3] In this paper an experimental HPT regime with cycling of the compression pressure during torsion was proposed and investigated on order to enhance heterogeneity of a sample microstructure and properties.

1. Material and methods

The material selected for the study was the titanium VT-6 alloy (Ti-6Al-4V), the initial coarse-grained structure of which had an average grain size of 10 µm and consisted of α + β phases. UFG structure formation in this alloy is rather attractive, as it allows increasing not only the alloy strength but also its fatigue properties [5,6].

The HPT processing was performed on a hydrostatic press with a maximum force of 160 tons on a Skrudg-200 unit adapted for changing the torsion parameters. Two anvils were used in this process, the first one was flat and the second one had a 0.8 mm deep groove. For HPT 2 mm thick disc-shaped samples were used. The samples were cut from rods of 20 mm in diameter, which were subjected to two processing regimes.

According to the first conventional regime, the HPT was performed at room temperature under the constant pressure of 4 GPa, with a number of revolutions equal to 10 and the rotational speed equal to 0.2 rev/min.
According to the second regime, the torsion was implemented under the same conditions, but with cyclically applied force, when after each revolution the pressure was increased by 2 GPa, from 4 to 6 GPa, and then reduced to 4 GPa. The time of applied pressure change was about 5 seconds.

After HPT processing the samples had 20 mm in diameter and 0.9 mm in thickness. The microhardness measurement along a sample diameter was performed on an Omnimet 5101 unit with HV values at a load of 100 g and holding time of 10 s. 70 measurements were taken for each sample with a step of 0.2 mm. The obtained mean values are shown in Fig. 2. The measurement error was 30 HV.

Microstructural studies were performed on a transmission electron microscope JEOL JEM-2100. Thin foils were fabricated from samples after HPT through thinning and further electropolishing in an electrolyte.

2. Results of research and discussion

Fig. 1a displays a TEM image of the alloy structure after HPT processing in the conventional regime. Strong microstructure refinement took place and an ultrafine-grained (UFG) structure with an average size of grains of the α-phase matrix lower than 300 nm formed out of the central part of samples. The β-phase dispersed to particles with a size about 80 nm. The structure is quite homogeneous in this zone of a sample. Such character of structural changes corresponds to the results of previous studies of the alloy subjected to HPT processing [7].

At the same time another microstructure is observed in the central part of the sample about 5 mm in diameter after this regime (Fig. 1b). Strong microstructure refinement takes place, which is connected not with formation of ultrafine grains, but with strongly deformed areas with a high dislocation density. Such type of the structure is intermediate and conditioned by a lower strain degree in the central part of the sample subjected to HPT [3].
Fig. 1 TEM image of the microstructure of Ti-6Al-4V in the conventional regime, (a) – sample edge, (b) - central part of the sample.

It was discovered that quite a homogeneous UFG structure is formed in the entire sample after HPT with cycled pressure. The structure was similar to that shown in Fig. 1a. The microhardness measurements (Fig. 2) correlate well with the results of structure studies. Fig. 2a demonstrated the values of HV measured across the diameter of the sample subjected to conventional HPT regime. It is seen that the hardness level is significantly lower in the central part of the 5-6 mm sample. Similar pattern is observed in the alloy at an applied pressure of 6 GPa and more [7]. However, HPT with cycling of the pressure leads to rather uniform distribution of HV in different parts of the sample, the average hardness level increased and was 450 HV.

Thus, the conducted experiment shows that cycling of the applied pressure leads to a more efficient refinement of the alloy structure, when a homogeneous structure is formed along the entire sample diameter, and the average microhardness considerably increases from 380 to 450 HV. The origin of this phenomenon is obviously explained by the fact that the microstructure evolution during HPT is controlled not so much by applied stresses as by internal stresses induced by complex shear and compressive strains [2]. One may expect that cycling of imposed pressure can influence more strongly on a variation of internal stresses and therefore lead to higher homogeneity.

Thus, the investigation demonstrated that the use of cycling instead of steady-state applied pressure enabled significantly improving the uniformity of grain refinement along the sample diameter, and also greatly enhancing the alloy microhardness.
Fig. 2. Microhardness measurements along the sample diameter after HPT with the conventional regime (a) and with cycling of the compression pressure (b).

These results support that the applied pressure is an important technical parameter affecting the formation of an UFG structure during HPT.

3. Conclusions
In the course of implemented experiments and investigations it was established that the drawback of a conventional HPT regime with processing of the titanium Ti-6Al-4V alloy at room temperature, 10 revolution and constant applied pressure was non-uniform grain refinement as well as the heterogeneity of the structure. This problem can be improved essentially by cycling of the compression pressure during HPT.

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