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SOLID-PHASE JOINT FORMATION IN Ti-6Al-4V ALLOY UNDER CONDITIONS OF LOW TEMPERATURE SUPERPLASTICITY

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Abstract. The actual problem of modern aeronautical engineering is an urgent necessity in decreasing (by 150 °C and more) temperature of solid-phase welding for producing articles out of titanium alloys.

The experiments on solid-phase joining of bulk nanostructured semi-finished products out of Ti-6Al-4V alloy performed under conditions of low temperature superplasticity allowed establishing that the process of joining is of a deformation origin mainly. It has been established that under conditions of low temperature superplasticity (SP) the quality of a solid-phase joint of bulk nanostructured Ti-6Al-4V alloy parts depends on a strain value, and the strain required for processing a joint with strength and plasticity values of a basis material increases with decreasing temperature. The obtained result testifies a governing role of deformation and can be basic for developing a model of solid-phase joining under conditions of low temperature superplasticity.

1. INTRODUCTION

The available experimental data [1-15] on the influence of superplsaticity (SP) on solid-phase weldability of alloys are rather discrepant. In works [1,3-5] the role of superplastic deformation comes down only to accelerate formation of physical contact due to plastic collapse of surface asperity, that is, local deformation in the joint area. According to [3] dislocation slip plays one of the most important roles in the process of surface activation. Other researchers [2,9] concentrate their attention on the predominantly diffusion nature of joint process. It is generally assumed [3-5] that the occurrence of recrystallization and the appearance of common grains in the zone of joint indicate the completion of solid-phase joint (SPJ) formation. So, as a rule, the available studies [1,3-5,9] poorly take into account the role of grain boundary sliding (GBS), being a determining mechanism of superplastic deformation, and its influence on SPJ formation [6,10,12,14,15].

The actual problem of modern aeronautical engineering is an urgent necessity in decreasing (by 150 °C and more) temperature of solid-phase welding for producing articles out of titanium alloys [16,17].

The solution of this problem is possible by using a process of solid-phase welding of bulk nanostructured Ti-6Al-4V under conditions of low temperature SP [18-20].

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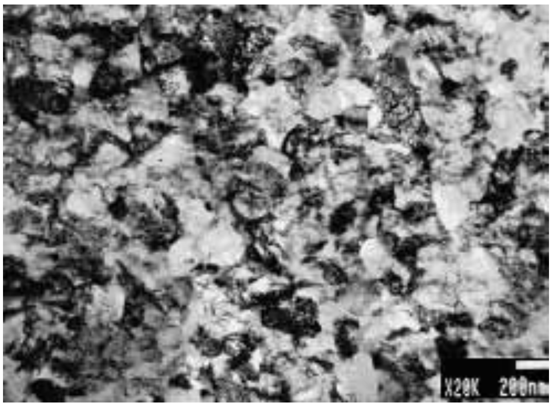

Fig. 1. Ti-6Al-4V alloy in state 1. Transmission electron microscopy. 20000 x magnification.

The aim of the work is to present the results of pressure welding experiments performed with samples of bulk nanostructured Ti-6Al-4V alloy under conditions of low temperature SP.

2. EXPERIMENTAL PROCEDURE

Samples out of titanium alloy Ti-6Al-4V were used having a mean grain size within the range 0.2 - 2 μm. For state 1 the mean grain size was 0.2 μm (Fig. 1). For state 2 the mean grain size was 2 μm. For state 1 the characteristic length scale of microstructure is closely near to 100 nanometers. That's why we consider States 1 as nanostructured. State 2 corresponds to conventional Ti-6Al-4V alloy with microcrystalline structure. The mean grain size in materials was determined on a transmission electron microscope JEM-2000 EX. Studies of welding joint structure at different magnification levels were performed on a scanning electron microscope JSM-840 and an optical microscope.

Pressure welding was carried out in vacuum of $2x10^{-3}$ Pa in the temperature-rate conditions of manifestation of the low temperature SP effect. The flat welded surfaces of the specimens were subjected to polishing and degreasing by rinsing in carbon tetrachloride. The degree of deformation was varied in the range 5-40%. The quality of welded joint was evaluated by metallographic examination and by tensile tests at room temperature on INSTRON 1185 machine. The zone of the welded joint was placed in the central part of the tested specimen across the axis of tensile loading.

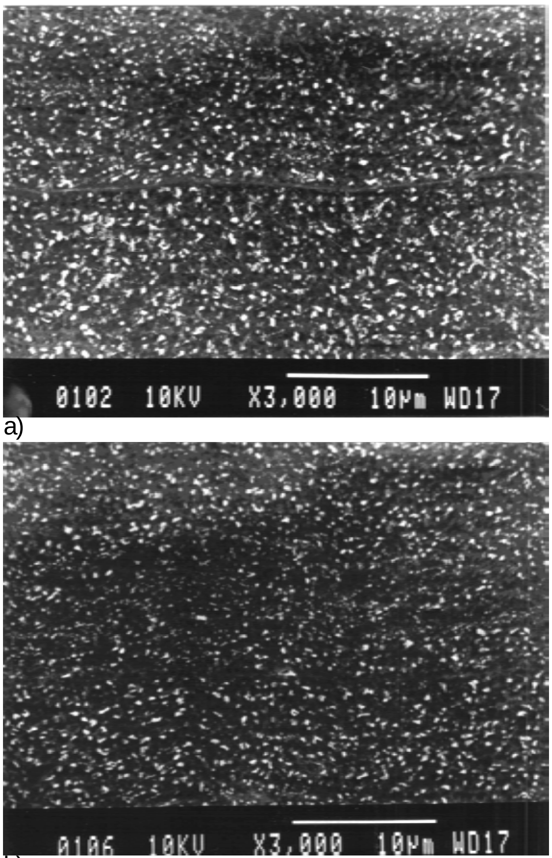

Fig. 2. Microstructure of SPJ area for nanostructured Ti-6Al-4V alloy after welding at 550 °C (a) and 600 °C (b). The welding interfaces are located horizontally in the center. 3000x magnification.

3. RESULTS AND DISCUSSION

The main results of experiments on pressure welding of samples of nanostructured Ti-6Al-4V are shown below. It is possible to bond samples without pores already at 550 °C (Fig. 2a). But there is a thin oxide film between the samples welded. Thickness of the oxide film (Fig. 2a) is about 20 nanometers. The oxide film strongly decreases the strength of the solid-phase joint.

It has been established that the quality of solid-phase joint of nanostructured Ti-6Al-4V alloy parts strongly depends on a strain value. The strain required for processing a sound joint increases with decreasing welding temperature (Tables 1-3). For example, a sound joint for nanostructured Ti-6Al-4V alloy can be processed at 600 °C after deformation of 35% (Table 1). The strain value of 15% is not sufficient for processing bonded parts. The increase in the strain value up to 25% is also insufficient for

Table 1. Tensile mechanical properties at room temperature of nanostructured samples of Ti-6Al-4V joined at 600 °C.

ε - *strain value*,%	*Mechanical properties*			
	UTS (MPa)	YS (MPa)	Elongation (%)	Reduction of area (%)
15	-	-	-	-
25	1156	1047	1.6	3.6
35	1149	1082	13.1	32.4

Table 2. Tensile mechanical properties at room temperature of nanostructured samples of Ti-6Al-4V joined at 650 °C.

ε - *strain value*,%	*Mechanical properties*			
	UTS (MPa)	YS (MPa)	Elongation (%)	Reduction of area (%)
10	-	-	-	-
20	1124	1061	2.7	4.3
25	1068	1025	13.3	24.8

Table 3. Tensile mechanical properties at room temperature of nanostructured samples of Ti-6Al-4V joined at 700 °C.

ε - *strain value*,%	*Mechanical properties*			
	UTS (MPa)	YS (MPa)	Elongation (%)	Reduction of area (%)
5	1054	1047	4.3	7
10	1052	1046	17	61
15	1020	1013	19	65

processing a joint with mechanical properties (plasticity) at room temperature having the level of the base material.

With increasing welding temperature up to 650 °C the sound solid-phase joint for nanostructured Ti-6Al-4V alloy with full mechanical properties correspond to level of base material can be processed already at a strain value of 25% (Table 2).

Subsequent increase in welding temperature up to 700 °C provides a sound solid-phase joint without pores already after strain of 10% (Table 3).

It is known, that at 700 °C developed enhanced diffusivity starts in Ti-6Al-4V alloy. In this connection additional experiment on vacuum annealing was carried out. The vacuum annealing of jointed samples with some pores at 700 °C does not cause essential changes in pore size and quantity in the joint area (Fig. 3).

The performed experiments on solid-phase joining under conditions of low temperature SP of bulk nanostructured parts out of Ti-6Al-4V alloy allowed establishing that this process is of a deformation origin mainly. Samples having porosity in the zone of joint have been produced and their mechanical properties have been evaluated. Vacuum annealing of this samples within the temperature range of 550-700 °C neither eliminates porosity of joint nor improves mechanical properties. It has been established that under conditions of low temperature SP the quality of a solid-phase joint of bulk nanostructured Ti-6Al-4V alloy parts depends on a strain value, and the strain required for processing a joint with strength and plasticity values of a basis material increases with decreasing temperature (Tables 1-3).

The obtained experimental data were bases for creating a physical model of solid-phase joining under conditions of low temperature superplasticity for the Ti-6Al-4V alloy.

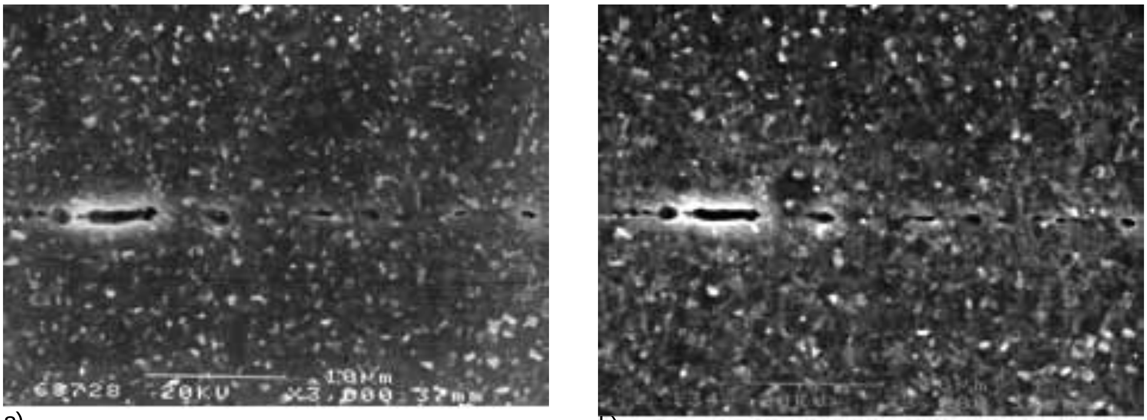
a) b)

Fig. 3. Effect of the vacuum annealing of nanostuctured Ti-6Al-4V at 700 °C on the porosity of the solid-phase joint. (a) - Initial state before vacuum annealing, (b) - The same place after vacuum annealing at 700 °C – 5 h.

The main principles of this model are the following:

- a joining material is considered as a ductile body displaying superplastic flow and structure transformations occurring in the zone of a solid-phase joint are determined by deformation processes within the material interior [21];
- deformation of microroughness on the joining surface of the material and deformation of the whole joining material interior are considered as an integral process of superplastic deformation that results in the absence of strain hardening in the local zone of solid-phase joining [14];
- the initial surface of joining samples is б-lay covered (~20 nm) that prevents formation of interactomic bonds between surface atoms of the joining alloy;
- development of grain boundary sliding at SP deformation initiates diffusion at grain boundaries which provides juvenile surfaces and accelerates processing of solid-phase joining [2,14];
- primary grip centers occur in the vicinity of grain boundaries and are attributed to the development of bands of cooperative GBS or usual GBS of separate grains [21];
- development of grain boundary sliding results in accelerated healing of pores in the zone of a solid-phase joint via mutual shift or rotation of adjacent grains [10,15];
- Development of grain boundary sliding transforms a plane interface to a state corresponding to the one of typical random grain boundaries apt to the joining superplastic material [15].

So, the developed concept of SPJ formation is not reduced to simple local smooth of microroughness and diffusion mass transfer for healing micropores in the joining area. The SPJ formation is determined by both the development of deformation mechanisms and their influence on joining process. Such an approach is new and based on the experimental facts revealing the influence of mechanisms of SP deformation on mechanism and kinetics of SSJ formation as well as the preservation of porosity in the zone of joining during long term vacuum annealing at the temperature of low temperature superplasticity.

The scheme of SPJ formation comprises three steps (Fig. 4):

1. Formation of a physical contact and closed cavities at deformation.
2. Destruction and dissolution of an oxide film and healing of micropores.
3. Disappearance of a plane joining interface.

The enhanced practical interest to the experimental data obtained is due to the fact that application of an intermediate nanostructured sheet layer provides performing low temperature joining of both nanostructured (State 1) and microcrystalline (State 2) titanium alloys within the temperature range 600-700 °C (Fig. 5). The main idea – is localization of superplastic deformation in bonded area to get a sound joint. Superplastic deformation healing of pores in the zone of joint due to mutual displacement of grains in the process of grain boundary sliding [10]. It is known [2], that superplastic deformation initiation of grain boundary diffusion due occurrence of grain boundary sliding. The required value

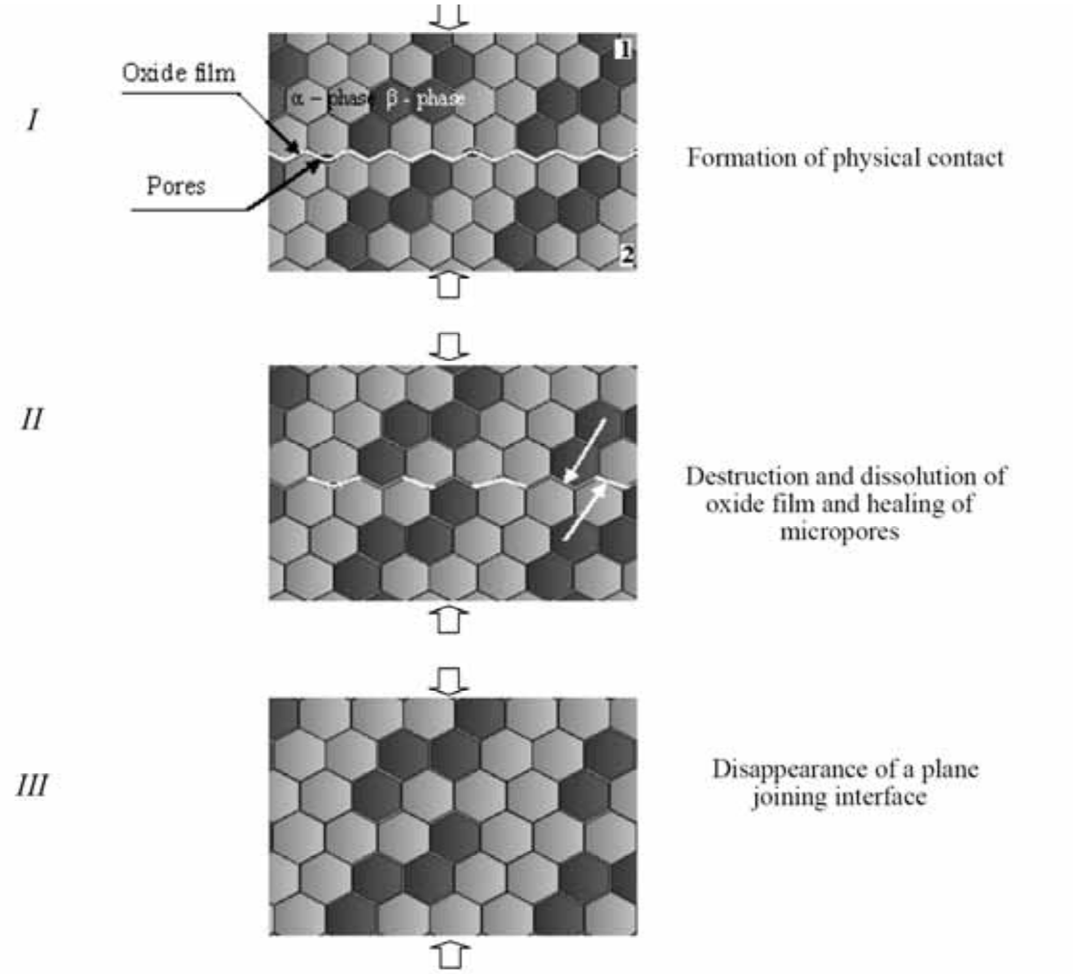

Fig. 4. Solid-phase joint formation in nanostructured Ti-6Al-4V alloy under conditions of low temperature SP.

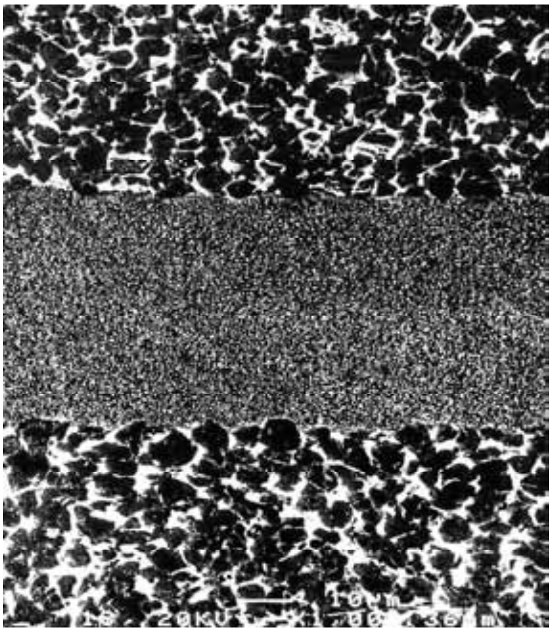

Fig. 5. Micrograph of solid-phase joint area after pressure welding of Ti-6Al-4Vparts at 600 °C using nanostructured pad.

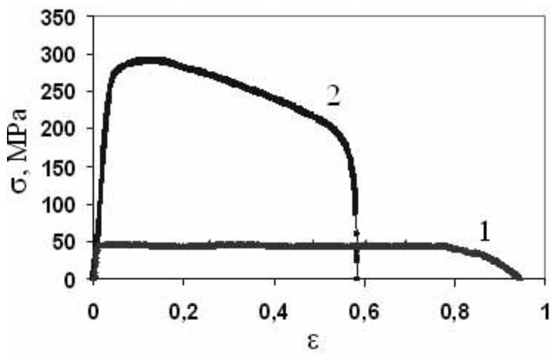

Fig. 6. Dependence of yield stress of Ti-6Al-4V alloy (1 – State 1 and 2 – State 2) on strain at 650 °C with the same strain rate (~7.5x10^{-4} s^{-1}).

of SP strain in the local zone of joining of traditional microcrystalline alloy Ti-6Al-4V [22] can be attained by using an intermediate nanostructured sheet. The SP flow stress for a nanostructured material at 600-700 °C is much lower than that of the microcrystalline one (Fig. 6). The application of such pads provides an opportunity to process a high sound joining at temperatures of exhibition of low temperature SP for Ti-6Al-4V alloy. The results of the experiments can be used for developing a method of producing a hollow fan blade for modern aircraft engines [23].

4. CONCLUSIONS

1. Nanostructure processing provides performing solid-phase welding of Ti-6Al-4V alloy within the temperature range 600-700 °C being lower than traditional diffusion bonding by 200-300 °C.
2. The physical model of low temperature superplastic deformation joining for nanostructured Ti-6Al-4V alloy samples is proposed.
3. Application of nanostructured processing pads provides localizing superplastic deformation in the bonded zone and producing a sound joint at the temperature of solid-phase welding lowered to 600 °C for microcrystalline Ti-6Al-4V alloy.

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