Research Progress on Toughening and Strengthening Mechanism of Ternary Boride Base Cermets

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Abstract. Cermet materials cover a wide range of applications in many related industries, such as aerospace key parts, automotive, mold, etc., and are often used to prepare various wear-resistant and corrosion-resistant roller tables, liners, molds and tools, etc. Ternary boride-based cermet materials are considered to be the most promising class of cermet materials because of their advantages such as high melting point, high hardness, high wear resistance and high oxidation resistance. However, ternary boride-based cermets exhibit some defects of large brittleness and low toughness. This article summarizes the latest research progress on ternary boride based cermets, and mainly discusses the influence of mechanical properties of ternary boride based cermets and the application of ternary boride based cermets by reinforcements and alloy elements. The current situation and the research direction of ternary boride based cermets are prospected.

Keywords: ternary boride; cermet; alloying elements; mechanical properties.

1. Introduction
Cermets are heterogeneous composite materials composed of metal or alloy and one or more ceramic phases, in which the ceramic phase accounts for about 15%-85% (volume fraction) and exists in the metal or alloy binder matrix [1]. Boride-based cermets are interstitial compounds, Boron and boron atoms can form strong covalent bonds and boron atoms can also form ionic bonds with other metal atoms. Therefore, they have high hardness, high melting point and high wear resistance, and are widely used in mechanical parts working in harsh environments such as wear resistance, high temperature resistance and corrosion resistance [2-7].

Binary boride cermets B₄C, TiB₂ and ZrB₂ have been studied by many researchers because of their high hardness, high strength and excellent wear resistance [8-14]. However, the brittleness and poor sinterability of binary borides have limited their application in the industrial field. Takagi et al.[15, 16] developed a new sintering process, called reaction boronizing sintering, as shown in Fig.1, which effectively solved this problem. Mo₂FeB₂, Mo₂NiB₂ and WCoB ternary boride base cermets with high wear resistance, corrosion resistance and high temperature resistance have been successfully prepared.
by this method [17]. Because of their excellent performance, these cermets are widely used in wear-resistant and corrosion-resistant industries such as stainless steel coatings, aviation, automobiles, etc.

![Figure 1. Schematic illustration of reaction boronizing sintering involving liquid phase to form a ternary boride base cermet.](image)

2. Influence of reinforcement on ternary boride based cermet

Although the ternary boride-based cermet has high temperature resistance and corrosion resistance, its brittleness severely limits its application. Researchers have found that fibers and whiskers can effectively enhance the transverse rupture strength (TRS) and fracture toughness (KIC) of the cermet. Carbon nanotubes (CNTS) in fiber toughened materials have the characteristics of complete structure, high strength and toughness, and are the most ideal toughened materials [18-22]. Compared with fiber reinforcement, whiskers are more conducive to preparing isotropic composite materials, which have ultra-high strength one-dimensional single crystal, high elastic modulus high strength and good thermal stability. At present, whiskers used as reinforcing phase most are SiC whiskers (SiCw) and Si3N₄ whiskers (Si3N₄w) [23-26]. The application of carbon nanotubes, SiCw and Si3N₄w in cermets in recent years will be mainly discussed below.

Liao Huang et al. [27] prepared Mo₂FeB₂-based cermets containing nickel-plated carbon nanotubes (Ni-CNTs) and CNTs. The results indicate that both Ni-CNTs and CNTs can refine the grains of hard phase and reduce the pores, but the toughening effect of Ni-CNTs on cermet is more remarkable. The Rockwell hardness, bending strength and fracture toughness of cermet containing 0.5wt% Ni-CNTs were increased by 20%, 28.6% and 19.6%, respectively, compared with those without Ni-CNTs. When the content of Ni-CNTs or CNTs is high, it is easy to agglomerate in the matrix to produce large pores, resulting in a significant decrease in hardness and bending strength. HaiZhou Yu et al. [28] Mo₂FeB₂-based cermets containing SiC whiskers were prepared, and the results indicate that when the SiCw content was 0.5wt%, the TRS of the cermet reached the maximum value of 2023 MPa, which was 14.0% higher than that of the cermet without whisker. Although the wettability of bonding relative hard phase was decreased by the addition of SiCw, SiCw located at grain boundary prevented grain boundary migration and restrained the grain growth. While TRS was improved by grain refinement. Yingjun Pan research group [27, 29, 30] studied the effects of nickel-plated Si₃N₄w (Ni-Si₃N₄w) and Si₃N₄w on the microstructure and mechanical properties of WCoB, Mo₂NiB₂, and Mo₂FeB₂-based cermets. The results show that Ni-Si₃N₄w significantly improves the performance of cermets than Si₃N₄w. The TRS of WCoB-based cermets with Ni-Si₃N₄w increased by 8.2%-26.9%, and the fracture toughness increased by 10.2%-25.6%. The cermet with 0.6wt% Ni-Si₃N₄w has the highest fracture toughness and TRS of 9.86 MPa·m 1/2 and 1080.2 MPa. The TRS and fracture toughness mechanics of the cermet Mo₂NiB₂ reach the maximum values of 1887.4MPa and 19.24mpa m1/2 when the content of Ni-Si₃N₄w is 0.6wt%. The Rockwell hardness, TRS and fracture toughness of Mo₂FeB₂ fund cermet with Ni-Si₃N₄w content of 0.5wt% increased by 20.1%, 23.1% and 10.4%, and the tearing edge and dimple of the fracture were the most obvious and developed. The above experimental methods all adopt vacuum liquid phase sintering, and the performance of the above experiments is summarized in detail as shown in Table 1.
Table 1. Effect of different reinforcements on mechanical properties of ternary boride base and toughening mechanism

| Cermet    | Reinforcements | Fibers/whiskers content (wt%) | TRS       | KIC      | Toughening mechanisms                                      |
|-----------|----------------|-------------------------------|-----------|----------|----------------------------------------------------------|
| Mo₂FeB₂   | CNTs           | 0.3                           | +12.9%    | +10.3%   | CNTs bridging, CNTs pull-out, crack deflection           |
| Mo₂FeB₂   | Ni-CNTs        | 0.5                           | +28.6%    | +19.6%   | CNTs bridging, CNTs pull-out, crack deflection           |
| Mo₂FeB₂   | Si₃N₄w         | 0.5                           | +10.8%    | +7.5%    | whisker bridging, whisker pull-out, crack deflection     |
| Mo₂FeB₂   | Ni-Si₃N₄w      | 0.5                           | +23.1%    | +10.4%   | whisker bridging, whisker pull-out, crack deflection     |
| Mo₂FeB₂   | SiCw           | 0.5                           | +14.0%    | +6.3%    | grain refinement, whisker bridging, crack deflection    |
| Mo₂NiB₂   | Ni-Si₃N₄w      | 0.5                           | +32%      | +26.2%   | Microcracks toughen                                     |
| WCoB      | Ni-Si₃N₄w      | 0.6                           | +26.9%    | +25.6%   | Bridging, whisker pull-out, crack deflection             |

As shown in Table 1, CNTs and whiskers can effectively improve TRS and fracture toughness of ternary boride based cermet. The toughening effect of the modified reinforcement is more obvious than that of the untreated reinforcement, which indicates that the modified reinforcement is the key to toughen cermet. Modification of the reinforcement used in ternary boride based cermet is nickel plating on the surface of the reinforcement, and the dispersibility, surface activity and wettability of the substrate of the reinforcement are improved. The improved dispersibility makes the reinforcement uniformly dispersed in the matrix, and the improved wettability makes the bonding force between the reinforcement and the matrix stronger. Currently, there are no other methods for modifying ternary boride based cermet reinforcements. In addition, as shown in Table 1, the toughening mechanisms of CNTs and whiskers mainly include crack deflection, fiber/whisker bridging and fiber/whisker pulling out. The toughening mechanisms of the three toughening mechanisms are shown in Fig. 2 [31]. The external load on cermet causes cracks, and the cracks propagate forward through the surface of reinforcements, resulting in two results: The reinforcement bridging is shown in fig.2 (a). The bridge exerts a compressive stress on the crack to increase the crack propagation resistance. The bridge occurs near the crack tip, where the crack track remains unchanged and the crack is divided into several segments by the reinforcement. The other is that cracks deflect as shown in fig.2 (b). The change of crack direction increases the crack path and reduces the stress intensity of crack. As shown in fig.2 (c), cracks passing through the reinforcement produce two results: When the internal bonding force of the reinforcement is less than that of the reinforcement with the matrix, then the reinforcement will produce fracture and absorb fracture energy. When the bonding force inside the reinforcement is greater than that between the reinforcement and the matrix, the reinforcement will be debonded from the matrix and then pulled out. Many fine cracks will be produced when the reinforcement is pulled out, which will relax the crack tip and slow down the crack propagation. Although the reinforcement can improve TRS and fracture toughness of ceram, due to the imperfect dispersion modification technology of the reinforcement, the amount of reinforcement added is relatively small. Excessive addition of reinforcingers will cause large pores in the matrix, reduce the wettability of binder phase relatively hard phase, and thus reduce the performance of cermet. Therefore, a better method of reinforcement dispersion modification is expected to toughen and strengthen ternary boride based cermet more significantly.
3. Influence of alloying elements on ternary boride based cermet

In order to improve the mechanical properties of ternary boride based cerments, researchers explored not only the enhancement of the reinforcement to cerments, but also the influence of various alloying elements on its properties. Researchers found that several alloying elements such as Cr, V, Mn and Ni can effectively improve the mechanical properties of cerments. Vacuum liquid phase sintering technique is used in the following literatures.

Ken-ichi et al. [15, 32, 33] explored the influence of nine alloying elements Fe, Co, Ti, Mn, Zr, Nb, W, Cr, and V on the microstructure and properties of Mo$_2$NiB$_2$ based cerments. It is found that only Cr and V can change orthorhombic Mo$_2$NiB$_2$ (O-Mo$_2$NiB$_2$) into tetragonal Mo$_2$NiB$_2$ (T-Mo$_2$NiB$_2$), and the structure of T-Mo$_2$NiB$_2$ is similar to that of Mo$_2$FeB$_2$ as shown in Fig.3 [34]. T-Mo$_2$NiB$_2$ has small anisotropy, fine grains and uniform structure. The TRS and rockwell hardness of Mo$_2$NiB$_2$ based cerments with 10wt% Cr addition reached 2300MPa and 86.8HRA. The TRS and rockwell hardness of Mo$_2$NiB$_2$ based cerments with 12.5wt% V addition reached 2500MPa and 90.5HRA. Although Mn cannot transform the crystal lattice, adding Mn to the Mo$_2$NiB$_2$ based cermet with added V or Cr can improve the wettability of the binder relatively hard phase, thereby increasing the bending strength of the cermet. The bending strength of Mo$_2$NiB$_2$ based cerments containing 12.5wt%V and 2.5wt%Mn reaches the highest value of 3500MPa. Lei Zhang et al. [35] explored the influence of different Ni content on the mechanical properties of Mo$_2$NiB$_2$ based cerments. It is found that cerments with Ni/B atomic ratio of 1.1 have the best mechanical properties as shown in Fig.4. An appropriate amount of Ni can promote the liquid phase flow and particle rearrangement in the sintering process, and improve the densification process of cerments. However, excessive Ni will lead to a decrease in hardness.

![Figure 2. Whisker/ fiber toughening mechanisms diagram: (a) bridging mechanism; (b) crack deflection mechanism; (c) Whisker / fiber pull-out mechanism](image)

![Figure 3. Crystal structures of three ternary borides: (a) Mo$_2$FeB$_2$; (b) T-Mo$_2$NiB$_2$; (c) O-Mo$_2$NiB$_2$.](image)
Figure 4. Mechanical properties of Mo$_2$NiB$_2$ based cermets with different Ni content. Ni/B atomic ratio A.0.9; B.1.0; C.1.1; D.1.2

Hao Wu et al. [36] studied the effect of Cr and w addition on Mo$_2$FeB$_2$ based cermets. It is found that the hardness of cermets increases with the increase of Cr content, and obviously decreases when it exceeds 5wt%. When 2.5wt%Cr was added to the ceramic, the wettability of binder phase relative to the hard phase was significantly improved, the porosity was significantly reduced, and the bending strength reached the maximum of 2179 MPa. The performance of cermets is improved because Cr diffuses and dissolves into Mo$_2$FeB$_2$ during liquid phase sintering, and Cr replaces part of Mo in Mo$_2$FeB$_2$ hard phase and part of Fe in binder phase, which makes Mo$_2$FeB$_2$ grains change from anisotropic shape to isotropic shape, which is consistent with the research results in reference [37]. Haizhou Yu et al [38] studied the effect of V on the microstructure of Mo$_2$FeB$_2$ based cermets. The Mo$_2$FeB$_2$ based cermet with V content between 0 and 0.75wt% and increment of 2.5wt%. It is found that Mo$_2$FeB$_2$ based cermets with 2.5 wt% V has the smallest grain size as shown in fig.5, which is consistent with the viewpoint in literature [39]. Xiao Yifeng et al. [40] studied the effect of adding different contents of V and Nb on Mo$_2$FeB$_2$ based cermets, and found that V can increase the isotropy in the growth process of hard phase particles. In addition, V can inhibit the dissolution and precipitation process of Mo element and refine the grains. Fenghao Yang et al. [41] studied the influence of Mn(0-10wt%) on Mo$_2$FeB$_2$ based cermets. It is found that the addition of Mn will refine the hard phase grains and distribute them evenly in the binder phase. Due to grain refinement and solid solution strengthening, the mechanical properties of cermets with Mn addition are improved. Weiwei Gong et al. [42] studied the influence of Ni on the properties of Mo$_2$FeB$_2$ based cermets. It is found that the bending strength of cermets increases with the increase of Ni content, and the highest bending strength of cermets with Ni content of 2.5wt% is 1293 MPa. With the increase of Ni content, ferrite in the binder phase changes to austenite, and austenite grains expand, which leads to the generation of microcracks and increases the bending strength. This conclusion has also been confirmed in literature [43]. So cermets with high toughness and hardness can be obtained by adding proper amount of Ni.
Deqing Ke [44] explored the influence of Cr and Ni on WCoB based cermet, and found that doping Cr at the position of Co atoms improves the bulk elastic modulus of cermet, but adding too much cermet to excessive Cr will reduce the bulk elastic modulus. The average grain size of the cermet hard phase with 2% Cr additive is the smallest, as shown in Fig.6. The Rockwell hardness, flexural strength and fracture toughness of the cermet are 92.3 HRA, 906.5 MPa and 12.45 MPa m$^{1/2}$. The TRS of cermet increased with the increase of Ni content, and the hardness first increased and then decreased with the increase of Ni content. The maximum TRS and fracture toughness of cermet containing 9.0wt%Ni were 895.6MPa and 11.85MPa m$^{1/2}$, respectively. The addition of Ni can improve the wettability of binder phase relative hard phase during sintering, and meanwhile increase the density of cermet, reduce the porosity, refine the

Figure 5. Microstructure of cermet with V content of: (a) 0 wt.%; (b) 2.5 wt.%; (c) 5.0 wt.%; (d) 7.5 wt.%

Figure 6. Average grain size of hard phase in WCoB based cermet with different Cr content

To sum up, alloying elements toughened ternary boride cermet mainly through three ways: increasing the wettability of binder phase relative hard phase, improving the isotropy of grain, and refining grain. The addition of the four alloying elements of Cr, V, Mn, and Ni will improve the wettability of the cermet bonding relative to the hard phase, and reduce the dihedral angle between the boride phase and the matrix phase, promote the densification process, and reduce Porosity, thus improving the bending strength of cermet. There are two main ways to strengthen the isotropic grains: adding Cr and V will transform the Mo$_2$NiB$_2$ based cermet lattice, from orthorhombic crystals to more
isotropic tetragonal crystals. In addition, Cr will replace the positions of Mo atoms, and the isotropy of the cermet increases after being replaced by Cr. The reasons of grain refinement by adding alloy elements in cermets are as follows: the growth of hard phase grains obeys the dissolution-precipitation mechanism, the solid solution of alloying elements into the binder inhibits the dissolution of the hard phase in the binder phase, and the hard phase crystals The growth rate of the grains is suppressed, and the grains are refined. In addition, literature [45] also found that V can react with C during the sintering process of cermets to form a grain inhibitor VC, which inhibits grain growth and refines the grains. The addition of alloying elements makes the crystal grains of cermets smaller and increases the strength or hardness, which is consistent with the Hall-Petch relationship given by [46]:

\[
\sigma = \sigma_0 + k d^{1/2}
\]

(1)

Where \(\sigma\) is the yield stress, \(\sigma_0\) is the lattice friction stress, \(k\) is a constant and \(d\) is the grain size.

Alloying elements increase the bending strength and fracture toughness of cermets, but also reduce their hardness. The addition of Ni in the ternary boride based cermet forms B-Ni bonds to increase the elastic modulus, and the formation of Mo-Ni bonds reduces the shear modulus, improves the toughness of the cermet and reduces the hardness [47]. The addition of V forms B-V covalent bonds in ternary borides and cermets. Although the ductility of cermets will increase, the shear modulus and hardness will decrease due to the weak B-V covalent bonds. Adding alloying elements Cr, V, Mn and Ni will change the mechanical properties such as fracture toughness, bending strength and hardness of cermets. In practical application, the content of alloying elements can be adjusted to obtain cermets with required properties.

4. Prospects

Nowadays ternary boride fund ceramics are widely used in stainless steel coating, aviation, automobile and tool industries. Compared with Mo$_2$NiB$_2$ and WCoB based cermets, Mo$_2$FeB$_2$ based cermets have attracted a lot of researchers’ research because of their cheap raw materials and good wear resistance. In the future, however, Mo$_2$NiB$_2$ and WCoB based cermets have a broad application prospect in the preparation of corrosion-resistant and high-temperature mechanical parts. Especially, Mo$_2$NiB$_2$ ceramics modified by alloy elements Cr or V have high hardness, high bending strength and corrosion resistance, which will have a wide application space in the preparation of parts in harsh environment in the future. Some progress has been made in improving the comprehensive performance of ternary boride-based cermets by adding carbon nanotubes/whiskers and alloying elements, but the performance of ternary boride-based technical ceramics needs to be improved. The future research directions of ternary boride-based cermets mainly include the following aspects: The first is to study the mechanism of the influence of various alloying elements on the microstructure and properties of ternary boride-based cermets. The second is to study the toughening mechanism of ternary boride-based cermets by carbon nanotubes and whiskers. The dispersion and modification of reinforcements are essential for toughening cermets. Better dispersion technology is expected to toughen ternary boride-based cermets more effectively. Finally, the influence model of reinforcing phase on the properties of cermets is established, which has far-reaching research significance for predicting the properties of ternary boride-based cermets.

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References

[1] Q. Jun, The Research on the Reinforcement Technology and Microstructure, Mechanical Properties of Ti(C,N)-based Cermets, Huazhong University of Science and Technology
[2] J.K. Sonber, A.K. Suri, Synthesis and consolidation of zirconium diboride: review, Advances in Applied Ceramics 110(6) (2013) 321-334.

[3] F. Cao, K. McEnaney, G. Chen, Z. Ren, A review of cermet-based spectrally selective solar absorbers, Energy & Environmental Science 7(5) (2014).

[4] H. Wu, Y. Zheng, J. Zhang, G. Zhang, Z. Ke, X. Xu, X. Lu, W. Zhou, Preparation of Mo2FeB2-based cerments with a core/rim structure by multi-step sintering approach, Ceramics International 45(17) (2019) 22371-22375.

[5] Y. Haizhou, L. Wenjun, F. Ping, Z. Yong, Synthesis and microstructure evolution during vacuum sintering of Mo2FeB2 based cerments, International Journal of Refractory Metals and Hard Materials 45 (2014) 48-52.

[6] Y. Yamasaki, M. Nishi, K.-i. Takagi, Development of very high strength Mo2NiB2 complex boride base hard alloy, Journal of Solid State Chemistry 177(2) (2004) 551-555.

[7] X. Ren, L. Yu, Y. Liu, H. Li, J. Wu, Z. Liu, Effects of extra boron addition on the liquid-state sintering process and properties of hard Mo 2 FeB 2-based cerments, International Journal of Refractory Metals and Hard Materials 61 (2016) 207-214.

[8] X. Li, Y. Gao, S. Wei, Q. Yang, Tribological behaviors of B 4 C-hBN ceramic composites used as pins or discs coupled with B 4 C ceramic under dry sliding condition, Ceramics International 43(1) (2017) 1578-1583.

[9] X. Li, Y. Gao, S. Wei, Q. Yang, Z. Zhong, Dry sliding tribological properties of self-mated couples of B4C-hBN ceramic composites, Ceramics International 43(1) (2017) 162-166.

[10] X. Li, Y. Gao, L. Song, Q. Yang, S. Wei, L. You, Y. Zhou, G. Zhang, L. Xu, B. Yang, Influences of hBN content and test mode on dry sliding tribological characteristics of B4C-hBN ceramics against bearing steel, Ceramics International 44(6) (2018) 6443-6450.

[11] X. Li, Y. Gao, Q. Yang, Sliding tribological performance of B4C-hBN composite ceramics against AISI 321 steel under distilled water condition, Ceramics International 43(17) (2017) 14932-14937.

[12] F. Ghafuri, M. Ahmadian, R. Emadi, M. Zakeri, Effects of SPS parameters on the densification and mechanical properties of TiB2-SiC composite, Ceramics International 45(8) (2019) 10550-10557.

[13] M.G.B. R. Gonzfilez, D. Ona, J.M. Sfinchez, A. Vilellas, A. Valea, F. Castro, New binder phases for the consolidation of TiB2 hardmetals, Materials Science and Engineering A216 (1996) 185-192.

[14] X. Li, S. Wei, Q. Yang, Y. Gao, Z. Zhong, Tribological performance of self-matching pairs of B4C/hBN composite ceramics under different frictional loads, Ceramics International 46(1) (2020) 996-1001.

[15] K.-i. Takagi, Development and application of high strength ternary boride base cerments, Journal of Solid State Chemistry 179(9) (2006) 2809-2818.

[16] K.-i. Takagi, High tough boride base cerments produced by reaction sintering, Materials Chemistry and Physics 67 (2001) 214–219.

[17] T.S. J. Kergnen, T. Mantyla, T. Lepisto Microstructural characterization of detonation gun-sprayed boride-based cermet coatings Surface and Coatings Technology 82 (1996) 29-37.

[18] M. Shahedi Asl, I. Farahbakhsh, B. Nayebi, Characteristics of multi-walled carbon nanotube toughened ZrB 2 –SiC ceramic composite prepared by hot pressing, Ceramics International 42(1) (2016) 1950-1958.

[19] J. Sumfleth, K. Prehn, M.H.G. Wichmann, S. Wedekind, K. Schulte, A comparative study of the electrical and mechanical properties of epoxy nanocomposites reinforced by CVD- and arc-grown multi-wall carbon nanotubes, Composites Science and Technology 70(1) (2010) 173-180.

[20] H. Chu, L. Wei, R. Cui, J. Wang, Y. Li, Carbon nanotubes combined with inorganic nanomaterials: Preparations and applications, Coordination Chemistry Reviews 254(9-10)
[21] L. Liu, R. Bao, J. Yi, C. Li, J. Tao, Y. Liu, S. Tan, X. You, Well-dispersion of CNTs and enhanced mechanical properties in CNTs/Cu-Ti composites fabricated by Molecular Level Mixing, Journal of Alloys and Compounds 726 (2017) 81-87.

[22] E. Zapata-Solvas, D. Gómez-García, A. Domínguez-Rodríguez, Towards physical properties tailoring of carbon nanotubes-reinforced ceramic matrix composites, Journal of the European Ceramic Society 32(12) (2012) 3001-3020.

[23] H. Xiong, Z. Li, K. Zhou, TiC whisker reinforced ultra-fine TiC-based cermets: Microstructure and mechanical properties, Ceramics International 42(6) (2016) 6858-6867.

[24] Y. Peng, Z. Peng, X. Ren, H. Rong, C. Wang, Z. Fu, L. Qi, H. Miao, Effect of SiC nano-whisker addition on TiCN-based cermets prepared by spark plasma sintering, International Journal of Refractory Metals and Hard Materials 34 (2012) 36-40.

[25] P. Wu, Y. Zheng, Y. Zhao, H. Yu, Effect of SiC whisker addition on the microstructures and mechanical properties of Ti(C, N)-based cermets, Materials & Design 32(2) (2011) 951-956.

[26] H. Kwon, C.Y. Suh, W. Kim, Preparation of a highly toughened (Ti,W)C-20Ni cermet through in situ formation of solid solution and WC whiskers, Ceramics International 41(3) (2015) 4223-4226.

[27] H. Liao, Effect of Carbon nanotubes and Si3N4 whiskers on Microstructure and Properties of Mo2FeB2-based Cermets, Wuhan University of Science and Technology (2019).

[28] H.Z. Yu, W.J. Liu, L. Ying, M. You, Microstructure and Mechanical Properties of Mo2FeB2 Based Cermets Containing SiC Whisker, Advanced Materials Research 625 (2012) 304-307.

[29] P. Yinghui, P. Yingjun , K. Deqing , G. Zhanghua, X. Xin, Effect of Si3N4 whiskers on microstructure and properties of in situprepared Mo2NiB2 cermet, 2020.

[30] W. Pan, The Preparation and Properties of WCoB-TiC Ceramic Composites, Wuhan University of Science and Technology (2018).

[31] E. Chicardi, Y. Torres, J.M. Córdoba, M.J. Sayagués, J.A. Rodríguez, F.J. Gotor, Effect of sintering time on the microstructure and mechanical properties of (Ti,Ta)(C,N)-based cermets, International Journal of Refractory Metals and Hard Materials 38 (2013) 73-80.

[32] K.-i. Takagi, W. Koike, A. Momozawa, T. Fujima, Effects of Cr on the properties of Mo2NiB2 ternary boride, Solid State Sciences 14(11-12) (2012) 1643-1647.

[33] K.-i. Takagi, Y. Yamasaki, Effects of Mo/B Atomic Ratio on the Mechanical Properties and Structure of Mo2NiB2 Boride Base Cermets with Cr and V Additions, Journal of Solid State Chemistry 154(1) (2000) 263-268.

[34] Y. Jian, Z. Huang, X. Liu, J. Xing, Comparative investigation on the stability, electronic structures and mechanical properties of Mo2FeB2 and Mo2NiB2 ternary borides by first-principles calculations, Results in Physics 15 (2019).

[35] L. Zhang, Z. Huang, Y. Liu, Y. Shen, K. Li, Z. Cao, Z. Ren, Y. Jian, Effect of Ni content on the microstructure, mechanical properties and erosive wear of Mo2NiB2–Ni cermets, Ceramics International 45(16) (2019) 19695-19703.

[36] H. Wu, Y. Zheng, J. Zhang, G. Zhang, Z. Ke, X. Xu, X. Lu, Influence of Cr and W addition on microstructure and mechanical properties of multi-step sintered Mo2FeB2-based cermets, Ceramics International 46(8) (2020) 10963-10970.

[37] Y. Shen, Z. Huang, P. Xiao, L. Zhang, K. Li, Z. Cao, Y. Jian, Sintering mechanism, microstructure evolution and nanomechanical properties of Cr-added Mo2FeB2 based cermets, Ceramics International 46(10) (2020) 15482-15491.

[38] H. Yu, Y. Zheng, W. Liu, J. Zheng, W. Xiong, Effect of V content on the microstructure and mechanical properties of Mo2FeB2 based cermets, Materials & Design (1980-2015) 31(5) (2010) 2680-2683.

[39] L. Wanfa, Z. Jia, W. Hao, L. Xupeng, Z. Yong, Effect of V Addition Amount on Microstructure and Mechanical Properties of Mo2FeB2-Based Cermets, 43 (2019) 32-36.

[40] X. Yifeng, G. Weiwei, X. Yanfei, W. Liang, Q. Jinwen, Z. Qiankun, H. Yuehui, Effects of NbC
and V content on microstructure and properties of Mo2FeB2-based cermet, Transactions of Materials and Heat Treatment 39 (2018) 137-142.

[41] F. Yang, Y. Wu, J. Han, J. Meng, Microstructure, mechanical and tribological properties of Mo2FeB2 based cermets with Mn addition, Journal of Alloys and Compounds 665 (2016) 373-380.

[42] G. Weiwei, X. yifeng, Study on Microstructure and Properties of Mo2FeB2 Based Cermet Prepared by Vacuum Sintering, Xiangtan University (2018).

[43] M.B. Ivanov, T.N. Vershinina, V.V. Ivanisenko, The effect of composition and microstructure on hardness and toughness of Mo2FeB2 based cermets, Materials Science and Engineering: A 763 (2019).

[44] K. Deqing Composition Design, Microstructure Control and Properties of WCoB-TiC Based Cermets, Wuhan University of Science and Technology (2019).

[45] H. Bing, P. Yingjun, W. Qingfang, Z. Huimin, X. Ming, Influence of addition element Cr and V on microstructure and properties of Mo2FeB2 based cermet, 36 (2011) 29-32.

[46] A. Loucif, R.B. Figueiredo, T. Baudin, F. Brisset, R. Chemam, T.G. Langdon, Ultrafine grains and the Hall–Petch relationship in an Al–Mg–Si alloy processed by high-pressure torsion, Materials Science and Engineering: A 532 (2012) 139-145.

[47] S. Wang, Y. Pan, Y. Lin, C. Tong, Influence of doping concentration on mechanical properties of Mo2FeB2 alloyed with Cr and Ni from first-principle calculations, Computational Materials Science 146 (2018) 18-25.