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Microstructure and Mechanical Characteristics of Layered Titanium-Based Materials Manufactured with Blended Elemental Powder Metallurgy

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Press-and-sinter blended elemental powder-metallurgy approach using hydrogenated titanium powder is used to manufacture nearly-dense commercially-pure titanium, Ti–6Al–4V alloy, and metal-matrix composites based on them and reinforced with TiC particles. The potential for variation of mechanical characteristics of these materials depending on the matrix composition and TiC content within 10–40% is determined using hardness and compression tests. Highly-porous titanium samples (with 60–64% pores) are manufactured using titanium-hydride and space-holder powders. Impregnation of porous titanium with polymers based on epoxyurethanes and epoxides is used to affect deformation ability. Polymers based on epoxyurethanes improve the stress–strain characteristics of porous titanium under compression, which is useful for better energy-adsorption characteristics. Nearly-dense metal-matrix composites, porous titanium, and nearly-dense alloy lay-

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ers are joined in various combinations using polymer to create layered structures. The mechanical behaviour of layered structures is determined with three-point flexure tests. It is shown the effect of intermediate porous layers for the decrease in strength and Young's modulus, but for the increase in deformation ability of the layered structure as a whole. Proper selection of material combinations and thickness of layers gives wide potential for controllable and useful adjustment of strength, ductile, and damping characteristics of layered materials.

Key words: titanium-based layered materials, titanium alloys and metal-matrix composites, porous titanium, polymer, mechanical characteristics.

Методом пресування та спікання порошку гідриду Титану та порошкових сумішей на його основі одержано малопористі технічно чистий титан, стоп Ti–6Al–4V та металоматричні композити, зміцнені додаванням до цих матеріялів частинок TiC. Потенціял зміни механічних характеристик в залежності від хемічного складу матриці та вмісту частинок TiC в межах 10–40% було оцінено під час випробування на стиск і мірянням твердости. Пористий (60–64% пор) технічно чистий титан, одержаний з використанням порошків гідриду Титану та пороутворювача, просочено полімерами на основі епоксиуретану й епоксиду для підвищення здатности до деформування. Полімери на основі епоксиуретану під час випробувань на стиск поліпшують міцність і деформаційні характеристики, які визначають поліпшене вбирання енергії. Різні комбінації шарів малопористих металоматричних композитів і стопів, а також пористого титану було з'єднано полімерами з формуванням шаруватих структур. Механічну поведінку шаруватих структур досліджено під час випробувань на триточковий вигин. Показано вплив проміжного шару пористого титану на пониження міцности та модуля Юнґа за одночасного поліпшення деформаційної здатности шаруватих структур. Правильний вибір комбінацій вказаних матеріялів і товщини окремих шарів дає можливість керовано реґулювати показники міцности, пластичности та здатности до вбирання енергії під час деформування шаруватих матеріялів.

Ключові слова: шаруваті матеріяли на основі титану, стопи та металоматричні композити, пористий титан, полімер, механічні характеристики.

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1. INTRODUCTION

Today's realities, such as military operations and the growing risk of terrorist threats over the world, require a significant amount of work by engineering and sapper services to detect and neutralize explosive objects. An important task is the development of advanced materials for the manufacture of protective ammunition for personnel and equipment (shields, helmets, body armour, containers for transportation of explosive materials, *etc.*), which would effectively protect

against the striking elements of explosive devices, fragments, and the destructive and striking effect of shock waves. For effective and safe work of the sapper service, a reduced mass of protective ammunition, its paramagnetic, high strength and plasticity characteristics are required. However, the materials currently used in this area have certain disadvantages.

To protect personnel and equipment, steel, ceramics, high-modulus synthetic materials such as Kevlar, carbon fibre composites [1–5] and their combinations are currently used. However, such products do not always provide reliable protection having a number of disadvantages: Kevlar has very limited protective characteristics; fragile ceramic products are destroyed when hit by the first high-energy striking element, not providing effective protection in the future. Steel protective structures have a large mass and are therefore not sufficiently mobile. Moreover, ferromagnetic properties of steel products are a significant disadvantage when used by the enemy with magnetic mines. In addition, steel, ceramic and Kevlar materials, while protecting against bullets and fragments, are not effective in damping the energy of shock waves, which can cause significant damage to personnel and equipment.

Contrary, paramagnetic titanium alloys [6, 7] are considered as extremely attractive materials for the manufacture of protective ammunition owing to the unique combination of low specific weight (of about 4.5 g/cm^3), high strength (up to 1300–1600 MPa) and plasticity (elongation of 10–25% depending on the chemical composition). The strength of titanium alloys reaches the corresponding parameter of high-strength steels, while they are non-magnetic and half as light as steel counterparts are, giving a significant advantage in terms of personnel safety and ease of operation. A certain disadvantage of titanium alloys is their low hardness (not more than 300–350 *HV*) compared to steels. However, the hardness increases significantly (from 400 to 800 *HV* and higher [8–10]) for metal-matrix composites (MMC) based on titanium or its alloys, which are strengthened by high-modulus particles of TiC or TiB phases. At high hardness, such composites possess a desirable low specific weight and can achieve high strength levels.

It is generally recognized that a significantly improved complex of physical and mechanical, and, accordingly, protective and service characteristics, can be achieved by replacing individual materials with layered structures that combine them [1, 6, 11, 12]. The general principles of constructing such structures are well known from previously published data and are valid for a number of materials, including titanium [8, 9]. The advantage of layered structures is the combination of materials with significantly different mechanical characteristics: hard and high-strength MMC as the front layer, while ductile titanium alloys as the back layer. Such combination provides a unique set of high strength and ductile characteristics of the material as a whole, while

reducing the thickness of the material. Moreover, the inclusion of intermediate layers of highly porous titanium or titanium alloys in the layered structures contributes to the effective absorption of shock wave energy by deformation of such porous materials on impact loading.

The combination of titanium alloys and MMCs with different chemical and phase compositions, as well as highly porous layers, in one material can provide a unique set of physical and mechanical characteristics that are unattainable for each material separately. In particular, various combinations of the noted materials provide the potential to control the balance of all mechanical characteristics and to change parameters of strength, hardness, ductility and the ability to absorb shock wave energy, which will ensure the achievement of the desired protective characteristics of the entire layered material.

The aim of present study is to evaluate the potential for controlled change the mechanical characteristics of layered materials combining commercially-pure titanium (CP-Ti), Ti–6Al–4V alloy, MMCs on their base reinforced with TiC particles, as well as highly porous CP-Ti layers. These data will ensure development of layered titanium-based materials with promising physical and mechanical characteristics for effective protection against the damaging effects of explosive devices, including striking elements and shock waves.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

A number of titanium-based materials, which differ significantly in their chemical and phase composition, and, accordingly, change their mechanical characteristics in a wide range, were selected (Table 1) to be included in layered structures. Commercially-pure titanium (CP-Ti) was chosen as the most-ductile and low-strength material. The most widely used Ti–6Al–4V (% wt.) composition was selected as medium

TABLE 1. Composition of studied materials.

No.	Composition	Raw powders used for manufacturing
1	commercially-pure titanium (CP-Ti)	TiH_2
2	Ti + 10% TiC MMC	TiH_2, TiC
3	Ti + 20% TiC MMC	TiH_2, TiC
4	Ti + 40% TiC MMC	TiH_2, TiC
5	Ti–6Al–4V alloy	TiH_2, Al master alloy
6	Ti–6Al–4V + 10% TiC MMC	TiH_2, Al–V master alloy, TiC
7	Ti–6Al–4V + 40% TiC MMC	TiH_2, Al–V master alloy, TiC
8	highly-porous CP-Ti	TiH_2, ammonium carbonate

strength alloy. These materials were also used as metal matrixes to create composites reinforced with 10%, 20% and 40% (by volume) of high-modulus TiC particles to achieve enhanced strength and hardness characteristics. Comparison of CP-Ti and Ti–6Al–4V allows determining the influence of corresponding matrix material, while variation in TiC content allows evaluating the strengthening effect of TiC particles in the composites. To study the ability of porous structures to absorb energy during their deformation, highly-porous CP-Ti samples were manufactured.

All the above materials were manufactured using press-and-sinter blended elemental powder metallurgy. Titanium-hydride powder TiH_2 and powder blends on its base were used as raw materials, taking into account the positive role of hydrogen as a temporary alloying element for titanium [13–15].

Titanium-hydride powder (less than 100 μm in size), 60% Al–40% V master alloy (less than 63 μm) and titanium carbide TiC (less than 30 μm) powders were used as raw materials. The powders were blended in appropriate proportions to achieve the given composition of specific blends, after which the blends were pressed at room temperature in moulds at 620 MPa to obtain rectangular (65×10×10 mm) and cylindrical (diameter of 10 mm, height of 10 mm) compacts. The compacts were sintered in vacuum furnace (heated at a rate of 10°C/min to 1250°C, and kept at this temperature for 4 hours). In this thermal cycle, complete desorption of hydrogen from titanium hydride occurred, activating solid-state diffusion in dehydrogenated titanium [13–15]. As a result, redistribution of alloying elements (aluminium, vanadium) in titanium and sintering of powder particles led to formation of nearly-dense and chemically-uniform matrixes. When creating composites, the strengthening TiC particles remained quite inert in relation to the surrounding CP-Ti or Ti–6Al–4V alloy matrixes. Typical microstructures of sintered materials are shown in Fig. 1.

Manufacturing highly-porous CP-Ti included blending a fairly-large TiH_2 powder (63–125 μm) with ammonium carbonate particles (up to 400 μm in size), which was used as a space holder. Titanium hydride was blended with ammonium carbonate in proportions of 1:1, the blend was pressed at 150–250 MPa into rectangular (65×10×10 mm) compacts. Then, ammonium carbonate was removed as volatile compound from the compacts in two stages: by heating in air to 120°C and subsequent heating in vacuum to 300°C. After removing ammonium carbonate was completed, titanium-hydride powder compacts were heated in vacuum furnace up to 1000°C and exposed for 2 hours to remove hydrogen and sinter.

The microstructure of the sintered materials was investigated by scanning electron microscopy (VEGA III TESCAN equipped with a Brucker EDX detector to determine local chemical composition). The

Vickers hardness of the materials was determined using Wolpert 432 SVD machine. The compression characteristics of individual sintered materials were determined using cylindrical samples at Instron 8802 device under quasi-static loading conditions using rates of 10^{-3} and 10^{-1} mm·s^{-1}. To assess the potential for increasing the energy-absorbing (damping) characteristics of porous CP-Ti under compaction loading, their impregnation with polymers based on epoxyurethanes (PEU-1 and PEU-7) and modified epoxies was used. The polymers were developed at the Institute of Macromolecular Chemistry, N.A.S. of Ukraine, and recommended as damping materials.

To create layered materials, sintered rectangular samples (65×10×10 mm) of nearly-dense CP-Ti, Ti–6Al–4V alloy, MMCs and porous titanium were cut by spark erosion to obtain flat plates with a thickness of 2.5 to 5 mm, 65 mm length and 10 mm width. The plates of different materials were bonded each other in various combinations using polymers to form layered structures. Liquid polymers were deposed on the surfaces of individual materials, which were joined together to create 'sandwiches' and subsequently heated in drying chamber up to temperature range of 90–130°C for 3–6 hours to harden the polymers. Such operations led to joining the plates with the formation of a strong bond between the individual layers. The resulting layered structures of different compositions were subjected to three-point flexure tests on Instron 8802 machine, since the loading scheme during three-point flexure is similar to the loading on shock wave or projectile impact on the material.

3. RESULTS AND DISCUSSION

3.1. Microstructures and Compression Characteristics of Individual Sintered Materials

Typical microstructures of sintered nearly-dense materials are shown in Fig. 1. CP-Ti consisted of relatively-coarse α-phase lamellae (thickness is up to 50–70 μm) and globules having size up to 100 μm (Fig. 1, *a*). About of 1.5% residual pores of spherical shape up to 30–40 μm in size were presented in microstructure. Sintered Ti–6Al–4V alloy (Fig. 1, *b*) is characterized with noticeably finer lamellar α + β microstructure inside grains of 80–100 μm in size, and 2% residual pores (up to 30 μm in size). Microstructure of sintered MMC (see Fig. 1, *c* as an example) consists of lamellar CP-Ti or Ti–6Al–4V matrixes and reinforcing spherical TiC particles, which were not obviously changed in size and shape during sintering. A number of TiC particles form conglomerates, being not quite evenly redistributed over the matrixes. Residual porosity of MMCs is some higher than for matrixes itself, being within 3–8%.

As the first research stage, main mechanical characteristics of indi-

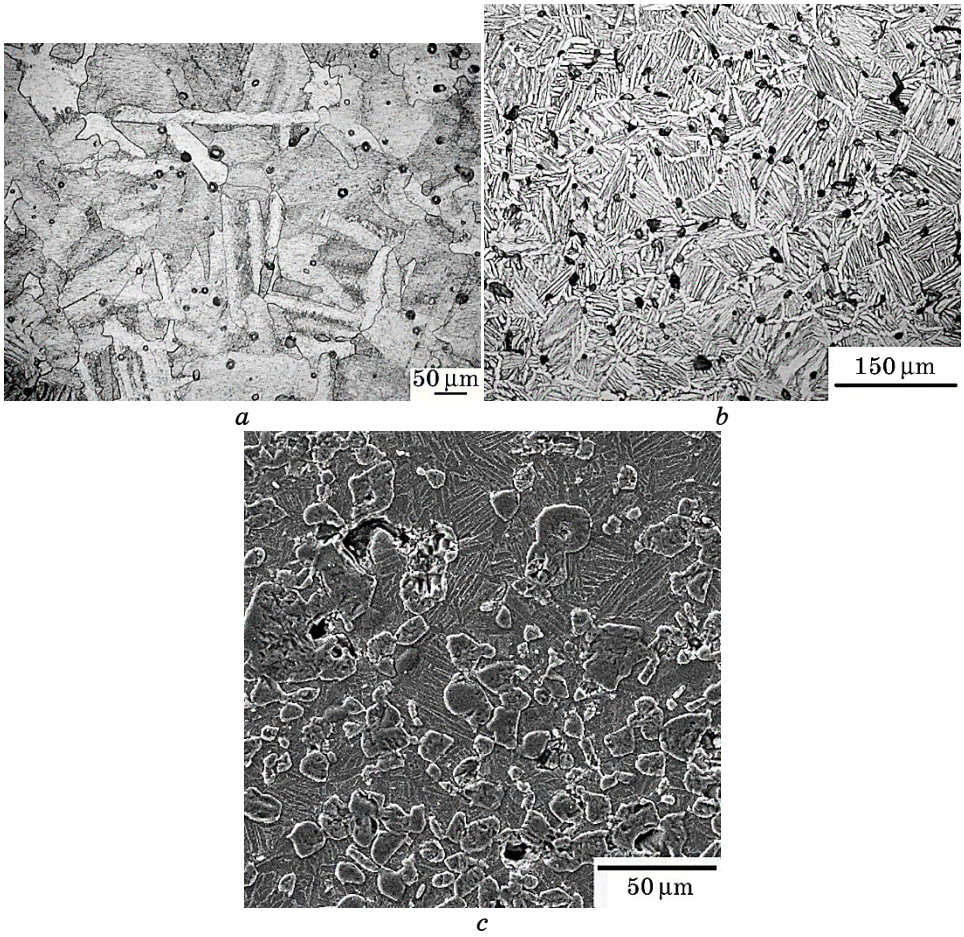

Fig. 1. Typical microstructures of sintered CP-Ti (*a*), Ti–6Al–4V alloy (*b*) and Ti–6Al–4V + 40% TiC composite (*c*).

vidual sintered materials were determined to evaluate the potential for characteristics modification with changing their chemical composition (Table 2). Corresponding stress–strain compression curves are presented in Fig. 2 together with tested samples.

Taking into consideration the data presented in Table 2 and Fig. 2, it was demonstrated that the yield strength and hardness values obviously increase, when replacing the CP-Ti matrix with an alloyed matrix of Ti–6Al–4V composition (yield strength (YS) from 590 to 1124 MPa, hardness from 260 to 357 *HV*). The similar result was achieved with introduction of reinforcing TiC phase in both matrixes and increase in TiC content. At the same time, with matrix alloying and increasing TiC phase content in MMC, the ability to deform (strain values correspond-

TABLE 2. Main mechanical characteristics of individual sintered materials.

No.	Material	Hardness, *HV*	Compression rate, 10^{-3}·mm·s^{-1}			Compression rate, 10^{-1}·mm·s^{-1}		
			YS, MPa	Ultimate strength, MPa	Strain, %	YS, MPa	Ultimate strength, MPa	Strain, %
1	CP-Ti	260	590	2086	52.5	613	2096	58
2	Ti–10% TiC	288	812	1792	38	966	1947	43
3	Ti–20% TiC	337	919	1411	23	1036	1325	21
4	Ti–40% TiC	449	976	1203	9	1236	1292	10
5	Ti–6Al–4V	357	1124	1714	29.5	1165	1616	31.5
6	Ti–6Al–4V–10% TiC	379	1163	1601	22	1260	1553	22.5
7	Ti–6Al–4V–40% TiC	560	1257	1600	11	1453	1661	10

ing sample fracture) was reduced from 52–58% to 9–11%. Furthermore, severe deformation of CP-Ti and Ti–6Al–4V alloy resulted in significant material hardening; thus, the ultimate strength values achieved (stress, at which samples were fractured) are highest (≅ 2090 MPa and ≅ 1600–1700 MPa) among tested samples. The higher content of TiC particles in the CP-Ti matrix led to reduced hardening ability of CP-Ti-based MMCs due to lower deformation. However, the tendency for reduced ultimate strength with higher TiC content is not obvious for MMCs based on Ti–6Al–4V matrix.

Increase in deformation rate within 10^{-3}–10^{-1} mm/s range resulted in some higher YS and strain values recorded, while tendency for changing ultimate strength values was not clearly observed at increase in deformation rate.

Microstructures of tested Ti–6Al–4V alloy and MMC samples are shown in Fig. 3 as an example of typical deformed microstructures. Traces of intensive deformation such as bended α-phase lamellae and severely-deformed residual pores were observed for both CP-Ti and Ti–6Al–4V matrixes without TiC particles (see Fig. 3, *a* for Ti–6Al–4V alloy). As for MMCs (Fig. 3, *b*), reinforcing TiC particles prevent intensive deformation of matrix. Samples were crushed with cracks propagation through matrix/TiC interfaces and particle conglomerates, forming crushed TiC fragments. The number of cracks increases

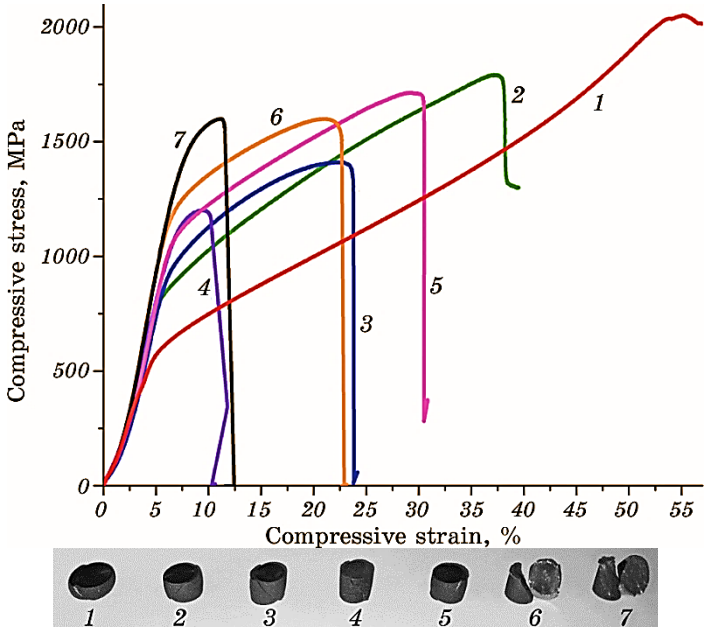

Fig. 2. Typical stress–strain curves for individual sintered materials (deformation rate 10^{-3} mm/s): *1*—CP-Ti, *2*—CP-Ti + 10% TiC, *3*—CP-Ti + 20% TiC, *4*—CP-Ti + 40% TiC, *5*—Ti–6Al–4V alloy, *6*—Ti–6Al–4V + 10% TiC, *7*—Ti–6Al–4V + 40% TiC. Corresponding tested samples (*1* to *7*) are shown below.

with increasing TiC-phase content, gradually leading to a transition from a ductile fracture mode to a completely brittle one, which is especially characteristic for MMCs based on the Ti–6Al–4V alloy with 10% and 40% TiC phase. In areas, where intense stresses occur, in particular, on the surfaces of brittle fracture of MMC, crashed TiC particles are clearly visible.

The results above suggested useful combination of either CP-Ti or Ti–6Al–4V alloy layers (as materials possessing highest ductile characteristics) together with MMCs reinforced with 40% TiC (as a materials demonstrating highest YS and hardness values) to achieve improved set of characteristics for entire layered materials.

3.2. Characteristics of Porous CP-Ti and Their Modifying with Polymer Impregnation

As well-known [16, 17], presence of pores in sintered materials resulted in degradation of their strength and ductile characteristics. So, manufacturing of porous CP-Ti was aimed on achievement not only specified and uniform porous structure desirable for improved damping charac-

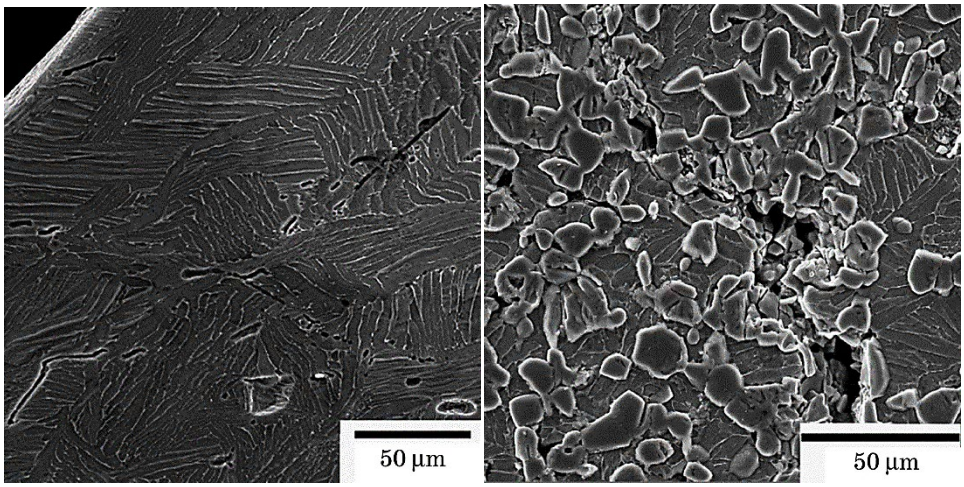

Fig. 3. Typical microstructures of deformed Ti–6Al–4V alloy (*a*) and Ti–6Al–4V + 40% TiC MMC (*b*).

teristics, but also to attain sufficient strength and ductile levels.

Selected modes of ammonium carbonate removal from the powder compacts and parameters of subsequent vacuum sintering at 1000°C allowed completed dehydrogenation of TiH_2 particles and formation of highly-porous sintered CP-Ti material with a density of 1.63–1.73 g/cm^3, which corresponds to a porosity level of 60% to 64% (Fig. 4, *a*, *b*). The pores are evenly distributed over the volume of sintered CP-Ti with preservation of open pore channels between the voids (Fig. 4, *a*). The pore sizes are up to 200–400 microns (Fig. 4, *b*) that corresponds to the size of space holder particles used.

Despite enhanced porosity, sintered CP-Ti ensures sufficient compressive strength and significant degree of deformation before fracture (Fig. 5, curve *1*), promising for its using as damping material. However, ability to absorb energy on deformation (other words, better damping characteristics) should be as high as possible, which, in turn, needs increased deformation degrees. For this reason, the potential to increase deformation ability of porous titanium using its saturation with special polymers developed at the Institute of Macromolecular Chemistry, N.A.S. of Ukraine was investigated. The idea was to create a specific composite material by impregnating porous titanium with polymers in the liquid state, followed by their solidification, which was supposed to improve further the toughness and elastic properties of porous titanium and to increase its deformation degree before the fracture. As once more extremely important task, the polymers characterized by high adhesiveness and sufficient strength in solidified condition

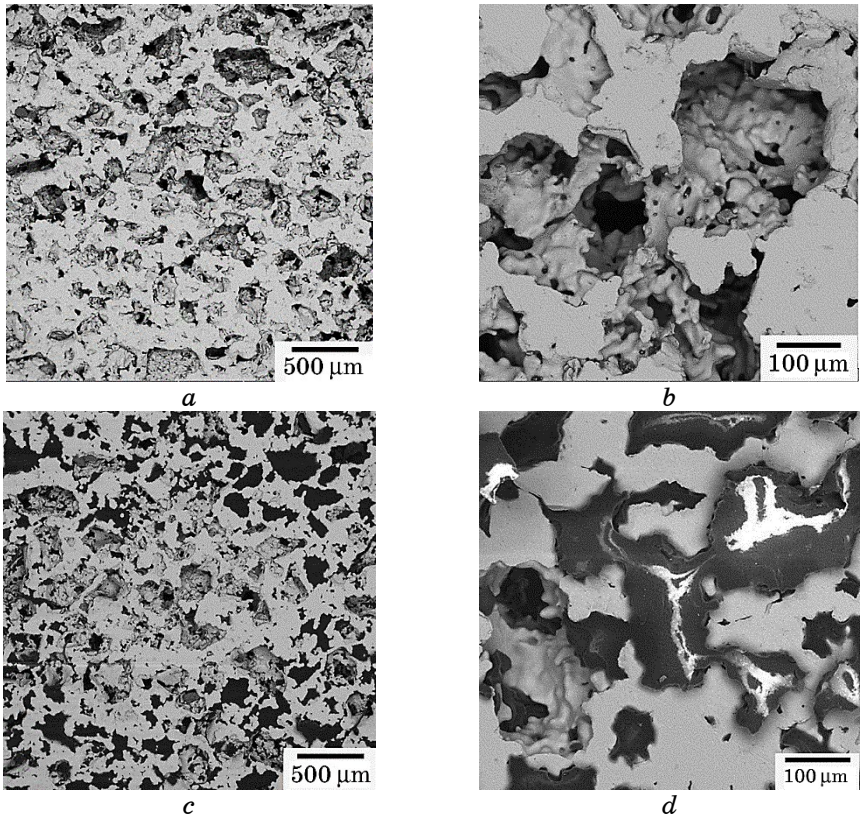

Fig. 4. SEM images (BSE mode) of sintered porous CP-Ti microstructure (*a*, *b*) and after its impregnation with polymers (*c*, *d*, polymer PEU-7 is used as an example). Pores filled with polymers are dark; those not filled are light.

can be used to join the surfaces of various titanium-based materials (including porous layers, alloys and MMCs) into entire layered structures.

On impregnation process, liquid polymers having a different, but sufficiently high fluidity partially fill the voids of porous CP-Ti (Fig. 4, *c*). Owing to good adhesion, polymers densely join with the internal surfaces of the porous material (Fig. 4, *d*), ensuring strong bond after polymer solidification. For used SEM BSE images, pores filled with polymers appear as dark zones, while pores not filled with polymers are light. The density of porous CP-Ti samples (of 1.63–1.73 g/cm^3) increases somewhat after impregnation process; the densities after polymer impregnation are of 2.152 g/cm^3 (Ti + PEU-1), 2.019 g/cm^3 (Ti + PEU-7), and 2.317 g/cm^3 (Ti + epoxy-based polymer). Different density values after impregnation are in accordance with the varying degrees of saturation of CP-Ti with the corresponding polymers due to their different fluidity characteristics.

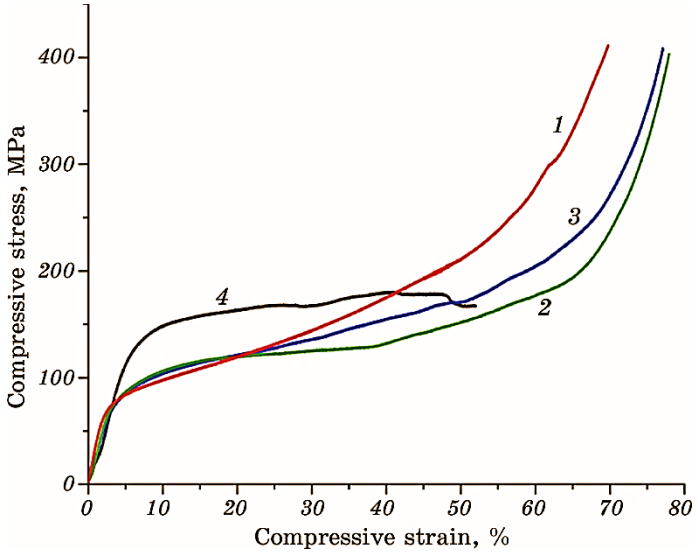

Fig. 5. Compression stress–strain characteristics of porous CP-Ti (*1*) and their changes under the influence of various polymer impregnations: PEU-1 (*2*), PEU-7 (*3*), epoxy-based (*4*). Deformation rate of 10^{-3} mm/s.

Impregnation with polymers noticeably affects the stress–strain compressive characteristics of porous CP-Ti (Fig. 5, curves *2*–*4*, compare with curve *1*). At the initial stages of loading (up to 66–67 MPa at both used deformation rates of 10^{-3} and 10^{-1} mm/s), the studied materials deform elastically. At higher compression stresses, they mainly demonstrate typical plastic behaviour without fracture of the samples (with the exception of the sample impregnated with an epoxy-based polymer).

At the beginning, plastic deformation of porous material occurs by a gradual decrease in the pore volume (areas of flat 'plateaus', located horizontally or with a slight slope), as a result of which a compacted poreless materials are gradually formed, which leads to deformation hardening and an increase in the slope of the curves with increasing stresses. Porous CP-Ti without polymers (Fig. 5, curve *1*) has a yield strength of 66–67 MPa and plastically deforms to a relative compression strain of about 65–70% before the appearance of certain signs of sample failure ('teeth' and bend points on the stress–strain curves). The epoxy-based polymer (Fig. 5, curve *4*) significantly increases the strength of porous titanium (yield strength of 105–221 MPa depending on deformation rates of 10^{-3} and 10^{-1} mm/s, correspondingly), but reduces its ability to deform (relative compression strain decreases to 25–50%, at which sample failure takes place). Impregnation with PEU-1 and PEU-7 polymers (Fig. 5, curves *2* and *3*) has a fairly similar

effect on the mechanical behaviour of porous titanium, only slightly increasing its strength at the initial stages of deformation (yield strength is of up to 67–84 MPa depending on deformation rate), but reducing the slope of the curves with further development of plastic deformation and continuing the flat sections of the stress–strain curves ('plateau') to deformation values of 40–48%, at which the first signs of the development of the failure process appear, however, without fracture of the sample as a whole. At the same time, the sample impregnated with PEU-1 polymer (Fig. 5, curve *2*) demonstrates the lowest slope of the stress–strain curve with a longest horizontal 'plateau', which indicates the practical absence of hardening, hence, improved ability to absorb energy owing to enhanced deformation degree compared to other samples.

Based on results above, it was determined that the impregnation with polymers PEU-1 and PEU-7 demonstrates similar plastic behaviour, which should make the desired contribution to increasing energy absorption during deformation, with PEU-1 being determined as the best suitable polymer for further experiments. PEU-1, having sufficient fluidity in liquid state, penetrates quite easily inside the depth of the porous CP-Ti during impregnation. Moreover, PEU-1 does not increase the strength of porous titanium, but provides better deformation characteristics (a longer horizontal plateau on stress–strain curve, and, accordingly, the enlarged area under it (Fig. 5), which corresponds to greater absorbed energy on deformation and indicates better damping characteristics).

3.3. Layered Structures and their Characteristics

The task of the next research stage was to manufacture layered samples using polymer PEU-1 to bond layers of different titanium materials, and to assess the mechanical behaviour of layered structures of different composition under loading conditions that simulate the loading conditions during the action of shock waves.

Two-, three- and four-layered samples of different design on the base of CP-Ti and Ti–6Al–4V alloy were manufactured (Fig. 6) to comparatively assess their mechanical characteristics and to understand the role of each individual material in the overall deformation behaviour. The samples *1* and *4* contain MMCs with high content (of 40%) of TiC phase as front layer, and back ductile layer of either CP-Ti or Ti–6Al–4V alloy. An intermediate layer of porous CP-Ti was included for samples *2* and *5*; thickness of porous layer was furtherly increased for samples *3* and *6*. The polymer PEU-1 impregnated intermediate porous CP-Ti layer and covered the adjacent surfaces of layers to ensure sufficient bonding between them. The overall thickness of each sample was of about 10 mm, while thickness of individual layers was variable with-

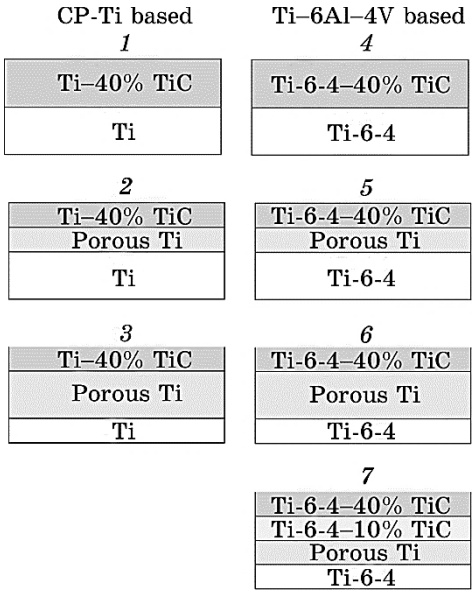

Fig. 6. Scheme of tested layered sample design: samples Nos. *1–3* are based on CP-Ti, while Nos. *4–7* on Ti–6Al–4V alloy.

in approximately 2.5–5 mm range to evaluate the influence of each layer thickness. Once more sample (*7*) included additional intermediate MMC layer with low TiC content (10%) to evaluate the role of gradual decrease of reinforced particle content from surface to the depth of layered material. The samples were tested with 3-point flexure; load was applied from MMC layer side (Fig. 7).

The comparison of flexure stress–flexure strain curves for samples based on CP-Ti (Fig. 8, *a*) and based on Ti–6Al–4V alloy (Fig. 8, *b*)

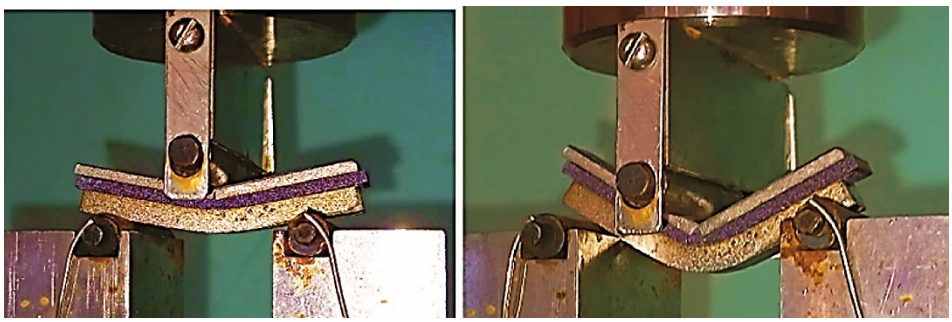

Fig. 7. Various stages of three-point flexure testing layered sample consisted of Ti–40% TiC MMC (upper), porous CP-Ti (intermediate) and bulk CP-Ti (bottom) layers.

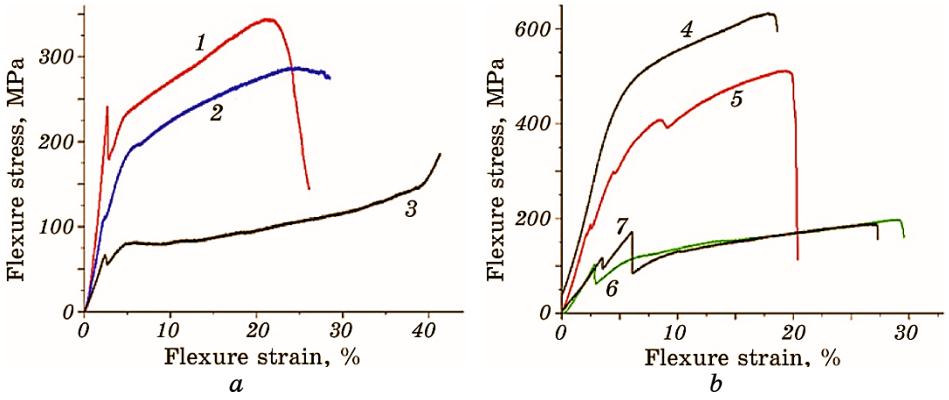

Fig. 8. Stress–strain curves for 3-point flexure tests of layered samples on the base of CP-Ti (*a*) and Ti–6Al–4V alloy (*b*), sample numbers correspond to samples shown in Fig. 6.

clearly demonstrates that alloying the matrix with aluminium and vanadium leads to noticeably higher strength values, but lower ductile characteristics than those for the unalloyed CP-Ti matrix. However, the other features of mechanical behaviour are quite similar for both groups of samples.

The characteristic feature of all layered materials is the presence of 'teeth' at stress–strain curves, mainly, within the elastic deformation stage at stresses in the range from 70 MPa to 400 MPa (depending on the type of layered samples; Fig. 8). The teeth are associated with the destruction of the polymer bonding the layers, delamination of individual layers and their cracking. The appearance of cracks mainly observed for the upper MMC layers, which are hard and have low fracture toughness, as well as for highly-porous layers, both of which are vulnerable to crack propagation in places of significant stress concentration. With an increase in the deformation degree, as a rule, the nucleation and growth of cracks is first observed in the upper MMC layer, then in the porous layer, and lastly in the bottom ductile layer.

The inclusion of highly porous titanium layers (which are relatively ductile and have lowest strength) between the layers of MMC and alloy leads to a decrease in the yield strength and the strength of the layered structure as a whole (compare samples *1* and *2* in Fig. 6 and corresponding curves in Fig. 8, *a*, as well as samples *4* and *5*, Fig. 6, and corresponding curves in Fig. 8, *b*). At the same time, presence of intermediate porous layer increases ability to deform (increasing the plastic deformation stage of the stress–strain curves, which indicates a better ability to absorb energy during deformation). Increasing the thickness of the porous layers (comparison of curves *2* and *3* in Fig. 8, *a*, as well as curves *5* and *6* in Fig. 8, *b*) further demonstrates this trend.

It should be noted that the slope of the load curves gradually decreases with the inclusion of a porous CP-Ti layer between MMC and alloy layers and with an increase in its thickness from 2.5 mm (samples *2* and *5*) to 5 mm (samples *3* and *6*). We can draw a general conclusion about the decrease in Young's modulus of layered structures as a whole, with an increase in the thickness of their porous layers. This result is logical, taking into account the well-known data on the gradual decrease in Young's modulus [18, 19] for materials having higher porosity.

Sample *7* (four-layer), in which two composite layers with 40% and 10% TiC were used, demonstrates rather similar strain, strength, and Young's modulus characteristics in comparison to those for three-layer sample *6* (Fig. 8, *b*). Obviously, potential effect of additional MMC layer on mechanical characteristics was hidden with simultaneous reduction of porous layer thickness for sample *7* and with relatively low strength of polymer joins.

Thus, from the experiments conducted, it can be concluded that proper combinations of the studied materials and the thickness of individual layers allow wide range adjustment of strength characteristics (yield stress of 70–420 MPa, tensile strength of 80–600 MPa), plasticity (deformation of 18–40%) and Young's modulus of layered structures. An important result is the confirmation of the positive role of the inclusion of highly-porous CP-Ti in layered structures to reduce Young's modulus and to increase their overall deformation degree before the beginning of their destruction process, which is useful for controllable adjustment of strength, ductile, and damping characteristics of layered structures.

4. CONCLUSIONS

1. Nearly-dense commercially-pure titanium (CP-Ti), Ti–6Al–4V alloy and MMCs based on them with a content of high-modulus TiC particles from 10 to 40% were manufactured with powder metallurgy approach using hydrogenated titanium powder. The potential for variation of mechanical characteristics of these materials depending on the composition of the matrix and TiC content was determined using hardness and compression tests in quasi-static conditions.
2. Highly-porous CP-Ti samples (with 60–64% pores) were manufactured using titanium-hydride powder and ammonium carbonate as a space holder. Porous CP-Ti samples were impregnated with polymers based on epoxyurethanes (PEU-1 and PEU-7) and epoxide to evaluate the potential to affect deformation ability of porous CP-Ti. Polymers PEU-1 and PEU-7 similarly improve the stress–strain characteristics of porous titanium under compression loading, which is useful for higher energy adsorption characteristics on deformation.
3. Nearly-dense MMC and alloy layers, as well as porous CP-Ti one were joined in various combinations using PEU-1 polymer to create layered

structures. The mechanical behaviour of layered structures during three-point flexure tests was determined. The inclusion of porous layers and an increase in their thickness in layered structures leads to a decrease in strength and Young's modulus, but an increase in deformation ability of the layered structure as a whole. Proper selection of material combinations and thickness of layers gives wide potential for controllable and useful adjustment of strength, ductile and damping characteristics of layered structures.

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REFERENCES

1. M. Übeyli, R. O. Yıldırım, and B. Ögel, *Mater. Design*, **28**, Iss. 4: 1257 (2007).
2. Y. H. Cheng, H. Wu, R. G. Zhao, and F. Zhou, *J. Constructional Steel Research*, **197**: 107502 (2022).
3. R. Yadav, M. Naebe, X. Wang, and B. Kandasubramanian, *RSC Advances*, **6**: 116 (2016).
4. W. Gooch, *Advances in Ceramic Armor VII: Ceramic Engineering and Science Proceedings (Eds. J. J. Swab, S. Widjaja, and D. Singh) (American Ceramic Society: 2011)*, p. 1931.
5. R. Stopforth and S. Adali, *Defence Technol.*, **15**, Iss. 2: 186 (2019).
6. J. S. Montgomery, M. G. H. Wells, B. Roopchand, and J. W. Ogilvy, *JOM*, **49**: 45 (1997).
7. J. C. Fanning, *J. Mater. Eng. Perform.*, **14**: 686 (2005).
8. S. V. Prikhodko, O. M. Ivasishin, P. E. Markovsky, D. G. Savvakin, and O. O. Stasiuk, *Proc. NATO SPS Cluster Workshop on Advanced Technologies (Sept. 17–18, 2019)* (Leuven: Springer: 2020), p. 127.
9. O. M. Ivasishin, P. E. Markovsky, D. G. Savvakin, O. O. Stasiuk, M. N. Rad, and S. V. Prikhodko, *J. Mater. Process. Technol.*, **269**: 172 (2019).
10. P. E. Markovsky, D. G. Savvakin, O. O. Stasyuk, M. Mecklenburg, M. Pozuelo, C. Roberts, V. Ellison, and S. Prikhodko, *Mater. Design*, **234**: 112208 (2023).
11. A. Petterson, P. Magnusson, P. Lundberg, and M. Nygren, *Int. J. Impact Eng.*, **32**, Iss. 1–4: 387 (2005).
12. R. M. Gamache, C. B. Giller, G. Montella, D. Fragiadakis, and C. M. Roland, *Mater. Design*, **111**: 362 (2016).
13. D. G. Savvakin, M. M. Humenyak, M. V. Matviichuk, and O. H. Molyar, *Mater. Sci.*, **47**: 651 (2012).
14. O. M. Ivasishin and D. G. Savvakin, *Key Eng. Mater.*, **436**: 113 (2010).
15. O. M. Ivasishin, D. G. Savvakin, M. M. Humenyak, and O. B. Bondarchuk, *Key Eng. Mater.*, **520**: 121 (2012).
16. *Titanium Powder Metallurgy: Science, Technology and Applications* (Eds. Ma Qian and F. H. Froes) (Elsevier: 2015).
17. Z. Z. Fang, J. D. Paramore, P. Sun, K. S. Ravi Chandran, Y. Zhang, Y. Xia, F. Cao, M. Koopman, and M. Free, *Int. Mater. Rev.*, **63**, Iss. 7: 407 (2018).
18. J. C. Wang, *J. Mater. Sci.*, **19**: 801 (1984).
19. B.-K. Jang and H. Matsubara, *Mater. Lett.*, **59**, Iss. 27: 3462 (2005).