Microstructure and Mechanical Properties of Titanium Alloys

Artur Shugurov *

Institute of Strength Physics and Materials Science, Siberian Branch, Russian Academy of Sciences,
634055 Tomsk, Russia

1. Introduction and Scope

Titanium and its alloys are widely used engineering materials within the aerospace, automotive, energy, and chemical industries. Their unique combination of high strength-to-weight ratio, strong resistance to creep, excellent corrosion resistance, and low heat conductivity makes them suitable for many applications. A large variety of microstructures, including lamellar, martensitic, equiaxed globular, and bimodal (duplex) microstructures, can be obtained in titanium alloys depending on the thermomechanical processing routes. Despite a large amount of work in the investigation of microstructure evolution and mechanical properties of titanium alloys, detailed studies of the effect of their microstructure on the mechanical behaviour are still necessary because of ever-increasing demands for structural materials to optimize their properties for different applications, by varying processing parameters and resulting microstructures.

This Special Issue focuses on various aspects of microstructure evolution in titanium alloy samples obtained using traditional and additive technologies and subjected to different processing techniques, as well as on the relation between their microstructure and mechanical behaviour. The presented original articles cover the areas of preparation and experimental characterization of titanium alloys, as well as computer simulation of their mechanical behaviour under different loading conditions.

2. Contributions

Seventeen papers of high scientific quality have been published in the present Special Issue of *Metals*, covering the fields of thermomechanical processing, mechanical behaviour, surface modification, electrochemical micromachining, and bonding mechanisms of different titanium alloys. The contents of the published manuscripts are briefly summarized below.

Despite a large variety of developed thermomechanical processing routes, the issue of thermomechanical treatment of titanium alloys is still very topical because of the emergence of new titanium and titanium-based alloys and the need to further improve the performance of existing alloys and therefore modify their microstructure. This is confirmed by the fact that eight papers consider microstructure evolution and the mechanical properties of Ti-based alloys subjected to different thermomechanical treatments. The investigation of the two-pass thermal compression behaviour of a near- β Ti-55511 alloy revealed the characteristic features of its dynamic recovery and recrystallization [1]. The evolution of inelastic and plastic strains in a Ti_{49.3}Ni_{50.7} alloy subjected to torsional deformation was studied in [2]. It was found that in the temperature range studied, the maximum inelastic strain that could be obtained in the coarse-grained samples subjected to torsion could be completely returned due to the superelasticity effect of 4–7%. The effect of true strains on the microstructure and mechanical properties of a Ti_{49.8}Ni_{50.2} alloy subjected to isothermal abc pressing was analysed in [3]. It was shown that the grain structure of the alloy was refined by increasing the true strain, which increased its yield stress and strain-hardening coefficient. Defects of the crystal structure formed in Ti_{49.4}Ni_{50.6} and Ti₅₀Ni_{47.3}Fe_{2.7} alloys after equal-channel angular pressing were studied by positron

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lifetime spectroscopy [4]. The results obtained indicate that the formation of ultrafine-grained structures in a $\text{Ti}_{50}\text{Ni}_{47.3}\text{Fe}_{2.7}$ alloy does not change the martensite transformation sequence $\text{B2} \leftrightarrow \text{R} \leftrightarrow \text{B19}'$ but reduces the start temperature of the $\text{R} \leftrightarrow \text{B19}'$ transition by 18 K, and narrows the $\text{B19}' \rightarrow \text{R}$ temperature interval by 10 K. The microstructural evolution of a titanium-based Ti-3.3Al-5Mo-5V alloy subjected to hot pressing and radial forging was investigated [5]. The radial forging of the alloy was found to lead to structural refinement and changes in grain morphology from predominately lamellar to uniform globular, as well as to variations in the phase composition of the alloy and the suppression of powder formation. The microstructure and mechanical properties of a newly developed Fe-microalloyed Ti-6Al-4V titanium alloy subjected to different heat treatments were studied by Liu et al. [6]. Optimal mechanical performance of the alloy was shown to be achieved via β -annealing at 1005 °C for 70 min, followed by air cooling to room temperature and aging at 722 °C for 2 h with subsequent air cooling to room temperature. Kashin et al. reported the results of the experimental study of the microstructure and martensite transformations of $\text{Ti}_{49.8}\text{Ni}_{50.2}$ alloy after *abc* pressing at 573 K [7]. They showed that increasing the true strain resulted in grain-subgrain refinement on different scales and proposed possible mechanisms for this effect. The structure and multistage martensite transformation in nanocrystalline Ti-50.9Ni alloy was studied [8]. The research revealed that the presence of different types of internal interfaces in the nanostructure contributed to the heterogeneous distribution of coherent Ti_3Ni_4 nanoparticles in the volume of the B2 matrix, which was associated with the precipitation of particles in the region of low-angle sub-boundaries and the suppression of the Ti_3Ni_4 precipitation in nanograins with high-angle boundaries.

Two papers considered the mechanical behaviour of titanium alloys under different loadings. The first manuscript presents the results of systematic investigations of the cyclic behaviour of a Ti-3Al-8V-6Cr-4Mo-4Zr alloy with three different microstructures [9]. The cyclic stress response was shown to be highly related to the applied strain amplitude and precipitated phase. The second paper analysed the deformation behaviour of Ti-6Al-4V alloy samples with lamellar and bimodal microstructures subjected to scratch testing experimentally and using molecular dynamics simulation [10]. It was found that the scratch depth in the sample with a bimodal microstructure was twice as shallow as that measured in the sample with a lamellar microstructure. This effect was attributed to the greater hardness of the sample with a bimodal microstructure and the larger amount of elastic recovery of scratch grooves in this sample. Based on the results of molecular dynamics simulation, a mechanism was proposed, which associates the recovery of the scratch grooves with the inhomogeneous vanadium distribution in the β -areas.

Studies of the surface modification of titanium alloys also contributed a substantial part to the issue. Smyslova et al. investigated near-surface layer microstructure of Ti-6Al-4V alloy samples subjected to plasma electrolytic polishing with subsequent high-energy nitrogen ion implantation [11]. It was found that the initial structural state of the Ti-6Al-4V alloy substrate had a significant effect on the transformation of the dislocation substructure during the treatment. Experimental and theoretical studies of the surface roughening and the microstructure refinement in the surface layer of commercially pure titanium during ultrasonic impact treatment were performed in [12]. It was shown that the surface plastic strains of the titanium sample proceeded according to the plastic ploughing mechanism, which was accompanied by dislocation sliding, twinning, and the transformations of the microstructure and phase composition. The role of the electronic subsystem in the development of the strain-induced phase transformations during ultrasonic impact treatment was discussed. The titanium alloy surface was modified with copper ions to improve ceramic coatings' strength properties, adhesion, and thermal cycling resistance [13]. A multilevel micro- and nanoporous nanocrystalline structure was shown to form in the surface layer of the titanium alloy samples, which increased the adhesion and thermal cyclic resistance of the overlying Si-Al-N coating. The physical mechanism, reasons, and conditions of nanocrystal formation in an amorphous NiTi metal film stimulated by infrasonic action are formulated [14]. The transformation of the amorphous film into the nanostructured one

was explained by the accumulation of the potential energy of inelastic deformation to a critical value equal to the latent heat of the transformation.

Other papers are related to an analysis of the influence of sodium-chloride-based electrolytes on machining a Ti-6Al-4V alloy [15], the effect of the microstructure of a titanium alloy with a trimodal microstructure on plastic deformation and crack growth mechanisms [16], and the adhesion properties of the TiAl/TiO₂ interface estimated in dependence on interfacial layer composition and contact configuration using the projector-augmented wave method [17].

3. Conclusions and Outlook

The contributions included in the present Special Issue of *Metals* cover a wide range of research on titanium alloys, representing a well-balanced combination of theoretical and practical efforts. The papers provide a comprehensive overview of recent progress in designing and experimentally characterizing titanium alloys and investigating their microstructure evolution and mechanical behaviour. Hopefully, the present studies will be interesting for a wide range of readers and stimulate further investigations of titanium alloys' microstructure and mechanical properties.

As guest editor, I am very happy to report the success of this Special Issue and expect that the papers will be useful to scientists and engineers working in the development of new materials and improvement of their performance. I am sincerely grateful to the authors for their contributions and the reviewers for their significant efforts in providing high-quality publications. Sincere thanks to editors and editorial assistants of *Metals* for their continuous support during the preparation of this volume. In particular, I would like to warmly acknowledge Ms. Sammi Meng for her valuable assistance.

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