Titanium Alloys and Titanium-Based Matrix Composites

Maciej Motyka

Department of Materials Science/R&D Laboratory for Aerospace Materials, Rzeszow University of Technology,
35-959 Rzeszow, Poland; motyka@prz.edu.pl; Tel.: +48-17-7432416

1. Introduction and Scope

Titanium alloys have been considered unique materials for many years. Their development has led to the design of several groups of structural alloys, including single-phase α or β alloys, two-phase $\alpha + \beta$ alloys—the most popular ones—and TiAl intermetallic alloys. The main application areas of titanium alloys include transportation (mainly aerospace structures), machine building, the fuel–energy industry and medicine. Titanium alloys are also good materials for metal matrix composites (MMCs). Their main attractions are high strength and stiffness—which depend on the type of reinforcement. An important feature of titanium is its remarkable biocompatibility. The low Young’s modulus of titanium alloys—especially β alloys—makes them valuable biomaterials used for bone implants.

The constant development of titanium-based materials is also related to new technologies introduced—e.g., 3D printing or friction welding. It has restored the need for further research on titanium components produced using modern manufacturing and processing methods. This Special Issue covers various aspects of research on titanium alloys and Ti-based metal matrix composites—related to the development of their microstructure and operational properties by chemical composition modification, heat treatment and plastic deformation, but also by modern manufacturing and processing methods such as powder metallurgy, additive manufacturing or friction stir welding.

2. Contributions

Twenty articles—18 research ones, 1 review and 1 technical note—have been published in the present Special Issue of *Metals*. Their subject matter is quite extensive, encompassing the fields of deformation behavior, microstructure and properties development, as well as special applications (biomedical and functional ones) and technologies. For the ease of the reader, papers have been divided into three groups, although among them thematic links can be established.

2.1. Deformation Behavior

Four papers in this section concern the hot deformation behavior of metallic materials, including the evaluation of microstructure evolution and processing maps elaboration. Liu et al. [1] investigated the hot deformation process of metastable β Ti-6Cr-5Mo-5V-4Al alloy (Ti-6554), which is considered as a new type of high-strength and high-toughness titanium alloy for manufacturing large-scale aircraft structural parts. It is of great significance to improve the properties of the alloy. The results of hot compression tests at a temperature range of 715–840 °C and strain rate range of 0.001–1 s^{−1} were the basis of a processing maps calculation, enabling the determination of the instability regions in the process and improvement of forging effectiveness. Zharebtsov et al. [2] analyzed the deformation behavior of Ti-15Mo/TiB composite produced by spark plasma sintering. They found its gradual softening with an increase in deformation temperature in the range of 500–1000 °C to be associated with the dynamic recovery and recrystallization processes, in addition to the reorientation and shortening of TiB whiskers. The effect of pre-deformation on the hot plasticity of Ti-6Al-4V alloy was researched by Wu et al. [3]. It was found that pre-strain

Citation: Motyka, M. Titanium Alloys and Titanium-Based Matrix Composites. *Metals* **2021**, *11*, 1463. <https://doi.org/10.3390/met11091463>

Received: 7 September 2021

Accepted: 15 September 2021

Published: 15 September 2021

Publisher’s Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2021 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

of 0.05 enhanced flow stress and elongation in tensile tests at a temperature of 850 °C. Moreover, pre-strain promoted dynamic recrystallization by increasing the deformation substructure. Zhang et al. [4] analyzed the asymmetry of tension–compression behavior of an extruded Ti-6.5Al-2Zr-1Mo-1V alloy (TA15) at a temperature range of 650–750 °C. The corresponding yield stress and asymmetric strain hardening behavior were studied.

2.2. Development of Microstructure and Operational Properties

The largest section contains ten papers related to the development of the microstructure and operational properties of titanium-based materials—alloys and composites—by heat treatment, plastic deformation methods and modification of chemical composition.

The first six papers concern titanium alloys manufactured by conventional metallurgical methods, though with a reference to 3D printing techniques. Guo et al. [5] investigated the precipitation behavior of the ω phase and $\omega \rightarrow \alpha$ transformation in Ti-5Al-5Mo-5V-1Cr-1Fe near- β alloy (Ti-55511) during isothermal ageing at 450 °C. It was observed that the size of α precipitates increase with increasing ageing time, resulting from the $\beta \rightarrow \alpha$ and $\omega \rightarrow \alpha$ transformations. Phase transformations upon ageing in the other β alloy were the subject of research conducted by Bartha et al. [6]. Ti-15Mo alloy was subjected to two techniques of intensive plastic deformation—high-pressure torsion and rotary swaging at room temperature—leading to the formation of an ultrafine-grained microstructure. It was found that, after isothermal ageing in both deformed conditions, precipitations of the α phase remain small and equiaxed even after ageing at 500 °C for 16 h. The other β alloy—Ti-Nb-Zr-Fe-O—was investigated by Cojocaru et al. [7]. The influence of complex thermo-mechanical processing on its mechanical properties was analyzed. The advantages and disadvantages of such treatment were analyzed for expanding the database of possible β -Ti bio-alloys that could be used, depending on the specific requirements of different biomedical implant applications. Ding et al. [8] evaluated the solidification microstructure of Ti-6Al-4V- x Fe ($x = 0.1, 0.3, 0.5, 0.7$ and 0.9) alloys fabricated by levitation melting. The growth of grains in the function of Fe content, as well as the composition distribution mechanisms during the solidification process of the alloy, were discussed. Qiao et al. [9] researched the microstructure, corrosion behavior and tensile properties of a newly developed low-cost titanium alloy, Ti-4Al-2V-1Mo-1Fe, and compared it to the widespread Ti-6Al-4V alloy. It was revealed that the corrosion resistance and ductility of the Ti-4Al-2V-1Mo-1Fe alloy were higher than that of the Ti-6Al-4V alloy, with a slight reduction in strength. Motyka [10], in his review paper, pointed to another aspect. He noticed that the introduction of new manufacturing methods—e.g., 3D printing—requires further research on titanium alloys already considered as well-known and that have been described in detail in the case of conventional technologies. In his article, he focused on martensite formation and decomposition processes in two-phase titanium alloys and emphasized their important role in microstructure development during conventional and additive manufacturing processes.

The next four papers are devoted to titanium-based alloys and composites produced by powder metallurgy. The influence of the hot isostatic pressing (HIP) post-processing step on the microstructure, porosity and mechanical properties of Ti-35Nb-2Sn alloy was studied by Lario et al. [11]. They confirmed that field-assisted consolidation processes, such as HIP, can be employed to reduce residual porosity and to increase the chemical and phase homogeneity of sintered β titanium alloys intended for biomedical applications. Markovsky et al. [12] investigated the influence of a strain rate on the mechanical response and microstructure evolution of the selected titanium-based materials, i.e., Ti-6Al-4V alloy produced via a conventional cast and wrought technology, as well as fabricated using blended elemental powder metallurgy. It was found out, among others, that Ti-6Al-4V with a globular microstructure is characterized by high strength and high plasticity in comparison to this alloy with a lamellar microstructure, whereas Ti-6Al-4V obtained via the powder metallurgy method reveals the highest plastic flow stress, with good plasticity at the same time. Hou et al. [13] successfully manufactured TiB-whiskers-reinforced Ti-15Mo-3Al-

2.7Nb-0.2Si alloys by adding TiB₂ powder and pre-sintering followed by canned hot extrusion. It was observed that the extrusion led to grain refinement and the strengthening of the composite, especially at the process temperature of 1000 °C. Powder-metallurgy-titanium-based composites were also researched by Montealegre-Meléndez et al. [14]. Their study was aimed at the analysis of the reaction layer between the titanium matrix and reinforcement: B₄C particles and/or intermetallic Ti_xAl_y. The authors revealed that composites with ceramic reinforcement showed excellent hardness and good wear resistance.

2.3. Special Applications and Technologies

The last section comprises six papers and concerns special applications of titanium-based materials—such as the biomedical one—as well as modern technologies—such as additive manufacturing, plastic consolidation or friction stir processing. Regarding biomedicine, titanium alloys belong to the few biomaterials that naturally match the requirement of bone implants or bone tissue replacement in the human body. The mechanical and bio-functional behavior of a Ti-30Nb-13Ta alloy in the form of foam, fabricated by mechanical alloying and subsequent spark plasma sintering, was studied by Giner et al. [15]. The material was evaluated as a potential prosthetic biomaterial used for cortical bone replacement and compared with commercial, pure Ti used for bone replacement implants. Moiduddin et al. [16] proposed an integrated system methodology for the reconstruction of complex zygomatic bone defects, using Ti-6Al-4V ELI alloy, comprising several steps, right from the patient scan to implant fabrication, while maintaining proper aesthetic and facial symmetry. Finally, it was concluded that a mirror-designed titanium implant (fabricated by the electron beam melting method) satisfies the aesthetic, functional, and mechanical properties for efficient zygomatic bone reconstruction. Moreover, the authors stated that the proposed design methodology could also be applied for other bone reconstruction surgeries.

The next three papers describe the effects of unconventional manufacturing and processing methods. Topolski et al. [17] consolidated titanium chips into solid, bulk material by extrusion of the briquettes into the form of solid rods using the KOBO method. Structural aspects of the solid-state processing of various titanium chips were analyzed. It was found that the manufactured rods were consolidated and near fully dense. Kim et al. [18] applied the step rolling process for the production of ultrafine-grained Ti-6Al-4V sheets. This study clarified the effect of subsequent annealing on the tensile properties of step-rolled Ti-6Al-4V at room and elevated temperature. Mironov et al. [19] used friction stir processing for the development of a globular α microstructure in Ti-6Al-4V alloy. Characterization of the crystallographic aspects of such a microstructure was accomplished by the electron backscatter diffraction technique.

The last paper in this section covers issues related to micro-actuators based on shape memory alloys. The most popular among them is nitinol (NiTi), which in fact is a nickel-based alloy, but is quite often described together with functional titanium alloys. Shimoga et al., in their technical report [20], reflected on the characteristics of the NiTi coil spring structure with its phase transformations and thermal transformation properties. It was postulated that the micro-actuators based on NiTi could be used for advanced high-tech applications.

3. Conclusions and Outlook

A variety of interrelated topics have been raised in the present Special Issue of *Metals*, providing a wide overview of recent research developments on different aspects of titanium-based materials. The number of articles and the wide range of topics prove the continued interest in this group of materials. It is worth mentioning that the authors represent scientific institutions from 13 countries: Austria, China, the Czech Republic, Japan, Korea, Pakistan, Poland, Romania, Russia, Saudi Arabia, Spain, Ukraine and the USA.

As a Guest Editor of this Special Issue, I am very happy with the final result, and hope that the published papers will be useful to researchers working on titanium alloys and titanium-based composites. I would like to warmly thank all the authors for their

contributions, and all of the reviewers for their efforts in ensuring a high-quality publication. Thanks are also due to the *Metals* Editorial Office, especially to Toliver Guo, Assistant Editor, who managed and facilitated the publication process.

Funding: This research received no external funding.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Liu, Q.; Wang, Z.; Yang, H.; Ning, Y. Hot Deformation Behavior and Processing Maps of Ti-6554 Alloy for Aviation Key Structural Parts. *Metals* **2020**, *10*, 828. [\[CrossRef\]](#)
2. Zharebtsov, S.; Ozerov, M.; Klimova, M.; Moskovskikh, D.; Stepanov, N.; Salishchev, G. Mechanical Behavior and Microstructure Evolution of a Ti-15Mo/TiB Titanium–Matrix Composite during Hot Deformation. *Metals* **2019**, *9*, 1175. [\[CrossRef\]](#)
3. Wu, T.; Wang, N.; Chen, M.; Zuo, D.; Xie, L.; Shi, W. Effect of Pre-Strain on Microstructure and Tensile Properties of Ti-6Al-4V at Elevated Temperature. *Metals* **2021**, *11*, 1321. [\[CrossRef\]](#)
4. Zhang, C.; Li, D.; Li, X.; Li, Y. An Experimental Study of the Tension-Compression Asymmetry of Extruded Ti-6.5Al-2Zr-1Mo-1V under Quasi-Static Conditions at High Temperature. *Metals* **2021**, *11*, 1299. [\[CrossRef\]](#)
5. Guo, Y.; Wei, S.; Yang, S.; Ke, Y.; Zhang, X.; Zhou, K. Precipitation Behavior of ω Phase and $\omega \rightarrow \alpha$ Transformation in Near β Ti-5Al-5Mo-5V-1Cr-1Fe Alloy during Aging Process. *Metals* **2021**, *11*, 273. [\[CrossRef\]](#)
6. Bartha, K.; Stráský, J.; Veverková, A.; Veselý, J.; Čížek, J.; Málek, J.; Polyakova, V.; Semenova, I.; Janeček, M. Phase Transformations upon Ageing in Ti15Mo Alloy Subjected to Two Different Deformation Methods. *Metals* **2021**, *11*, 1230. [\[CrossRef\]](#)
7. Cojocaru, V.D.; Nocivin, A.; Trisca-Rusu, C.; Dan, A.; Irimescu, R.; Raducanu, D.; Galbinas, B.M. Improving the Mechanical Properties of a β -type Ti-Nb-Zr-Fe-O Alloy. *Metals* **2020**, *10*, 1491. [\[CrossRef\]](#)
8. Ding, L.; Hu, R.; Gu, Y.; Zhou, D.; Chen, F.; Zhou, L.; Chang, H. Effect of Fe Content on the As-Cast Microstructures of Ti-6Al-4V-xFe Alloys. *Metals* **2020**, *10*, 989. [\[CrossRef\]](#)
9. Qiao, Y.; Xu, D.; Wang, S.; Ma, Y.; Chen, J.; Wang, Y.; Zhou, H. Corrosion and Tensile Behaviors of Ti-4Al-2V-1Mo-1Fe and Ti-6Al-4V Titanium Alloys. *Metals* **2019**, *9*, 1213. [\[CrossRef\]](#)
10. Motyka, M. Martensite Formation and Decomposition during Traditional and AM Processing of Two-Phase Titanium Alloys—An Overview. *Metals* **2021**, *11*, 481. [\[CrossRef\]](#)
11. Lario, J.; Vicente, Á.; Amigó, V. Evolution of the Microstructure and Mechanical Properties of a Ti35Nb2Sn Alloy Post-Processed by Hot Isostatic Pressing for Biomedical Applications. *Metals* **2021**, *11*, 1027. [\[CrossRef\]](#)
12. Markovsky, P.E.; Janiszewski, J.; Bondarchuk, V.I.; Stasyuk, O.O.; Savvakina, D.G.; Skoryk, M.A.; Cieplak, K.; Dziewit, P.; Prikhodko, S.V. Effect of Strain Rate on Microstructure Evolution and Mechanical Behavior of Titanium-Based Materials. *Metals* **2020**, *10*, 1404. [\[CrossRef\]](#)
13. Hou, J.; Gao, L.; Cui, G.; Chen, W.; Zhang, W.; Tian, W. Grain Refinement of Ti-15Mo-3Al-2.7Nb-0.2Si Alloy with the Rotation of TiB Whiskers by Powder Metallurgy and Canned Hot Extrusion. *Metals* **2020**, *10*, 126. [\[CrossRef\]](#)
14. Montealegre-Meléndez, I.; Arévalo, C.; Beltrán, A.M.; Kitzmantel, M.; Neubauer, E.; Pérez Soriano, E.M. Reaction Layer Analysis of In Situ Reinforced Titanium Composites: Influence of the Starting Material Composition on the Mechanical Properties. *Metals* **2020**, *10*, 265. [\[CrossRef\]](#)
15. Giner, M.; Chicardi, E.; Costa, A.d.F.; Santana, L.; Vázquez-Gámez, M.Á.; García-Garrido, C.; Colmenero, M.A.; Olmo-Montes, F.J.; Torres, Y.; Montoya-García, M.J. Biocompatibility and Cellular Behavior of TiNbTa Alloy with Adapted Rigidity for the Replacement of Bone Tissue. *Metals* **2021**, *11*, 130. [\[CrossRef\]](#)
16. Moiduddin, K.; Hammad Mian, S.; Umer, U.; Ahmed, N.; Alkhalefah, H.; Ameen, W. Reconstruction of Complex Zygomatic Bone Defects Using Mirroring Coupled with EBM Fabrication of Titanium Implant. *Metals* **2019**, *9*, 1250. [\[CrossRef\]](#)
17. Topolski, K.; Jaroszewicz, J.; Garbacz, H. Structural Aspects and Characterization of Structure in the Processing of Titanium Grade4 Different Chips. *Metals* **2021**, *11*, 101. [\[CrossRef\]](#)
18. Kim, G.; Lee, T.; Lee, Y.; Kim, J.N.; Choi, S.W.; Hong, J.K.; Lee, C.S. Ambivalent Role of Annealing in Tensile Properties of Step-Rolled Ti-6Al-4V with Ultrafine-Grained Structure. *Metals* **2020**, *10*, 684. [\[CrossRef\]](#)
19. Mironov, S.; Sato, Y.S.; Kokawa, H.; Hirano, S.; Pilchak, A.L.; Semiatin, S.L. Microstructural Characterization of Friction-Stir Processed Ti-6Al-4V. *Metals* **2020**, *10*, 976. [\[CrossRef\]](#)
20. Shimoga, G.; Kim, T.-H.; Kim, S.-Y. An Intermetallic NiTi-Based Shape Memory Coil Spring for Actuator Technologies. *Metals* **2021**, *11*, 1212. [\[CrossRef\]](#)