Research Article

Formation and Properties of the Ta-Y₂O₃, Ta-ZrO₂, and Ta-TaC Nanocomposites

J. Jakubowicz¹ ,¹ M. Sopata,¹ G. Adamek,¹ P. Siwak,² and T. Kachlicki¹

¹*Institute of Materials Science and Engineering, Poznan University of Technology, Jana Pawla II 24, 61-138 Poznan, Poland*

²*Institute of Mechanical Technology, Poznan University of Technology, Piotrowo 3, 60-965 Poznan, Poland*

Correspondence should be addressed to J. Jakubowicz; jaroslaw.jakubowicz@put.poznan.pl

Received 19 February 2018; Accepted 9 May 2018; Published 3 June 2018

Academic Editor: Akihiko Kimura

Copyright © 2018 J. Jakubowicz et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The nanocrystalline tantalum-ceramic composites were made using mechanical alloying followed by pulse plasma sintering (PPS). The tantalum acts as a matrix, to which the ceramic reinforced phase in the concentration of 5, 10, 20, and 40 wt.% was introduced. Oxides (Y₂O₃ and ZrO₂) and carbides (TaC) were used as the ceramic phase. The mechanical alloying results in the formation of nanocrystalline grains. The subsequent hot pressing in the mode of PPS results in the consolidation of powders and formation of bulk nanocomposites. All the bulk composites have the average grain size from 40 nm to 100 nm, whereas, for comparison, the bulk nanocrystalline pure tantalum has the average grain size of approximately 170 nm. The ceramic phase refines the grain size in the Ta nanocomposites. The mechanical properties were studied using the nanoindentation tests. The nanocomposites exhibit uniform load-displacement curves indicating good integrity and homogeneity of the samples. Out of the investigated components, the Ta-10 wt.% TaC one has the highest hardness and a very high Young's modulus (1398 HV and 336 GPa, resp.). For the Ta-oxide composites, Ta-20 wt.% Y₂O₃ has the highest mechanical properties (1165 HV hardness and 231 GPa Young's modulus).

1. Introduction

Refractory materials of the melting point higher than 3000°C are the most desired in design and manufacturing of heavy load-bearing components where resistance to high temperature and wear plays a crucial role. Additionally, these materials usually have high corrosion resistance in very aggressive environments as well as high mechanical properties [1]. The examples of refractory materials are pure metals such as Ta, W, or Mo and their alloys [2]. Other most commonly used refractory materials are ceramics such as oxides (ZrO₂ and Y₂O₃), carbides (TaC, ZrC, and WC), or nitrides (TiN and Si₃N₄) [3–5]. Both types of refractory materials, that is, metals and ceramics have found applications in the design of bulk parts or coatings. Due to their high hardness, refractory materials (particularly ceramics) are brittle. Both materials can be joined together in the form of composites, which usually constitutes a combination of

the best properties of both the metals and the ceramics [6–8]. Particularly, the high brittleness of ceramics can be limited by the addition of a metallic phase and vice versa, and the addition of ceramic phase into the metallic matrix leads to the improvement of the hardness and wear resistance of refractory metals. Refractory materials require high temperature processes for the formation of materials and products. For example, powder metallurgy requires the sintering temperature of at least 1500°C (usually above 2000°C) for proper microcrystalline powder consolidation [9]. Conventional high temperature and longtime sintering processes can be applicable for coarse-grained materials of micrometer size grains. Nanomaterials, compared to microcrystalline ones, can be consolidated for a shorter time and at significantly lower temperatures to achieve optimum properties. The consolidation processes used for nanocrystalline powders are usually different than conventional powder metallurgy used for microcrystalline powders. For

example, for the consolidation of nanomaterials, the hot pressing working in the heating mode of the spark plasma sintering (SPS) or pulse plasma sintering (PPS) gives the best results [10, 11]. In these processes of consolidation, both the pressure and the temperature increase simultaneously, which results in a shortening of the time for which the material is kept at a given high sintering temperature, and this process can be done at a significantly lower consolidation temperature compared to conventional pressureless sintering [12]. Both factors (temperature and time) are crucial for the reduction of the grain growth and the maintenance of the nanostructure or ultrafine structure [13]. Differences in the absence of wetting and the densities of the melted metal and ceramic components result in their segregation, which requires special casting techniques [14]. Therefore, powder metallurgy is very useful for the formation of homogeneous composites [15]. In the process of preparation of the refractory composites, the powders of metallic and ceramic components of the designed chemical composition are mixed together and then consolidated using hot pressing, SPS, PPS, or other relevant techniques [16–18]. For the formation of nanocomposite powders, the mechanical alloying process can be applied, in which the reduction of microcrystalline into nanocrystalline grains is provided by high-energy impacts of the balls in the milling vial [19]. In the mechanical alloying process, the final powders' mixture comes in the form of agglomerates of the micrometer or submicrometer size composed of nanometer size grains of metallic as well as ceramic phases uniformly distributed in the entire volume of the material [20].

New prospects for refractory nanomaterials are related to their outstanding mechanical properties [21], whereas high-temperature applications are limited due to excess grain growth at elevated temperatures [22]. At high temperatures, the nanostructure is unstable and grows up, which leads to deterioration of the mechanical properties.

In this work, the authors focus on the preparation and properties of tantalum-based nanocomposites, reinforced by ceramic Y_2O_3 , ZrO_2 , and TaC. Ta has the melting point of $3017^\circ C$ and the density of 16.4 g/cm^3 . The ceramics have the melting point of 2690, 2715, and $3985^\circ C$ for Y_2O_3 , ZrO_2 , and TaC, respectively. The density of ceramics is 5.03, 5.68, and 14.5 g/cm^3 for Y_2O_3 , ZrO_2 , and TaC, respectively. The nanocomposites having 5, 10, 20, and 40 wt.% of the ceramic phase were formed using mechanical alloying and PPS. The paper studies the formation of nanocomposites and their structure, microstructure, and mechanical properties.

2. Materials and Methods

In this work, nanocrystalline Ta- xY_2O_3 , Ta- $xZrO_2$, and Ta- $xTaC$ composites ($x = 5, 10, 20$, and 40 wt.% of the ceramic phase) were synthesized using mechanical alloying (MA) followed by hot pressing in the mode of pulse plasma sintering (PPS). In the MA process, the tantalum powder ($<44\text{ }\mu\text{m}$, purity $>99.97\%$; Alfa Aesar) was intensely mixed and milled with the Y_2O_3 powder ($<50\text{ nm}$, purity $>99.9\%$; Sigma-Aldrich) as well as the ZrO_2 powder ($0.1\text{--}2\text{ }\mu\text{m}$, stabilized

with 5.4% of Y_2O_3 ; Goodfellow) and TaC ($<45\text{ }\mu\text{m}$, purity $>99.5\%$; Goodfellow). The mixture of a total of 5.5 g of the metallic and ceramic powders was loaded and reloaded into the milling vial in the Unilab glove box (MBraun) providing a high purity Ar 5.0 atmosphere. For each composite composition, several syntheses were performed to provide material for 5 consolidated samples with 8 mm in diameter and 4 mm in height. In the mechanical alloying process (SPEX 8000M Mixer/Mill; SpexSamplePrep), the two types of powders (Ta + selected ceramic one) were high-energy mixed and milled for 48 h at the room temperature in the Ar 5.0 atmosphere. The steel-hardened vial with ball bearings ($>62\text{ HRC}$) was used for proper mixing. Due to the milling of the ceramic phase, the Fe impurity was introduced to the nanocomposites, but, its content did not exceed 2 wt.%. The as-milled powders were axially hot-pressed (Elbit) at 4 Pa vacuum. The graphite die and the graphite movable punches were coated by boron-nitride lubricant spray (HeBoCoat) during the process. The pressure of the punches directed at the powder was 50 MPa. The pulse plasma sintering mode (PPS) was used for the heating. The heating rate, sintering temperature, and time were set at $650^\circ C/\text{min}$, $1300^\circ C$, and 5 s. The other setup parameters for the PPS process were automatically selected to maintain proper heating rate and sintering temperature.

For comparison, the nanocrystalline pure tantalum was made using high-energy ball-milling (HEBM) and PPS. In the MA process, at least two different powders (Ta and ceramic powders) are mixed and milled together, whereas in HEBM, only the one component (Ta powder) is mixed and milled. Both processes were conducted in SPEX mill at the same conditions.

The structure and microstructure were investigated using Empyrean XRD (Panalytical) with $CuK\alpha$ radiation, SEM Vega 5135 (Tescan) with EDS PGT Prism 200 Avalon (Princeton Gamma-Tech), AFM Q-Scope 250 (Quesant), and TEM CM 20 Super Twin (Philips). For the AFM and SEM observations, all the bulk samples were grinded up to 1000 grit, polished in the Al_2O_3 suspension, and etched in an $H_2SO_4 + HNO_3 + HF$ mixture to reveal the grain morphology. More details regarding the above equipment used by the authors have been provided in [23].

The mechanical properties were measured using a Picodentor HM500 (Fischer) nanoindentation tester. The following parameters were measured: HV, Vickers hardness; E_{IT} , indentation modulus; C_{IT} , indentation creep; W_t , total mechanical work of indentation; and N_{plast} , plastic deformation portion. The indentation force load was 300 mN for 20 s. The load-displacement curves were recorded. For the measurement of the mechanical properties, the authors used unetched samples to avoid incorrect measurement results.

3. Results

The tantalum metal of a cubic structure (Figures 1(a), 2(a), and 3(a)) was mixed and milled with ceramic Y_2O_3 (cubic), ZrO_2 (monoclinic), and TaC (cubic) powders (Figures 1(b), 2(b), and 3(b), resp.) of different crystallographic parameters. During the intense milling, the ceramic phase is

FIGURE 1: XRD of the pure Ta (a) and Y_2O_3 (b) powders; Ta-5 Y_2O_3 (c) and Ta-40 Y_2O_3 (d) nanocomposites' powder mixture after mechanical alloying; and Ta-5 Y_2O_3 (e) and Ta-40 Y_2O_3 (f) bulk nanocomposites after consolidation.

homogenously distributed in the mixture of powders. For the Ta composites of low ceramic content (Figures 1(c), 2(c), and 3(c)), the MA process results mainly in the formation of a solid solution or a highly dispersed ceramic phase in the tantalum matrix. No visible peaks of the oxide ceramic phase are present (Figures 1(c) and 2(c)); however, carbides are visible (Figure 3(c)). An increase in the content of the ceramic phase leads to a typical composite structure, showing peaks (tantalum and the ceramic phase) (Figures 1(d), 2(d), and 3(d)). The consolidation process conducted at an elevated temperature in a graphite die can lead to additional carburization and formation of additional tantalum carbides (Figures 1(e) and 1(f)). High temperature can lead to diffusion of oxygen from the oxides and formation of (Y, Ta) O at a higher ceramic phase content (Figure 1(f)). The made materials are classified as composites, in which the metallic phase coexists with the ceramic phase.

FIGURE 2: XRD of the pure Ta (a) and ZrO_2 (b) powders; Ta-5 ZrO_2 (c) and Ta-40 ZrO_2 (d) nanocomposites' powder mixture after mechanical alloying; and Ta-5 ZrO_2 (e) and Ta-40 ZrO_2 (f) bulk nanocomposites after consolidation.

During the milling process, the ceramic phase affects the crystallographic parameters of the tantalum (Figure 4(a)) and vice versa—the tantalum affects the crystallographic parameters of the ceramic phase (Figure 4(b)). The ceramic phase has significantly different lattice parameters compared to tantalum. All the used materials have a cubic-type structure, but the lattice constant for the Ta, Y_2O_3 , ZrO_2 , and TaC is 3.306, 10.604, 5.065, and 4.456 Å, respectively. The volume of the unit cell for these materials is 35.127, 1192.365, 129.939, and 88.478 Å³, respectively. Only Y_2O_3 of the highest lattice constant leads to an increase in the lattice and volume of the unit cell of the tantalum matrix, whereas ZrO_2 and TaC participate in a slight reduction of these parameters for tantalum (Figure 4(a)). Alternatively, the tantalum can affect the lattice constant of the ceramic phase (Figure 4(b)) leading to a decrease in the lattice constant and volume of the unit cell, especially for a high Y_2O_3 content.

FIGURE 3: XRD of the pure Ta (a) and TaC (b) powders; Ta-5TaC (c) and Ta-40TaC (d) nanocomposites' powder mixture after mechanical alloying; and Ta-5TaC (e) and Ta-40TaC (f) bulk nanocomposites after consolidation.

The example TEM images of Ta and Ta-Y₂O₃ have been shown in Figure 5. The results confirm the two-phase nanostructure of the composite powders. Ta and the presented Ta-Y₂O₃ have a grain size of approximately 40–100 nm. The dark spots, clearly visible in Figures 5(b)–5(d), belong to the Y₂O₃ grains that are uniformly distributed in the Ta matrix. Generally, an increase in the Y₂O₃ content leads to a tantalum matrix grain size reduction.

The grain size reduction with the increased Y₂O₃ content was confirmed in the AFM measurements (Figure 6). The grains of nanocrystalline Ta (170 nm) were estimated earlier [24]. The introduction of nanocrystalline Y₂O₃ significantly shifts the grain size towards lower values. For 5% Y₂O₃, the average grain size was estimated at 76 nm, whereas for 10, 20, and 40 wt.% of Y₂O₃ it changed to 55, 70, and 42 nm, respectively. The increases in the Y₂O₃ concentration lead to a narrower grain size distribution as well as a smaller size of the largest grains.

FIGURE 4: The effect of the Y₂O₃, ZrO₂, and TaC content in the Ta-xY₂O₃, Ta-xZrO₂, and Ta-xTaC composites on the Ta lattice constant and the Ta volume of the unit cell (after MA process) (a) and the effect of the Ta content in the Ta-xY₂O₃, Ta-xZrO₂, and Ta-xTaC composites on the Y₂O₃, ZrO₂, and TaC lattice constant and the volume of the unit cell (b); x = 0, 5, 10, 20, and 40 wt.%.

The comparison of the Ta-based composite microstructure with different ceramic phases (all 40 wt.% for Y₂O₃, ZrO₂, and TaC) has been shown in Figure 7. The smallest grains have their composites reinforced with nanocrystalline Y₂O₃ (a, b), whereas the largest grains have the composites reinforced with TaC (e, f), but are the most homogenous. As for the tantalum-based composites reinforced with ZrO₂, they are inhomogeneous and concentrated ZrO₂ precipitations are present (c).

FIGURE 5: TEM images of the mechanically milled nanocrystalline Ta (a) and mechanically alloyed Ta-5Y₂O₃ (b), Ta-10Y₂O₃ (c), Ta-20Y₂O₃ (d), and Ta-40Y₂O₃ (e) nanocomposite powders; the smaller and darker particles correspond to ceramic phase, whereas bigger and lighter to tantalum matrix; the example grains are marked.

FIGURE 6: Continued.

FIGURE 6: AFM pictures (a, c, e, g) and grain size distribution (b, d, f, h) of the mechanically alloyed and consolidated bulk nanocomposites: Ta-5Y₂O₃ (a, b), Ta-10Y₂O₃ (c, d), Ta-20Y₂O₃ (e, f), and Ta-40Y₂O₃ (g, h).

FIGURE 7: Example of SEM (a, c, e) and AFM (b, d, f) images of the consolidated bulk Ta-40Y₂O₃ (a, b), Ta-40ZrO₂ (c, d), and Ta-40TaC (e, f) nanocomposites.

The average grain size (estimated using AFM) of all the investigated bulk composites has been shown in Figure 8. In all the composites, the grains are smaller in comparison to pure nanocrystalline tantalum. The smallest grains have the composites reinforced with Y₂O₃ and ZrO₂. Generally, the

majority of the composites have the grain size significantly below 100 nm.

The ceramic phase grains are well visible on the TEM images of the powders (Figure 5) and are well identified by AFM in the bulk samples (Figure 9). The example

FIGURE 8: Average grain size for the Ta- x Y₂O₃, Ta- x ZrO₂, and Ta- x TaC bulk nanocomposites ($x = 0, 5, 10, 20$, and 40 wt.%); data measured using AFM (not all AFM images and grain size distributions have been shown in this paper).

microstructure of the Ta-20ZrO₂ bulk nanocomposite shows two-phase morphology (Figure 9(a)), with slightly larger Ta grains (Figure 9(b)) compared to the ZrO₂ grains (Figure 9(c)). The corresponding EDS spectra show the grain composition of both the metallic and the ceramic phases. On the lower magnified image (Figure 9(a)), the ceramic phase grains are well visible, because after chemical etching, they are flatter compared to the Ta grains (the samples for the microscopic observations were grinded, polished, and chemically etched to reveal the grains, hence, the etched craters among the sintered agglomerate particles).

The mechanical properties (Figure 10, Table 1) show that the nanocrystalline materials have high strength. The hardness of pure microcrystalline Ta (447 HV) is lower compared to pure nanocrystalline Ta (584 HV). An introduction of the reinforced ceramic phase results in an increase in the hardness up to 1398 HV for Ta-10TaC. Up to the 20 wt.% content of the ceramic phase, the hardness remains very high for all the investigated materials: the highest for the Ta-TaC and the lowest for the Ta-ZrO₂ composites. As for the composites of the 40 wt.% content of the ceramic phase, their content is too high to achieve full material integration at the sintering temperature of 1300°C (this needs further investigation at a higher consolidation temperature); therefore, the hardness is significantly lower compared to other composites. Young's modulus increases from 164 GPa for nanocrystalline Ta to the highest value of 346 GPa for Ta-40TaC nanocomposites. The other parameters for composites (W_b , total mechanical work of indentation; N_{plast} , plastic deformation portion; and C_{IT} , indentation creep) are the highest for the 40 wt.% content of the ceramic phase, pointing to the too low sintering temperature (or time) to achieve full integrity of the samples (especially in the case of oxide-reinforced composites). The load-displacement curves (5 indents made on each sample at different spots) in most cases overlap one another indicating very good homogeneity of the microstructure and uniform material deformation during force loading-unloading. Consequently, the mechanical properties have a low value of standard deviation. At the highest oxide ceramic phase content, the curves have a relatively broad spectrum, which

is reflected in the low mechanical properties of these composites.

4. Discussion

The mechanical alloying applied to the tantalum and the ceramic phase particles leads to the formation of nanocrystalline mixture of both tantalum and ceramic grains. The grains have the size of several nanometers. The hot pressing in the PPS mode (performed at an elevated but relatively low temperature) leads to diffusion processes, which is necessary for strong particle bonding. The elevated temperature, however, is also the driving force for the grain growth. The relatively fast heating rate, short sintering time, and low sintering temperature result in a limited grain growth. The large volume of the grain boundaries of the nanocrystalline material should improve the densification process through the sliding mechanism. The agglomerates (formed in the mechanical alloying), which have significant voids between them work against high densification [25]. The pressure acting on the powders when the temperature increases (to the constant sintering temperature) improves the densification and reduces the voids between the consolidated powders. In general, for the densification of the nanocrystalline material, the consolidation temperature can be significantly lower compared to the microcrystalline material [13, 25]. The ceramic phase in the tantalum-based composites can suppress grain growth during consolidation. Hence, all the nanocomposites have a significantly lower grain size compared to pure nanocrystalline tantalum. The higher content (40 wt.%) of the oxide phase acts as a diffusion barrier; thus, in the Ta-40ZrO₂ and Ta-40Y₂O₃ composites, full microstructure integration during hot pressing at given conditions was not obtained. This is reflected in the mechanical properties, which are the worst for the Ta-40ZrO₂ and Ta-40Y₂O₃ composites. The high affinity of tantalum to oxygen leads to the formation of grain boundary oxides that cause embrittlement and grain size growth and the high temperature intensifies this effect [26]. In the case of the Ta-40TaC composite, the aforementioned process is limited. The high-temperature contact of the Ta-based powders with the graphite die and the punches leads to the diffusion of carbon and the

FIGURE 9: Example AFM images and EDS analysis showing the phase distribution in the consolidated bulk Ta-20ZrO₂ nanocomposite: larger area view (a), magnified area of the Ta grains (b), and ZrO₂ grains (c) with the corresponding EDS analysis.

formation of tantalum carbides, which was also observed by other authors [27].

The nanocomposites (composed of refractory tantalum as the metal matrix with the embedded refractory ceramic phase such as Y₂O₃, ZrO₂, and TaC) have very high mechanical properties, particularly the nanocrystalline Ta-TaC materials, which are promising in terms of heavy load conditions.

5. Conclusions

In this work, nanocomposites based on the Ta matrix reinforced by the ceramic phase of the Y₂O₃, ZrO₂, and TaC particles were developed. The mechanical alloying followed by hot pressing working in the pulse plasma sintering mode was applied for the bulk nanocomposite formation. We

FIGURE 10: Continued.

FIGURE 10: Load-displacement curves for consolidated bulk nanocrystalline composites: Ta-5Y₂O₃ (a), Ta-10Y₂O₃ (b), Ta-20Y₂O₃ (c), Ta-40Y₂O₃ (d), Ta-5ZrO₂ (e), Ta-10ZrO₂ (f), Ta-20ZrO₂ (g), Ta-40ZrO₂ (h), Ta-5TaC (i), Ta-10TaC (j), Ta-20TaC (k), and Ta-40TaC (l); for comparison bulk consolidated nanocrystalline Ta (m) and microcrystalline Ta (n).

TABLE 1: Mechanical properties of the investigated hot-pressed Ta-ceramic nanocomposites (data for micro- and nanocrystalline Ta for comparison).

	Mechanical properties				
	HV	E_{IT} (GPa)	W_t (μ J)	N_{plast} (%)	C_{IT} (%)
Ta micro	447 ± 17	211 ± 5	0.17 ± 0.01	81.6 ± 0.5	1.92 ± 0.08
Ta nano	584 ± 19	164 ± 8	0.16 ± 0.01	71.1 ± 2.5	1.54 ± 0.19
<i>Ta nanocomposites:</i>					
Ta-5Y ₂ O ₃	1055 ± 23	248 ± 2	0.12 ± 0.01	63.6 ± 0.7	1.14 ± 0.08
Ta-10Y ₂ O ₃	835 ± 23	234 ± 2	0.14 ± 0.01	68.7 ± 0.5	1.56 ± 0.07
Ta-20Y ₂ O ₃	1165 ± 8	242 ± 1	0.12 ± 0.01	60.0 ± 0.2	1.26 ± 0.03
Ta-40Y ₂ O ₃	436 ± 52	114 ± 10	0.20 ± 0.04	70.3 ± 3.5	1.70 ± 0.48
Ta-5ZrO ₂	821 ± 24	231 ± 4	0.14 ± 0.01	69.6 ± 1.0	1.66 ± 0.08
Ta-10ZrO ₂	920 ± 24	240 ± 8	0.13 ± 0.01	67.3 ± 0.5	1.72 ± 0.09
Ta-20ZrO ₂	1003 ± 3	246 ± 1	0.13 ± 0.01	64.7 ± 0.1	1.30 ± 0.03
Ta-40ZrO ₂	366 ± 44	115 ± 3	0.21 ± 0.02	75.5 ± 2.6	2.15 ± 0.17
Ta-5TaC	984 ± 21	273 ± 3	0.13 ± 0.01	67.8 ± 0.4	1.29 ± 0.05
Ta-10TaC	1398 ± 46	336 ± 5	0.11 ± 0.01	61.6 ± 0.9	1.01 ± 0.05
Ta-20TaC	1252 ± 69	303 ± 11	0.12 ± 0.01	63.5 ± 1.2	1.17 ± 0.07
Ta-40TaC	994 ± 48	346 ± 12	0.12 ± 0.01	70.1 ± 1.6	2.17 ± 0.69

HV, Vickers hardness; E_{IT} , indentation modulus; W_t , total mechanical work of indentation; N_{plast} , plastic deformation portion; C_{IT} , indentation creep.

made Ta composites with addition of up to 40% of the ceramic phase. The nanocomposite materials have the average grain size of approximately 40–100 nm, significantly lower than nanocrystalline Ta (170 nm). The lowest grain size has the composites reinforced by oxides. Both reinforced factors, the fine-grained nanostructure and the ceramic phase, lead to significant increase in the hardness as well as Young's modulus. For Ta-10TaC, the hardness and the Young's modulus reach 1398 HV and 336 GPa, respectively. For comparison, pure nanocrystalline Ta has the value of 584 HV and 164 GPa, respectively, whereas microcrystalline Ta has the value of 447 HV and 211 GPa, respectively. The combination of the MA and PPS processes has a potential in developing nanocomposites of high mechanical properties.

Data Availability

The original data files are the property of the Poznan University of Technology and are located in its repository.

Access will be considered by the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The work has been financed by the National Science Centre, Poland, under project identification DEC-2015/19/B/ST5/02595.

References

- [1] G. Samsonov, *Handbook of Refractory Compounds*, Springer-Verlag, New York, NY, USA, 2012.
- [2] C. L. Briant, "The properties and uses of refractory metals and their alloys," *MRS Proceedings*, vol. 322, pp. 305–314, 1993.

- [3] H. O. Pierson, *Handbook of Refractory Carbides and Nitrides. Properties, Characteristics, Processing and Applications*, Noyes Publ., New York, NY, USA, 1996.
- [4] S. A. Ghaffari, M. A. Faghihi-Sani, F. Golestani-Fard, and M. Nojabayy, "Diffusion and solid solution formation between the binary carbides of TaC, HfC, ZrC," *International Journal of Refractory Metals and Hard Materials*, vol. 41, pp. 180–184, 2013.
- [5] E. P. Simonenko, N. P. Simonenko, Y. S. Ezhov, V. G. Sevastyanov, and N. T. Kuznetsov, "Study of the synthesis of nanocrystalline mixed tantalum–zirconium carbide," *Physics of Atomic Nuclei*, vol. 78, no. 12, pp. 1357–1365, 2015.
- [6] L. Xu, S. Wei, J. Li, G. Zhang, and B. Dai, "Preparation, microstructure and properties of molybdenum alloys reinforced by in-situ Al_2O_3 particles," *International Journal of Refractory Metals and Hard Materials*, vol. 30, no. 1, pp. 208–212, 2012.
- [7] F. Xiao, L. Xu, Y. Zhou et al., "Preparation, microstructure, and properties of tungsten alloys reinforced by ZrO_2 particles," *International Journal of Refractory Metals and Hard Materials*, vol. 64, pp. 40–46, 2017.
- [8] M. Battabyal, R. Schäublin, P. Spätig, and N. Baluc, "W-2 wt.% Y_2O_3 composite: microstructure and mechanical properties," *Materials Science and Engineering A*, vol. 538, pp. 53–55, 2012.
- [9] S. A. Ghaffari, M. A. Faghihi-Sani, F. Golestani-Fard, and S. Ebrahimi, "Pressureless sintering of Ta0.8Hf0.2C UHTC in the presence of MoSi_2 ," *Ceramics International*, vol. 39, no. 2, pp. 1985–1989, 2013.
- [10] M. A. Hussein, C. Suryanarayana, and N. Al-Aqeeli, "Fabrication of nano-grained Ti–Nb–Zr biomaterials using spark plasma sintering," *Materials and Design*, vol. 87, pp. 693–700, 2015.
- [11] A. Michalski and D. Siemiaszko, "Nanocrystalline cemented carbides sintered by the pulse plasma method," *International Journal of Refractory Metals and Hard Materials*, vol. 25, no. 2, pp. 153–158, 2007.
- [12] R. Chaim, "Superfast densification of nanocrystalline oxide powders by spark plasma sintering," *Journal of Materials Science*, vol. 41, no. 23, pp. 7862–7871, 2006.
- [13] Z. Fang, P. Maheshwari, X. Wang, H. Y. Sohn, A. Griffo, and R. Riley, "An experimental study of the sintering nanocrystalline WC-co powders," *International Journal of Refractory Metals and Hard Materials*, vol. 25, no. 4–6, pp. 249–257, 2005.
- [14] M. K. Surappa and P. K. Rohatgi, "Preparation and properties of cast aluminium-ceramic particle composites," *Journal of Materials Science*, vol. 16, no. 4, pp. 983–993, 1981.
- [15] L. Olmos, C. L. Martin, and D. Bouvard, "Sintering of mixtures of powders: experiments and modelling," *Powder Technology*, vol. 190, no. 1–2, pp. 134–140, 2009.
- [16] R. Orrù, R. Licheri, A. M. Locci, A. Cincotti, and G. Cao, "Consolidation/synthesis of materials by electric current activated/assisted sintering," *Materials Science and Engineering R*, vol. 63, no. 4–6, pp. 127–287, 2009.
- [17] M. S. Yurlova, V. D. Demenyuk, Y. L. Lebedev, D. V. Dudina, E. G. Grigoryev, and E. A. Olevsky, "Electric pulse consolidation: an alternative to spark plasma sintering," *Journal of Materials Science*, vol. 49, no. 3, pp. 952–985, 2014.
- [18] J. Q. Li, W. A. Sun, W. Q. Ao, K. M. Gu, and P. Xiao, " Al_2O_3 –FeCrAl composites and functionally graded materials fabricated by reactive hot pressing," *Composites Part A*, vol. 38, no. 2, pp. 615–620, 2007.
- [19] S. S. Nayak, M. Wollgarten, J. Banhart, S. K. Pabi, and B. S. Murty, "Nanocomposites and an extremely hard nanocrystalline intermetallic of Al–Fe alloys prepared by mechanical alloying," *Materials Science and Engineering A*, vol. 527, no. 9, pp. 2370–2378, 2010.
- [20] G. Zhang and D. Gu, "Synthesis of nanocrystalline TiC reinforced W nanocomposites by high-energy mechanical alloying: microstructural evolution and its mechanism," *Applied Surface Science*, vol. 273, pp. 364–371, 2013.
- [21] O. B. Zgalat-Lozinskii, "Nanocomposites based on refractory compounds, consolidated by rate-controlled and spark-plasma sintering (review)," *Powder Metallurgy and Metal Ceramics*, vol. 53, no. 1–2, pp. 19–30, 2014.
- [22] T. Niu, W.-W. Chen, H.-W. Cheng, and L. Wang, "Grain growth and thermal stability of nanocrystalline Ni– TiO_2 composites. Transactions of Nonferrous Metals," *Society of China*, vol. 27, no. 10, pp. 2300–2309, 2017.
- [23] J. Jakubowicz, G. Adamek, M. Sopata, J. K. Koper, T. Kachlicki, and M. Jarzebski, "Microstructure and electrochemical properties of refractory nanocrystalline Tantalum-based alloys," *International Journal of Electrochemical Science*, vol. 13, pp. 1956–1975, 2018.
- [24] J. Jakubowicz, G. Adamek, and M. Sopata, "Characterization of high-energy ball-milled and hot-pressed nanocrystalline tantalum," *IOP Conference Series: Materials Science and Engineering*, vol. 216, p. 012006, 2017.
- [25] S. H. Yoo, T. S. Sudarshan, K. Sethuram, G. Subhash, and R. J. Sowding, "Consolidation and high strain rate mechanical behavior of nanocrystalline tantalum powder," *Nanostructured Materials*, vol. 12, no. 1–4, pp. 23–28, 1999.
- [26] M. Bischof, S. Mayer, H. Leitner et al., "On the development of grain growth resistant tantalum alloys," *International Journal of Refractory Metals and Hard Materials*, vol. 24, no. 6, pp. 437–444, 2006.
- [27] Y. Kim, E. P. Kim, J. W. Noh, S. H. Lee, Y. O. Kwon, and I. S. Oh, "Fabrication and mechanical properties of powder metallurgy tantalum prepared by hot isostatic pressing," *International Journal of Refractory Metals and Hard Materials*, vol. 48, pp. 211–216, 2015.