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Mechanical properties of Ti-6Al-4V three-layer material

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The paper presents the results of studies on the mechanical behavior under impact and tensile loading of a Ti-6Al-4V three-layer material obtained by diffusion bonding at 800°C. Diffusion bonding is the process that integrates one material with another by pressure at a temperature below the melting points of materials. Diffusion bonding of Ti-6Al-4V alloy is particularly interesting for aerospace structures, ballistic armor and sports equipment manufacturing. Predominantly single spherical pores are present in the joint zone; chains of pores are extremely rare. The static mechanical properties of the laminate are at the level of properties of monolithic material. The laminate is characterized by a different fracture resistance depending on the layer orientation relative to the direction of impact load action. The impact strength value of the laminate is minimum in the crack short-transverse orientation due to the lower energy of crack propagation. The energy of crack nucleation in the studied laminate is the same for all studied orientations of crack propagation. The results of the evaluation of the relative value of the impact strength showed that the laminate has the highest fracture resistance for the crack divider orientation. The studied layer orientations relative to the direction of impact load action are characteristic for the real diffusion-bonded structures.

Keywords: titanium alloy, laminate, diffusion bonding, mechanical properties, impact strength.

1. Introduction

Titanium alloys are widely used as structural materials due to a set of useful physical and mechanical properties and good weldability in various industries [1–7]. Diffusion bonding of Ti-6Al-4V alloy is particularly interesting for aerospace structures, ballistic armor and sports equipment manufacturing [3–5]. The information on the mechanical behavior of these structures under the action of various loads is important for ensuring their durability and reliability. The mechanical behavior of a laminate under impact loading depends on many factors [8–15], one of which is the oriented arrangement of the layers relative to the direction of the impact load action. Three principal orientations of crack propagation are distinguished in laminates: divider (the crack propagates simultaneously through all the layers), arrester (the crack propagates sequentially from one layer to another) and short-transverse (the crack propagates between the layers along an interface) [8, 9].

Diffusion bonding (DB) is the process that integrates one material with another by pressure at a temperature below melting points of materials. It is well known [16–18] that the diffusion bonding in superplasticity conditions exerts a favorable effect on the formation of a solid-state joint. When the optimal conditions of the diffusion bonding are not observed, the processes of formation of physical contact and volume interaction may not be completed and pores may be present in the interfaces.

The aim of this paper is to study the microstructure and mechanical behavior of Ti-6Al-4V three-layer material obtained by diffusion bonding and to determine the effect of layer orientation relative to the direction of impact load action on the fracture characteristics.

2. Materials and experimental procedure

The initial materials were commercial Ti-6Al-4V plate and sheet with the thicknesses of 30 ± 0.05 mm and 1 ± 0.02 mm, respectively. The chemical composition of these materials complies with Russian standards (GOST 19807-91). The titanium sheet alloy has improved superplastic properties [19]. The three-layer material was obtained by diffusion bonding of the two plates with the intermediate sheet at temperature 800°C in a vacuum furnace under argon pressure using a flexible membrane. The contact surfaces of the plates and sheet with sizes of 220 mm in length and 105 mm in width were mechanically polished, then washed in alcohol and finally in acetone.

The mechanical properties of the monolithic and laminate materials were estimated by means of tensile and impact tests at room temperature. Tensile tests were carried out on an Instron-1185 testing machine using cylindrical specimens with the length of 22 mm and diameter 4 mm. In these tests, the welding interfaces were located transversely to the deformation axis. The impact tests were carried out according to ASTM E23 on an Instron CEAST 9350 testing machine that enables recording of dynamic loading diagrams. Two millimeters U-notched type layered and monolithic samples with dimensions of 10×10×55 mm^3 and a notch of 1 mm in radius were cut from the diffusion bonded laminate in the normal and transverse directions. Crack propagation in the three-layer material has been studied in three principal orientations [10], as shown schematically in Fig. 1.

The impact strength (the resistance of material to fracture) was calculated as a ratio of the fracture energy to the cross-section area of the samples. The division of the total energy of fracture into its components such as the energy of crack initiation and the energy of crack propagation was performed on the basis of an analysis of the experimental diagrams of dynamic loading [20]. The area under the ascending part of the experimental curve corresponds to the crack initiation energy, the area under the descending part of the curve corresponds for the crack propagation energy. The values of mechanical properties were determined based on the results of three measurements.

The microstructural studies were carried out using a scanning electron microscope "TESCAN MIRA3 LMU".

3. Results and Discussion

Detailed investigations of the Ti-6Al-4V sheet were carried out in [19], where it was shown that the material had a homogeneous ultrafine-grained structure with an average grain size of 1.2 μm. The best superplastic properties of this sheet are observed in the temperature range from 700 to 850°C. The material has isotropic properties.

The microstructure of the Ti-6Al-4V plate is heterogeneous (Fig. 2). There are areas in the form of bands with elongated α-grains on the background of a homogeneous structure with equiaxed α-grains.

Fig. 3 shows the microstructures observed on the cross-sections of the laminate at different magnifications. The interfaces are located in the middles of the images. It can be seen that in the joint zone there are predominantly single spherical pores; chains of pores are extremely rare. The pores are located along the interface and have a size of ~1 μm. It should be noted that such a residual fraction of pores will always be present in the structural components manufactured by diffusion bonding.

The results of comparative tensile tests show that the properties of the layered samples are comparable to those of the monolithic samples (Fig. 4). The layered samples failed along the base material, and not along the interface between the layers. These results are consistent with the literature data [21–23], which indicate that when a fraction of pores is small the properties of the diffusion bonded joints are at the level of properties of the base material. Only when the fraction of pores is significant, the strength decreases and the fracture occurs along the interface.

The results of impact tests indicate a significant effect of layer orientation relative to the direction of load action on the mechanical behavior of the laminates. The laminates in the crack divider and arrester orientations have a higher value of impact strength in comparison to the crack short-transverse orientation. It should be noted that the samples tested in the crack short-transverse orientation have a wide scatter in the impact strength values, which varies from 0.28 to 0.40 MJ/m^2. The fracture of these samples took place along the interface between two layers. Such a difference in the impact toughness is apparently due to the different fractions of interface pores. A quantitative assessment of the characteristics of impact fracture made it possible to elucidate the reason for the different values of impact strength. Analysis of these data showed that the crack initiation energy was the same for all samples, but the crack propagation energy was significantly different. The crack propagation energy for the laminate in the crack-short transverse orientation is minimal, its value varies from 7 to 13 MJ/m^2. At the same time, the crack propagation energy for the laminate in the crack arrester and divider orientations is equal to 30 and 22 J, respectively. The results of impact tests are in good agreement with the literature data [8], where it is reported that when a crack propagates along the interface, the impact strength of the layered material is minimal in comparison with other principal crack orientations. However, this behavior of the three-layer material can also be associated with the properties of its constituent materials. In this regard, the impact test of the monolithic material was carried out. The monolithic samples were cut from the laminate in the normal direction (SL) and transverse direction with different

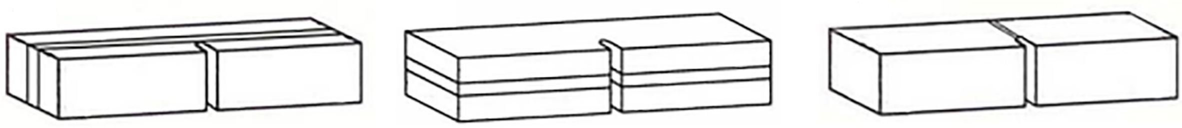


Fig. 1. Samples for impact test: crack arrester orientation (a), crack divider orientation (b) and short-transverse orientation (c).

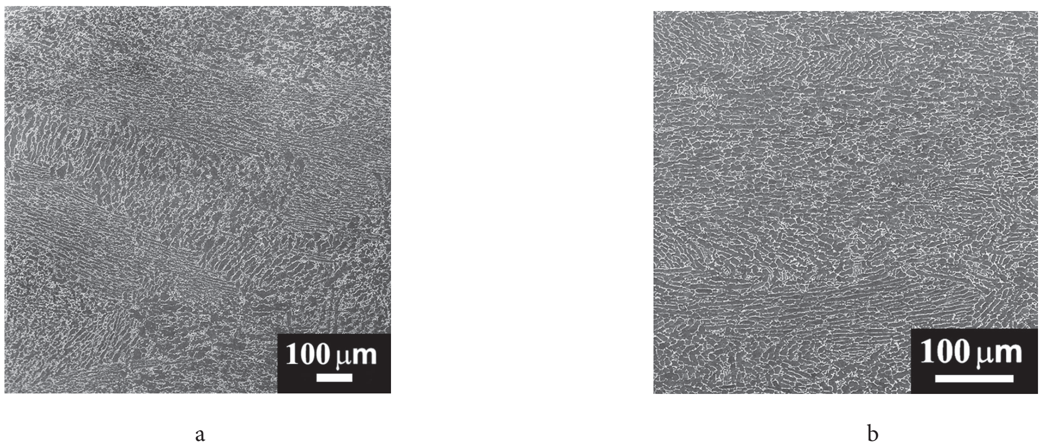
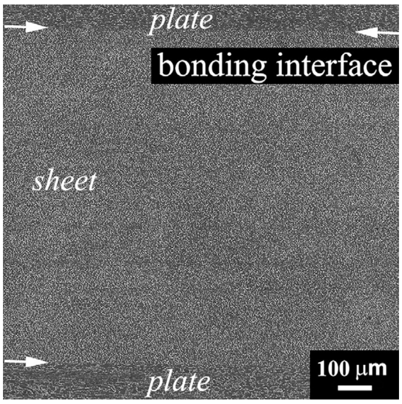


Fig. 2. The microstructure of Ti-6Al-4V plate in the rolling plane (a) and rolling direction (b).



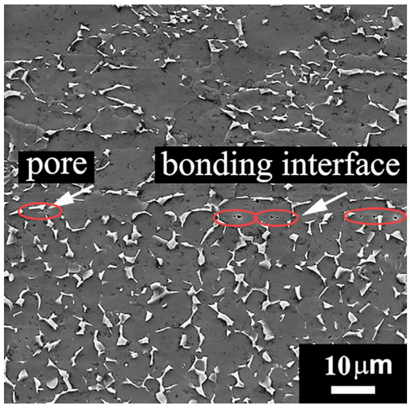


Fig. 3. The microstructure of laminate in bonding zone.

orientations of a notch tip relative to the rolling plane (TS and TL). It was found that the SL-samples had decreased impact strength (KCU = 0.48 MJ/m^2). The impact strength is highest for the samples when the notch direction is parallel to the rolling plane of plate and is equal to 0.76 MJ/m^2 (TS-samples). The results of evaluating the relative value of the impact strength made it possible to clearly establish the effect of layer orientation (Fig. 5). It is seen that the fracture resistance of the laminate is highest for the crack divider orientation and the smallest for the crack short-transverse orientation. The impact strength of the laminate in the crack short-transverse orientation is 0.77 of the impact strength level of the monolithic material. At the same time, the tensile properties of the laminate are at the level of properties of the monolithic material (Fig. 4). These experimental data also indicate that the impact tests are the most sensitive method to assess the quality of diffusion bonded joints in comparison with the tensile tests. According to the data from literature [21–23], the tensile properties of DB joints can decrease at a more significant volume fraction of interface pores.

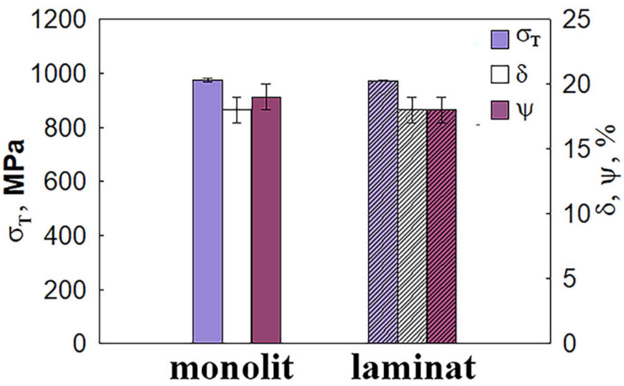


Fig. 4. (Color online) Results of tensile tests for laminate and monolithic Ti-6Al-4V alloy (plate).

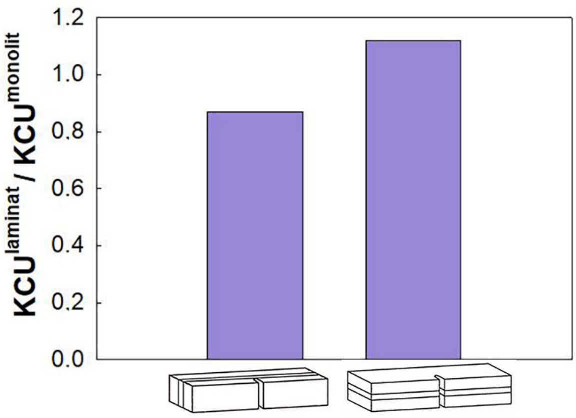


Fig. 5. Relative impact strength.

4. Conclusions

The results of mechanical tests demonstrate that the impact strength is the most sensitive characteristic to assess the quality of diffusion bonded joints. Using the impact testing machine with recording dynamic loading diagrams allows a quantitative assessment of the fracture characteristics and understanding the mechanical behavior of the laminate. The laminate has minimal impact strength value in the crack short-transverse orientation due to the decreased energy of crack propagation. The location of the layers relative to the direction of load action affects only the energy of crack nucleation, the energy of crack propagation is the same. The results of impact tests can be used in the designing and analysis of the mechanical behavior of Ti-6Al-4V multilayer structures manufactured by diffusion bonding.

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References

1. Titanium and Titanium Alloys: Fundamentals and Applications. 1rd edn (ed. by C. Leyens, M. Peters). Weinheim, Wiley-VCH (2003) 523 p. Crossref
2. L. M. Kang, C. Yang. Advanced Engineering Materials. 21 (8), 1801359 (2019). Crossref
3. J. C. Williams, R. R. Boyer. Metals. 10 (6), 705 (2020). Crossref
4. W. Beck, L. Duong, H. Rogall. Materialwissenschaft und Werkstofftechnik. 39 (4–5), 293 (2008). Crossref

5. R. V. Safiullin. Lett. Mater. 2 (1), 36 (2012). (in Russian) [Р. В. Сафиуллин. Письма о материалах. 2 (1), 36 (2012).] Crossref
6. A. A. Kruglov, R. Ya. Lutfullin, M. Kh. Mukhametrakhimov et al. Lett. Mater. 11 (4), 457 (2021). (in Russian) [А. А. Круглов, Р. Я. Лутфуллин, М. Х. Мухаметрахимов и др. Письма о материалах. 11 (4), 457 (2021).] Crossref
7. E. Yu. Klassman, V. V. Astanin. Lett. Mater. 10 (1), 10 (2020). (in Russian) [Е. Ю. Классман, В. В. Астанин. Письма о материалах. 10 (1), 10 (2020).] Crossref
8. R. W. Hertzberg, R. P. Vinci, J. L. Hertzberg. Deformation and Fracture Mechanics of Engineering Materials. 4th edn. Inc, John Wiley & Sons (2021).
9. J. D. Embury, N. J. Petch, A. E. Wraith, E. S. Wright. Transaction of the Metallurgical Society of AIME. 239 (1), 114 (1967).
10. X. He, Y. Dong, Y. Li, X. Wang. Int. J. Fatig. 106, 1 (2018). Crossref
11. A. A. Sarkeeva, A. A. Kruglov, R. Ya. Lutfullin et al. Composites Part B. 187, 107838 (2020). Crossref
12. A. A. Sarkeeva. Letters on Materials. 10 (3), 345 (2020). (in Russian) [А. А. Саркеева. Письма о материалах. 10 (3), 345 (2020).] Crossref
13. C. M. Cepeda-Jiménez, J. M. Garcia-Infanta, M. Rozuelo et al. Scr. Mater. 61 (4), 407 (2009). Crossref
14. R. P. Weber, K. K. Chawla, J. C. Miguez Suarez. Mater. Sci. Eng. A. 580, 279 (2013). Crossref
15. A. A. Sarkeeva, A. A. Kruglov, R. Ya. Lutfullin. IOP Conf. Ser.: Mater. Sci. Eng. 1008, 012071 (2020). Crossref
16. D. V. Dunford, A. Wisbey. Materials Research Society Symposium Proceedings. 314, 39 (1993). Crossref
17. A. K. Akhunova, V. A. Valitov, E. V. Galieva. Lett. Mater. 11 (3), 254 (2021). (in Russian) [А. Х. Ахунова, В. А. Валитов, Э. В. Галиева. Письма о материалах. 11 (3), 254 (2021).] Crossref
18. R. Ya. Lutfullin, O. A. Kaibyshev, R. V. Safiullin et al. Acta Metall Sin. 13, 561 (2000).
19. A. R. Safiullin, R. M. Galeyev, O. R. Valiakhmetov et al. Lett. Mater. 6 (4), 281 (2016). (in Russian) [А. Р. Сафиуллин, Р. М. Галеев, О. Р. Валиахметов и др. Письма о материалах. 6 (4), 281 (2016).] Crossref
20. M. Georgiev. Impact Crack-Resisting of Metals. Sofia, Bulvest 2000 (2007) 231 p. (in Bulgarian) [М. Георгиев. Пукнатиноустойчивост на металите при ударно натоварване. София, БУЛВЕСТ 2000 (2007) 231 с.]
21. S. M. Gurevich, V. N. Zamkov, V. E. Blashuk et al. Metallurgiya i tekhnologiya svarki titana i ego splavov. 2th edn. Kiev, Naukova dumka (1986) 240 p. (in Russian) [С. М. Гуревич, В. Н. Замков, В. Е. Блащук и др. Металлургия и технология сварки титана и его сплавов. Киев, Науковадумка (1986) 240 с.]
22. N. F. Kazakov. Diffusion bonding of materials. Oxford, Pergamon (2015) 304 p.
23. J. Xiong, Y. Peng, M. Samiuddin, L. Yuan, J. Li. Journal of Materials Engineering and Performance. 29 (5), 3277 (2020). Crossref