Study of structure and properties of multilayer materials based on titanium alloys

A I Plokhikh$^1$, S V Putirskiy$^2$ and Tao Wang$^3$

$^1$Bauman Moscow State Technical University named after N.E. Bauman (National Research University); (Bauman MSTU, 2nd Baumanskaya Str., bldg. 1, 105005, Moscow, Russian Federation)

$^2$Federal State Unitary Enterprise All-Russian Scientific Research Institute of Aviation Materials State Research Center of the Russian Federation (FSUE VIAM), 105005, Moscow, Radio street, 17

$^3$TYUT-UOW Joint Research Centre, Taiyuan University of Technology, Taiyuan 030024, China

E-mail: 1plokhikh@bmstu.ru, 2s.putirskiy@gmail.com

Abstracts. The article presents the results of the study of the structure and properties of multilayer materials based on titanium alloys of various classes. The selection of initial compositions founded upon the approach previously tested in the development of multilayer materials based on steels is presented. The basic possibility of forming a laminar structure in titanium multilayer materials has been shown. Based on the analysis of the microstructure, especially the interlayer boundaries, the starting composition that is most suitable for this purpose has been proposed. In reliance upon the conducted tensile tests, it was established that multilayer materials based on titanium alloys have a complex of mechanical properties characteristic of this class of materials. The impact hardness tests performed, as well as the subsequent fractographic studies, allowed concluding about the effect of the condition of the interlayer boundary on the increase in the resistance of the material to dynamic fracture.

1. Introduction

The studies are well known in which for obtaining a layered microstructure in materials based on a single metal, large total plastic deformations are used, achieved through the implementation of the ARB method [1-3]. Pressure welding is also used to create layered structures [4]. However, the technological approach that uses hot pack rolling as a basis for obtaining multilayer materials, in our opinion, remains the most interesting, due to the prospect of promoting mass production of such materials [5-9].

In the example of steels, according to the pilot process flow (Fig. 1), it is shown that the formation of a multilayer structure in a material based on a single metal is possible if alloys selected on the basis of specially developed recommendations are included in the initial composition. For example, the formation of a multilayer structure and its perdurance during the repetition of production cycles is very successful if the composition contains alloys having different types of crystalline lattices at the hot rolling temperature [10]. The peculiarity of the materials obtained during the implementation of one or two technological cycles is the laminar structure consisting of hundreds or thousands of layers with thicknesses of the micron or submicron range, which are separated by large angular boundaries. Formation and perdurance of such structure under dynamic conditions of hot plastic deformation is a very difficult task.
It is necessary to take into account a number of factors, for example, interlayer diffusion of alloying elements, which leads to a change in the chemical composition and, as a result, in the temperature intervals of phase transformations occurring directly during rolling [11-13]. The main condition for obtaining such structure, unlike bimetals, is the inadmissibility of structural recrystallization processes at the boundaries between layers, which can lead to the formation of common grains, which will make subsequent thinning of layers in the material during plastic deformation impossible [14]. Therefore, it is of particular interest to test the described approach for metals that, like iron, are characterized by polymorphism and have high values of specific strength characteristics. Such metals include titanium and alloys based on it [15-17].

2. Materials and research methods
Titanium alloys VT5-1, VT14, VT35 (Table 1) were selected as the main objects of the study, on the basis of which three compositions (VT5-1+VT14), (VT5-1+VT35), (VT35+VT14) were formed.

Table 1. Characteristics of alloys of multilayer compositions

| Alloy grade | Chemical composition, % | α→β transition temperature | Phase composition at \( T_{	ext{tr}} = 900 \) °C |
|-------------|---------------------------|----------------------------|--------------------------------------------|
| VT5-1       | Al 4,3–6,0, Zr, V, Mo, Cr, Sn 2,0–3,0 | 950 - 990 | α |
| VT14        | 3,5–6,3, 0,9 – 1,9, 2,5 – 3,8, 2,0 – 4,0 | 920 - 960 | α+β |
| VT35        | 2,0 – 4,0, 0,5 – 2,0, 14 – 16, 0,5 – 2,0, 2,0 – 4,0 | 780 - 810 | β |

Based on the temperature ranges of the \( \alpha \rightarrow \beta \) transition, a rolling temperature of 900 °C was selected. Selection of such temperature allowed joint deformation of multilayer compositions in the following combinations. For the VT5-1+VT35 composition, the combination of phase composition of layers was \( \alpha - \beta \), for VT5-1+VT14, the combination was \( \alpha - (\alpha+\beta) \), for the VT35+VT14 composition, the combination was \( \beta - (\alpha+\beta) \), respectively.

Two types of specimens were manufactured from 10 mm thick blanks for impact hardness testing (Fig. 2), and specimens for uniaxial static tensile testing were made from 2 mm thick blanks [18].
The obtained structure was studied by optical and electron microscopy, using Neophot microscope, VEGA TS5130 scanning electron microscope in the mode of energy-dispersive analysis with secondary electrons at an accelerating voltage of 5 to 20 kV.

![Image of sample structure]

Figure 2. Schematic manufacture of impact hardness test specimens

Impact hardness tests were carried out on HP 450 (Waler+Bai AEG) pendulum impact machine with a potential energy reserve of 300 J. Determination of the fracture energy was carried out by means of a regular program for data collection and processing. Impact hardness values were calculated in accordance with the procedure of GOST 9454 – 78.

3. Results and discussion

The study of the microstructure for the samples of the investigated compositions showed that after rolling the blanks to a thickness of 10 mm, a multilayer structure is formed in the samples. However, at the same time, local violations of the laminar structure are observed, which manifest themselves in the form of a deviation from the parallelism and uniform thickness of the material layers along the cross-section of the blank (Fig. 3).

The condition of interlayer boundaries in multilayer materials after metallographic etching is also indicative. While the boundary is clearly identified for the VT5-1+VT14 composition, a transition zone is observed in the VT5-1+VT35 and VT14+VT35 compositions, which is etched out darker than the base layer.

Carrying out further hot rolling to a blank thickness equal to 2 mm shows that the disturbance of the laminar structure in the multilayer compositions increases, and primarily in the VT5-1+VT14 composition.

The study of mechanical properties carried out on samples with a thickness of 2 mm showed that there was a decrease in the elastic modulus along the rolling direction, characteristic of this type of materials [19], which can indicate the appearance of a texture, as well as a significant decrease in plasticity characteristics compared to the initial alloys (Table 2).
The reason for this decrease was investigated in [20] by finite element modeling. It has been shown that the destruction of multilayer samples occurs by the mechanism of formation of inner necks in the material layers. The implementation of this mechanism is only possible with a local disruption of the interlayer bonding, i.e. with the formation of stratification cracks. At the same time, it is the localization of deformation caused by the presence of undisturbed bonds with adjacent layers near the destruction site that leads to low values of the total elongation of the multilayer sample under uniaxial tension.

As can be seen from the above results (Table 3), the impact hardness of the samples of multilayer materials, demonstrating higher values compared to those of alloys included in the composition, does not have a single upward trend, except for the VT5-1+VT35 composition. In the same case, if VT14 alloy is present in the composition, there is an increase in impact hardness at a parallel impact (VT5-1+VT14 composition) and the actual preservation of the values at an impact in the perpendicular direction, or there is an exactly opposite situation with the VT14+VT35 composition.

Figure 3. Microstructure of the investigated compositions after rolling a multilayer blank to a thickness of 10 mm

a) VT5-1+VT14, b) VT5-1+VT35, c) VT14+VT35
Table 2. Mechanical properties of Ti alloys and multilayer materials based on them

| Materials        | Condition    | E   | σ₀₂ | σ₅₀ | δ  | ψ  |
|------------------|--------------|-----|-----|-----|----|----|
| VT5-1* alloy     | annealing    | 110 | 700-800 | 735-931 | 10-15 | 32 |
| VT35* alloy      |              | 92  | 747-763 | 763-778 | 17  | -  |
| VT14* alloy      |              | 110 | -   | 900-1070 | 8-10 | -  |
| VT5-1 + VT14     | hot rolling  | 97  | 803 | 924 | 2.0 | 10.3 |
| VT5-1 + VT35     |              | 84  | 750 | 842 | 1.0 | 4.1 |
| VT14 + VT35      |              | 86  | 761 | 819 | 1.3 | 1.0 |

Table 3. KCU values of Ti alloys and multilayer materials based on them

| Material | KCU, J/cm² | KSUₜ, J/cm² | KCUᵢ, J/cm² |
|----------|------------|-------------|-------------|
| VT5-1    | 45         | -           | -           |
| VT-35    | 40         | -           | -           |
| VT-14    | 45         | -           | -           |
| VT5-1 + VT14 | -         | 49         | 100         |
| VT5-1 + VT35 | -         | 110        | 112         |
| VT14 + VT35 | -         | 140        | 50          |

The fractographic study showed that the surface of the samples of the investigated compositions differed significantly from each other (Fig. 4). So, the electronic image of the surface of the impact samples, obtained at a slight magnification, shows a very insignificant surface processing of the sample of the VT5-1+VT14 composition. At the same time, the samples of the other two compositions were laminated to form characteristic tongues that indicate significant plastic deformation at the impact bending. Taking all of this into account, it can be taken that the interlayer boundary α- (α+β) of the VT5-1+VT14 composition does not provide crack retardation, apparently due to a significant number of "bridges" α-α, as well as due to the close crystallographic orientation of these grains. This assumption is confirmed by the image of the fracture surface of the sample tested in a parallel direction. Unlike the other compositions, the interlayer cracks are virtually absent, indicating a reliable bond between the layers.

The analysis of fractures of the VT14+VT35 composition shows that the interlayer boundary β-(α+β) differs from the boundary discussed above. For example, when testing the samples in a perpendicular direction, it is possible to observe a transition from a dimple structure to a cleaved section in the adjacent layer on the fracture surface. At the same time, the rods on the interlayer boundary also indicate a reliable bond between the layers. It can be assumed that for the α - β structure of the interlayer boundary, there is no continuous contact of grains of one phase, which provides for the lowest rate of grain growth in the observed structure [21]. Thus, from the point of view of preserving the laminar structure of the material, it is preferable to alternate the layers with the α and β structure of the alloys.
Conclusion

The studies have shown that there is a fundamental possibility of synthesis of a multilayer material with a laminar structure based on titanium alloys by hot pack rolling. Forming such a structure in a package based on titanium alloys will make it possible to obtain a material with high values of specific strength characteristics, having high fracture resistance under impact loads. At the same time, the analysis of the structure of the compositions consisting of titanium alloys of different classes showed that the most promising composition should be that including titanium α- and pseudo-β alloys. In this case, the contact of the same phases at the layer boundary is minimized, which to some extent reduces the intensity of recrystallization processes leading to the formation of common grains at the interlayer boundary and the loss of laminarity of the material structure. The observed curvature and uneven thinning of the layers indicates the need to adjust the hot rolling modes.

References

[1] Tsuji N, Ito Y, Saito Y and Minamino Y 2002 Strength and Ductility of Ultrafine Grained Aluminum and Iron Produced by ARB and Annealing Scripta Mater Vol 47 No 12 pp 893-899.
[2] Kodzhaspirov G Ye, Dobatkin S V, Rudskoy A I, Naumov A A 2007 Production of ultra-fine grained sheet from ultra-low-carbon steel by pack rolling Metal Science and Heat Treatment No 12 pp 13–16.
[3] Rudskoy A I, Kodzhaspirov G Ye, Dobatkin S V 2012 Prospective technologies for the production of rolled sheets with an ultra-fine grained structure Metals No 1 pp 88–92.
[4] Sarkeyeva A A 2012 Mechanical behavior during impact loading of structural composite made of VT6 titanium alloy Letters on materials V 2 pp 166–169.
[5] Lesuer D R, Syn C K, Sherby O D, Wadsworth J, Lewandowski J J Hunt W H 1996 Mechanical behavior of laminated metal composites Int. Mater. Rev. Vol 41(5) pp. 169–197.

Figure 4. Electronic image of fractures of the samples of multilayer materials after impact hardness testing in the direction perpendicular to the layers.
[6] Yu X X, Lee W B 2000 The design and fabrication of an alumina reinforced aluminum composite material Compos. Part A. Vol 31 pp 245–258.

[7] Pozuelo M, Carreno F, Cepeda-Jimenez C M, Ruano O A 2008 Effect of Hot Rolling on Bonding Characteristics and Impact Behavior of a Laminated Composite Material Based on UHCS-1.35 Pct C Metall. Mater. Trans. A. Vol 39A pp 666–671.

[8] Cepeda-Jimenez C M, Garcia-Infanta J M, Pozuelo M, Ruano O A, Carreno F 2009 Impact toughness improvement of high-strength aluminium alloy by intrinsic and extrinsic fracture mechanisms via hot roll bonding Scripta Mater. Vol 61 pp 407–410.

[9] Khorev A I 1979 Modern methods of increasing the structural strength of titanium alloys M.: Voyenizdat 256 p.

[10] Kolesnikov A G, Plokhikh A I, Mikhaltsevich I Yu 2010 Study of the possibility for obtaining a submicro- and nano-sized structure in multilayer materials by the hot rolling method Rolling production No 3 pp 25–31.

[11] Plokhikh A I, Vlasova D V, Khovova O M, Polyansky V M 2011 Study of the influence of diffusion mobility of alloying elements on the stability of the structure of multilayer metal materials Science and education: electronic scientific and technical publication No 11 URL: http://technomag.edu.ru/doc/262116.html (date of retrieval: 09.06.2016).

[12] Tabatchikova T I, Plokhikh A I, Yakovlev I L, Klyueva S Yu 2013 Structure and properties of a steel-based multilayer material produced by hot pack rolling The Physics of Metals and Metallography V 114 Issue 7 pp 580-592.

[13] Petelin A L, Plokhikh A I 2013 Diffusion along grain boundaries in multilayer materials Steel in translation N 11 pp 710-713.

[14] Tabatchikova T I, Yakovlev I L, Plokhikh A I, Del’gado Reina S Yu 2014 Studying a multilayer material based on stainless steels and produced by hot pack rolling The Physics of Metals and Metallography V 115 Issue 4 pp 403-412.

[15] Nochovnaya N A, Panin P V, Alekseyev E B, Bokov K A 2014 Economically alloyed titanium alloys for layered metal-polymer composite materials Proceedings of VIAM: electronic scientific and technical journal No 11 pp 02. URL: http://www.viam-works.ru (date of retrieval: 25.04.2016). DOI: 10.18577/2307-6046-2014-0-11-2-2.

[16] Khorev A I 2013 Fundamental and applied studies on structural titanium alloys and promising directions of their development VIAM Proceedings: electronic scientific and technical journal No 2 P 04 URL: http://www.viam-works.ru (date of retrieval: 13.07.2016).

[17] Khorev A I, Nochovnaya N A, Yakovlev A I 2012 Microalloying of titanium alloys with rare-earth metals Aviation materials and technologies No S pp 206–212.

[18] Yerasov V S, Grinevich A V, Senik V Ya, Konovalov V, Trunin Yu P, Nesterenko G I 2012 Calculated values of strength characteristics of aviation materials Aviation Materials and Technologies No 2 pp 14–16.

[19] Kolesnikov A G, Plokhikh A I, Komisarchuk Yu S, Mikhaltsevich I Yu 2010 A study of special features of formation of submicro- and nanosize structure in multilayer materials by the method of hot rolling Metal Science and Heat Treatment V 52 N 5–6 pp 273–278.

[20] Plokhikh A I, Putirskiy S V 2015 Modeling of the mechanism for destruction of multilayer metal materials under uniaxial static tension Volga State Technical University Proceedings V 160 No 5 pp 92–96.

[21] Belov S P, Brun M Ya, Glazunov S G et al. 1992 Titanium alloys. Metallurgy of titanium and its alloys. City: Metallurgy 352 p.