UDC 621.316.13

Andrii Skrebtsov — Candidate of Technical Sciences, Associate Professor of the Department of Theoretical and Applied Mechanics, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: nic_tz@ukr.net*, ORCID: 0000-0002-4669-9625

Andrii Kononenko — Postgraduate Student of the Department of Mechanics of the National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: andrju3952@gmail.com*, ORCID: 0009-0005-4268-0854

Julia Kononenko — Senior Lecturer of the Department of Physical Materials Science of National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: juliakon7335@gmail.com*, ORCID: 0000-0002-0676-4015

Svetlana Kruzhnova — Senior lecturer of the Department of Theoretical and Applied Mechanics, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-male: krulana2017@gmail.com*, ORCID: 0000-0002-7554-0322

Olga Omelchenko — Senior lecturer of the Department of Theoretical and Applied Mechanics, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-male: omelchenko15@ukr.net*, ORCID: 0000-0001-8925-4178

Oleksiy Omelchenko — Postgraduate Student of the Department of machinery and foundry technology of the National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail*: *Kartzpua@gmail.com*, ORCID: 0009-0009-1693-395X

INFLUENCE OF STRUCTURAL FACTOR OF POWDER MATERIAL ON ELEMENTS STRENGTH

Purpose. *To investigate the influence of porosity and chemical composition on the strength of titanium structural components made from the unalloyed titanium alloy VT1-0, manufactured by powder metallurgy. The work aims to refine the methodology for calculating such components while taking into account the specific features of their structure, since the presence of pores contradicts the traditional hypothesis of material continuity.*

Research methods. *For the experiment, thermomechanical titanium powder PT5 was used. After pressing (700 MPa) and vacuum sintering (1250 °C, 180 min), the VT1-0 alloy was obtained. A comparative analysis of the structure and mechanical properties of the sintered material and its cast counterpart was carried out.*

Results. *The key structural distinction is the porosity of the sintered alloy, which is 13 %, with pores located mainly along grain boundaries. In terms of chem-ical composition, powder-based VT1-0 has twice the oxygen content (0.20 wt%) compared to the cast alloy (0.10 wt%). It is known that oxygen significantly increases the strength of titanium alloys; however, the ultimate strength of the sintered VT1-0 alloy was 330.5 MPa, which is 45.5 MPa lower than that of its cast counterpart (376.0 MPa). This is due to the presence of pores in the metal structure. Eliminating these pores will increase strength compared to a cast material of similar chemical composition and reduce its dispersion to that of a cast alloy.*

Scientific novelty. *The main conclusion of the study is that the reduction of the effective metal cross-section bearing the load (due to 13 % porosity) outweighs the strengthening effect of the higher oxygen and other substance's content. The presence of pores also leads to a significant increase in the scatter of strength and in some cases microhardness values. If we make a correction for the effective cross-sectional area minus the pores, the actual strength of the powder sample would be higher due to the increased oxygen and other substance's content.*

Practical value. *It was proved that the actual negative effect of porosity on strength is significantly outweighed by the strengthening effect resulting from microalloying with impurities during sintering. Given the high dispersion of the strength index, this effect can be explained by the fact that the influence of porosity on the ultimate strength is multidimensional and depends on factors such as pore shape and size, the presence of sharp corners in them and their volume fraction.*

Key words: *powder metallurgy, additive alloys, pores, material strength hypotheses, mechanical properties, strength, stress.*

© Andrii Skrebtsov, Andrii Kononenko, Julia Kononenko, Svetlana Kruzhnova, Olga Omelchenko, Oleksiy Omelchenko, 2026

DOI 10.15588/1607-3274-2026-1-3

Introduction

The development and implementation of powder metallurgy in the production of structural components requires refining the methods used to calculate the strength of these elements, taking into account the specific features of their structure. In the mechanics of materials, the assumption of material continuity states that a material must be solid and uninterrupted – meaning it should not contain cavities, cracks, or pores of various origins, as these act as stress concentrators. Materials produced from powders inherently contain pores of different shapes and sizes. One such material is the structural, non-alloyed titanium VT1-0, obtained via powder technology (PT).

For the sintered VT1-0 titanium alloy, its strength characteristics correspond to those of cast titanium of the same grade. However, some discrepancies in properties are observed. Specifically, the average ultimate strength of VT1-0 for bar-rolled products is 425 MPa, whereas for cast ingots this value is only 350 MPa. This discrepancy arises from differences in the structure of the billets, which, despite identical chemical composition, are influenced by technological parameters and the manufacturing method.

Analysis of research and publications

Titanium alloys are critically important materials for high-tech industries such as aerospace, automotive, and medical sectors due to their unique combination of high specific strength, corrosion resistance, and biocompatibility [1]. Traditional metallurgy for producing titanium castings is extremely expensive and energy-intensive, which motivates the development of alternative, cost-effective manufacturing methods. Powder metallurgy (PM), including its various forms (pressing and sintering) as well as additive manufacturing, offers pathways for producing near-net-shape components that significantly reduce material waste and machining costs. [1, 2] However, the widespread adoption of PM-titanium is limited by the need to ensure mechanical properties comparable to those of cast analogues. A similar challenge arises in additive manufacturing, where powders are also used. The main factors influencing the final material properties are residual porosity, impurity control, and thermomechanical processing technologies. [2, 3, 5].

Porosity is the most significant defect in powder-derived materials because pores act as stress concentrators, leading to premature failure. Studies on TiNbZrTa alloys, which are promising for biomedical applications, have shown that samples produced with minimal porosity exhibit significantly higher hardness compared to their porous counterparts [4]. This demonstrates the direct negative effect of porosity on static characteristics. Other studies [3, 5] have focused on controlling the final microstructure of the alloy to achieve the required performance characteristics.

Thus, there are two main approaches to reducing porosity: optimization of the sintering process and secondary processing. In [6], the authors investigated the influence of hot-pressing parameters on titanium with a bimodal microstructure, confirming that controlled adjustment of temperature and pressure is an effective means of managing the final porosity and mechanical behavior. The authors of [3] also established the importance of sintering temperature, using inductive hot pressing to produce titanium composites.

Complete elimination of porosity is not always necessary – for example, to ensure osteointegration in implants [7, 5]. In [7], it was shown that surface engineering through nitriding and burnishing significantly improves the wear resistance of a highly porous titanium alloy by closing surface pores and forming a nitride layer, without altering the properties of the underlying core.

As noted above, porosity regulation is a critical issue for titanium alloys. It can be addressed at the synthesis stage, but there are also methods and technologies that allow porosity reduction after the billet has been produced. Thermomechanical treatment is highly effective for titanium alloys. In [8], a sintered titanium alloy containing 5% iron and produced via powder metallurgy with a porosity of 10% was studied. The samples failed in a brittle manner, but hot rolling complicated the fracture process due to a sharp reduction in porosity. It was also reported that this treatment increased the tensile strength of the alloy to 960 MPa. These results indicate that porosity has a significant influence on alloy strength, and that additional thermomechanical processing can compensate for the limitations of the basic powder metallurgy process by effectively eliminating pores.

The effect of porosity becomes especially critical under cyclic loading. In [9], it was shown that for Ti-6Al-4V produced via Binder Jetting – a form of PM – residual internal porosity remains the primary cause of low fatigue life, even at relatively high densities (up to 95%). The authors demonstrated that to achieve reliability comparable to cast Ti-6Al-4V, hot isostatic pressing (HIP) is a necessary secondary operation. HIP effectively closes internal pores, raising the density to 99.8% and restoring fatigue strength [9].

In additive manufacturing, for example Electron Beam Melting (EBM), the microstructure and mechanical properties of the resulting material are influenced by technological factors such as build geometry and powder reuse. This highlights that quality-control challenges found in traditional PM remain relevant in advanced AM technologies as well, requiring careful parameter regulation [10].

Titanium powders typically contain an elevated oxygen content, which significantly increases material strength. However, excessive oxygen leads to brittleness and a drastic decrease in ductility. Therefore, controlling the material properties requires precise regulation of oxygen content in

© Andrii Skrebtsov, Andrii Kononenko, Julia Kononenko, Svetlana Kruzhnova, Olga Omelchenko, Oleksiy Omelchenko, 2026
DOI 10.15588/1607-3274-2026-1-3

titanium. Studies [2, 11] present a new sintering-deoxygenation process for Ti-6Al-4V powder that enables reduction of oxygen content, which is critically important for ensuring adequate ductility and reliability of the final material.

Titanium powders contain an elevated oxygen content, which significantly increases the material's strength. However, an excess of oxygen leads to brittleness and a substantial reduction in ductility. Therefore, controlling the material's properties is possible only through precise regulation of the oxygen content in titanium. Studies [2, 11] describe a new sintering – deoxygenation process for Ti-6Al-4V powder that allows reducing the oxygen content – critically important for ensuring the required ductility and reliability of the final material.

As in [8], the authors of [2, 7, 11] have shown that strength can be increased – while maintaining a controlled reduction in ductility – through the presence of "harmful" impurities in titanium (iron, oxygen, nitrogen). Thus, there is a clear relationship between porosity, impurity content (oxygen, nitrogen, iron), and the resulting mechanical properties.

Purpose

This scientific and practical work is devoted to a comprehensive analysis of the mechanical properties of structural elements made of technically pure unalloyed titanium alloy of the VT1-0 brand by the powder metallurgy method. Special emphasis is placed on the relationship between the level of residual porosity, chemical composition and actual strength of products made of such materials. The relevance of the work is due to the need for a fundamental review and improvement of existing methods of engineering calculation of structural components of mechanical engineering made of powders, since the specific microstructure of such materials, saturated with internal pores, directly contradicts the classical hypothesis of material continuity, which is the basis for the fundamental academic course of materials resistance. The study considers how the morphology of pores and the concentration of impurities affect the distribution of internal defects, which allows us to offer certain clarifications for predicting the reliability and durability of titanium parts in real operating conditions, ensuring the optimal balance between the weight of the structure and its ability to withstand critical loads. The aim of the work is to prove the need to improve the methods of calculating the strength of structural elements made of powder titanium alloy VT1-0 through a comprehensive analysis of the influence of porosity and chemical composition.

Material and research methods

To produce the sintered titanium alloy, thermomechanical titanium powder PT5 (Technical Specifications (of Ukraine) 14-10-026-98) (Table 1) was used as the base material, without fractional sieving (fraction −0.50/+0.16), i.e., in the as-supplied condition.

Table 1 – Chemical composition (impurities) of PT5 powder, wt% [12]

Fe	Cl	C	Si	N	O	H	Ti
0,08	0,06	0,03	0,04	0,03	0,20	0,01	base

After sintering the thermomechanical titanium powder PT5, the unalloyed titanium alloy VT1-0 was obtained. The requirements of the state standard for this alloy with respect to impurities are summarized in Table 2.

Table 2 – Chemical composition (impurities) of VT1-0, wt% [12].

Fe	C	Si	N	O	H	Ti
up to 0,25	up to 0,07	up to 0,1	up to 0,04	up to 0,2	up to 0,01	base

Compaction of the titanium samples was carried out on a DB2432A hydraulic press with a working pressure of 700 MPa. Sintering was performed in a laboratory vacuum electric furnace model SNVE-1.3.1/16 according to the following technological scheme: heating at a rate of V_{heat} = 20 C/min, followed by an isothermal hold of 180 minutes at a temperature of 1250 °C ± 10 °C in a protective atmosphere—vacuum at 13.3 Pa. After the hold, the samples were cooled together with the furnace, also under vacuum. The chemical composition of the experimental titanium alloys was determined using the spectral method with a SPECTROMAX spectrometer (manufactured by SPECTRO) in accordance with standard procedures from GOST 19863.1-91 to GOST 19863.12-91. The content of gaseous impurities – nitrogen, oxygen, and hydrogen – was measured separately according to industry standard OST 190013, using an ON900 gas analyzer (manufactured by ELTRA) at SE "ZTMK" as part of joint research work.
Samples for metallographic examination were prepared using the standard procedure involving sequential grinding and polishing. Etching of the prepared sections was carried out in a special reagent containing 10 ml HF, 25 ml HNO_3, and 65 ml glycerin. Microstructural analysis was performed using a NEOPHOT-32 inverted reflected-light microscope manufactured by Carl Zeiss. Quantitative evaluation of porosity (volume fraction of pores) was conducted using the Rozival line method on an MIM-8M optical microscope.

Microhardness measurements were performed in accordance with the standard procedure DSTU 3827:2004 on a PMT-3 microhardness tester at a load of 0.49 N. Final microhardness values for different structural constituents were determined as the average of five measurements, based on the diagonal dimensions of the indentations. Mechanical testing was conducted according to the standard methodology.

© Andrii Skrebtsov, Andrii Kononenko, Julia Kononenko, Svetlana Kruzhnova, Olga Omelchenko, Oleksiy Omelchenko, 2026

DOI 10.15588/1607-3274-2026-1-3

p-ISSN 1607-6885 Нові матеріали і технології в металургії та машинобудуванні. 2026/1
e-ISSN 2786-7358 New materials and technologies in metallurgy and mechanical engineering. 2026/1

Research results and their discussion

To evaluate the structure, metallographic analysis was performed on both the cast and the sintered VT1-0 titanium alloy produced from PT5 powder. Analysis of the microstructure of VT1-0 in the cast condition revealed the presence of β-transformed grains with a size of 150–200 μm. These grains consist of packets of parallel α-plates with a thickness of 4–10 μm, whose linear dimensions are comparable to the size of the primary β-grains (Fig. 1*a*).

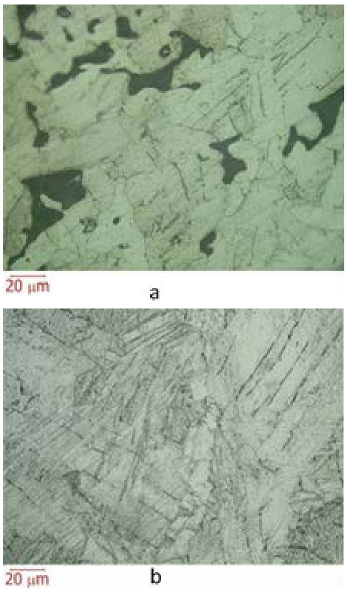

Figure 1. Microstructure of VT1-0 titanium alloy [12]:
a – cast VT1-0; *b* – powder-based VT1-0 (PT5)

The structure of the sintered powder titanium alloy produced from PT5 powder (see Fig. 1, b) consisted of α-phase grains and pores of various geometric shapes and sizes. The pores were located both within the grain volume and along grain boundaries, with the latter being the predominant location. The average size of the elongated α-grains did not exceed 100 μm.

Analysis of the structure (see Fig. 1*b*) shows that the sintered VT1-0 titanium alloy produced from PT5 powder contained pores of complex configuration, unevenly distributed throughout the volume of the workpiece. The pore area fraction on the polished section was 13 %, which resulted in a low material density, and their average size did not exceed 60 μm. Thus, the only difference between the alloys under investigation is their porosity.

Analysis of the microhardness measurements of the alloy grains showed that the values for the sintered titanium alloy are 50 MPa higher than those for the cast alloy (Table 3). At the same time, dispersion analysis indicated that the microhardness values do not exhibit the same spread relative to their mean. The microhardness dispersion of the sintered alloy is 5 units higher than the corresponding value for the cast titanium alloy.

Table 3 – Results of mechanical property testing of titanium alloys manufactured using different technologies [12]

Alloy		Mechanical properties								
		$\sigma_в$, MPa	$S_{\sigma_в}$	δ, %	S_δ	ψ, %	S_ψ	H^{04}, MPa	$S_{H\mu}$	ρ, %
cast	ВТ1-0	376,0	23,35	14,2	0,56	24,1	0,62	1400	45,46	-
sintered	ВТ1-0 (ПТ5)	330,5	75,12	5,0	0,21	7,5	0,25	1450	50,44	87,3

The ultimate strength of the sintered titanium alloy samples was 330.5 MPa, which is 45.5 MPa lower than the ultimate strength of cast VT1-0 titanium (376.0 MPa). However, analysis of the dispersion of this parameter showed that its value is significantly higher for the sintered alloys compared to the cast ones (75.12 and 23.35, respectively), which is attributed to the presence of pores.

The lower ductility of sintered powder alloys compared to cast VT1-0 is due to the presence of titanium compounds with nitrogen, oxygen, and hydrogen on the surface of the powder particles [13–15]. According to the literature [13 – 15], these compounds decompose under sintering temperatures, and the elements released during decomposition diffuse into the metal, thereby reducing its ductility. DSTU ISO 6892-1:2019 specifies that the ultimate tensile strength is calculated using a formula that is universally accepted for stress calculations in general engineering mechanics disciplines (such as strength of materials):

$$\boldsymbol{\sigma}_\text{В} = \frac{\boldsymbol{P}}{\boldsymbol{F_0}},$$

where $\boldsymbol{F_0}$ – cross-sectional area of the specimen; for a circular cross-section;

$$\boldsymbol{F_0} = \frac{\boldsymbol{\pi d^2}}{\boldsymbol{4}};$$

$\boldsymbol{d}$ – diameter of the cross-section;

$\boldsymbol{P}$ – value of the force that deforms the sample.

The cross-sectional area of the sample is determined by the formula $F_0 = 0{,}25\pi d^2$ and does not include the resulting pore area. When using the powder-derived VT1-0 titanium alloy, the effective cross-sectional area is reduced by the area of the pores present within the cross section. This can be taken into account in the formula for determining the ultimate strength as follows:

$$\boldsymbol{\sigma}_{\text{В}\boldsymbol{pores}} = \frac{\boldsymbol{N_{max}}}{\boldsymbol{F_0 - F_{pores}}},$$

where $\boldsymbol{F_{pores}}$ – the area of pores that fall into the plane of the cross section.

© Andrii Skrebtsov, Andrii Kononenko, Julia Kononenko, Svetlana Kruzhnova, Olga Omelchenko, Oleksiy Omelchenko, 2026
DOI 10.15588/1607-3274-2026-1-3

As noted in Tables 1 and 2, the chemical composition requirements for the materials are almost identical. The results of the chemical composition analysis of the examined materials are summarized in Table 4.

Table 4 – Chemical composition of the studied materals

Material	Average content of elements, wt%				
	Fe	**Si**	$\mathbf{O_2}$	$\mathbf{N_2}$	$\mathbf{H_2}$
Cast	**0,25**	**0,1**	**0,10**	**0,040**	**0,01**
Powder-based	-	-	**0,20**	**0,042**	**0,01**

As seen from the data in Table 4, the oxygen content in the VT1-0 structural titanium alloy produced from PT5 powder is twice as high. As previously noted, oxygen significantly increases the strength of the alloy. [14]. For every 0.1 wt% increase in oxygen, the strength of a titanium alloy increases by approximately 100 MPa. From Table 3, it can be seen that the ultimate tensile strength is 376.0 MPa and 330.5 MPa for the cast and powder-sintered alloys, respectively. Thus, the strength of the sintered alloy is 45.5 MPa lower, although, according to Table 4, its oxygen content is 0.1% higher. Assuming the sintered titanium alloy contained no pores and that the specimen cross-sectional area was the same, the strength of such a material could reach 450–500 MPa due to oxygen strengthening alone.

The pore content in the powder-sintered alloy was 13 %, which means a 13 % reduction of the cross-sectional area F_0 in the formula used to calculate ultimate strength. In other words, the actual cross-sectional area of the titanium specimen (for specimens with a working diameter of 5 mm) is 17.074 mm² instead of 19.625 mm². This implies that the ultimate strength of the sintered alloy should have been higher for the same applied force used in the laboratory test.

Taking into account both the higher oxygen content compared to the cast alloy and the reduced cross-sectional area due to the porosity of the sintered material, its strength should have been significantly higher than that of the cast alloy. However, the study revealed the opposite. As noted above, porosity led to an increase in the dispersion of ultimate strength values. In other words, the actual negative impact of porosity on strength far outweighs the strengthening effect produced by alloying.

Considering the high dispersion, this effect can be explained by the fact that the influence of porosity on ultimate strength is multidimensional and depends on factors such as pore shape, pore size, the presence of sharp edges, and their volumetric fraction.

Conclusions

The lower overall strength of the sintered sample, despite its elevated oxygen content, is attributable to its porosity. This strength can be increased by eliminating the pores.

The influence of pores on ultimate strength is complex and requires consideration of their shape, size, the presence of sharp edges, and their volumetric fraction.

References

1. Lario Femenia, J., Poler Escoto, R., Amigó Borras, V. (2023). Powder Metallurgy: A New Path for Advanced Titanium Alloys in the EU Medical Device Supply Chain. Metals 13, 372. https://doi.org/10.3390/met13020372

2. Gan, X., Li, S., Xiao, S. et al. (2024). Integrated high-performance and accurate shaping technology of low-cost powder metallurgy titanium alloys: A compre-hensive review. Int J Miner Metall Mater 31, 413–426 https://doi.org/10.1007/s12613-023-2774-7

3. Arévalo, C., Montealegre-Meléndez, I., Ariza, E., Kitzmantel, M., Rubio-Escudero, C., Neubauer, E. (2016). Influence of Sintering Temperature on the Microstructure and Mechanical Properties of In Situ Reinforced Titani-um Composites by Inductive Hot Pressing. Materials 9, 919. https://doi.org/10.3390/ma9110919

4. González-Guillén, C., Al Hawajreh Kamel, G., Degalez-Duran, E., Klyatskina, E., Naeem, M., Romero-Resendiz, L., Gonzalez, G., Amigó Borrás, V. (2023). The Effect of Ti/Ta Ratio and Processing Routes on the Hardness and Elastic Modulus of Porous TiNbZrTa Al-loys. Materials 16, 7362. https://doi.org/10.3390/ma16237362)

5. Pascu, C.I., Nicolicescu, C., Cioateră, N., Gheorghe, Ș., Geonea, I., Didu, A. (2022). Characterization of Tita-nium Alloy Obtained by Powder Metallurgy. Materials 15, 2057. https://doi.org/10.3390/ma15062057

6. Chávez-Vásconez, R., Lascano, S., Sauceda, S., Reyes-Valenzuela, M., Salvo, C., Mangalaraja, R.V., Gotor, F.J., Arévalo, C., Torres, Y. (2022). Effect of the Processing Parameters on the Porosity and Mechanical Behavior of Titanium Samples with Bimodal Microstruc-ture Produced via Hot Pressing. Materials 15, 136. https://doi.org/10.3390/ma15010136

7. Lavrys, S., Pohrelyuk, I., Padgurskas, J., Shliakhetka, K. (2023). Improving Wear Resistance of Highly Porous Titanium by Surface Engineering Methods. Coatings, 13, 1714. https://doi.org/10.3390/coatings13101714

8. Romero, C., Yang, F., Wei, S., Bolzoni, L. (2020). Thermomechanical Processing of Cost-Affordable Powder Metallurgy Ti-5Fe Alloys from the Blended Elemental Approach: Microstructure, Tensile Deformation Behavior, and Failure. Metals 10, 1405. https://doi.org/10.3390/met10111405

9. Alegre, J.M., Díaz, A., García, R., Peral, L.B., Lorenzo-Bañuelos, M., Cuesta, I.I. (2024). Mechanical and Fatigue Properties of Ti-6Al-4V Alloy Fabricated Using Binder Jetting Process and Subjected to Hot Isostatic Pressing. Materials 17, 3825. https://doi.org/10.3390/ma17153825

10. Wanjara, P., Backman, D., Sikan, F., Gholipour, J., Amos, R., Patnaik, P., Brochu, M. (2022). Microstructure and Mechanical Properties of Ti-6Al-4V Additively

© Andrii Skrebtsov, Andrii Kononenko, Julia Kononenko, Svetlana Kruzhnova, Olga Omelchenko, Oleksiy Omelchenko, 2026
DOI 10.15588/1607-3274-2026-1-3

Man-ufactured by Electron Beam Melting with 3D Part Nesting and Powder Reuse Influences. J. Manuf. Mater. Process. 6, 21. https://doi.org/10.3390/jmmp6010021

11. Mingyuan Zhang, Taotao Cai, Weiliang Lu, Shili Zheng, Ying Zhang, Yi Zhang (2023). Fabrication of Ti-6Al-4V alloy powder by a novel sintering-deoxygenation process. Journal of Alloys and Compounds. Volume 935, Part 1, 15. https://doi.org/10.1016/j.jallcom.2022.168113

12. Skrebtsov, A. A. (2015). Improving the mechanical and service properties of sintered titanium alloys: dis. cand. tech. sciences: 05.02.01. Zaporozhye

13. T. Chen, C. Suryanarayana, C. Yang (2023). Advanced titanium materials processed from titanium hydride powder. Powder Technology, Volume 423, 1 June. https://doi.org/10.1016/j.powtec.2023.118504

14. Zhang, H., Wang, C., Guo, J., Li, W., Cheng, C., Xiang, N., Huang, T., Niu, H., Zhang, D., Chen, F. (2004). Phase Transformation, Microstructural Evolution and Tensile Properties of a TiH_2-Based Powder Metallurgy Pure Titanium. Metals 14, 1218. https://doi.org/10.3390/met14111218

15. Radulescu R, Meleşcanu Imre M, Ripszky A, Rus F, Popa A, Moisa M, Funieru C, Ene R, Pituru S. (2024). Exploring the Broad Spectrum of Titanium-Niobium Implants and Hydroxyapatite Coatings-A Review. Materials (Basel). Dec 19; 17(24):6206. https://doi.org/10.3390/ma17246206

Received 16.02.2026
Accepted 01.03.2026
Published 31.03.2026

ВПЛИВ СТРУКТУРНОГО ФАКТОРУ ПОРОШКОВОГО МАТЕРІАЛУ НА МІЦНІСТЬ ЕЛЕМЕНТІВ

Андрій Скребцов — канд. техн. наук, доцент кафедри теоретичної та прикладної механіки Національного університету "Запорізька політехніка", м. Запоріжжя, Україна, *e-mail: nic_tz@ukr.net,* ORCID: 0000-0002-4669-9625

Андрій Кононенко — аспірант кафедри кафедри теоретичної та прикладної механіки Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: andrju3952@gmail.com,* ORCID: 0009-0005-4268-0854

Юлія Кононенко — старший викладач кафедри фізичного матеріалознавства Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: juliakon7335@gmail.com,* ORCID: 0000-0002-0676-4015

Світлана Кружнова — старший викладач кафедри кафедри теоретичної та прикладної механіки Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: krulana2017@gmail.com*, ORCID: 0000-0002-7554-0322

Ольга Омельченко — старший викладач кафедри теоретичної та прикладної механіки Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: omelchenko15@ukr.net,* ORCID: 0000-0001-8925-4178

Олексій Омельченко — аспірант кафедри машин і технологій ливарного виробництва Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: Kartzpua@gmail.com*, ORCID: 0009-0009-1693-395X

Мета роботи. *Дослідити вплив пористості та хімічного складу на міцність титанових конструкційних компонентів, виготовлених з нелегованого титанового сплаву ВТ1-0, отриманого методом порошкової металургії. Метою роботи є удосконалення методології розрахунку таких компонентів з урахуванням особливостей їхньої структури, оскільки наявність пор суперечить традиційній гіпотезі про суцільність матеріалу.*

Методи дослідження. *Для експерименту було використано термомеханічний титановий порошок ПТ5. Після пресування (700 МПа) та вакуумного спікання (1250 °С, 180 хв) було отримано сплав ВТ1-0. Було проведено порівняльний аналіз структури та механічних властивостей спеченого матеріалу та його литого аналога.*

Отримані результати. *Ключовою структурною відмінністю є пористість спеченого сплаву, яка становить 13%, з порами, розташованими переважно вздовж меж зерен. За хімічним складом порошковий ВТ1-0 має вдвічі більший вміст кисню (0,20 мас.%) порівняно з литим сплавом (0,10 мас.%). Відомо, що кисень значно підвищує міцність титанових сплавів. Ключовою структурною відмінністю спеченого сплаву є його пористість, яка становить 13%. За хімічним складом порошковий сплав ВТ1-0 містить вдвічі більше кисню (0,20 мас.%) порівняно з литим сплавом (0,10 мас.%). Відомо, що кисень значно підвищує міцність титанових сплавів; однак границя міцності спеченого*

© Andrii Skrebtsov, Andrii Kononenko, Julia Kononenko, Svetlana Kruzhnova, Olga Omelchenko, Oleksiy Omelchenko, 2026

DOI 10.15588/1607-3274-2026-1-3

сплаву ВТ1-0 становила 330,5 МПа, що на 45,5 МПа менше, ніж у його литого аналога (376,0 МПа). Це пов'язано з наявністю пор у структурі металу. Усунення цих пор збільшить міцність порівняно з литим матеріалом аналогічного хімічного складу та зменшить його дисперсію порівняно з литим сплавом.

Наукова новизна. *Основний висновок дослідження полягає в тому, що зменшення ефективного поперечного перерізу металу, що несе навантаження (через 13% пористість), переважує ефект зміцнення від вищого вмісту кисню та інших речовин. Наявність пор також призводить до значного збільшення розкиду значень міцності, а в деяких випадках і мікротвердості. Якщо зробити поправку на ефективну площу поперечного перерізу за вирахуванням пор, фактична міцність порошкового зразка буде вищою через збільшення вмісту кисню та інших речовин.*

Практична цінність. *В роботі доведено, що фактичний негативний вплив пористості на міцність значно переважає ефект зміцнення, що виникає внаслідок мікролегування домішками при спіканні. Враховуючи високу дисперсію показника міцності, цей ефект можна пояснити тим, що вплив пористості на границю міцності є багатовимірним і залежить від таких факторів, як форма та розмір пор, наявність у них гострих кутів та їх об'ємна частка.*

Ключові слова: *порошкова металургія, адитивні сплави, пори, гіпотези опору матеріалів, механічні властивості, міцність, напруження.*

Список літератури

1. Lario Femenia, J. Powder Metallurgy: A New Path for Advanced Titanium Alloys in the EU Medical Device Supply Chain / Lario Femenia, J., Poler Escoto, R., Amigó Borras V. // Metals. − 2023. – No. 13. – 372 p. https://doi.org/10.3390/met13020372

2. Integrated high-performance and accurate shaping technology of low-cost powder metallurgy titanium alloys: A comprehensive review / Gan, X., Li, S., Xiao, S. et al. // Int J Miner Metall Mater 31, – 2024. – P. 413–426. https://doi.org/10.1007/s12613-023-2774-7

3. Influence of Sintering Temperature on the Microstructure and Mechanical Properties of In Situ Reinforced Titanium Composites by Inductive Hot Pressing / Arévalo, C., Montealegre-Meléndez, I Ariza, E. et al. // Materials. − 2016. – No. 9. – 919 p. https://doi.org/10.3390/ma9110919

4. The Effect of Ti/Ta Ratio and Processing Routes on the Hardness and Elastic Modulus of Porous TiNbZrTa Alloys / González-Guillén, C., Al Hawajreh Kamel, G., Degalez-Duran, E. et al. // Materials. − 2023. – No. 16, 7362 p. https://doi.org/10.3390/ma16237362

5. Characterization of Titanium Alloy Obtained by Powder Metallurgy / Pascu, C.I., Nicolicescu, C., Cioateră, N. et al. // Materials. − 2022. − No. 15. – 2057 p. https://doi.org/10.3390/ma15062057

6. Effect of the Processing Parameters on the Porosity and Mechanical Behavior of Titanium Samples with Bimodal Microstructure Produced via Hot Pressing / Chávez-Vásconez, R, Lascano, S., Sauceda, S. et al. // Materials. − 2022. – No. 15. – 136 p. https://doi.org/10.3390/ma15010136

7. Improving Wear Resistance of Highly Porous Titanium by Surface Engineering Methods / Lavrys, S., Pohrelyuk, I., Padgurskas, J., Shliakhetka, K. // Coatings. − 2023. – No. 13. – 1714 p. https://doi.org/10.3390/coatings13101714

8. Thermomechanical Processing of Cost-Affordable Powder Metallurgy Ti-5Fe Alloys from the Blended Elemental Approach: Microstructure, Tensile Deformation Behavior, and Failure / Romero, C., Yang, F., Wei, S., Bolzoni, L. // Metals. − 2020. − No. 10. – 1405 p. https://doi.org/10.3390/met10111405

9. Mechanical and Fatigue Properties of Ti-6Al-4V Alloy Fabricated Using Binder Jetting Process and Subjected to Hot Isostatic Pressing / Alegre, J.M., Díaz, A., García, R. et al. // Materials. − 2024. – No. 17. – 3825 p. https://doi.org/10.3390/ma17153825

10. Microstructure and Mechanical Properties of Ti-6Al-4V Additively Manufactured by Electron Beam Melting with 3D Part Nesting and Powder Reuse Influences / Wanjara, P., Backman, D., Sikan, F. et al. // Manuf. Mater. Process. − 2022. – No. 6. – 21 p. https://doi.org/10.3390/jmmp6010021

11. Fabrication of Ti-6Al-4V alloy powder by a novel sintering-deoxygenation process / Mingyuan Zhang, Taotao Cai, Weiliang Lu et al. // Journal of Alloys and Compounds. Volume 935, Part 1, 15 February 2023. https://doi.org/10.1016/j.jallcom.2022.168113

12. Скребцов, А. А. Підвищення механічних та службових властивостей спечених титанових сплавів: дис. канд. техн. наук: 05.02.01 / А. А. Скребцов. – Запоріжжя, 2015.

13. Advanced titanium materials processed from titanium hydride powder / T. Chen, C. Suryanarayana, C. Yang // Powder Technology, Volume 423, 1 June 2023. − 118504. https://doi.org/10.1016/j.powtec.2023.118504

14. Phase Transformation, Microstructural Evolution and Tensile Properties of a TiH_2-Based Powder Metallurgy Pure Titanium / Zhang, H., Wang, C., Guo, J. et al. // Metals. − 2024. − No. 14. – 1218 p. https://doi.org/10.3390/met14111218

15. Exploring the Broad Spectrum of Titanium-Niobium Implants and Hydroxyapatite Coatings-A Review / Radulescu R, Meleşcanu Imre M, Ripszky A et al. // Materials (Basel). − 2024. − Dec 19;17(24):6206. https://doi.org/10.3390/ma17246206

© Andrii Skrebtsov, Andrii Kononenko, Julia Kononenko, Svetlana Kruzhnova, Olga Omelchenko, Oleksiy Omelchenko, 2026

DOI 10.15588/1607-3274-2026-1-3