Letters on Materials 12 (4s), 2022 pp. 499-503 www.lettersonmaterials.com

https://doi.org/10.22226/2410-3535-2022-4-499-503

Impact fracture characteristics of multilayer laminate based on near-alpha titanium alloy

A. A. Sarkeeva

aigul-05@mail.ru

Institute for Metals Superplasticity Problems of the RAS, Ufa, 450001, Russia

Titanium near-alpha alloy Ti-6Al-2Zr-1.2Mo-1.3V was used to manufacture a multilayer laminate by diffusion bonding. The laminate consisted of thirteen sheets stacked relative to each other in a way that they all had common rolling direction. The influence of cutting orientation of specimens on the mechanical behavior under impact loading of the laminate was determined. The results of quantitative assessment of the impact fracture characteristics for the studied specimens was analyzed. The transverse specimens had a higher impact strength value in comparison to the longitudinal specimens. The results of fractographic studies showed the presence of minor delaminations on the surfaces of fractured specimens.

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

1. Introduction

Titanium alloys are widely used in various industries due to a good combination of weight, strength, impact strength, corrosion resistance and good weldability [1–5]. This is achieved through the appropriate design of microstructures as a result of thermal deformation processing and host of phase transformations in these alloys [1, 4, 6]. However, this traditional method for improving the properties of titanium alloys has practically exhausted its possibilities. The application of the layering principle is a promising direction for solving this problem. It is known that multilayer laminates in comparison to monolithic ones are characterized by higher impact strength, crack resistance and fatigue life at the same level of strength [7–14]. Two types of toughening mechanisms can be conventionally distinguished in the multilayer materials. Intrinsic toughening is related to the structural state of the laminate. Extrinsic toughening is related to the internal interfaces between layers which contribute to a change in the trajectory of the main crack propagation, a decrease in the crack propagation rate and the crack re-initiation probability [11]. There are different technological methods for manufacturing multilayer materials from titanium alloys, one of which is diffusion bonding [7, 8,10–15]. Diffusion bonding or diffusion welding is a solid-state bonding process used most extensively in the aerospace industries for joining materials to obtain shapes that otherwise could not be made [16–18]. It is known that the quality of diffusion-bonded joints depends on the temperature, pressure, holding time, quality of vacuum and surface preparation of components to be joined [16–21]. Diffusion bonding is carried out at a temperature below the melting point of materials. Moreover, the optimal temperature of diffusion bonding is the temperature of superplastic deformation of the material [19–21]. The mechanical behavior of a diffusion-bonded multilayer laminate based on $\alpha+\beta$ titanium alloy Ti-6Al-4V was studied in detail in [22, 23]. The authors of [22] analyzed the influence of the interface pores on the total energy of fracture, the energies of crack initiation and crack propagation. In [23], the anisotropy of impact strength of the Ti-6Al-4V laminate was studied. Meanwhile, taking account for the variety of titanium alloys, the study of the behavior of multilayer material from titanium alloys of a different phase composition is not only of scientific interest but also has a technical importance. Therefore, the aim of the present work was to determine the impact fracture characteristics of diffusion-bonded multilayer laminate based on a near-alpha type titanium alloy.

2. Materials and experimental methods

The initial material was commercial Ti-6Al-2Zr-1.2Mo-1.3V alloy sheets manufactured by the VSMPO-AVISMA corporation, Verkhnyaya Salda, Russia. The thickness of the sheets was equal to 0.8 ± 0.02 mm. The chemical composition of the studied alloy is presented in Table 1.

Thirteen sheets were used for the fabrication of the multilayer laminate. The contact surfaces of the sheets of 220 mm length and 105 mm width were cleaned with a metal brush, then washed in alcohol and finally in acetone. When assembling into a package, the sheets were stacked relative

Table 1. Chemical composition of Ti-6Al-2Zr-1.2Mo-1.3V alloy (wt.%) according Russian standards (GOST 19807-91).

Alloying elements	Al	V	Mo	Zr	Si	Fe	O	H	N	C	Ti
Content, wt.%	5.5 – 7.0	0.8 – 2.5	0.5 – 2.0	1.5 – 2.5	0.15	0.25	0.15	0.015	0.05	0.1	base

to each other so that they had a common rolling direction. Then the package was placed between the heavy plates of the die set. A flexible membrane was placed between the package and the upper plate to provide the possibility to use an inert gas for diffusion bonding. The total set was fixed by a wedge lock, and this locked set was placed into the electrical vacuum furnace OKB-8086. After the required temperature was achieved, the inert gas (argon) was fed to the total set by means of the flexible membrane. Diffusion bonding was carried out at 950°C and holding time of 2 hours under pressure. Heating, pressing and cooling to room temperature were performed under the vacuum conditions of $2 \cdot 10^{-3}$ Pa.

The specimens with dimensions of $10 \times 10 \times 55$ mm^3 and with a 2 mm deep U-notch were used in the impact tests. The specimens were cut from the diffusion-bonded laminate in the rolling direction (RD) and transverse direction (TD); they were defined as longitudinal (L-T) and transverse (T-L) specimens, respectively (Fig. 1). These specimens were tested in the crack divider orientation. In this type of specimen, the initial notch/crack tip intersects all the layers of the test specimen so that a propagating crack intersects all layer interfaces simultaneously [9]. The impact tests were carried out according to ASTM E23 standard on an Instron CEAST 9350 testing machine with recording dynamic loading diagrams at room temperature. 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_{pr}) was performed on the basis of an analysis of the experimental diagrams of dynamic loading in accordance with the recommendations in [24,25]. 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 the mechanical properties were determined based on the results of three measurements.

Microstructural and fractography analyses were carried out using a TESCAN MIRA3 LMU scanning electron microscope (SEM) equipped with backscattered electron imaging setup.

3. Results and discussion

The Ti-6Al-2Zr-1.2Mo-1.3V sheet in the as-received state had a pronounced structural heterogeneity. Figure 2 shows the microstructure of material in the rolling plane. It can be seen that there are areas with a structural component elongated in the rolling direction. The grain boundaries are indistinguishable in the SEM.

The microstructures of the manufactured laminate in the rolling plane and longitudinal section are presented in Fig. 3. The microstructure of the material after diffusion bonding is predominantly homogeneous with equiaxed α-grains. The average size of α-grains is approximately 10 μm. It should be

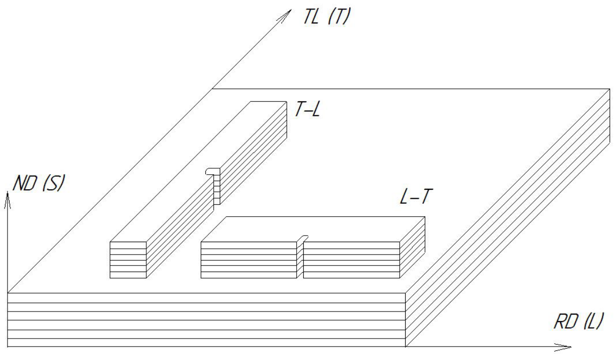


Fig. 1. Schematic illustration of impact specimen cutting from multilayer laminate in the crack divider orientation.

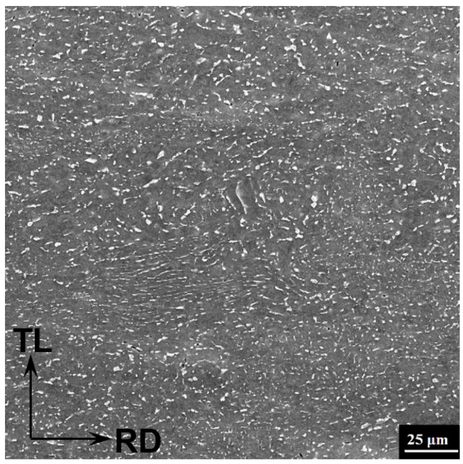
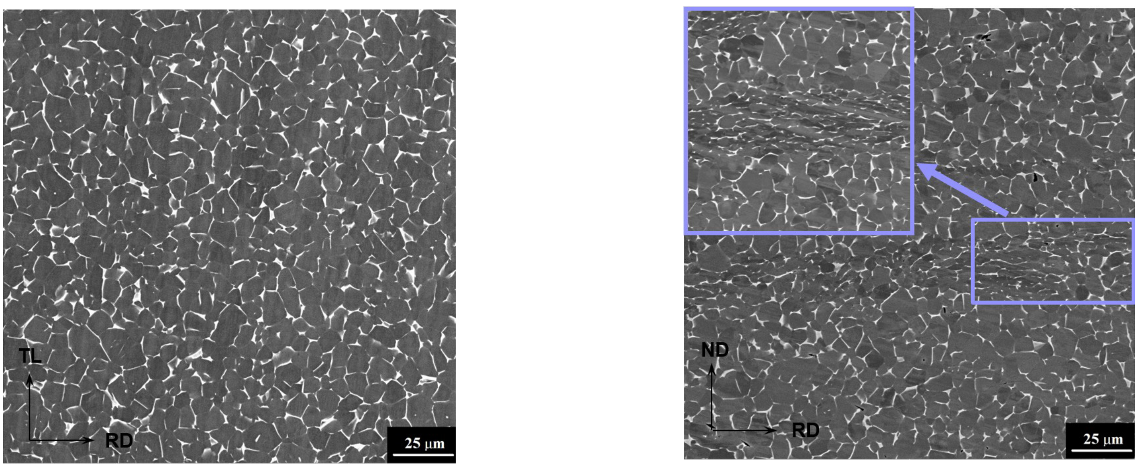


Fig. 2. The microstructure of Ti-6Al-2Zr-1.2Mo-1.3V sheet in the rolling plane.



a

b

Fig. 3. The microstructure of laminate in the (a) rolling plane and (b) longitudinal section.

noted that areas in the form of bands with α-grains elongated in the rolling direction remain in the cross section. Thus, it can be concluded that the laminate is characterized by a metallographic texture.

From to the results of the microstructural analysis, it follows that the solid-state joints without interfacial pores were formed as a result of diffusion bonding. Moreover, the interfaces between the layers are not distinguishable from the BSE images.

The results of impact tests indicate that the manufactured laminate is characterized by an anisotropy of impact strength relative to the cutting direction of specimens (Fig. 4). The transverse specimens have a higher impact strength value (KCU = 1.7 MJ/m^2) in comparison with the longitudinal specimens (KCU = 1.3 MJ/m^2). These results are in full agreement with the experimental data of the study of diffusion-bonded multilayer laminate based on $\alpha+\beta$ titanium alloy [23]. For the manufacture of the latter, the sheets were stacked relative to each other the same way as in the assembly of the package of the near-alpha titanium alloy used in the present study. The Ti-6Al-4V laminate in the crack divider orientation had improved fracture resistance along transverse direction too. The value of the impact strength of longitudinal specimens was equal to 0.57 MJ/m^2 and for the transverse specimens to 0.73 MJ/m^2. The interface pores in the Ti-6Al-4V laminate were practically absent. Thus, from a comparative analysis of the obtained experimental and literature data, it follows that the fracture resistance of the studied Ti-6Al-2Zr-1.2Mo-1.3V laminate in the crack divider orientation is 2.3 times higher than that for the similar Ti-6Al-4V laminate.

Figure 5 shows the impact loading diagrams of the investigated multilayer specimens. It is seen that the shapes of the curves for the longitudinal and transverse specimens are similar only on their ascending parts. The diagram of the longitudinal specimen (Fig. 5 a) is characterized by a steeper load drop than the diagram of the transverse specimen (Fig. 5 b). Thus, these diagrams indicate a different mechanical behavior of the manufactured Ti-6Al-2Zr-1.2Mo-1.3V laminate depending on the cutting direction of impact specimens.

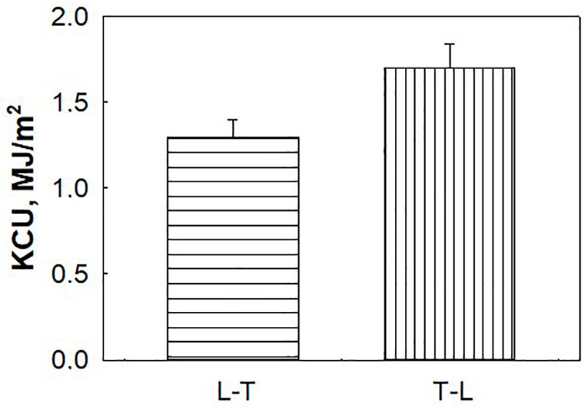


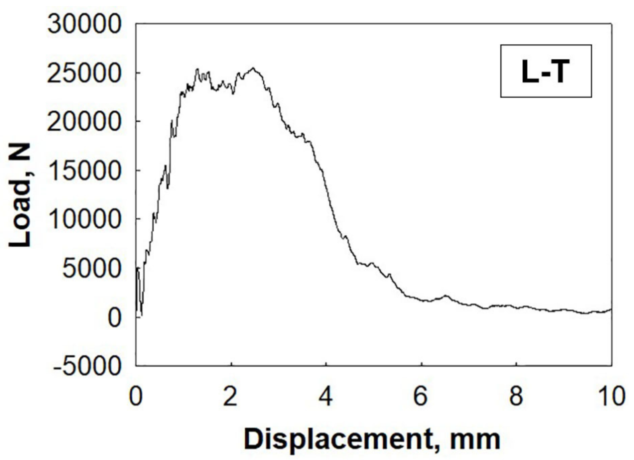
Fig. 4. Impact strength of the longitudinal (L-T) and transverse (T-L) specimens of the laminate in the crack divider orientation.

The results of the quantitative assessment of the impact fracture characteristics for the specimens of the Ti-6Al-2Zr-1.2Mo-1.3V laminate are presented in Table 2. It is seen that for all studied specimens the energy of the crack propagation is higher than the one of the crack initiation. It should be noted that this is most pronounced for the transverse specimens. The crack propagation energy for the transverse specimens is 2.4 times higher than that the crack initiation energy.

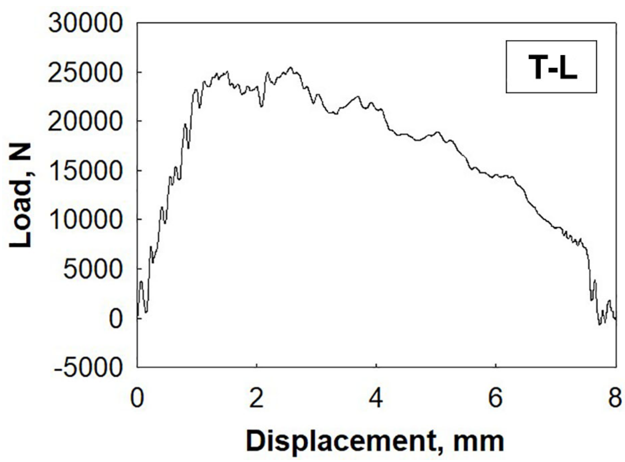
An analysis of the presented results also shows that the crack initiation energy is practically the same for all specimens. In contrast, the crack propagation energy for the specimens is significantly different. Its value for the transverse specimens is 1.7 times higher than that for the longitudinal specimens. The quantitative assessment of the fracture characteristics

Table 2. The total energy of fracture (A), the energy of crack initiation (A_i) and the energy of crack propagation (A_{pr}) for the longitudinal and transverse specimens of the Ti-Al-Zr-Mo-V laminate in the crack divider orientation.

Specimens	A(J)	A_i (J)	A_{pr} (J)
Longitudinal (L-T)	104.53	46.99	57.54
Transverse (T-L)	134.85	40.17	94.68

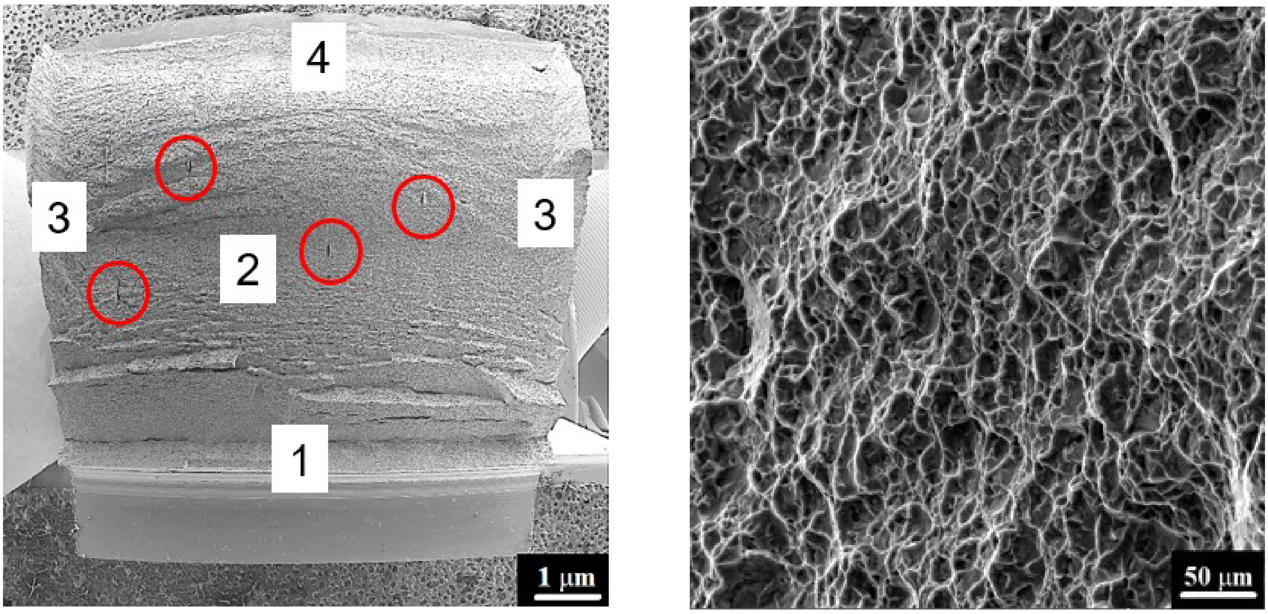


a



b

Fig. 5. Impact loading diagrams for the (a) longitudinal (L-T) and (b) transverse (T-L) specimens tested in the crack divider orientation.



a b

Fig. 6. Results of fractographic studies: macrographs (a) and micrographs (b) of fractured impact specimen of the Ti-6Al-2Zr-1.2Mo-1.3V laminate tested in the crack divider orientation.

made it possible to clearly establish that the higher impact strength value of the transverse specimens is related to the increased energy of crack propagation.

The results of fractographic studies are presented in Fig. 6. The surfaces of fractured specimens of the Ti-6Al-2Zr-1.2Mo-1.3V laminate (Fig. 6a) consist of four characteristic zones similar to the fracture surface of Ti-6Al-4V laminate [21]. As seen from Fig. 6b, the fracture surface is lusterless and has a dimpled ductile character.

Small delamination cracks are observed on the fracture surfaces of all tested specimens (Fig. 6a, enclosed in red circles). These cracks are located along the interfaces between the layers. Moreover, according to the published data [22,26], the delamination cracks are located perpendicularly to the direction of the main crack propagation. It was noted in [22] that the ability of the diffusion-bonded multilayer titanium laminate to delamination was enhanced with an increase in the porosity of the interface. It is known that the delamination cracks are formed on the weakest interfaces in a material [27]. The strength of diffusion-bonded joint can be reduced if the process of formation of solid-state joint is incomplete. It is known that the process of formation of solid-state joint takes place in three stages [16–18]: 1) the formation of a physical contact between the joining materials as a result of their plastic deformation; 2) activation of contact surfaces; 3) volumetric interaction in which strong metallic bonds are formed between the joining materials.

When taking into account the formation of delamination on the fracture surfaces of impact specimens, it can be concluded that the formation of strong metal bonds over the entire surface bonded Ti-6Al-2Zr-1.2Mo-1.3V sheets did not occur. Summarizing the obtained experimental data, it also follows that the absence of interface pores during metallographic examination does not yet indicate the formation of high-quality solid-state joint.

4. Conclusions

In this study, the Ti-6Al-2Zr-1.2Mo-1.3V laminate was manufactured by diffusion bonding of thirteen sheets stacked relative to each other with a common rolling direction. This laminate is characterized by the anisotropy of impact strength relative to the cutting direction of specimens. The transverse specimens have a higher impact strength value in comparison with the longitudinal specimens that is related to the increased value of crack propagation energy.

Acknowledgements. The author is grateful to Dr. A. A. Kruglov and S. N. Gerasimenko for help in the manufacture of Ti-6Al-2Zr-1.2Mo-1.3V laminate. The work was supported by the IMSP RAS State assignment No. AAAA-A17-117041310221-5. Microstructural studies were carried out in the facilities of shared services center of the Institute for Metals Superplasticity Problems of the Russian Academy of Sciences "Structural and Physical-Mechanical Studies of Materials", mechanical impact test — in the Center for collective use of "Nanotech" USATU.

References

1. V.N. Moiseyev. Titanium Alloys. Russian Aircraft and Aerospace Applications. 1st Edition. Florida, CRC Press (2005) 216 p. Crossref
2. Titanium and Titanium Alloys: Fundamentals and Applications. 1rd edn (ed. by C. Leyens, M. Peters). Weinheim, Wiley-VCH (2003) 523 p. Crossref
3. J.C. Williams, R.R. Boyer. Metals. 10 (6), 705 (2020). Crossref
4. A.I. Horev. Aviaczionny`e materialy` i tekhnologii. 1, 204 (2007). (in Russian)
5. A. A. Kruglov, R. Ya. Lutfullin, M. Kh. Mukhametrakhimov,

O. A. Rudenko, A. A. Sarkeeva, R. V. Safiullin. Lett. Mater. 11 (4), 457 (2021). (in Russian) Crossref
6. X. Li, Q. Zhu, S. Liu, F. Li, F. Chen, H. Wang, H. Chang. Journal of Materials Research and Technology. 18, 1704 (2022). Crossref
7. A. I. Plokhikh, S. V. Putirskiy, T. Wang. Journal of Physics: Conference Series. 1990 (1),012005 (2021). Crossref
8. A. A. Sarkeeva, A. A. Kruglov, R. Ya. Lutfullin. IOP Conference Series: Materials Science and Engineering, 1008 (1), 012071 (2020). Crossref
9. R. W. Hertzberg, R. P. Vinci, J. L. Hertzberg. Deformation and Fracture Mechanics of Engineering Materials. 4th edn. Inc, John Wiley & Sons (2021).
10. R. P. Weber, K. K. Chawla, J. C. Miguez Suarez. Mater. Sci. Eng. A. 580, 279 (2013). Crossref
11. C. M. Cepeda-Jiménez, J. M. Garcia-Infanta, M. Rozuelo et al. Scr. Mater. 61 (4), 407 (2009). Crossref
12. W. Sun, F. You, F. Kong, X. Wang, Y. Chen. Journal of Alloys and Compounds. 820, 153088 (2020). Crossref
13. D. R. Lesuer, C. K. Syn, O. D. Sherby, et al. International Materials Reviews. 41 (5), 169 (1996). Crossref
14. S. V. Kuteneva, S. V. Gladkovsky, D. I. Vichuzhanin, P. V. Kosmachev, P. D. Nedzvetsky. Lett. Mater. 12 (3), 225 (2022). Crossref
15. A. A. Sarkeeva. Letters on Materials. 11 (4s), 571 (2021). Crossref
16. N. F. Kazakov. Diffusion bonding of materials. Oxford, Pergamon (2015) 304 p.
17. H. S. Lee. In: Welding and Joining of Aerospace Materials. Woodhead Publishing (2012) pp. 320 – 344. Crossref
18. T. Gietzelt, V. Toth, A. Huell. Chapter 9. Diffusion Bonding: Influence of Process Parameters and. Material Microstructure. In: Joining Technologies. 1st edition. Intech (2016) 282 p. Crossref
19. D. V. Dunford, A. Wisbey. Materials Research Society Symposium Proceedings. 314, 39 (1993). Crossref
20. A. K. Akhunova, V. A. Valitov, E. V. Galieva. Lett. Mater. 11 (3), 254 (2021). (in Russian) Crossref
21. R. Ya. Lutfullin, O. A. Kaibyshev, R. V. Safiullin et al. Acta Metall Sin. 13, 561 (2000).
22. A. A. Sarkeeva, A. A. Kruglov, R. Ya. Lutfullin et al. Composites Part B. 187, 107838 (2020). Crossref
23. A. A. Sarkeeva. Letters on Materials. 10 (3), 345 (2020). (in Russian) Crossref
24. Russian standart GOST 22848-77.
25. M. Georgiev. Impact Crack-Resisting of Metals. Sofia, Bulvest 2000 (2007) 231 p. (in Bulgarian)
26. H. L. Haskel, E. Pauletti, J. P. Martins, A. L. M. Carvaiho. Materials Research. 17 (5), 1238 (2014). Crossref
27. C. M. Cepeda-Jiménez, A. Orozco-Caballero, A. A. Sarkeeva, et al. Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Sciencethis link is disabled. 44 (10), 4743 (2013). Crossref