

https://doi.org/10.51885/3134-7983_CATMSP_2026_3_8

SRSTI 55.22.23

OPTIMISATION OF INTENSIVE PLASTIC DEFORMATION PROCESSES FOR TITANIUM ALLOYS TO IMPROVE THE BIOMECHANICAL COMPATIBILITY OF THE 'BONE-IMPLANT' SYSTEM

Aidar Kengesbekov ^{1,2}, Daur Kakimzhanov ^{3*}, Ali Coruh ⁴,
Asem Kochneva ¹, Daryn Baizhan ⁵

¹NJSC «D. Serikbayev East Kazakhstan technical university», Ust-Kamenogorsk, Kazakhstan

²Institute of Composite Materials, Ust-Kamenogorsk, Kazakhstan

³LLP «PlasmaScience», Ust-Kamenogorsk, Kazakhstan

⁴Sakarya University, Sakarya, Turkey;

⁵Sarsen Amanzholov East Kazakhstan University, Ust-Kamenogorsk, Kazakhstan

*Corresponding author: Daur Kakimzhanov, e-mail: d.kakimzhanov19@gmail.com

Keywords:

titanium, alloy, implant,
plastic deformation, structure
hardness.

ABSTRACT

This study investigates the effect of intensive plastic deformation on the microstructure and mechanical properties of a titanium material with potential for use in bone-implant systems. To achieve an ultra-fine-grained microstructure, a combined treatment was employed, comprising quenching at 1000 °C followed by water cooling, ABC pressing, subsequent rolling to dimensions of 10×10×L mm, and annealing at 300 °C. Microstructural analysis showed that, following treatment, the initial coarse-grained structure was significantly refined, resulting in a more homogeneous ultrafine-grained microstructure. X-ray diffraction analysis confirmed the preservation of the α -phase of titanium without the formation of additional phases, whilst the formation of a pronounced deformation texture was observed. Following intensive plastic deformation, the microhardness increased from 1940 to 3342 MPa, the tensile strength from 452 to 921 MPa, and the yield strength from 383 to 795 MPa. The results obtained confirm the effectiveness of the combined treatment for strengthening titanium and enhancing its potential as an implant material.

INTRODUCTION

At present, the development of new metallic materials for orthopaedic, dental and trauma implants is one of the most pressing areas of biomedical materials science. The main requirement for such materials is not only their chemical inertness and biocompatibility, but also their ability to function reliably over the long term under complex mechanical loading within the 'bone-implant' system. Once in place, the implant must ensure secure fixation, uniform load distribution and resistance to fatigue failure, corrosion and wear, whilst at the same time not causing an adverse reaction from the surrounding tissues.

Among metallic biomaterials, titanium and titanium alloys occupy a special place; they are widely used in medicine due to their high specific strength, corrosion resistance and low density. Consequently, titanium materials are regarded as among the most promising for the manufacture of endoprostheses, bone plates, screws, dental implants and other devices that come into contact



© 2026 R.B. Abylkalikova, L.I. Kveglis, D.T. Kurmanova, Z.A. Espolova,
Zh.K. Uazyrhanova, G.A. Baizakova
This work is licensed under a Creative Commons Attribution 4.0
International License (CC BY 4.0).

with bone tissue (Geetha M et al., 2009). However, despite their widespread use, traditional titanium alloys have a number of limitations. One of the main problems is the mismatch between the mechanical properties of the implant and those of the bone tissue. The modulus of elasticity of most metallic implants is significantly higher than that of bone, which can lead to a stress-shielding effect. In this case, a significant proportion of the mechanical load is borne by the implant, whilst the surrounding bone tissue is subjected to insufficient loading. Consequently, bone resorption may develop, osseointegration may be compromised, fixation stability may be reduced, and the service life of the implant system may be shortened [(Niinomi M 2008).

To improve the biomechanical compatibility of the 'bone-implant' system, it is necessary not only to reduce the difference in stiffness between the implant and the bone tissue, but also to ensure that the material possesses high strength, ductility, fatigue life and crack resistance. It is particularly important to achieve an optimal balance between strength and ductility, as implants within the body are subjected to repeated cyclic loads. Insufficient strength can lead to structural failure, whilst excessive stiffness disrupts the natural redistribution of mechanical stresses within the bone tissue.

One promising approach to improving the properties of titanium alloys is the use of intensive plastic deformation techniques. Intensive plastic deformation enables the formation of an ultrafine-grained or nanostructured microstructure in metals without significantly altering the shape of the workpiece and without the introduction of additional alloying elements. The most common methods include equal-channel angular pressing, high-pressure torsion, multi-axial forging, intensive rolling, screw extrusion and combined thermomechanical processing schemes (Valiev R.Z et al., 2006). The formation of an ultrafine-grained structure in titanium and titanium alloys is accompanied by grain refinement, an increase in the proportion of high-angle grain boundaries, a rise in dislocation density and a change in the material's texture. These structural changes have a significant impact on the mechanical properties. A number of studies have shown that, following intensive plastic deformation, titanium exhibits increased strength, hardness and fatigue life compared with its coarse-grained state (Valiev R.Z et al., 2008; Semenova I.P et al., 2008;). This is particularly important for implants, as increased strength can allow for a reduction in the size of the structure, minimise the invasiveness of surgical intervention and, at the same time, maintain the required load-bearing capacity.

An important advantage of intensive plastic deformation is the ability to increase the strength of high-purity titanium to a level comparable to that of certain titanium alloys. This is of great significance for biomedical applications, as the use of high-purity titanium reduces the risk of adverse effects from certain alloying elements. For example, the literature has repeatedly highlighted the need to limit the use of potentially undesirable elements, such as vanadium and aluminium, in materials intended for long-term contact with body tissues (Geetha M et al., 2009; Oldani C et al., 2012).

The optimisation of intensive plastic deformation conditions is of particular importance. The effect of the treatment depends on the deformation temperature, the degree of accumulated deformation, the number of passes, the deformation path, the deformation rate, the initial phase and microstructural state of the alloy, and the subsequent heat treatment. An insufficient degree of deformation may fail to ensure the formation of a uniform ultrafine-grained structure, whilst excessive deformation or an incorrectly selected temperature regime may lead to the accumulation of residual stresses, a reduction in ductility, the development of structural inhomogeneities or a deterioration in corrosion resistance. It is therefore important for biomedical titanium alloys to determine processing conditions that achieve an optimal balance between strength, ductility, fatigue life, corrosion resistance and biocompatibility.

Recent research indicates that combining intensive plastic deformation with subsequent heat treatment or surface treatment is a promising approach for the development of a new

generation of titanium implants. In particular, once an ultrafine-grained structure has been formed, chemical etching, anodising, the application of bioactive coatings, micro-arc oxidation or other surface modification techniques may be employed. This integrated approach allows simultaneous control of both the material's internal structure and its surface properties, which is particularly important for enhancing the effectiveness of bone-implant interaction (Baek S.M et al., 2017; Kalantari K et al., 2021; Gurau C et al., 2020; Semenova I.P et al., 2022).

Consequently, the optimisation of intensive plastic deformation regimes for titanium alloys is a pressing scientific and practical challenge. Solving this challenge will make it possible to enhance the mechanical reliability of implants, improve their fatigue life, reduce the risk of failure and enhance their biomechanical compatibility with bone tissue. Investigating the patterns of how intensive plastic deformation parameters affect the structure, mechanical properties and biological response of titanium alloys is an essential foundation for the development of functionally adapted implant materials that ensure the long-term and stable performance of the 'bone-implant' system.

The aim of this study is to optimise the conditions of intense plastic deformation of titanium alloys to achieve a microstructural state that enhances the strength characteristics, fatigue resistance and biomechanical compatibility of the 'bone-implant' system.

RESEARCH MATERIALS AND METHODS

The titanium Grade 2 (Figure 1) was selected as the subject of the study.

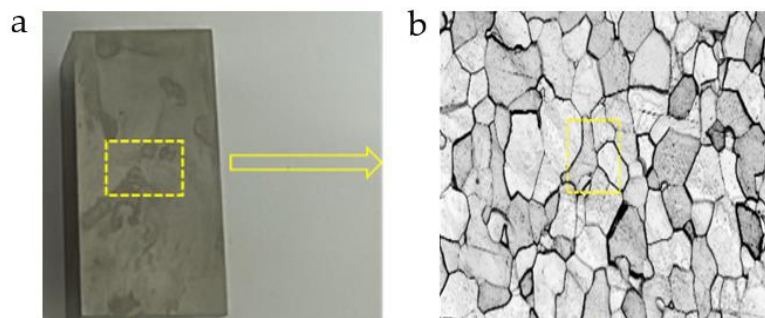


Figure 1. Appearance (a) and structure (b) of titanium Grade 2

Microhardness measurement. The microhardness of polished titanium specimens was determined using the Vickers method on an 'HVS1MDTAXY' instrument, with a load of 100 g and a holding time of 10 seconds. An Olympus GX51 optical microscope was used for qualitative and quantitative analysis of the microstructure. The average grain size d was determined with a confidence level of 0.9 in accordance with GOST 21073.3-75 using the grain intersection counting method. To determine the mechanical properties of titanium in various structural states, tensile tests were carried out in accordance with GOST 1497-84. The tests were conducted on a 'WDW 100kN' machine with a mechanical drive. X-ray phase analyses of the samples were carried out using X-ray diffraction analysis on a DW-27 mini diffractometer. Diffractograms were recorded using $\text{CuK}\alpha$ radiation ($\lambda = 2.2897 \text{ \AA}$) at a voltage of 40 kV and a current of 30 mA. The diffractograms were analysed using the HighScore software. The surface morphology was investigated by scanning electron microscopy on an SEM3200 microscope.

RESULTS AND DISCUSSION

To achieve a nanostructured state in titanium, a combined intensive plastic deformation process was employed, comprising repeated uniaxial pressing (ABC pressing) followed by rolling. In the first stage, the billets were subjected to ABC pressing at a specified temperature.

After each pressing cycle, the direction of the deforming load was sequentially changed by rotating the billet through 90°, ensuring deformation along three mutually perpendicular directions. This processing scheme promotes the uniform accumulation of plastic deformation throughout the entire volume of the material, intensive refinement of the original grains and the formation of a well-developed sub-grain structure. As a result of repeated ABC pressing, there is an increase in dislocation density, the formation of low-angle and high-angle boundaries, and a gradual transformation of the initial coarse-grained structure of the titanium into an ultra-fine-grained state. Upon completion of this stage, the dimensions of the billets were approximately 20 × 20 × 40 mm. In the second stage, the deformed blanks were rolled at a temperature of 300 °C. The use of an elevated temperature made it possible to maintain sufficient ductility of the titanium during further deformation and to reduce the likelihood of cracks and other defects forming. During the rolling process, the cross-sectional area of the billets was progressively reduced to 10.5 × 10.5 mm, which ensured the accumulation of further plastic deformation, further refinement of the grain and sub-grain structure, and an improvement in the structural homogeneity of the material (Fig. 2).



Figure 2. Appearance of titanium produced by ABC pressing and rolling, with a cross-section of 10.5 × 10.5 mm and a length of 14.5 mm

Figure 3 shows a comparison of the microstructure of the as-received titanium, which has a coarse-grained structure (average grain size 35 μm), and that of the titanium following intensive plastic deformation (ultrafine-grained state(UFG)). The structure of the titanium is characterised by distinct grain boundaries and grain heterogeneity. Indentations from microhardness measurements are observed in the structure, evenly distributed across the surface. The microstructure of the titanium after intensive plastic deformation, on the other hand, is characterised by significantly finer grains, high homogeneity and uniformity of structure. The formation of the ultrafine-grained state indicates a significant reduction in the size of the original grains and an increase in the density of defects in the crystal lattice, which directly influences the hardening of the material and improves its mechanical properties.

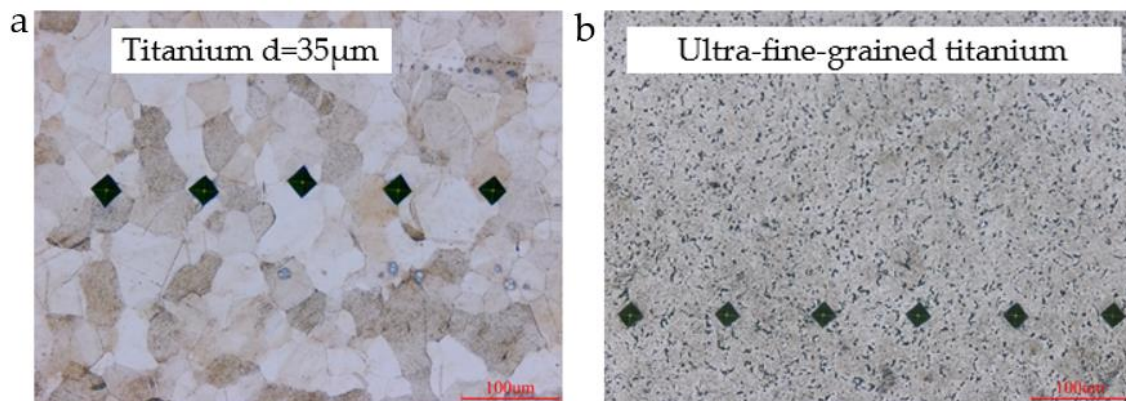


Figure 3. The microstructure of titanium before (average grain size 35 μm) (a) and after intensive plastic deformation (ultrafine-grained state, UFG) (b)

According to SEM analysis (Figure 4), following intensive plastic deformation, a homogeneous, fine-grained structure with a uniform grain distribution is observed (Figure 5). The surface of ultrafine-grained titanium is characterised by a high density of subgrains and the absence of distinct boundaries typical of a coarse-grained state. This microstructural state contributes to an increase in the material's microhardness, strength and biomechanical compatibility, making ultrafine-grained titanium a promising candidate for use in medical implants.

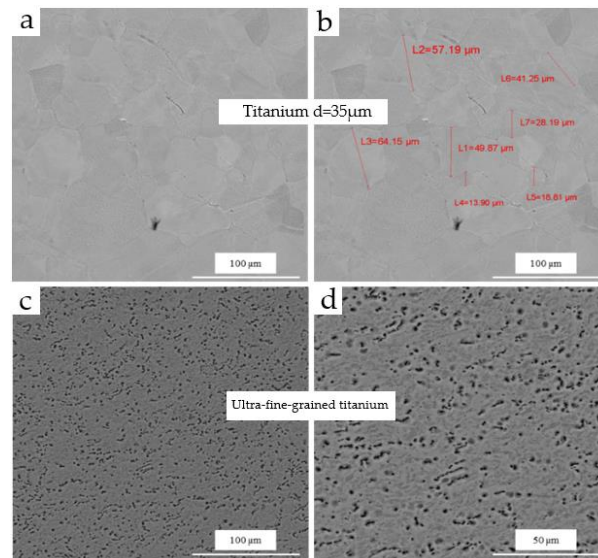


Figure 4. Results of SEM analysis of the microstructure of titanium before (average grain size 35 μm) (a-b) and after intensive plastic deformation (ultrafine-grained state, UGF) (c-d)

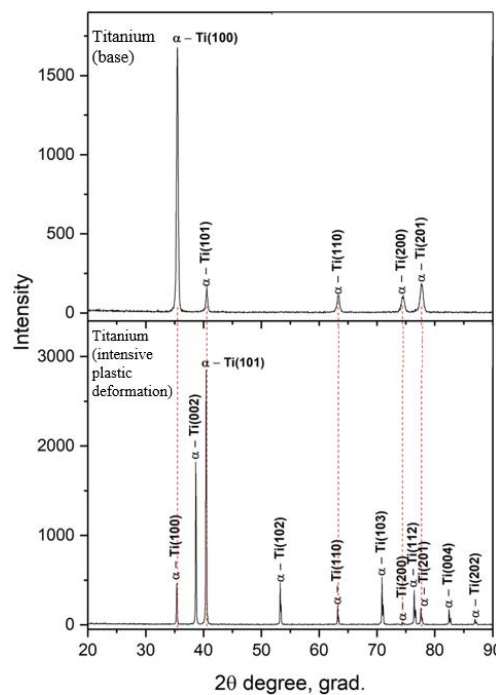


Figure 5. X-ray diffraction patterns of titanium in its as-received state and after intensive plastic deformation

The figure shows X-ray diffraction patterns of titanium in its as-received state and after intensive plastic deformation. Following intensive plastic deformation (IPD), a significant change in the relative intensity of the diffraction peaks is observed. In the as-received state, the most prominent reflections are α -Ti(002) and α -Ti(101), which is characteristic of coarse-grained titanium with a relatively less pronounced deformation texture. Following intensive plastic deformation, the α -Ti(100) peak becomes dominant, its intensity increasing significantly compared with the other reflections. This redistribution of intensities indicates the formation of a pronounced crystallographic texture of deformation origin. The formation of texture following IPD is associated with the directional plastic flow of the material, the rotation of crystallites, and the predominant orientation of individual crystallographic planes relative to the direction of deformation. As a result of repeated deformation, not only does the grain structure become finer, but there is also a redistribution of crystallite orientations, which manifests itself in a change in the intensity ratios of the diffraction peaks. The dominance of the α -Ti(100) reflection following IPD indicates a predominant orientation of the grains in the deformed state.

Figure 6 shows the change in the microhardness of titanium in its as-received condition and following intensive plastic deformation. In its as-received coarse-grained condition, the material's microhardness is 1940 MPa. Following intensive plastic deformation (IPD), the microhardness increases to 3342 MPa, which corresponds to an increase of approximately 72% compared with the as-received state. Such a significant increase in microhardness indicates effective strengthening of the titanium as a result of deformation treatment. The increase in microhardness following IPD is primarily due to the formation of an ultrafine-grained structure, an increase in dislocation density, and an increase in the length of intergranular and subgranular boundaries. As the grain size decreases, the number of boundaries increases, acting as effective barriers to dislocation movement. Consequently, the material's resistance to plastic deformation increases, which manifests as an increase in microhardness.

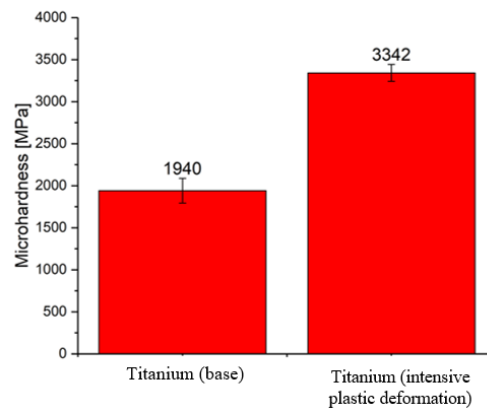


Figure 6. Microhardness results for the samples before and after IPD

The figure 8 shows the stress–strain curves for titanium in its as-received condition and after intensive plastic deformation. It can be seen that the as-received titanium is characterised by pronounced ductility and a comparatively low level of strength. Once the yield strength is reached, the material exhibits an extended yield zone, with failure occurring at a relative elongation of around 20 per cent. This behaviour is characteristic of coarse-grained titanium, which possesses a high capacity for plastic deformation due to the relatively free movement of dislocations and a smaller number of intergranular barriers.

Following intensive plastic deformation, the nature of the curve changes significantly. The processed titanium exhibits a sharp increase in yield stress already at the initial stage of deformation, indicating a significant increase in resistance to plastic deformation. The maximum

stress following intensive plastic deformation reaches approximately 900 MPa, whereas for the as-received condition it is around 450 MPa. Thus, intensive plastic deformation results in a more than twofold increase in the material's strength properties. The increase in strength following IDP is associated with the formation of an ultrafine-grained structure, an increase in dislocation density, the development of a subgrained structure, and the formation of a large number of intergranular boundaries. Grain and subgrain boundaries act as effective barriers to dislocation motion, thereby increasing the stress required to continue plastic deformation. An additional contribution to hardening may be made by the deformation texture formed during the process of intensive plastic deformation. Alongside the increase in strength, a marked reduction in ductility is observed. For titanium following IDP, fracture occurs at a significantly lower strain, around 5–7 per cent, whereas the original titanium retains the capacity for plastic deformation up to ~20 per cent. Such a reduction in elongation is typical of ultrafine-grained and heavily deformed metallic materials. It is associated with restricted dislocation mobility, a reduction in the material's capacity for uniform strain hardening, and earlier localisation of plastic deformation.

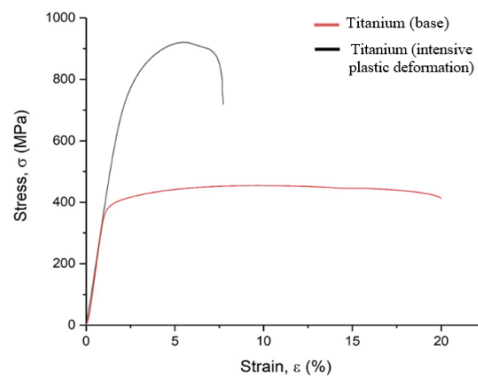


Figure 7. Typical stress–strain curves obtained by uniaxial tensile testing of specimens

Figure 8 shows the microstructure of a titanium material in various structural states. In its as-received state, the material is characterised by a coarse-grained equiaxed structure with clearly defined grain boundaries. This morphology indicates a relatively low degree of accumulated strain and a comparatively low density of defects in the crystal lattice. This condition can be regarded as a reference state for assessing the effect of subsequent heat treatment and deformation. After rolling the material in its as-delivered condition, a marked change in the microstructure is observed. In the longitudinal direction, an elongated, deformed structure forms, oriented predominantly along the rolling direction. This is due to the directional plastic flow of the material, the elongation of the grains and the formation of a deformation texture. In the transverse direction, the structure also retains signs of plastic deformation, but is characterised by a more fragmented and heterogeneous nature. The differences between the longitudinal and transverse directions indicate the formation of structural anisotropy following rolling. The most significant refinement of the microstructure is observed following a combined treatment comprising quenching at 1000 °C with water cooling, ABC pressing, rolling to dimensions of 10×10×L mm, and subsequent annealing at 300 °C. In the longitudinal direction, a highly deformed, finely dispersed structure is formed, which is due to the accumulation of significant plastic deformation during the ABC pressing and rolling processes. Such treatment promotes the fragmentation of the original grains, the formation of sub-grain boundaries, an increase in dislocation density and the formation of an ultrafine-grained state. In the transverse direction, following a similar combined treatment, pronounced refinement of the structure is also observed. However, the microstructure differs from that in the longitudinal direction in terms of morphology, which is due to the anisotropic nature of the deformation during rolling. However,

in both directions, a common feature of the ultrafine-grained state is retained: a high degree of structural fragmentation and the absence of large equiaxed grains characteristic of the starting material. Following rolling and subsequent annealing at 800 °C for 3 hours, the microstructure becomes coarser and equiaxed. This indicates that work hardening and recrystallisation processes have taken place, accompanied by a reduction in dislocation density, partial relief of internal stresses and coarsening of the grain structure. This state differs from that of the ultrafine-grained material in that it exhibits a lower degree of fragmentation and more pronounced grain growth, which explains the reduction in microhardness following high-temperature annealing. Thus, microstructural analysis shows that rolling leads to the formation of a deformed and textured structure, whilst subsequent high-temperature annealing promotes recrystallisation and a reduction in the degree of strain hardening. The most effective process for achieving an ultrafine-grained state is a combined treatment comprising quenching at 1000 °C, water cooling, ABC pressing, rolling and annealing at 300 °C. It is precisely this treatment regimen that ensures the most pronounced refinement of the microstructure, which is consistent with an increase in the microhardness and strength properties of the material.

Figure 8 shows the results of microhardness measurements on titanium in various structural states. In its as-received state, the material's microhardness is approximately 1.8 gpa. Following a combined treatment comprising quenching at 1000 °c with water cooling, ABC pressing, rolling to dimensions of 10×10×1 mm and annealing at 300 °c, a marked increase in microhardness is observed in both the longitudinal and transverse directions. This is attributed to strain hardening, grain refinement, the accumulation of crystal lattice defects and the formation of sub-grain boundaries. Rolling the material in its as-delivered condition also leads to an increase in microhardness, indicating the contribution of plastic deformation and the formation of a deformation texture. The maximum microhardness value is observed for the deformed state, confirming the effectiveness of the treatment aimed at forming a strengthened structure. At the same time, subsequent annealing at 800 °c for 3 hours leads to a decrease in microhardness, which may be associated with recrystallisation, dislocation density reduction and partial relief of internal stresses.

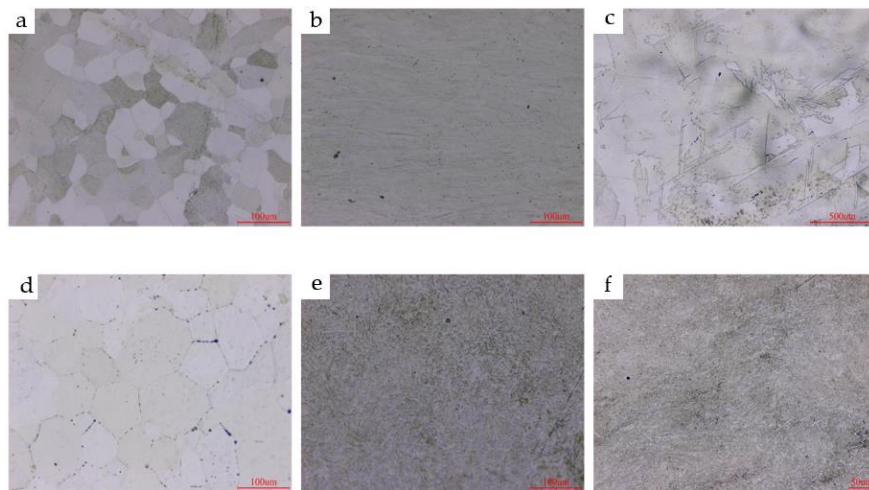


Figure 8. The microstructure of a titanium alloy in various states: a-Titanium (base); b-rolling of material in the as-supplied condition, in the longitudinal direction; c- hardening at 1000 °C followed by water quenching + ABC pressing + rolling to dimensions 10×10×L + annealing at 300 °C, longitudinal direction; d-rolling of the material in its as-supplied condition + annealing at 800 °C for 3 hours, followed by cooling in the furnace; e-rolling of material in the as-supplied condition, transverse direction (UFG); f-hardening at 1000 °C followed by water quenching + ABC pressing + rolling to dimensions 10×10×L + annealing at 300 °C cross-directional

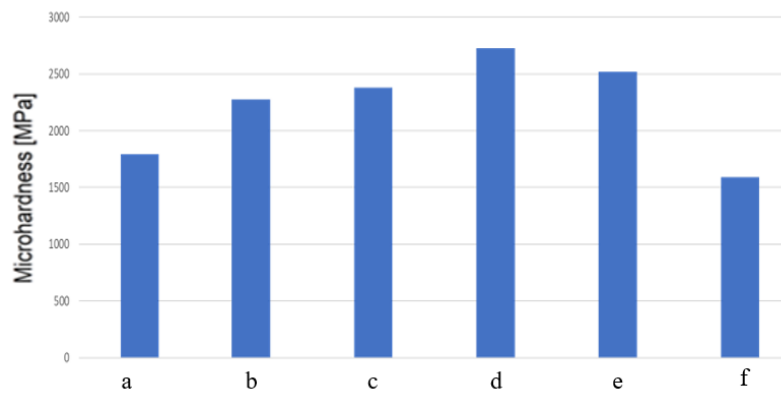


Figure 9. Hardness test results: a-Titanium (base); b- hardening at 1000 °C followed by water quenching + ABC pressing + rolling to dimensions 10×10×L + annealing at 300 °C, longitudinal direction; c- hardening at 1000 °C followed by water quenching + ABC pressing + rolling to dimensions 10×10×L + annealing at 300 °C cross-directional. d- rolling of material in the as-supplied condition, transverse direction (UFG); e- rolling of material in the as-supplied condition, in the longitudinal direction; f- rolling of the material in its as-supplied condition + annealing at 800 °C for 3 hours, followed by cooling in the furnace

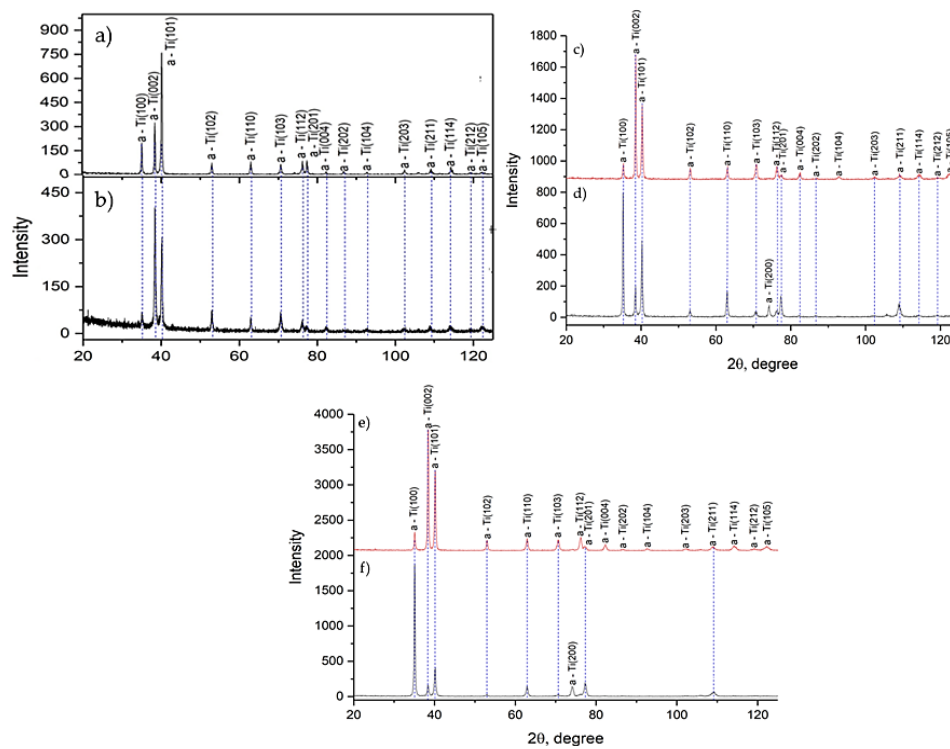


Figure 10. X-ray diffraction patterns of titanium in various structural states: a-Titanium (base); b- rolling of the material in its as-supplied condition + annealing at 800 °C for 3 hours, followed by cooling in the furnace; c- rolling of material in the as-supplied condition, in the longitudinal direction; d- rolling of material in the as-supplied condition, transverse direction (UFG); e- hardening at 1000 °C followed by water quenching + ABC pressing + rolling to dimensions 10×10×L + annealing at 300 °C, longitudinal direction; f-Hardening at 1000 °C followed by water quenching + ABC pressing + rolling to dimensions 10×10×L + annealing at 300 °C cross-directional

Figure 10 shows x-ray diffraction patterns of titanium in various structural states. In all the samples studied, reflections corresponding to the hexagonal α -phase of titanium were identified, indicating that the material retained its phase stability following thermal and thermomechanical treatment. No additional diffraction peaks associated with the formation of secondary phases were detected. At the same time, the change in the relative intensity of the diffraction peaks indicates the formation of a pronounced deformation texture. In the post-rolling state, a difference is observed between the longitudinal and transverse directions, indicating structural anisotropy formed as a result of directional plastic deformation. Following a combined treatment comprising quenching at 1000 °C with water cooling, ABC pressing, rolling to a size of 10×10×1 and annealing at 300 °C, the redistribution of peak intensities becomes more pronounced. This is due to the accumulation of significant plastic deformation, the rotation of crystallites and the formation of an ultrafine-grained, textured state. In the specimen, following rolling and subsequent annealing at 800 °C for 3 hours, the α -phase structure of titanium is retained; however, the nature of the diffraction peaks indicates partial relief of internal stresses and the development of stress-relief or recrystallisation processes. Thus, x-ray diffraction analysis shows that the change in mechanical properties following treatment is due primarily not to phase transformations, but to changes in texture, crystal lattice defects and the structural state of the material.

CONCLUSION

Research has shown that the use of a combined thermomechanical treatment, comprising quenching at 1000 °C followed by water cooling, ABC pressing, followed by rolling to dimensions of 10×10×L mm and annealing at 300 °C, is an effective method for achieving an ultrafine-grained microstructure in titanium material. This process ensures intensive refinement of the initial coarse-grained structure, improved material homogeneity, the formation of sub-grain boundaries, and the accumulation of a high density of crystal lattice defects.

Microstructural analysis showed that, in its as-received condition, the material is characterised by a coarse-grained equiaxed structure with an average grain size of approximately 35 μm . Following intensive plastic deformation, a finer-grained and more homogeneous structure is formed, indicating significant structural transformation of the material. Rolling the material in its as-delivered condition leads to the formation of a deformed and textured structure, whilst subsequent annealing at 800 °C for 3 hours promotes the processes of strain relief and recrystallisation, accompanied by a reduction in defect density and coarsening of the grain structure.

The microhardness measurement results confirmed a pronounced work-hardening effect following intensive plastic deformation. The microhardness of the as-received titanium was 1940 MPa, whereas after intensive plastic deformation it increased to 3342 MPa, corresponding to an increase of approximately 72 per cent. The increase in microhardness is attributed to grain refinement, an increase in the length of intergranular and subgranular boundaries, and a rise in the density of dislocations, which impede the plastic deformation of the material.

Mechanical tests showed that the material's strength properties improved significantly following intensive plastic deformation. The tensile strength increased from approximately 452 to 921 MPa, whilst the yield strength rose from 383 to 795 MPa. At the same time, the relative elongation decreased from 19.6 to 5.3 per cent, indicating the trade-off between increased strength and reduced ductility that is characteristic of ultrafine-grained metallic materials. Consequently, for practical application in implant systems, further optimisation of processing conditions should be aimed at maintaining a high level of strength whilst ensuring sufficient ductility and fatigue resistance.

X-ray diffraction analysis showed that the hexagonal α -phase of titanium is retained in all the states investigated, and no additional phase components were detected. This indicates the phase stability of the material following thermal and thermomechanical treatment. The main

changes following IPD are not associated with phase transformations, but rather with a redistribution of the intensity of diffraction peaks, the formation of a pronounced deformation texture, the accumulation of crystal lattice defects and a change in the orientation of the crystallites.

CONFLICT OF INTEREST: The authors declare that there is no conflict of interest.

FUNDING: This study was funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant number: BR24992862).

INSTITUTIONAL REVIEW BOARD STATEMENT: Not applicable. This study was a materials science and engineering investigation and did not involve human participants, animals, or biological samples.

INFORMED CONSENT STATEMENT: Not applicable. The study did not involve human participants.

DATA AVAILABILITY STATEMENT: The experimental data supporting the findings of this study, including microstructural, X-ray diffraction, microhardness, and mechanical testing data, are available from the corresponding author upon reasonable request.

ACKNOWLEDGEMENTS: The authors acknowledge the technical support provided during sample preparation, microstructural characterization, X-ray diffraction analysis, and mechanical testing.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE TECHNOLOGIES: OpenAI ChatGPT (GPT-5.6 Sol) was used for English-language editing, structural alignment with the journal template, and checking reference-format consistency. The authors independently verified all scientific interpretations, experimental data, references, and conclusions and take full responsibility for the manuscript.

REFERENCES

- Baek, S. M., et al. (2017). Superior pre-osteoblast cell response of etched ultrafine-grained titanium with a controlled crystallographic orientation. *Scientific Reports*, 7, 44213.
- Geetha, M., Singh, A. K., Asokamani, R., & Gogia, A. K. (2009). Ti based biomaterials, the ultimate choice for orthopaedic implants—A review. *Progress in Materials Science*, 54(3), 397–425. <https://doi.org/10.1016/j.pmatsci.2008.06.004>
- Gurau, C., et al. (2020). The influence of severe plastic deformation on microstructure and in vitro biocompatibility of the new Ti-Nb-Zr-Ta-Fe-O alloy composition. *Materials*, 13, 4853. <https://doi.org/10.3390/ma13214853>
- Kalantari, K., et al. (2021). Biological applications of severely plastically deformed nano-/ultrafine-grained biomaterials.
- Niinomi, M. (2008). Mechanical biocompatibilities of titanium alloys for biomedical applications. *Journal of the Mechanical Behavior of Biomedical Materials*, 1, 30–42. <https://doi.org/10.1016/j.jmbbm.2007.07.001>
- Oldani, C., & Dominguez, A. (2012). Titanium as a biomaterial for implants. In *Recent Advances in Arthroplasty*. <https://doi.org/10.5772/27413>
- Semenova, I.P., Valiev, R.Z., Yakushina, E.B., Salimgareeva, G.H., & Lowe, T.C. (2008). Strength and fatigue properties enhancement in ultrafine-grained Ti produced by severe plastic deformation. *Journal of Materials Science*, 43, 7354–7359. <https://doi.org/10.1007/s10853-008-2984-4>
- Semenova, I. P., et al. (2022). Strength and fatigue life at 625 K of the ultrafine-grained Ti-6Al-4V alloy produced by equal-channel angular pressing. *Metals*, 12, 1345. <https://doi.org/10.3390/met12081345>
- Valiev, R. Z., & Langdon, T. G. (2006). Principles of equal-channel angular pressing as a processing tool for grain refinement. *Progress in Materials Science*, 51, 881–981. <https://doi.org/10.1016/j.pmatsci.2006.02.003>

Valiev, R. Z., Semenova, I. P., Latysh, V. V., Rack, H., Lowe, T. C., et al. (2008). Nanostructured titanium for biomedical applications. *Advanced Engineering Materials*, 10(8), B15–B17.
<https://doi.org/10.1002/adem.200800026>

Information about authors



Kengesbekov Aidar Bakytbekuly – PhD, Senior Research Fellow at the «Protective and Functional Coatings» laboratory, East Kazakhstan Technical University named after D. Serikbaev, Ust-Kamenogorsk, Kazakhstan,
e-mail: kenesbekovaidar@gmail.com,
ORCID: <https://orcid.org/0000-0002-5630-9467>



Kakimzhanov Dauir Nurzhanuly – Researcher of LLP «PlasmaScience», Ust-Kamenogorsk, Kazakhstan,
e-mail: d.kakimzhanov19@gmail.com,
ORCID: <https://orcid.org/0000-0001-9453-0456>



Ali Coruh – Prof. Dr., Department of Physics, Sakarya University, Sakarya, Turkey,
e-mail: coruh@sakarya.edu.tr,
ORCID: <https://orcid.org/0000-0002-7362-6173>



Asem Kochneva – PhD student, D. Serikbayev East Kazakhstan Technical University, Ust-Kamenogorsk, Kazakhstan,
e-mail: kochnevaasem@gmail.com,
ORCID: <https://orcid.org/0009-0001-7876-9552>



Daryn Baizhan – Senior researcher «Research Center Surface Engineering and Tribology», Sarsen Amanzholov East Kazakhstan University, Ust-Kamenogorsk, Kazakhstan,
e-mail: daryn.baizhan1@gmail.com,
ORCID: <https://orcid.org/0000-0002-9105-3129>