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Microstructure and Ballistic Performance of Layered Metal-Matrix Composite Armour Based on Ti–6Al–4V Alloy and Strengthened with TiC

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The alloy Ti–6Al–4V and composites on its base reinforced with 5 to 80% vol. TiC are manufactured by press-and-sinter approach using TiH_2, Al–V master alloy and TiC powder blends. Increase in TiC content up to 40% provides effective structure consolidation and continuous rise of material hardness. Composites fabricated at higher than 40% TiC content demonstrate insufficient integrity of the sintered structure due to excessive porosity. Using these data, 3 and 4 layers plates consisted of Ti–6Al–4V alloy and composites on its base containing from 10% to 40% TiC are made. Fabricated plates with dimensions of 90×90 mm and a thickness of 11–32 mm demonstrate complete integration between the layers and are suitable for the ballistic examination. Performed ballistic tests reveal an enhanced resistance of multilayered plates against piercing by various bullets types, which exceeds the performance by 7–40% when compared to the conventional Ti–6Al–4V alloy in terms of the specific kinetic energy required for the plate piercing. Kinetic energy of bul-

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lets is mainly dissipated by the deformation of the hard surface composite layers with 20% and, especially, 40% TiC, leaving not much energy for bullet to penetrate deep into subsequent ductile alloy layer.

Key words: titanium alloys, metal matrix composites, layered microstructures, mechanical properties, projectiles, ballistic tests.

Стоп Ti–6Al–4V та металоматричні композити на його основі, зміцнені частинками TiC (5–80% за об'ємом), виготовлено методом пресування і спікання сумішей порошків TiH_2, ліґатури Al–V та TiC. Збільшення вмісту TiC до 40% забезпечує поступове підвищення твердості при отриманні необхідних мікроструктур композитів, проте вищий вміст фази TiC веде до надмірної пористості та недостатньої міцності спечених матеріалів. Беручи до уваги ці дані, виготовлено плити 90×90 мм та товщиною 11–32 мм, які складаються з 3-х та 4-х шарів стопу Ti–6Al–4V та композитів на його основі з вмістом TiC від 10% до 40%, з необхідною міцністю з'єднань між шарами. Проведено балістичні випробування, які показали підвищені характеристики стійкості багатошарових плит при ударі кулями з різною кінетичною енергією у порівнянні зі стандартним стопом Ti–6Al–4V — для пробивання багатошарових плит необхідна питома кінетична енергія вражаючих елементів на 7–40% вища. Кінетична енергія уражальних елементів витрачається, переважно, на деформацію поверхневих шарів твердих металоматричних композитів з 20% та, особливо, з 40% TiC, що мінімізує глибину проникнення вражаючих елементів в наступний шар в'язкого стопу.

Ключові слова: титанові стопи, металоматричні композити, шаруваті структури, механічні властивості, уражальні елементи, балістичні випробування.

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1. INTRODUCTION

Titanium alloys and metal-matrix composites (MMC) on their base are widely used in military industry as efficient elements for armour protection [1–3] owing to high strength and low specific weight. A significantly better balance of mechanical characteristics and anti-ballistic resistance for military purposes can be achieved by combining them in multilayered or gradient structures, individual layers of which are different in their phase and microstructural state and/or chemical composition that provides the varieties of physical and mechanical properties [4, 5]. The multilayered (ML) structures that unite hard and high-strength MMC at surface layers with ductile titanium alloys at the base of the armour provide a significantly better general combination of product characteristics, unreachable on homogeneous materials [5–7].

Powder metallurgy technologies are efficient methods of creating ML structures of titanium materials [5, 8]. In particular, by pressing and sintering multicomponent powder blends based on titanium hydride, structures combining 2–3 layers of Ti–6Al–4V% wt. alloy and MMC with the addition of 5–10% vol. of reinforcing particles were successfully fabricated and tested [4, 5]. For instance, TiC and TiB compounds are characterized by good thermal stability, high Young's modulus and thermal expansion coefficient close to the corresponding parameter of the matrix Ti–6Al–4V alloy, therefore, the noted compounds are considered as the most promising to achieve the required physical and mechanical characteristics of such composites [9]. Optimization of the press-and-sinter powder technology parameters provides the control over the microstructure, residual porosity, and, correspondingly, the characteristics of each individual layer resulting in enhanced properties of entire ML structures [5, 10]. The ML materials showed significantly higher characteristics of strength and ductility in 3-point flexure tests and better characteristics of armour resistance on ballistic impact when compared to homogeneous structures of Ti–6Al–4V alloy and MMCs [5]. It was found that by increasing of the TiC particles content within the individual layers their mechanical characteristics significantly changing: the strength and hardness is increasing, while the plasticity is dropping. Besides, the ML armour structures performance depends significantly not only on TiC content within the individual layers, but also on the layers' thickness. Initial study of anti-ballistic performance of ML structures indeed show very promising results, however the data were obtained on ML materials containing in the surface layer only 10% of TiC with gradually decreased amount of reinforcement at the deeper layers of the plates [6].

At the same time, the role of many other important factors was outside the objectives of that earlier study. The most obvious would be exploration of potentials on increasing of TiC content over 10% and its effect on microstructure and properties of uniform MMC produced with press-and-sinter powder approach. Also it could be very important to investigate the peculiarities of the formation of multilayered structures with individual layers containing higher amount of TiC particles. And finally, the credibility of such materials in ballistic resistance against projectiles with different kinetic energy, as well as consideration of bullet related factors such as extra-hard core, and the presence of the incendiary mixture. All the above aspects have not been studied yet, and that was the motivation in the present study.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

The first task of present study was to determine the influence of TiC content varied from 10 to 80% vol. on the microstructure of Ti–6Al–4V based MMC. The next step was to create ML plates with 3 and 4 layers that were suitable for ballistic examination with different types of projectiles.

Titanium hydride TiH_2 was used as the base of all powder blends in the study. It has some obvious advantages over conventional titanium powder use in production of alloys and composites utilizing Blended Elemental Powder Metallurgy (BEPM) approach [8, 11]. Titanium hydride powder was manufactured in this study by hydrogenation of TG-110 titanium sponge, followed by its grinding.

Size fraction <100 μm of TiH_2 powder was separated by sieving and blended with a corresponding amount of 60% Al–40% V master alloy (particles size <63 μm) to form blend corresponding to Ti–6Al–4V composition. To produce MMC containing 5, 10, 20, 30, 40, 50, 60, 70 and 80% vol. TiC phase, titanium carbide powder (particle size <30 μm) was additionally added to the blend at needed amount. For microstructure study and hardness tests the powder blends were pressed in dies to cylindrical green preforms with a height of 12 mm and a diameter of 10 mm at room temperature using 650 MPa pressure. The samples were sintered in a vacuum furnace at 1250°C for 4 hours, followed by furnace cooling. For the ballistic test ML plates structures with dimensions of 90×90 mm and a height of 11–32 mm, which consisted of 3 and 4 layers, were fabricated. The blends of the appropriate composition were put layer-by-layer into a plate mold and pressed, obtaining flat powder preforms. The used size of preforms was predetermined by the requirements of ballistic tests, however, the increase in the cross-area of the pressed preform did not allow applying (in laboratory conditions) the compaction pressure higher than 150 MPa. ML powder preforms were sintered under the same conditions as individual (single-layer) blends. The used sintering mode provided removal of hydrogen from TiH_2 and conversion of each powder blend into a bulk homogeneous material of corresponding composition (Ti–6Al–4V alloy or different MMCs), and the creation of ML structures simultaneous bonding of the layers.

Microstructure of sintered materials was studied with light optical (LOM; Olympus IX70) and SEM microscopy (TESCAN VEGA 3). Porosity was evaluated by quantitative analysis of the surfaces of metallographic sections. The Vickers hardness of each layer was determined using a Wolpert 452 hardness tester. Ballistic examination of ML structures were performed in a certified laboratory of the Ivan Chernyakhovskyi National Defence University of Ukraine using cartridges that differ in caliber, mass, kinetic energy and hardness of the bullet core.

3. RESULTS AND DISCUSSION

3.1. The Effect of TiC Content on Microstructure and Properties of Ti–6Al–4V–(X)TiC Metal Matrix Composites

The hydrogen desorption of titanium hydride powder and conversion of powder blends into a bulk Ti–6Al–4V alloy and composites on its base cause characteristic volume reduction of the samples during sintering. The observed linear shrinkage of green preforms was consistent with the amount of the reinforcement particles used: the shrinkage decreases with increasing TiC phase content in the powder blends. The maximum linear shrinkage of 15.5% was measured after sintering of the green preform sample composed using the powder blend of the Ti–6Al–4V alloy without any TiC particles added. The samples of MMC exhibited significantly lower reduction during sintering. For example, linear shrinkage of the 40% TiC composite was measured about 9% and 70–80% composite was only 3–4%.

The typical microstructures of individually sintered materials are shown in the Fig. 1. The involved temperature-time sintering regime provides the formation of chemical and microstructural homogeneity of the Ti–6Al–4V matrix (Fig. 1, *a*–*d*) due to the complete dissolution of Al–V master alloy particles and these elements diffusion into Ti. At the same time, some minor inhomogeneity of TiC particles distribution is observed within the matrix (Fig. 1, *b*, *c*). It is pre-determined by the blending conditions of powders and the initial localization of the TiC particles between the other components of the blend. The TiC phase has high melting point making particles sufficiently stable at the used sintering temperatures. There was no significant alteration of the particles shape was observed. However, some minor diffusion of carbon into the surrounding matrix and formation of a transition layer was not completely excluded [12].

When TiC content was 50% and higher (Fig. 1, *e*, *f*) the reinforcement phase actually becomes the base of the composite material and corresponding microstructures were markedly different from structures of composites with lower reinforcement fraction. As it was discussed before the volume changes of the samples during sintering depends on the TiC content in the blends. Increase in amount of TiC phase above 40% constrains the formation of fully consolidated material resulting in residual porosity, which was higher for a greater content of reinforcement particles. At a compaction pressure of 650 MPa used on small cylindrical specimens, Ti–6Al–4V alloy demonstrated residual porosity close to 1% (Fig. 1, *a*). The porosity fraction noticeably increases for MMC with 40% of TiC (Fig. 1, *b*–*d*). When TiC content is in the range 50–80% the applied temperature-time sintering regime forms highly porous (10–20% of pores) materials (Fig. 1, *e*, *f*). Besides, TiC particles form the conglomerates, which could be easily crashed, thus, preventing sufficient strength of such composites. This result is due to the used sintering temperature (1250°C) is sufficient for sintering of the alloy's particles, but not TiC. In powder technologies it is generally accepted to choose the sintering temperature in the range of $0.5–0.8T_m$ (where T_m is the melting point of the material).

Since the melting point of TiC is 3065°C and titanium is 1670°C, the sintering temperature of 1250°C used in this experiment was suitable for the alloy, but obviously was not sufficient for diffusion bonding of TiC particles.

The dependence of the Vickers hardness on TiC content up to 40% in Ti–6Al–4V matrix is presented in Fig. 2. The adequate hardness measurements on the samples with higher particles content was obscured by the premature fracturing of highly porous materials. However, shown in Fig. 2 data clearly demonstrates a significant increase in the MMC hardness with an increase of the high-modulus TiC particles content. When the particles content is higher than 40%, the relatively high re-

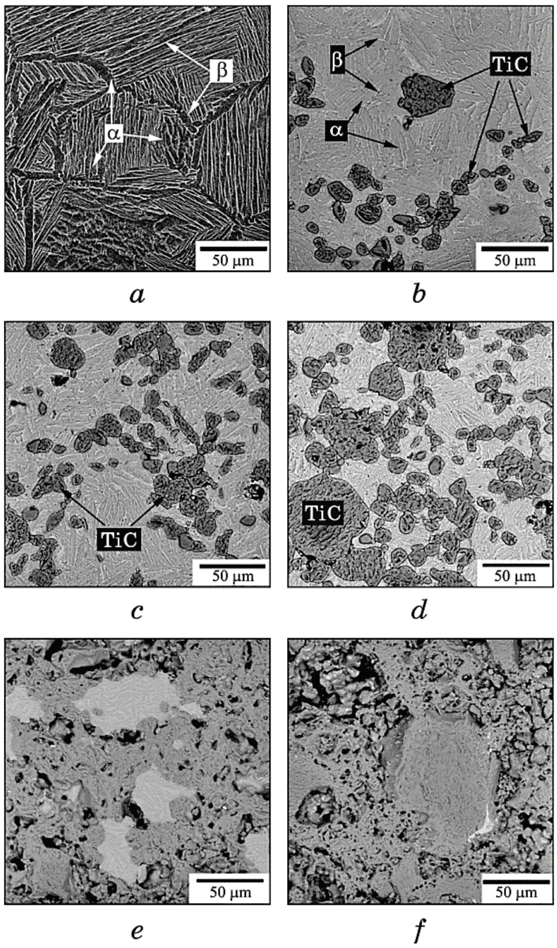


Fig. 1. Microstructure of some sintered materials: (*a*) Ti–6Al–4V alloy, and MMC on its base containing: (*b*) 10%, (*c*) 20%, (*d*) 40%, (*e*) 60%, and (*f*), 80% TiC. All samples were pressed at 650 MPa. SEM: (*a*) SE, (*b*–*f*) BSE.

sidual porosity and the insufficient bonding of the reinforcement particles embrittle the TiC conglomerates leading to premature destruction of specimens.

Hence, it could be concluded that the practical range for the composites reinforcement utilized in fabrication of the armour protecting elements using present BEPM processing should not exceed 40% of TiC particles by volume.

3.2. Microstructure of Multilayered Materials

The generally accepted concept of efficient antiballistic performance suggests the armour component of dual properties: with maximum hardness and durability at the surface (front) layers, and high ductility at the base (back) layer. Such approach was also utilized in this study to manufacture ML structures where the surface layers contain up to 40% of TiC particles and the base was made of ductile Ti–6Al–4V alloy with no reinforcement. The maintenance of the ML armour component integrity during their fabrication is a challenging technological problem due to significantly different volume changes (shrinkage) that occur in different adjacent layers with dissimilar TiC content during sintering of the powder blends. It is obvious that in order to minimalize the possibility of layers delamination and cracking the multilayered structures should be fabricated with adjacent layers sustaining a relatively small difference in volume changes during the sintering. Based on earlier reported data the difference in TiC content of the adjacent layers was chosen not to exceed 10–20% considering used plates dimension [4]. Adopted gradation of TiC concentration between the adjacent layers successfully compensate the stresses built up at the interface between the layers due to some variation of porosity in adjacent

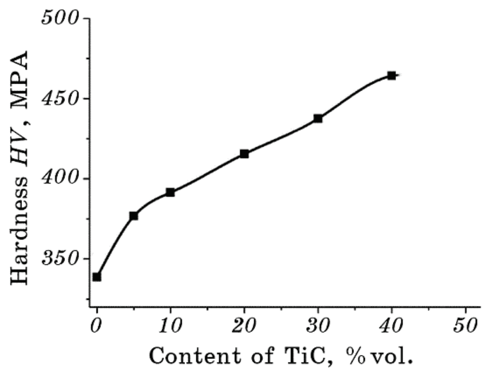


Fig. 2. The Vickers hardness dependence of the sintered Ti–6Al–4V + TiC(X) composites on TiC content.

materials.

To validate this approach, a number of 90×90 mm plates having 3 or 4 layers were fabricated (Fig. 3). The base or the backside of the plate was always made of the alloy Ti–6Al–4V with no reinforcement added. In cases of 4-layered structures, 2 transitional composite layers with 20% TiC and 10% TiC were added between the surface composite layer with 40% TiC and the base. In case of 3-layered plates, the surface composite layer used was 20% TiC and only one transition layer with 10% of TiC was added. Adopted approach on structure composition provides relatively smooth gradual change of physical and mechanical characteristics between the layers (Fig. 4), which prevents negative consequences during plates fabrication and a significant concentration of stresses under static and shock (including ballistic) loads.

The mentioned difference in volume changes during sintering (low shrinkage of MMC layers with high TiC content as compared to the layer of the Ti–6Al–4V alloy) still led to some minor distortion of the shape (bending) of flat ML plates, however, desired integrity with sufficient adhesion between the layers were achieved. Typical microstructures of ML materials are shown in Fig. 5. It is clearly seen that there are no cracks observed on the bond line between the layers. At the same

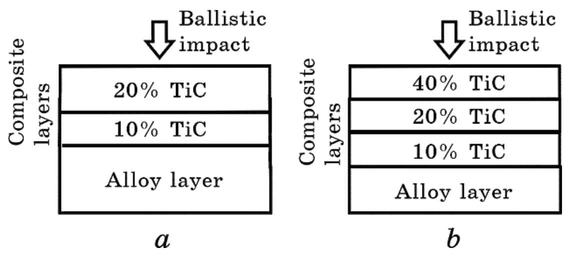


Fig. 3. Schematic presentation of the structure of the manufactured (*a*) 3-, and (*b*) 4-layered plates and the direction of the ballistic impact during the tests.

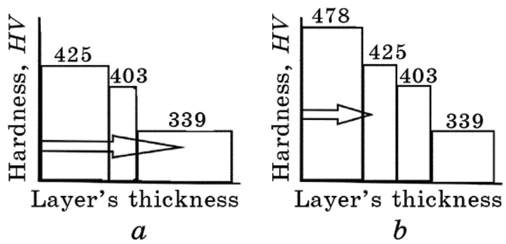
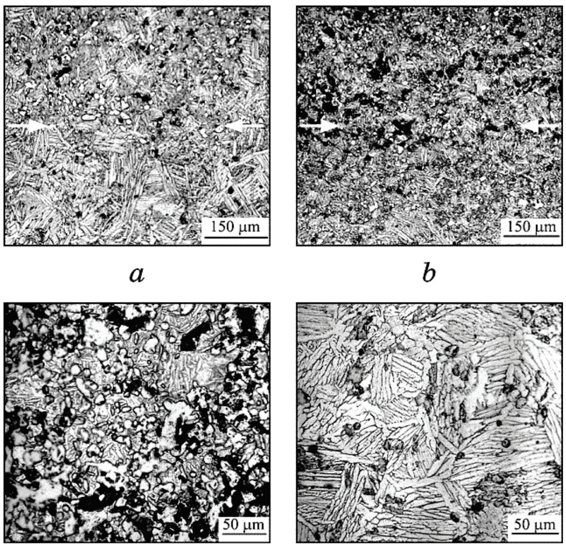


Fig. 4. Schematic distribution of hardness in depth of (*a*) 3- and (*b*) 4-layered plates with a total thickness of 15.5 mm. The arrows schematically show the penetration depth of PP-type bullets (see Table 1).

time reduced pressure (not higher than 150 MPa) used for the compaction of 90×90 mm plates caused in a relatively higher porosity in all layers as compared to cylindrical specimens that were pressed at 640 MPa (compare Figs. 2 and 5). The pores volume fraction increases significantly with increasing TiC content, reaching about 2–3% for the Ti–6Al–4V alloy layer (Fig. 5, *a*, bottom), being even higher for MMC with 10% TiC layer (Fig. 5, *d*) and approaching about 15% for the composite layer with 40% TiC (Fig. 5, *c*).

3.3. Ballistic Tests

The ML plates with 3 and 4 layers were further subjected to a ballistic test that schematically shown in Fig. 3. The thickness of the individual layers was not less than 2 mm, while the total thickness of the plates varied from 11 to 28 mm. Besides, the thickness ratio between individual layers was changed keeping the same total thickness of the plates. That allowed checking the effect of the thickness ratio between the ductile back layer of the Ti–6Al–4V alloy and combined thickness of used MMC layers, which ranged from 2:1 to 1:2.



c *d*

Fig. 5. Typical microstructures (LOM) of ML plates; images *a* and *b* show the area in the visinity of the joint indicated by arrows, *a*—between MMC layer containing 10% TiC (top) and Ti–6Al–4V alloy layer (bottom); *b*—between MMC layers containing 20% (top) and 10% (bottom) of TiC; images (*c*) and (*d*) show the bulk of the layers containing 40% (*c*) and 10% (*d*) of TiC. Compaction pressure of 150 MPa.

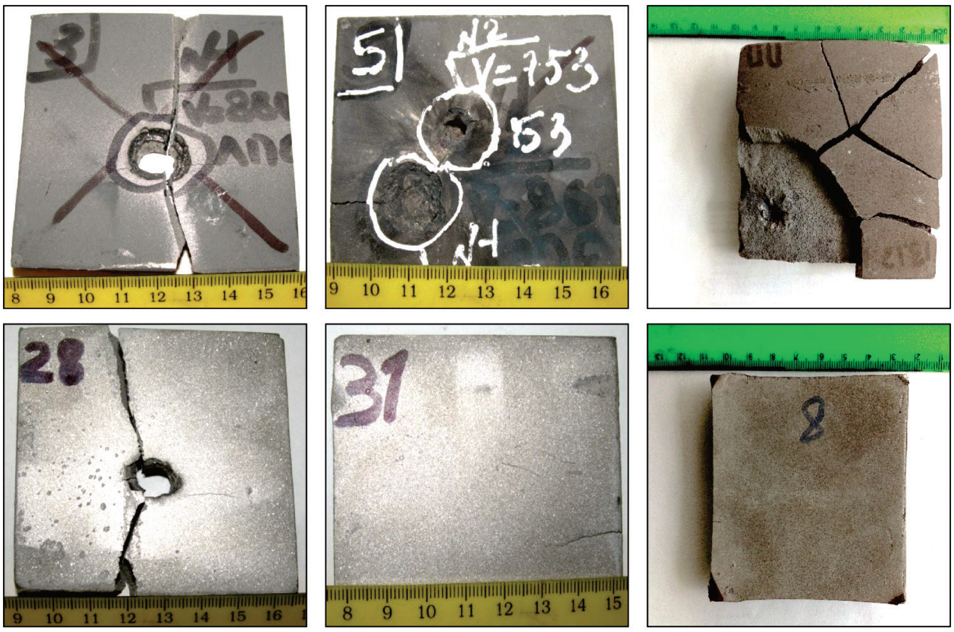
TABLE 1. Cartridges and some characteristics of bullets used in ballistic tests of ML materials.

No.	Cartridges/ bullets, caliber	Bullets mass, g	Bullets speed, m/s	Kinetic energy of bullets, J	Specific energy (kinetic energy/bullet cross-section), J/m^2	Affecting factors
1	Machine-gun cartridge PP (7H10), 5.45 mm	3.61	910	1495	$64.16 \cdot 10^6$	2: Kinetic impact + hardened steel core
2	Machine-gun cartridge BZ (57-БZ-231s), 7.62 mm	7.4	772	2205	$48.35 \cdot 10^6$	3: Kinetic impact + hardened steel core + incendiary mixture
3	Rifle cartridge LPS (57-H-323s) 7.62 mm	9.6	850	3468	$76.05 \cdot 10^6$	1: Kinetic impact
4	Rifle cartridge B32 (57-БZ-323) 7.62 mm	10.4	830	3582	$78.56 \cdot 10^6$	3: Kinetic impact + hardened steel core + incendiary mixture

Ballistic tests were performed using cartridges of different caliber, mass and velocity of bullets, and therefore delivering a different kinetic energy, as well as having additional striking factors (Table 1). It should be specified, that used cartridges and bullets were characterized by three striking factors, namely: i) kinetic energy impact, ii) hardened (above 700 *HV*) steel core, and iii) presence of incendiary mixture. One LPS bullets have only the first affecting factor, PP bullets—two factors, while BZ and B32 bullets—all three affecting factors.

Typical examples of different plates after ballistic tests are presented in Fig. 6. Piercing or fracture of these specimens took place, usually without essential deformation observed on the front and on the back of the plates. In the case of piercing all deformation was realized in the form of 'knocking out the cork' (Fig. 6, *a*). When the piercing did not occur, there was no any deformation observed on the backside of the plate (Fig. 6, *b*). At the same time, there were brittle fracture of the top 40% TiC layer was observed as well as its total separation from the adjacent 20% TiC layer along the interface between them in 4-layered plates (Fig. 6, *c*). It could be underlined that despite of some penetration of the bullet into deeper layers containing 20% TiC and 10% TiC, these layers still not fractured and the backside of the plate has no signs of deformation.

We believe that the main reason of detouching of 4-layered plates structure along the interface between MMCs with 40% and 20% TiC can be explained by relatively high difference in TiC content, which causes essential residual stresses between the layers due to difference in volume changing taking place during sintering. The lowered ductility and increased porosity of the MMC under higher content of the TiC phase are most likely among few other negative factors affecting the ballistic resistance of tested material. These factors are effectively contributed to the nucleation and propagation of the cracks even at relatively low loads. Therefore, despite the absence of visible defects (cracks, conglomerates of pores) between these layers after their sintering, precisely the interface between these two MMCs' is the weakest link. Such adverse effect is not observed at the interfaces between other layers, when the TiC content was differs by only 10%. This fact allows concluding that for higher reliability of layered materials to ballistic impact the difference in TiC content between adjacent layers should not exceed 10%.



a *b* *c*

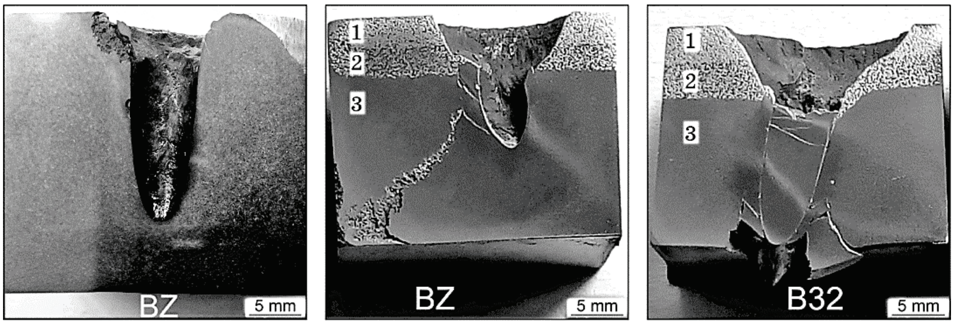
Fig. 6. General view of tested plates on the front (top) and back sides (bottom): *a*—3-layered 11 mm in thickness; *b*—3-layered 22 mm in thickness; *c*—4-layered plate 15,5 mm with 40% TiC in the top layer.

It should be specifically emphasized that during the ballistic tests of such MMC, when there is no penetration observed throughout the plates and the bullet gets stuck inside them, there are no signs of deformation taking place on the back side (Fig. 6, *b*, *c*), in contrast to the usual deformed titanium alloy [1, 6, 13].

The general advantage of ML structures in comparison with the homogeneous Ti–6Al–4V alloy, made by the same powder approach and used as a reference, is clearly demonstrated by the depth of penetration of an armour-piercing incendiary bullet caliber 7.62 mm (BZ—p. 2 in Table 1) into these materials (both were not pierced). The depth of penetration into the ML structures was in various experiments from 11 to 18 mm (Fig. 7, *b*), while the depth of penetration of the same bullets into a homogeneous alloy—19–23 mm (Fig. 7, *a*). At the same time testing with more powerful B32 (p. 4 in Table 1) bullets caused in partial piercing of this 3-layered plate (Fig. 7, *c*). Also, it can be mentioned that the hard steel core bullet was cracked despite hardness of all layers (Fig. 4, *a*) was essentially lower than hardness of the projectile core (above 700 *HV*).

Analysis of the deformed microstructures in the vicinity of ballistic impact (Fig. 7) showed that the presence of hardened with TiC surface MMC layers requires significant energy dissipation on their deformation, which in turn essentially inhibits the penetration of the piercing elements into the deeper layers of material. Traces of localized significant deformation of both composite layers and alloy layer are observed in the areas near the ballistic impact site, with the formation of adiabatic shear bands in their structure (Fig. 8). This issue is discussed in more details elsewhere [1, 6, 14].

The ballistic test results were analyzed taking into account the fol-



a *b* *c*

Fig. 7. Cross-sectional images of the plates after ballistic test: *a*—homogeneous Ti–6Al–4V alloy produced with powder metallurgy approach; *b*, *c*—three-layered plates consisted of No. 1—20% TiC MMC, No. 2—10% TiC MMC, No. 3—Ti–6Al–4V alloy. Plates tested by bullets (*a*, *b*) BZ, and (*c*) B32.

lowing striking factors: kinetic energy of the bullet, the hardness of the bullet core, and the presence of the incendiary mixture. Besides the main features of the ML structures including their composition and layers thicknesses allowed to specify the following important conclusions. Firstly, the effect of kinetic energy should be considered in its specific value, *i.e.* taking into account the caliber (cross-sectional area) of the bullets used [1, 6], which determines the volume of material deformed as a result of the ballistic impact. In this study we were focused on complicated cartridges and bullets which, in addition to kinetic energy (LPS), also has two additional damaging factors: a hardened core (PP) and an incendiary mixture (BZ, and B32).

The results obtained in this study can be conveniently compared to the earlier reported data obtained for the conventional (cast and wrought) Ti–6Al–4V alloy armour. It is appropriate to present the data in the form of dependencies of the specific kinetic energy over the thickness of the tested materials as it is shown in Fig. 9. The dotted lines on the chart represent the conventional Ti–6Al–4V alloy tested with the bullets having soft (*1*), hard core (*2*), and addition of incendiary mixture (*3*). The areas above and to the left of each line correspond to the combination of kinetic energy and the thickness of the material providing piercing while the areas below and to the right of these lines correspond to full protection against the piercing. The results of current study for 3- and 4-layered plates added to this chart correspond to the no-piercing cases. The arrows adjacent to the experimental point illustrate how much they surpass similar cast and wrought alloy material in terms of their ballistic resistance.

Results on ballistic evaluation of ML armour plates could be summarized in a few statements:

i) ML plates of both kinds tested in this study have a sufficient resistance for the piercing by all three types of bullets. The overall ballistic performance of ML plates significantly exceeds the performance of the conventional Ti–6Al–4V alloy plates.

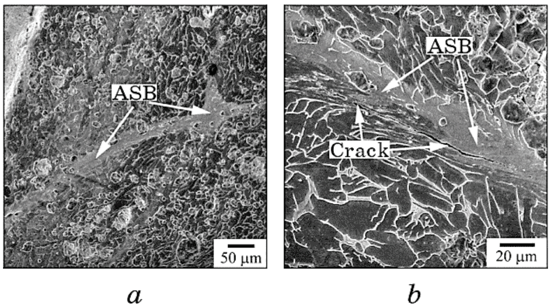


Fig. 8. Microstructure of deformed areas near bullet penetration channel in (*a*) MMC containing 20% TiC and (*b*) 10% TiC. SEM, SE.

ii) For the high-energy LPS bullets the SKE required to pierce the 3-layered plate of 22 mm thick surpass the energy required to pierce the standard Ti–6Al–4V alloy armour plate of the same thickness by about 7%; while for the 4-layed plates with a thickness of 15.5 mm this value is surpassing the reference on 40% (!)

iii) For the PP bullets class having strengthened steel core both types of layered plates (3 and 4) surpass the resistance of the standard Ti–6Al–4V alloy plate by more than 40%.

iv) For the bullets with all three impact-destruction factors, the test results depend on the level of kinetic energy: for BZ bullets with lower kinetic energy, both types of plates (15.5 mm thick) were characterized by sufficient ballistic resistance, while for more powerful B32 bullets, 3- and 4-layers plates with a thickness of 22 mm were resistant.

Additionally, few important remarks could be made on the depth of bullets penetration. From the comparison of ballistic tests of 3- and 4-layered plates with PP type ammunition (bullets with heat - strengthened core) it follows that at the same total thickness, increased ballistic resistance is demonstrated by 4-layered structures with the surface

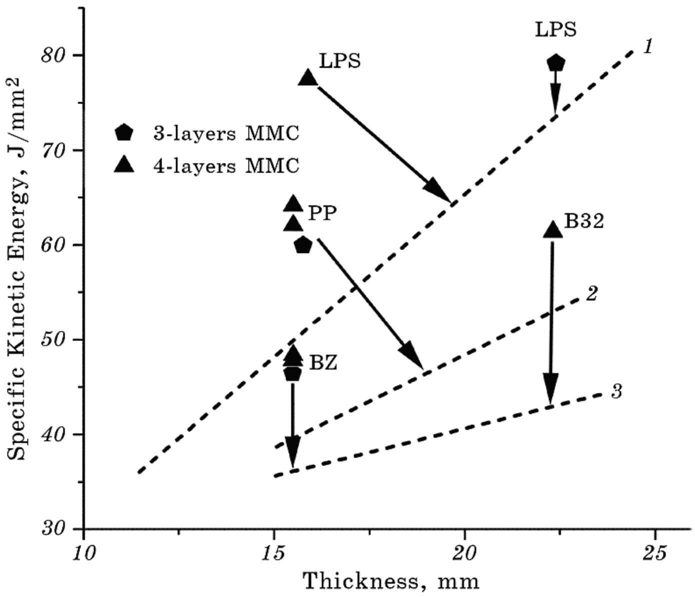


Fig. 9. The dependence of Specific Kinetic Energy (SKE) on the thickness of the armour plates tested for different classes of the bullets. The lines shows the dependence for the cast and wrought Ti–6Al–4V tested with: is the 'soft' core bullets (7.62 caliber, [1]) (*1*); is the hard steel core (*2*); and is the hard steel core + incendiary mixture (*3*) [6]. Arrows illustrate the superiority of the tested in this study ML plates over the cast and wrought Ti–6Al–4V alloy plates for corresponding classes of tested bullets.

layer built of 40% TiC composite. The depth of penetration of the bullet core into 4-layers structures is about 6 mm, the sphere penetrates the surface layer of the composite with 40% TiC with a thickness of 5.5 mm, and stops by the next layer with 20% TiC only partially deforming it. In contrary the 3-layered plates with the surface built of the same thickness but with 20% TiC the depth of the bullets penetration is 8–15 mm, *i.e.* the bullet pierces not only the surface layer, but also the next 10% TiC layer, stopping in the base one (Ti–6Al–4V) as Fig. 7, *b* shows. This observation suggests that for the same thickness of the surface layers having 40% and 20% TiC, composites with a higher content of reinforcement (despite their increased porosity and brittleness) provide significantly greater dissipation of kinetic energy of the bullets, which is spent on deformation and fracture of this layer during the ballistic impact. Furthermore, for the same thickness of ML structures, the change in the total thickness of the composite layers relative to the base Ti–6Al–4V layer has minor effect on the depth of bullet penetration into the material. For example, BZ bullet penetrates 17 mm into 3-layer structures where combined composites' layers thickness with 20% and 10% TiC have only 30% of the total thickness of the ML plate, and 16 mm if these two layers have 40% of the total thickness of the ML material. In general, the ballistic resistance characteristics of these armour materials are determined by the complex influence of such factors as the content of the reinforcing phase in MMC, the number of layers and their mutual thickness, the specific energy of the bullet related to its cross section, core hardness, and the presence of incendiary mixture. The solution of this multiple-factor problem requires additional research and possibly computer modelling to determine the impact of each specific factor and to optimize such structures.

4. CONCLUSIONS

1. Press-and-sinter blended elemental powder metallurgy using TiH_2 powder was employed to produce Ti–6Al–4V-based MMCs with content of reinforcing TiC particles varied in the range 5 to 80%. The used processing parameters allowed successful manufacturing of composites with TiC content up to 40%, while higher content of reinforcement particles resulted in excessive porosity and inappropriate integrity of sintered materials.
2. Three- and four-layered plates consisted of Ti–6Al–4V alloy as basic layer and MMC on its base containing from 10% to 40% TiC were produced with complete integration of the layers and absence of the defects (cracks, enhanced porosity) on the interface between the layers.
3. ML plates tested in this study have an excellent ballistic performance against piercing by various types of bullets, which for the most

bullet classes significantly exceed the performance of the conventional Ti–6Al–4V alloy of the same thickness.
4. For the high-energy bullets having additional impact factors (hard core and incendiary mixture), ML plates surpass the resistance of the conventional Ti–6Al–4V alloy by about 7–40% in terms of the specific kinetic energy required for the plate piercing.

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