# The highly dense titanium based metal matrix composites reinforced TiC densified by hot pressing

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***Abstract:*** *Titanium–titanium boride (Ti/TiC) metal matrix composites have been widely identified as promising materials for various applications. The traditional ingot metallurgy processing strategies used to fabricate these materials are energy intensive and have fallen short of their perceived mass production potentials. Powder metallurgy processing of Ti/TiC composites from titanium and TiC powder blends, is currently widely used for the cost-efficient production of such composites. Additional processing by the method of hot pressing improves the structure and mechanical properties of this class of materials. The composites have the heterogenous microstructure with areas high hardness area over 1173 HV. While matrix and inclusions had the value of 700 HV.*

**Keywords:** TITANIUM HYDRIDE, MICROSTRUCTURE, POWDERS, MMC, HOT PRESSING

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**Introduction.** Titanium alloys play a crucial role in modern aerospace, automotive, shipbuilding, and military technologies due to their high specific strength, fracture toughness, fatigue strength, corrosion resistance, non-magnetic properties, and other specialized physical-mechanical characteristics [1-3]. However, traditional titanium alloys, which are alloyed with various elements typically categorized as α- or β-phase stabilizers, often fall short in meeting the desired combination of physical and mechanical properties. For example, these alloys tend to have low wear resistance, susceptibility to fretting corrosion, and relatively low hardness [4,5]. These limitations can be addressed by developing titanium based Metal Matrix Composites (MMC) that incorporate fine hard particles such as carbides or borides [6, 7].

To eliminate the drawback mentioned above, it is necessary significantly (2 or more times) to increase the hardness of the titanium material. Among others, this will improve other properties, such as wear resistance.

Previously, in works [5-7] it was shown that employing synthesis the of mixtures of elemental powders allows to obtain a metal-matrix composite based on a Ti64 matrix reinforced with high-modulus TiC or TiB particles. Depending on the amount of the introduced hardening phase, such a material can have a hardness in a wide range from 600 to 1000 HV and even more.

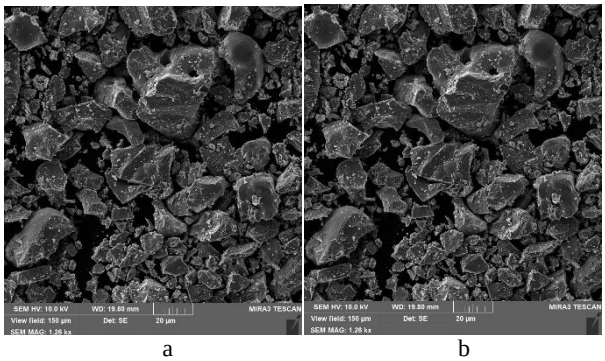
However, residual pores, which number and size increases with increase of introduced into the initial powder mixture amount of TiC particles, significantly reduces standard mechanical properties, both strength and ductility. As it was shown in [8] application to sintered MMC's of hot isostatic pressure (HIP) allows reduce residual porosity to almost zero. Moreover, because of long-term high-temperature exposure under the loading of external forces inside the MMC strengthened by TiC diffusional processes between these particles and metallic matrix took place essentially changing initial phase composition and microstructure.

The hot-pressing (HP) method is widely used for densification of ceramic and metal-ceramic composite. The main advantage of HP is the obtaining the fully dense materials by applying pressure and temperature during sintering. Technology of hot pressing in air using graphite layers led to significantly decrease the price of the proses in comparison with other technologies (HP in vacuum or spark plasma sintering). Another advantage is the speed of densification, which allows the save fine microstructure. Preservation of the fine microstructure leads to an increase mechanical properties of metal matrix composites.

**Materials and experimental procedure.**

The basic component of the powders charge to prepare the test samples was titanium hydride with a fraction of –100 μm (Fig. 1a), whose hydrogen content and phase composition corresponded to single-phase titanium hydride ($TiH_2$) and titanium diboride powders (Fig. 1b). In choosing high-modulus compounds as reinforcement components for the composite, we were guided by our previous efforts that showed that TiC was an effective reinforcing addition that actively interacted with the titanium matrix at sintering temperatures to release monoboride particles.

The particle size of the starting powders was determined with a Malvern Mastersizer 2000 laser diffraction analyzer. Considering that the powder particles could coagulate, we measured their grain-size composition both in starting state and under ultrasonic vibrations. The starting titanium hydride powder mixtures that contained TiC were prepared in a drum mixer. The resultant mixture were subjected to double-action compaction at 650 MPa to make sampels. In selecting the sintering conditions, we considered our findings [7] on the sintering kinetics and structurization of the TiH2 + TiB2 powder mixtures. The compacts were sintered in vacuum at 1250ºC with an isothermal holding time of 4 h. The compacts were heated to the sintering temperature at a rate of 10ºC/min. The samples were cooled down in the furnace after isothermal holding. The density and porosity of the compacts and sinters were determined by hydrostatic weighing.



a b

***Fig.1*** *Morphology of the starting titanium hydride (a) and titanium carbides (b) powders*

Samples were obtained by hot pressing without protective atmosphere at a pressure of 32 MPa in a temperature range of 1300−1500 °C under CO/CO2. The gas medium created by burning of the graphite fixture. In this apparatus, due to the CO → CO2+C reaction, efficient delivery of carbon throughout the porous volume and the reduction of oxides impurities on the surface of the sintering samples. The pre sintered composite were heated up to different temperatures using induction heating with a heat rate of 100 ◦C/min. An initial load of 7 MPa was applied until the peak temperature was achieved, and then the load was increased to 32 MPa. The dwell at the maximum temperature was 30 min, then the furnace was slowly cooled down (50 ◦C/min) to 1200 ◦C and further free cooling to room temperature to avoid crack formation.

Three-point flexural test were performed in compliance with ISO 12135 and ISO 12737 at room temperature employing an H5K-T produced by Hounsfield machine. The fracture patterns of the

samples after mechanical tests were examined by fractography and the fracture surfaces and microstructure were analyzed with a TESCAN VEGA 3 scanning electron microscope. The Vickers hardness was measured with a Wolpert hardness tester.

**Results and discussion.**

In our earlier studies [9], [10], we examined in detail the sintering behavior of MMCs, as well as the development of their final microstructure and properties.

As shown in Fig. 2a, pure titanium hydride exhibited a shrinkage of about 10% at 1200 °C. Under the same conditions, the Ti-6Al-4V alloy (Ti64) displayed nearly identical shrinkage of 9.5%. These shrinkage values indicate a high density of titanium-based materials produced via the hydride route.

The addition of TiC reinforcing particles to either titanium hydride or Ti64 significantly reduced shrinkage, limiting it to about 4–4.5% (Fig. 2a). This effect occurs because TiC particles—owing to their high melting point (3160 °C), thermal stability, and minimal interaction with the matrix—act as barriers to shrinkage. Consequently, composites containing 40 wt% TiC showed lower shrinkage (4.5–4%) compared to unreinforced materials (Fig. 2a).

Figure 2b presents the shrinkage behavior of composites with 40 wt% TiC during hot pressing at different temperatures. At 1300 °C, the shrinkage remained low (≈ 5%) due to the high content of the reinforcing phase, which restricts full densification. In contrast, hot pressing at 1500 °C increased shrinkage to about 7.5%, resulting in very low residual porosity (~ 1%).

Titanium exhibits a nearly linear decrease in yield strength with increasing temperature, reaching about 50 MPa at 600–800 °C. Ti-6Al-4V, however, has a yield strength of only 12 MPa at 1050 °C. Titanium matrix composites, benefiting from reinforcing phases, demonstrate higher yield strength and improved mechanical performance. As a result, higher hot-pressing temperatures are required. At 1500 °C, the material attains high plasticity, enabling complete pore closure under relatively low pressures (up to 32 MPa).

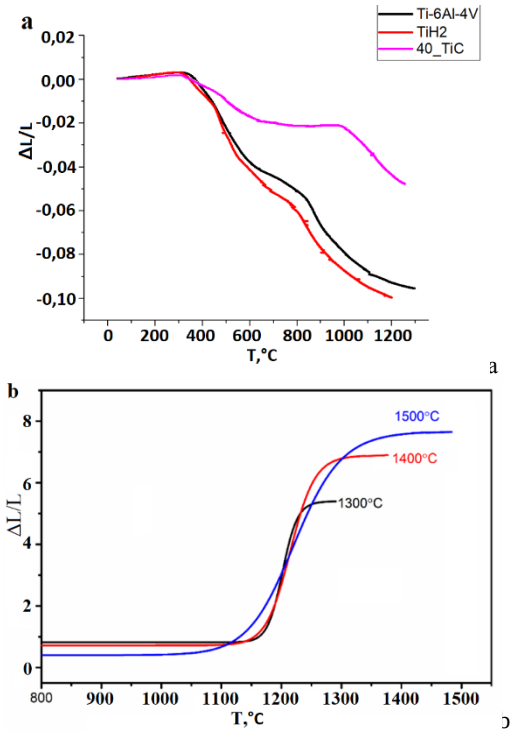



***Fig. 2.*** *Shrinkage of composite materials: a) during vacuum synthesis, b) during hot pressing*

The microstructure of the titanium matrix composite Ti–40 wt.% TiC after sintering followed by hot pressing is shown in Fig. 3. For comparison, Fig. 4 presents the microstructure of a composite based on the Ti-6Al-4V (Ti64) alloy matrix containing the same amount of reinforcing phase (40 wt.% TiC).

As reported in our earlier work [10], both titanium and Ti64 alloy composites with 40 wt.% TiC exhibit porosity levels of about 14–16%. During hot deformation, the high ductility of the metallic matrix enables complete closure of pores within the rigid framework formed by the reinforcing particles.

Figure 3a illustrates the fine microstructure of a titanium-matrix composite with embedded titanium carbide inclusions. Figures 3b and 3c reveal titanium inclusions located within titanium carbide regions. This is attributed to the presence of titanium at the boundaries of carbide particles after sintering. However, hot pressing results in a fully dense composite.

Small tungsten-enriched particles were also detected in the titanium matrix (Fig. 3c,d). This occurs because industrial titanium carbide contains trace amounts of WC, introduced during the grinding stage after carbide synthesis. The content of such inclusions is below 1%, and they are primarily distributed in the titanium matrix near large clusters of titanium carbide particles.

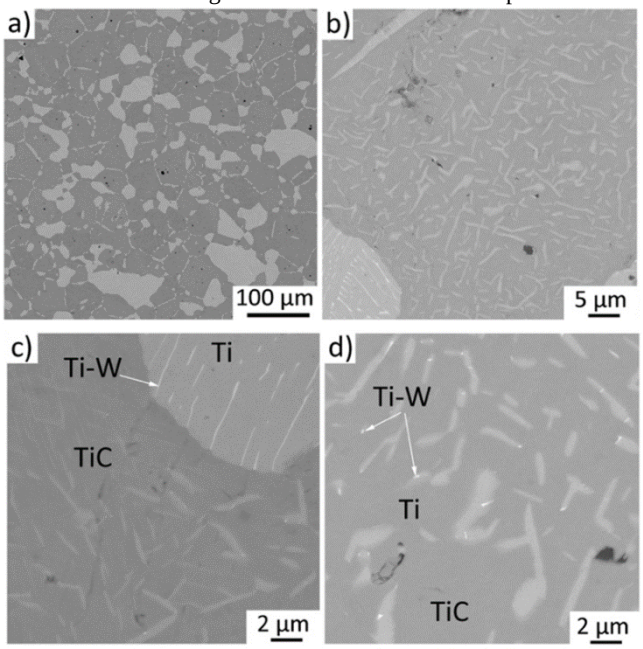


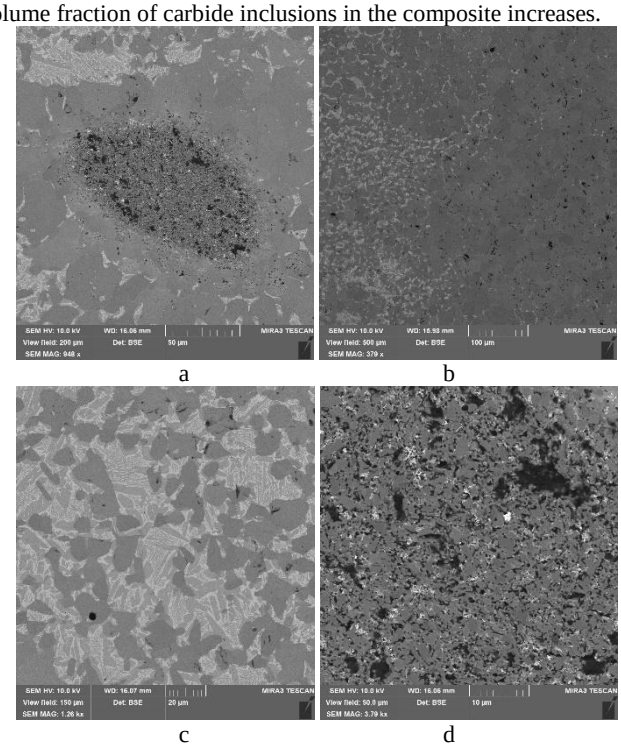

***Fig.3.*** *Microstructure of Ti-TiC: a) general view, b) region with needle like thin inclusion of Ti, c) grain boundaries between Ti-TiC, d) region with perception of the Ti-W.*

Three distinct microstructural zones were identified in the Ti64–40 wt.% TiC composite after hot pressing. The first zone consists mainly of rounded carbide grains approximately 15 µm in size, with a 1–5 µm-thick Ti-based matrix phase present along their boundaries (Fig. 4b). The second zone is characterized by a Ti64 alloy matrix with a typical uniform lamellar α+β structure, containing TiC particles of about 10 µm (Fig. 4c). The third zone is composed predominantly of titanium carbide (Fig. 4d) and exhibits residual porosity of 3–4%, as the hot-pressing temperature of 1500 °C is insufficient to achieve full densification of pure titanium carbide. This carbide-rich region forms during hot pressing. The addition of 60Al–40V ligature powder to the Ti–TiC mixture promotes coagulation of carbide particles during powder mixing prior to sintering.

For Ti–TiC composites, segregation of pure titanium carbide was not detected. Nevertheless, chemical analysis of the carbide particles is presented in Fig. 5. This figure illustrates a gradual concentration transition at the phase boundaries.

Elemental diffusion after hot pressing was investigated for Ti64–TiC composites, as three distinct zones were identified. Under the combined effects of high temperature and applied pressure, titanium carbide partially transforms into $Ti_2C$—an equilibrium phase at elevated temperatures. In BSE micrographs, subtle tonal variations can be observed within the carbide zones from the center toward the

periphery, indicating chemical heterogeneity. Localized chemical analysis confirmed variations in carbon and titanium concentrations: the central porous zone consists of stoichiometric TiC, while the boundary regions adjacent to TiC contain a phase with reduced carbon content but enriched in titanium. This occurs because carbon diffuses from the carbide particles into the titanium matrix, leading to the formation of a new phase. As a result, the volume fraction of carbide inclusions in the composite increases.



a b c d

***Fig.4.*** *Microstructure of Ti64- 40 wt% TiC: a) general view, b) region with high amount of TiC, c) region with high amount of Ti64, d) region of carbide phase.*

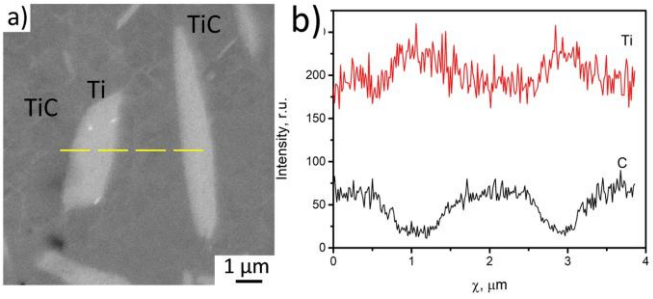



***Fig.5.*** *The microstructure of Ti-TiC after hot-presssing at 1500 °C (a) and distribution of chemical elements (b) though TiC-Ti-TiC-Ti particles yellow line in (a).*

Results Figs. 4–5 show that the microstructure of the composite material is heterogeneous, resulting in variations in hardness across different zones. For the Ti–40 wt.% TiC composite, the hardness is approximately 715 HV in zones containing the matrix phase, 774 HV in carbide-rich areas where the matrix phase is present between grains, and 895 HV in regions composed entirely of carbide phases (Fig. 6).

In the Ti64–40 wt.% TiC composite, the hardness of the matrix phase containing a small fraction of carbide particles is comparable to that of the titanium-matrix composite. Zones with carbide particles separated by thin matrix layers at the boundaries exhibit hardness values around 860 HV (Fig. 6). Carbide-rich regions, which retain ~5 vol.% residual porosity and have partially depleted carbon content due to diffusion into the matrix, display hardness values of 1170 HV. Surrounding these porous clusters, carbon diffusion promotes the formation of in-situ carbide phases, resulting in the highest measured hardness of 1335 HV.

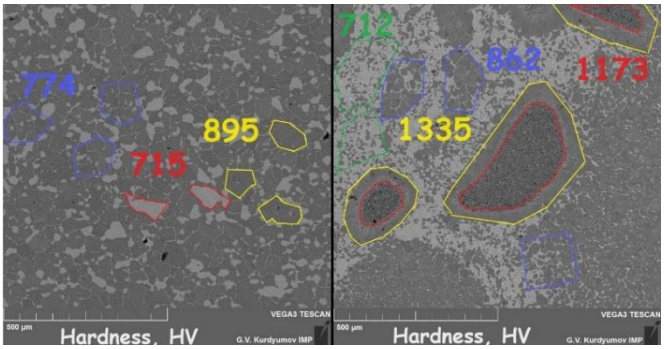



***Fig.6.*** *Hardness of Ti-40wt%TiC (a) and Ti64-40wt%TiC*

**Conclusions.**

1. Ti and Ti64 composites reinforced with TiC, produced by sintering followed by hot pressing, develop a heterogeneous, multi-zone microstructure consisting of a matrix phase with fine TiC inclusions.
2. Hot pressing at 1500 °C significantly reduces porosity and provides high material hardness, which varies by zone: for Ti–TiC, hardness ranges from 715 to 895 HV; for Ti64–TiC, hardness reaches up to 1335 HV in zones with in situ formed carbides. The combination of high-temperature processing and TiC reinforcement ensures increased density and strengthening of the composites.

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**References.**

1. J.S. Montgomery, M.G.H. Wells. Titanium armor applications in combat vehicles. JOM, 4 (2001), pp. 29-32
2. J. Fanning. Military application for β titanium alloys. J Mater Eng Perform, 14 (2005), pp. 686-690
3. Chao Cai et al. In-situ TiB/Ti-6Al-4V composites with a tailored architecture produced by hot isostatic pressing: microstructure evolution, enhanced tensile properties and strengthening mechanisms. Compos. B Eng. (2019)
4. Baglyuk, G.A. et al. The Effect of Charge Component Composition on the Structure and Properties of Titanium Matrix Sintered Composites with High-Modulus Compounds. Powder Metall Met Ceram 56, 45–52 (2017). https://doi.org/10.1007/s11106-017-9870-z
5. O.M. Ivasishin, et. al. Microstructure and properties of titanium-based materials promising for antiballistic protection. Progress in Physics of Metals. — 2019. — Vol. 20, No 2. — P. 285-309. DOI: https://doi.org/10.15407/ufm.20.02.285
6. Prikhodko, S.V., et. al.. Titanium Armor with Gradient Structure: Advanced Technology for Fabrication. In: Palestini, C. (eds) Advanced Technologies for Security Applications. NATO Science for Peace and Security Series B: Physics and Biophysics. Springer, Dordrecht. https://doi.org/10.1007/978-94-024-2021-0_13
7. P. E. Markovsky et al., "Mechanical Behavior of Titanium Based Metal Matrix Composites Reinforced with TiC or TiB Particles under Quasi-Static and High Strain-Rate Compression," Materials, vol. 14, no. 22, p. 6837, Nov. 2021, doi: 10.3390/ma14226837.
8. P. Markovsky et al., "Ballistic performance of titanium-based layered composites made using blended elemental powder metallurgy and hot isostatic pressing," Defence Technology, vol. 39, pp. 1–14, 2024, doi: https://doi.org/10.1016/j.dt.2024.04.002
9. Song, Y.; Dong, et al., Synthesis of Ti/TiB Composites via Hydrogen-Assisted Blended Elemental Powder Metallurgy. Front. Mater. 2020. https://doi.org/10.3389/fmats.2020.572005
10. Prikhodko, S.V., et al. Friction welding of conventional Ti-6Al-4V alloy with a Ti-6Al-4V based metal matrix composite reinforced by TiC. Weld World 65, 415–428 (2021). https://doi.org/10.1007/s40194-020-01025-8