Methods of controlling mechanical behavior of layered titanium material under impact loading

A A Sarkeeva, A A Kruglov and R Ya Lutfullin
Institute for Metals Superplasticity Problems of Russian Academy of Sciences, 39 Khalturin St., 450001 Ufa, Russia

E-mail: aigul-05@mail.ru

Abstract. The results of studies on the mechanical behavior of a Ti-6Al-4V laminated material obtained by diffusion welding are analyzed. It is shown that the impact behavior of the layered material depends on many factors including the interface defects, the orientation of the notch tip relative to interface, the number and microstructural state of the layers and their crystallographic texture.

1. Introduction

Layered materials (LMs) attract a great attention due to the possibility of significant improvements in their fracture toughness, fatigue and impact characteristics, wear and corrosion resistance and formability [1]. These materials are manufactured by various technological methods based on joining of both the similar and dissimilar metallic materials. Diffusion bonding, one of the joining processes, is carried out at a temperature below the melting temperature of materials under an applied pressure [2, 3]. The process of joint formation and the level of properties obtained by diffusion bonding can be controlled by selecting its parameters.

One of distinctive features of laminated materials in comparison with monolithic ones is the presence of numerous internal interfaces between the layers, which play a significant role in the mechanical behavior. The number of layers, interfacial properties and the type of arrangement of the interfaces relatively to the direction of impact load are critical factors. The properties of joints obtained by diffusion bonding depend on the microstructural characteristics in interfaces, in particular, on the presence of pores. It is worth noting that impact testing is the most sensitive method to assess the quality of joints processed by diffusion bonding [4]. The crack propagation in the layered materials is usually studied in two orientations: a) the crack divider orientation when the crack propagates simultaneously through all the layers; b) the crack arrester orientation when the crack propagates sequentially from one layer to another [5-7].

Another distinctive feature of layered materials is their ability to have a gradient structure. The production of materials, which are simultaneously strong and ductile, has been a permanent challenge for a long time. It is known, for example, that ultra-strong nanocrystalline materials usually have a low ductility [8]. Therefore, the development of materials with a gradient structure is important, since the strength and ductility are two of the most important mechanical properties but often are mutually exclusive. According to the published data [9], the combination of strong and plastic layers inhibits the crack development.
Mechanical properties of many materials depend not only on the structure but also on the texture [10, 11]. Texture effects play a significant role in the technological characteristics of titanium alloys [12]. The possible ways to control the mechanical behavior of diffusion bonded Ti–6Al–4V layered materials are shown in this paper.

2. Experimental

Ti-6Al-4V alloy sheets with microcrystalline (MC) and ultrafine-grained (UFG) structures were produced by VSMPO, Verkhnyaya Salda, Russia and multiple step forging [13] with subsequent isothermal rolling [14], respectively. Three types of layered materials were manufactured by diffusion bonding. The LM of type I consisted of thirteen MC sheets of an approximately 0.8 mm thickness, type II of seven MC sheets of ~ 1.5 mm thickness. The type III laminates were composed of six MC sheets of ~ 1.5 mm thickness and five UFG sheets of ~ 0.35 mm thickness assembled in an alternative sequence. Two methods of assembling sheets in a package were used when fabricating the layered material of types I: in one case, they were stacked relative to each other so that the rolling directions in them coincided, and in the other, they did not coincide, the angle between rolling directions in the neighboring sheets was 90°. Diffusion bonding of MC sheets was conducted at temperature 900°C, MC and UFG sheets at 600°C. The technology of diffusion bonding has been described in detail in Ref. [15].

The impact tests were carried out according to ASTM E23 at room temperatures using the impact testing machine that enables recording dynamic loading diagrams in the "load-displacement" coordinates. Full-sized U-notched Charpy specimens of dimensions 10×10×55 mm³, each with a 2 mm deep U-notch, were used in the tests. The samples were tested in the crack divider and arrester orientations, as shown schematically in figure 1. In the crack divider orientation (figure 1a), the initial notch/crack tip intersects all the layers of the test sample so that the crack propagates “sees” all the layers interfaces simultaneously. In the crack arrester orientation (figure 1b), the initial notch/crack tip ends within an individual layer of the test sample so that the crack front “sees” each layer interface sequentially during loading [5]. The division of the total energy of fracture (A) into its components such as the energy of crack initiation (A_i) and the energy of crack propagation (A_p) was performed on the basis of an analysis of the experimental diagrams of dynamic loading [16].

Figure 1. Samples for impact test: (a) crack divider orientation and (b) crack arrester orientation.

Metallographic examinations and fractography analysis were carried out using an optical microscope Nikon L150 and a TESCAN MIRA3 LMU scanning electron microscope.

3. Results and discussion

As previously published in Ref. [17], the as-received Ti-6Al-4V alloy sheets have a prismatic texture (11 20) [10 10]. The prismatic texture generates a difference in the properties along and transverse the rolling direction in the plane of a sheet. It is in such a texture that the strong anisotropy of fracture toughness is observed [18]. This texture is inherited by a layered material in which the sheets a stacked relative to each other so that the rolling directions in neighboring sheets coincide and thus causes the anisotropy in impact strength. The transverse samples of the 13-layer material in the crack divider orientation had a maximum impact strength value equal to 0.73 MJ/m². The layered material in which the sheets are stacked relative to each other so that the rolling directions in neighboring sheets do not coincide has the isotropy of properties due to practically the same distribution of the pole density of the basis in the rolling and transverse directions. The impact strength value of this material is equal to 0.66 MJ/m² for the crack divider orientation and 0.56 MJ/m² for the crack arrester orientation [15]. The laminated material in the crack divider orientation has higher impact strength due to the increased work of crack propagation. It is worth noting that the level of anisotropy in the layered material also can be
decreased by using UFG sheets with the isotropic mechanical properties as intermediate layers [19]. In addition, the application of UFG sheets allows manufacturing a layered material at a lower temperature of diffusion bonding.

The impact strength of the layered material in the crack arrester orientation can be improved by the presence of pores in interfaces which weaken them [19]. The results of studies of the 13-layer material showed that with a relative length of pores in the interfaces increasing from ~1 to 30%, the impact strength value decreases by 1.7 times for the crack divider orientation, and it increases by 14 times for the crack arrester orientation. The quantitative assessment of the fracture characteristics made it possible to clearly establish that the decrease in the impact strength of the laminate in the crack divider orientation is caused by a decrease in the work of crack propagation. Such a significant improvement in the fracture resistance of the layered material in the crack arrester orientation is determined by the need for multiple nucleation of new cracks and the higher dissipation of the fracture energy due to the formation of delamination. It is known that the delamination in layers ahead of the crack tip results in a reduction and redistribution of local stresses [20]. The delamination is formed along the interface between layers, and it is located perpendicularly to the direction of the main crack propagation. Delaminations are usually considered as a principal mechanism of crack arresting in layered materials [20, 21].

The level of properties of the layered material can be controlled by adjusting the number of layers [17]. The test results of the layered material without pores showed that when the crack propagates simultaneously through all layers (the crack divider orientation) the impact strength value is higher for the 7-layer material. In contrast, when the crack propagates sequentially from one layer to another (the crack arrester orientation) the impact strength value is higher for the 13-layer material. The decrease in the impact strength value of the layered material in the crack divider orientation with the number of layers is due to a decrease in both the crack initiation and propagation energies. In contrast, the improvement of impact strength of the layered material in the crack arrester orientation occurs due to the significant increase in the crack propagation energy at an insignificant decrease in the crack initiation energy.

To establish the effect of the gradient structure, a comparative analysis of the results of Charpy impact tests of the layered materials consisting of seven MC sheets and alternating sheets with MC and UFG structures (the latter is called structural composite) was carried out. The impact strength of the structural composite in the crack divider orientation is lower than that of the layered material (table 1). It is important to note that the structural composite is characterized by interfacial pores that facilitate the formation of delamination during fracture. On the other hand, this composite includes the UFG sheets. It is known that the Ti–6Al–4V alloy with UFG structure has a lower impact strength value due to the lower work of crack propagation [22]. The samples of structural composite tested in the crack arrester orientation did not fail as a result of the tests. The impact strength value was estimated by calculating the energy value expended on both the failure of the majority of the layers and the bend of the unfailed layers.

**Table 1.** The impact strength (KCU), the crack initiation energy ($A_i$) and the crack propagation energy ($A_{pr}$) of the layered material (MC/MC) and structural composite (MC/UFG) in the crack divider and arrester orientations.

| Material   | KCU (MJ/m²) | $A_i$ (J) | $A_{pr}$ (J) |
|------------|-------------|-----------|--------------|
|            | crack divider | crack arrester | crack divider | crack arrester | crack divider | crack arrester |
| MC/UFG     | 0.70        | > 1.74     | 21.1         | -             | 33           | -             |
| MC/MC [17] | 0.81        | 0.47       | 23.1         | 22.4          | 39.6         | 13.8          |
Figure 2. Macrographs of fractured impact samples of the structural composite: (a) crack divider orientation and (b) crack arrester orientation.

It is important to note that the studied orientations of interfaces relative to the direction of impact load action are characteristic for the real structures from titanium alloys manufactured by the DB/SPF process [23-25].

4. Conclusion

The technology methods of controlling properties of the layered material based on Ti-6Al-4V alloy are shown in the present work. The layered material with isotropic mechanical properties can be manufactured by assembling sheets in a package so that the rolling directions in them do not coincide or by alternation of MC and UFG sheets. The impact strength of the layered material in the crack arrester orientation can be improved by the presence of pores in interfaces contributing to the formation of delaminations. The impact strength of the layered material with an increasing number of layers decreases for the crack divider orientation and increases for the crack arrester orientation. The level of properties in the structural composite can be improved by optimizing the diffusion bonding conditions and the methods of combining layers with different structures.

Acknowledgment

This work was accomplished according to the state assignment of IMSP RAS No. AAAA-A17-117041310221-5.

References

[1] Lesuer D R, Syn C K, Sherby O D, Wadsworth J, Lewandowski J J and Hunt W H 1996 International Materials Reviews 41 169
[2] Kazakov N F 1985 Diffusion Bonding of Materials (Moscow: Publishers) 304 p [In Russian]
[3] Dunford D V and Wisbey A 1993 Materials Research Society Symposium Proceedings 314 39
[4] Gómez de Salazar J M, Ureña A and Carrión J G 1996 Scripta Materialia 35(4) 479
[5] Embury J D, Petch N J, Wraith A E and Wright E S 1967 Transaction of the Metallurgical Society of AIME 239 114
[6] He X F, Dong Y H, Li Y H and Wang X M 2018 International Journal of Fatigue 106 1
[7] Cepeda-Jiménez C M, Garcia-Infanta J M, Rozuelo M, Ruano O A and Carreno F 2009 Scripta Materialia 61(4) 407
[8] Valiev R Z, Zhilyaev A P and Langdon T G 2013 Bulk Nanostructured Materials: Fundamentals and Applications (Wiley-Blackwell) 440 p
[9] Petuhov A 2005 Dvigatel 5 6 [In Russian]
[10] Miklyaev P G and Fridman Ya B 1986 Anisotropy of Mechanical Properties of Metals (Moscow:
Bache M and Evans W J 2001 *Materials Science and Engineering A* **319** 409

Rubina E B and Betsofen S Ya 1990 *Physics of Metals and Metallography* **4** 191

Kaibyshev O A, Salishev G A, Galeyev R M, Lutfullin R Ya and Valiakhmetov O R 1998 Patent PCT/US97/18642, WO 9817836

Astanin V V and Kaibyshev O A 2008 Patent RU № 2320771

Sarkeeva A A, Kruglov A A, Lutfullin R Ya, Gladkovskiy S V, Zhilyaev A P and Mulyukov R R. 2020 *Composites Part B* **187** 107838

Georgiev M 2007 *Impact Crack-Resisting of Metals* 231 (Sofia: Bulvest 2000) 231 p [In Bulgarian]

Gorynin I V, Chechulin B B 1990 *Titanium in Mechanical Engineering* (Moscow: Mashinostroyeniye) 400p [In Russian]

Ganeeva A A, Kruglov A A and Lutfullin R Ya 2010 *Reviews on Advanced Materials Science* **25** 136

Rohatgi A, Harach D J, Vecchio K S and Harvey K P 2003 *Acta Materialia* **51** 2933

Cepeda-Jiménez C M, Garcia-Infanta J M, Rozuelo M, Ruano O A and Carreno F 2009 *Scripta Materialia* **61**(4) 407

Sarkeeva A A, Lutfullin RYa, Kruglov A A and Astanin V V 2012 *Letters on Materials* **2** 99

Mulyukov R R, Nazarov A A and Imayev R M 2018 *Letters on Materials* **8**(4s) 510

Beck W, Duong L and Rogall H 2008 *Materialwissenschaft und Werkstofftechnik* **4-5** 293

Kruglov A A, Mulyukov R R, Rudenko O A, Karimova A F and Enikeev F U 2019 *Letters on Materials* **9**(4) 433