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Short communication

The influence of the microstructure morphology of two phase Ti-6Al-4V alloy on the mechanical properties of diffusion bonded joints

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ABSTRACT

The influence of ultra fine grained (UFG) and coarse grained (CG) microstructure of the titanium alloy Ti-6Al-4V on the strength of a diffusion bonded (DB) joint was studied using a laboratory DB fixture and a new shear test rig. The DB process was carried out at 725 °C and 825 °C during 2 and 4 h in a vacuum furnace. Coarsening of grain structure resulting from different DB cycles was quantified. The chain pores were observed at 725 °C for both microstructure conditions bonded during 2 h. The increase of bonding time up to 4 h leads to subsequent elimination of the pores. The UFG samples bonded at 725 °C showed a higher level of the shear strength than CG samples for both bonding times. The CG material demonstrated the highest shear strength after 4 h of DB bonding at 825 °C. The increase of the creep deformation of UFG samples when compared to the CG condition was observed as a result of DB at of 725 °C during 4 h.

1. Introduction

The process of diffusion bonding and superplastic forming (DB/SPF) has been successfully used for the manufacture of complex shape parts for a long time. In particular, this technology has been used by Rolls-Royce Ltd for the manufacture of hollow blades [1]. However, the process is associated with high energy consumption and cost due to high temperature and long cycle time.

The refinement of material's microstructure, down to the ultra-fine grained (UFG) level (average grain size < 1 μm) benefits the regime of diffusion bonding, i.e. the finer microstructure the lower temperature of a DB cycle, or the shorter time of the process [2]. These effects will also have a financial benefit for manufacturers, i.e. energy savings, cheaper forming tools and reduced tool wear. Another advantage of materials with a UFG microstructure can be realised through the low temperature superplastic forming (SPF) [2], where the temperature of the SPF process could be lowered from the typically used 927 °C [3] down to 750 °C [4]. Lowering of the hot forming temperature down to 760 °C mentioned in [5] showed that die life could be extended to 3000 or more parts, so that no new die sets would be required over the production cycle of any particular aircraft. The lower temperature also exponentially improved press platen and heater life.

The UFG microstructure can be obtained by severe plastic deformation (SPD). There are several different types of SPD processes that were successfully used to manufacture samples with UFG microstructure. For example, refinement of the grain size in Ti-6Al-4V alloy was achieved through high pressure torsion (HPT) [6,7], multi-step isothermal forging [8] and equal-channel angular pressing (ECAP) as shown by Valiev in [9].

Previously, the authors [10] have shown that the application of the UFG microstructure can significantly reduce the temperature of diffusion bonding of Ti-6Al-4V, down to 725 °C. However, it is known, that the morphology of the formed microstructure is largely dependent on the processing conditions. In a number of studies on different microstructure morphology, it was shown that mechanical properties depend not only on the size of the structural elements, but also on their type and shape [11].

The two main types of microstructure formed in two phase titanium alloys are lamellar and equiaxed. The lamellar microstructure consists of α-phase lamellae colonies within a large body of the β-phase grains, and equiaxed microstructure is characterised by a globular α-phase dispersed in the β-phase matrix [11,12]. Relatively low ductility, moderate fatigue properties, and good creep and crack growth resistance could be achieved by the lamellar microstructure, while a better balance of strength and ductility at room temperature, as well as fatigue properties could be expected from the refinement of the grain size down to 0.1–0.3 μm and a bimodal microstructure [13].

In paper [10], it was shown that under otherwise equal conditions,

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UFG material demonstrated better bondability compared with CG material. The temperature of DB cycle at low pressure of 3.2 MPa was reduced down to 825 °C for UFG condition. This can be explained by higher diffusion rate that leads to low-temperature superplasticity of UFG Ti-6V-4Al. One of the authors has conducted research where diffusivity was investigated in the UFG CP-Ti processed by ECAP [2]. The results presented in the paper have provided evidence that non-equilibrium grain boundaries, which are massively generated during ECAP processing, contribute to atomic transport in SPD-processed materials and positively influence diffusion rate [14].

Another finding in [10] was that the parameters of the DB cycle could be enhanced through the reduction of the surface roughness of the contacting surfaces. Thus, providing high surface finish (Ra = 50 nm) made possible obtaining a homogeneous joint without any optically detectable defects and uniform structure in the whole volume of the sample already after 2 h of DB at 825 °C. The industrial requirement for checking bond quality is to use optical microscopy, which means that small size pores might be not visible.

It is well known that refinement of the microstructure has a significant effect on the optimisation of the SPF conditions, especially applied to Ti-6V-4Al alloy [2–5]. Therefore it is important to investigate the influence of the UFG structure on the parameters of DB cycle and understand potential impact of the microstructure refinement on the combined process of DB/SPF.

According to the ideas and achievements discussed above, the present investigation will be conducted on the samples prepared with high surface finish (Ra = 50 nm) and will include:

- understanding of the microstructure evolution of the material with different morphology;
- evaluation of porosity in the DB area;
- influence of these factors on the shear strength of the bonded couples.

2. Material and procedure

The chemical composition of a two phase Ti–6Al–4V alloy used in the experiment is presented in Table 1. Cylindrical billets, with 18 mm diameter and 150 mm length were produced at IPAM (Institute of Physics of Advanced Materials) in Ufa via the recently developed technology that included equal-channel angular pressing (ECAP) using a die-set with the channels intersection angle $\phi = 120^\circ$ at a temperature 700 °C, and subsequent conventional direct extrusion at 300 °C [15]. The microstructure was studied using a scanning electron microscope (SEM) Quanta FEG 250.

The CG and UFG conditions were obtained by the research group of Institute of Physics of Advanced Materials in Ufa, Russia and investigations of the obtained microstructure were patented in [16]. The initial CG microstructure was transformed by heat treatment into a duplex structure. The remaining microstructure was represented by thin lamellar alpha and beta with the primary α-phase grains (15 ± 5 μm) and areas with the plate (α + β) structure (see Fig. 1*a*). The volume fraction of the primary α-phase was approximately 65%. After ECAP, the UFG microstructure was obtained after fragmentation of globular microstructure into structural elements with low angle boundaries and thin lamellar microstructure transforming into UFG structure. The UFG microstructure investigated was characterised by a mixed, partially-deformed microstructure consisting of primary α-grains with an average size of 6 ± 3 μm and α + β deformed plates and UFG α + β grain with the size of 400 ± 20 nm that was formed as a result of the continuous dynamic recrystallisation during SPD (see Fig. 1*b*).

Two types of cylindrical samples with coarse and ultrafine grained microstructure were used for the DB cycle. Cylindrical samples with diameter of 5 and 7 mm and height of 5 mm were cut out from titanium billets. The contacting surfaces of the samples were polished with the grit paper P600 and P1200. For the final polishing step, the UltraPol synthetic polishing cloth was used with MetaDi 9 μm diamond suspension. The surface roughness was measured using Alicona 3D Infinite Focus optical microscopy. The average surface roughness of R_a = 50 nm was obtained.

The DB tests were carried out in the VFE/TAV TPH25/25/35 Horizontal Vacuum Furnace (Fig. 2a). Coupled samples were placed in the DB rig (Fig. 2b, c) and centred using spring washers (Fig. 2b). The pressure was applied using a dead weight to achieve the required level of 3.2 MPa. Heating was conducted under the vacuum of 10^{-4} mbar. Then specimens were kept under the specified temperature and pressure within an established period of time. Experiments were carried out at two temperatures, 825 °C and 725 °C, and workpieces were kept at these temperatures during 2 and 4 h.

For the assessment of strength of the diffusion bonded pairs, shear experiments were carried out. A special assembly for shear testing was developed as depicted in Fig. 3. The shear tool assembly was designed to induce shear as the only mode of deformation at the plane where the bonding should occur. It was assumed that bonding line would be in the plane where the samples with 5 mm and 7 mm diameter were in contact. The assembly consisted of a cylindrical tube and two semi-circle inserts, with lateral holes passing through them (Fig. 3). Two lateral screws (light green in Fig. 3) were additionally used for the initiation of a backpressure resulting from a torque of 5 Nm and 10 Nm, applied to the 5 mm and 7 mm sample screws respectively. The shear rig has been installed in a modified servo-hydraulic laboratory press with 250 kN capacity. All shear tests were carried out at a constant velocity of the upper plate equal 0.5 mm/sec. The process parameters, namely force, velocity and displacement were recorded during the test. At least two samples were tested for each set of parameters. The maximum value of force was recorded for each sample and used afterwards for the calculation of the average force for a given set of DB parameters (temperature and time of DB). The relative measurement error of the average force for two tested samples was ± 5.86% for the confidential interval of 95%.

Three bonded couples were obtained after each bonding cycle. One couple from each test condition was used for microstructure investigations and the remaining two couples were used for shear strength testing. For the investigation of microstructure, bonded couples were cut in the longitudinal direction. The samples for metallographic analysis were prepared following same procedure which have been used for preparation of the surface of the samples for DB experiments with additional final polishing step using ChemoMet cloth with colloidal silica. A series of back scattered electron diffraction (BSED) images were obtained using SEM.

3. Discussion and results

3.1. Microstructure observations

To understand the microstructure evolution in the diffusion bonded samples, the size and volume fraction of the alpha and beta phases were measured for both CG and UFG samples bonded at two temperatures,

Table 1
Chemical composition.

	Ti	Fe	C	Al	O	V	N	H	Si	Zr
Ti – 6Al-4V	Basis	0.18%	0.007%	6.6%	0.17%	4.9%	0.01%	0.002%	0.033%	0.02%