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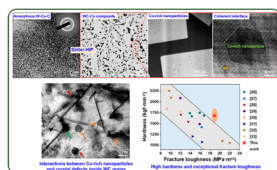
Microstructural evolution and toughening mechanism of WC-Co composite prepared by amorphous-crystallization method

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ABSTRACT

In this study, toughening of WC-Co composite prepared by amorphous-crystallization method was investigated. Co-rich nanoparticles, a Co(W,C) solid solution, were incorporated into the WC matrix through the process integrating crystallization of amorphous $\text{Co}_2\text{W}_4\text{C}$ powder and its in-situ reaction with carbon. The microstructural evolution of the ceramic-metal composite during fabrication was studied in detail. Owing to the interactions between Co-rich nanoparticles coherent with the WC matrix and the dislocations and stacking faults inside WC grains, the composite exhibited high hardness and strength combined with exceptional fracture toughness. The mechanisms for the synergistic improvement of mechanical properties of the composite were disclosed.



IMPACT STATEMENT

This study presents the novel preparation of WC-Co composite, characterized by the incorporation of Co-rich nanoparticles into the WC matrix via an amorphous-crystallization technique, yielding exceptional fracture toughness.

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KEYWORDS

WC-Co composite; amorphous-crystallization method; Co-rich nanoparticle; coherent interface; fracture toughness

1. Introduction

Compared with metals and alloys, ceramic and ceramic-metal (cermet) composite materials exhibit considerably less plasticity [1,2], a characteristic that facilitates crack nucleation and propagation within ceramic grains. This intrinsic limitation poses a significant hurdle in enhancing the strength and fracture toughness of ceramic-based materials. Nevertheless, substantial improvements in reinforcing the ceramic phase can be accomplished utilizing various techniques, including the refinement of grain size, the incorporation of solid solution atoms, and the control of grain boundary segregation [3–6]. In metals and alloys, precipitation strengthening, or second-phase strengthening, is an effective method of reinforcement. This method typically involves the utilization of non-deformable nanoparticles (e.g. Al_2O_3 , ZrO_2 , SiC , TiC [7,8]), which significantly hinder dislocation

movement. Additionally, deformable nanoparticles that have a coherent relationship with the matrix can also effectively strengthen the metal matrix [9]. However, due to the considerable challenge of incorporating heterogeneous particles into the interior of ceramic grains [10–12], few studies have focused on the second-phase strengthening and toughening of ceramic phases.

As a representative ceramic-metal composite material, the WC-Co cemented carbides can be strengthened by enhancing both the Co binder phase and the WC matrix using the second-phase particles. The incorporation of heterogeneous particles into Co inevitably sacrificed its plasticity while increasing the strength of the bulk materials [13]. For the enhancement of WC phase, the carbides such as TaC , ZrC , TiC , VC , NbC , Cr_3C_2 , have been employed. The results showed that the addition of TaC to WC-Co composites readily led to the

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formation of a hard and brittle (W,Ta)C phase [14,15]. The inadequate wetting between the (W,Ta)C and Co phases facilitates grain boundary sliding or penetration by the Co phase at elevated temperatures, which reduces the mechanical properties of the composites under high-temperature conditions [15]. In the WC-Ni composites with ZrC addition, the (Zr,W)C phase easily precipitates within coarse WC grains [16]. An investigation into the addition of 0.8 wt.% ZrC to WC-Co composite has shown that the precipitated phase in WC measures over 200 nm in size. Particularly, when the size of this precipitated phase decreases to below 150 nm, coherent interfaces are possibly formed between the precipitated phase and the WC matrix. Nevertheless, most of the interfaces between the precipitated phase and WC exhibit either no-coherence or semi-coherence [17]. Besides, the addition of TaC, TiC, VC, NbC and Cr₃C₂ may result in formation of ‘complexion’ at the phase boundaries of WC and Co in the sintering process of cemented carbides [18]. Using the conventional powder metallurgy routes [19,20], it is difficult to introduce particles into the WC grains with the aim to strengthen and toughen simultaneously the ceramic phase.

The amorphous-crystallization method is a feasible way to prepare nanocrystalline metallic materials with uniform microstructure [21,22]. Inspired by this method, a novel route consisting of powder amorphization, crystallization and subsequent in situ reaction processes to prepare dense WC-Co composite materials, was proposed [23,24]. Using this method, the WC-Co bulk material characterized by formation of many Co-rich nanoparticles inside WC grains was fabricated in this work. The formation mechanisms of the nanoparticles and the effects on the mechanical properties of the WC-Co composite were studied in detail. The results presented in this work will provide new insights into obtaining ceramics and ceramic-metal composites with high comprehensive mechanical properties.

2. Experimental

2.1. Materials preparation

First, the commercially available W powder (particle size < 1 µm, purity > 99.5%), Co powder (particle size < 1 µm, purity > 99.8%), and carbon black powder (particle size < 0.5 µm, purity > 99.8%) were mixed in stoichiometric proportions to synthesize the Co₂W₄C powder. The raw materials were purchased from Luoyang Golden Egret Geotools Co., Ltd. The mixed powders were heat-treated at 1300 °C for 2 h in a vacuum furnace, where the vacuum level was maintained at 10 Pa. Subsequently, the synthesized Co₂W₄C powder underwent

dry high-energy ball milling to achieve an amorphous state. The ball-to-powder ratio was set at 20:1 with a rotational speed of 580 rpm, and the milling time lasted for 80 h. To avoid the introduction of impurities, the WC-Co cemented carbide jars and balls were used in all the ball milling processes. Following this, the Co₂W₄C powder was blended with carbon black powder to ensure a uniform amorphous mixture. Based on the stoichiometric requirements of the in-situ reaction between Co₂W₄C and carbon, 4.0 wt.% of carbon black was incorporated into the amorphous powder. This mixture served as the precursor for the final WC-Co composite, which was designed to have a cobalt content of 13.62 wt.% and a precise phase composition. The mixing process was carried out using wet ball milling with a ball-to-powder ratio of 3:1 and a milling duration of 20 h. Finally, the prepared Co-W-C amorphous powder mixture was subjected to heat-treatment and sintering at 1390 °C using the sinter-HIP furnace (PVA COD433R), followed by cooling in the furnace to ambient temperature.

2.2. Characterizations

The phase constitution of both the powder and bulk samples was analyzed by X-ray diffraction (XRD, Rigaku Ultimate IV) using Cu K_α irradiation ($\lambda = 0.15406$ nm), a scanning step of 0.02° and a scanning speed of 2°/min. The microstructures of the samples were examined by transmission electron microscopy (TEM, FEI Tecnai G2 F20) and high-resolution TEM (HRTEM). For the powder samples, TEM test films were prepared by embedding the powder particles in a resinous organic solvent, followed by ultra-thin sectioning. For the bulk samples, the TEM test films were prepared by focused ion beam (FIB, FEI Helios G4 PFIB CXe) technology. To analyze the composition of the samples, energy dispersive spectroscopy (EDS) mappings were conducted using the high-angle annular dark-field (HAADF) imaging in an aberration-corrected scanning transmission electron microscope (STEM) operated at 300 kV.

The hardness and fracture toughness of the sintered samples were measured using a Vickers hardness tester under a load of 30 kg in accordance with the ISO-3878 standard. The fracture toughness (K_{IC}) was determined by measuring the crack length then calculating with the equation $K_{IC} = 0.0028(HP/L)^{1/2}$ [23], where H is the indentation hardness (N/mm²), P is the indentation load (N) and L is the total crack length (mm). Additionally, the sintered samples were machined into cylinder samples with dimensions of $\phi 3 \times 4$ mm. These cylinder samples were then subjected to compression testing at a strain rate of 0.5 s⁻¹ at room temperature to assess their mechanical performance.

3. Results and discussion

The phase constitutions of the synthesized powders and sintered WC-Co composite bulk with 13.62 wt.% Co are shown in Figure 1(a). After milling for 20 h, the powder mixture, consisting of $\text{Co}_2\text{W}_4\text{C}$ and 4.2 wt.% carbon black, transformed into an amorphous state, as indicated by the significantly broadened diffraction peaks. Upon sintering the amorphous powder at 1390 °C by sinter-HIP, the resulting bulk material consisted of WC and Co, confirming the completion of both crystallization and carbonization processes. The prepared composite bulk material obtained a pure phase constitution. It is worthy to note that it is possible to prepare WC-Co composites with different Co contents using the amorphous-crystallization method. On the one hand, other ternary carbides, such as $\text{Co}_6\text{W}_6\text{C}$ and $\text{Co}_3\text{W}_9\text{C}_4$ with different Co contents, can be utilized to adjust the proportion of Co in the target material. On the other hand, a small amount of additional Co powder can be added to meet the compositional requirements.

Figure 1(b) shows the HRTEM image of the powder mixture and its selected area electron diffraction (SAED) pattern. It is evident that there is no long-range ordered atomic cluster within the amorphous matrix. The SAED pattern exhibits a characteristic diffraction halo, further

confirming the typical amorphous structure. The SEM microstructure of the sintered WC-Co composite bulk is shown in Figure 1(c). The elemental mapping for Co, W, and C (Figure 1(d-f)) demonstrates that the WC and Co phases are uniformly distributed throughout the composite. As estimated, the composite has a mean WC grain size of approximately 0.71 μm and a relative density of nearly 100%, which enables the achievement of exceptional mechanical properties.

The HAADF-STEM images of the prepared WC-Co composite bulk are shown in Figure 2(a) and (b). Within the WC grains, a considerable number of fine and uniformly distributed nanoparticles with an average size of approximately 10 nm can be observed. The EDS mapping and line scanning analyses shown in Figure 2(b) and (c) reveal that the nanoparticles are predominantly enriched in Co, suggesting the presence of Co-rich nanophase within WC grains.

The equilibrium shape of WC crystals is typically characterized by the presence of two basal planes, denoted as $\{0001\}$, and three prismatic planes, referred to as $\{10\bar{1}0\}$ [25]. The characteristics of nanoparticles situated on these distinct surfaces of WC crystals will be detailedly studied to reveal their morphology, formation mechanisms and effects on the mechanical properties of the WC-Co composite.

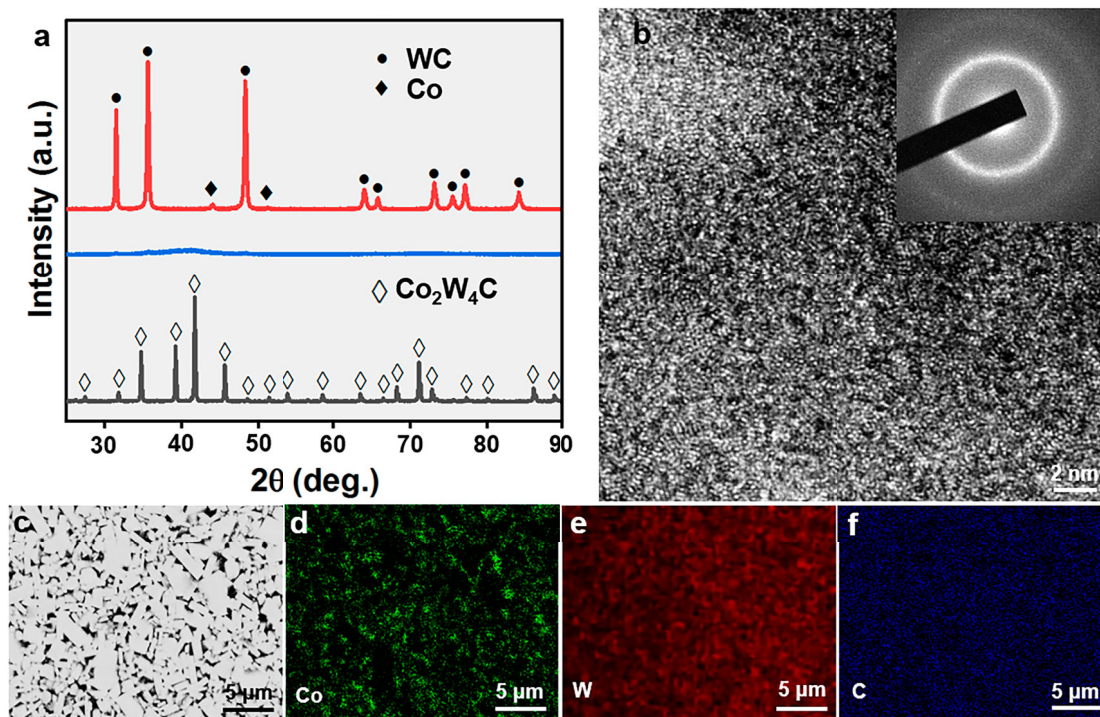


Figure 1. Phase and microstructural analyses of the WC-Co composite prepared via the sintering of amorphous powder using the sinter-HIP technique: (a) XRD patterns of the synthesized $\text{Co}_2\text{W}_4\text{C}$ powder, amorphous powder mixture and sintered WC-Co bulk; (b) HRTEM image and corresponding SAED pattern of the amorphous powder mixture; (c) SEM image of the sintered WC-Co bulk; (d-f) EDS elemental mapping for Co, W and C in (c).

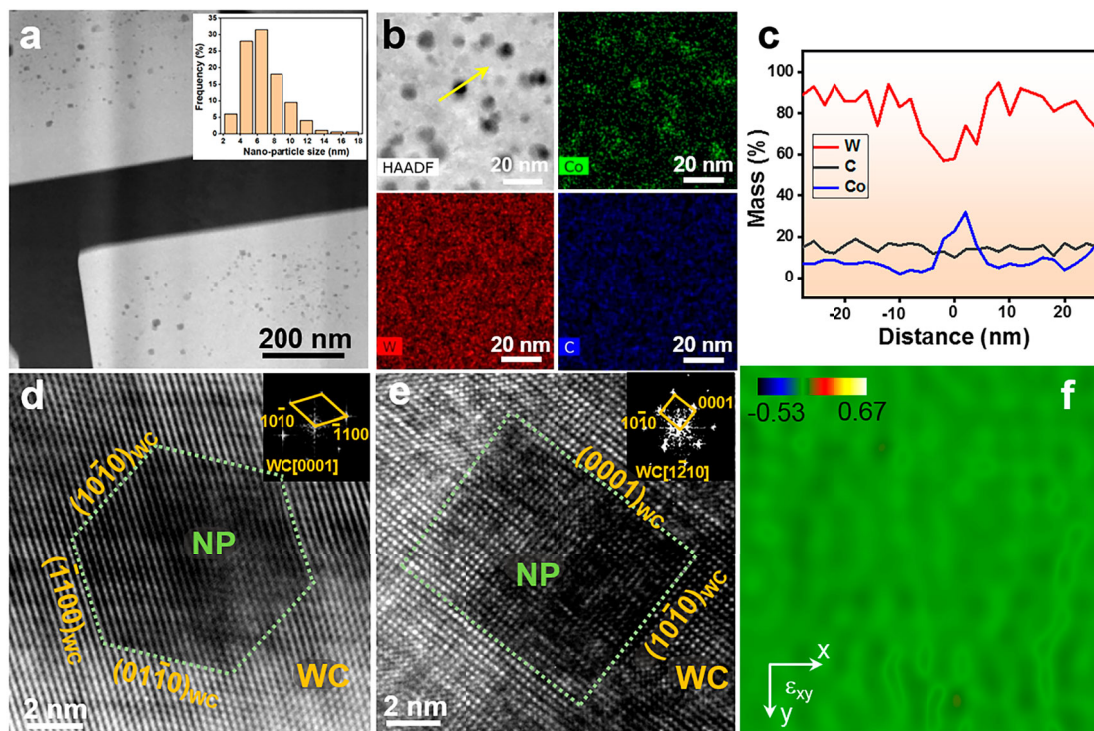


Figure 2. Characterizations of Co-rich nanoparticles within WC grains: (a) HAADF-STEM image and particle size distribution of nanoparticles within WC grains; (b) Enlarged image of nanoparticles and corresponding EDS elemental mapping for Co, W and C; (c) line scanning analysis across the nanoparticle; (d,e) Interfacial relationships between the nanoparticles and WC crystals with an axis of WC(0001) and WC($1\bar{2}10$), respectively; (f) Geometric phase analysis (GPA) of the interfaces between nanoparticles and WC

The nanoparticles on the WC(0001) plane exhibits an equilateral hexagon morphology, as depicted in Figure 2(d). This hexagonal shape aligns with the six $\{10\bar{1}0\}$ crystal planes of WC. The interface between the nanoparticles and the WC matrix is characterized by a straight boundary, suggesting a high degree of lattice matching and epitaxial growth. In contrast, the nanoparticles on the WC($1\bar{2}10$) plane has a quadrate shape, as shown in Figure 2(e). The quadrate nanoparticles are in contact with the $\{10\bar{1}0\}$ and $\{0001\}$ crystal planes of WC, highlighting the versatility of nanoparticle shapes in response to different crystallographic orientations. The difference in the length of the nanoparticles along WC[0001] and WC[$10\bar{1}0$] directions suggests that their dimensions are influenced by the crystallographic directions and the associated growth rate. The nanoparticles on the WC(0001) and WC($1\bar{2}10$) crystal planes show a coherent interfacial relationship with the WC matrix. Moreover, the geometric phase analysis (GPA) of the interfaces between the nanoparticles and WC, as presented in Figure 2(f), reveals that there is no stress concentration at the boundary.

To elucidate the formation mechanism of Co-rich nanoparticles in the WC matrix, the amorphous Co-W-C powder was subjected to a heat-treatment at 800 °C

for 2 h, in alignment with the thermodynamic conditions governing WC growth as indicated by literature [23,24]. The resulting powder at this temperature primarily consists of WC and $\text{Co}_3\text{W}_3\text{C}$, as depicted in Figure 3(a). The HAADF-STEM image of the powder reveals an extremely fine mean grain size of approximately 10 nm, as shown in Figure 3(b) and (c), suggesting that these nanocrystals originate from the crystallization of the amorphous Co-W-C matrix. The SAED pattern of the powder shows obvious polycrystalline diffraction rings (Figure 3(d)), corresponding to the crystal planes of WC(0001), WC($10\bar{1}1$) and $\text{Co}_3\text{W}_3\text{C}(331)$, respectively. The HRTEM image (Figure 3(e)) shows the interfacial structures between $\text{Co}_3\text{W}_3\text{C}$ and WC, within which there are no nanoparticles detected. The measured misfit of the interplanar spacing between the WC($01\bar{1}0$) plane and the $\text{Co}_3\text{W}_3\text{C}(004)$ plane is 0.005, while that between the WC(0001) plane and the $\text{Co}_3\text{W}_3\text{C}(331)$ plane is 0.02, suggesting the formation of coherent interfaces. The newly formed WC phase has an orientation relationship with the $\text{Co}_3\text{W}_3\text{C}$ matrix as WC(0001)//fcc- $\text{Co}_3\text{W}_3\text{C}(331)$, WC[$1\bar{2}10$]//fcc- $\text{Co}_3\text{W}_3\text{C}[110]$ and WC($01\bar{1}0$)//fcc- $\text{Co}_3\text{W}_3\text{C}(004)$, WC[0001]//fcc- $\text{Co}_3\text{W}_3\text{C}[110]$. These coherence interfaces, characterized by a low energy state, facilitated the nucleation and growth of the WC phase.

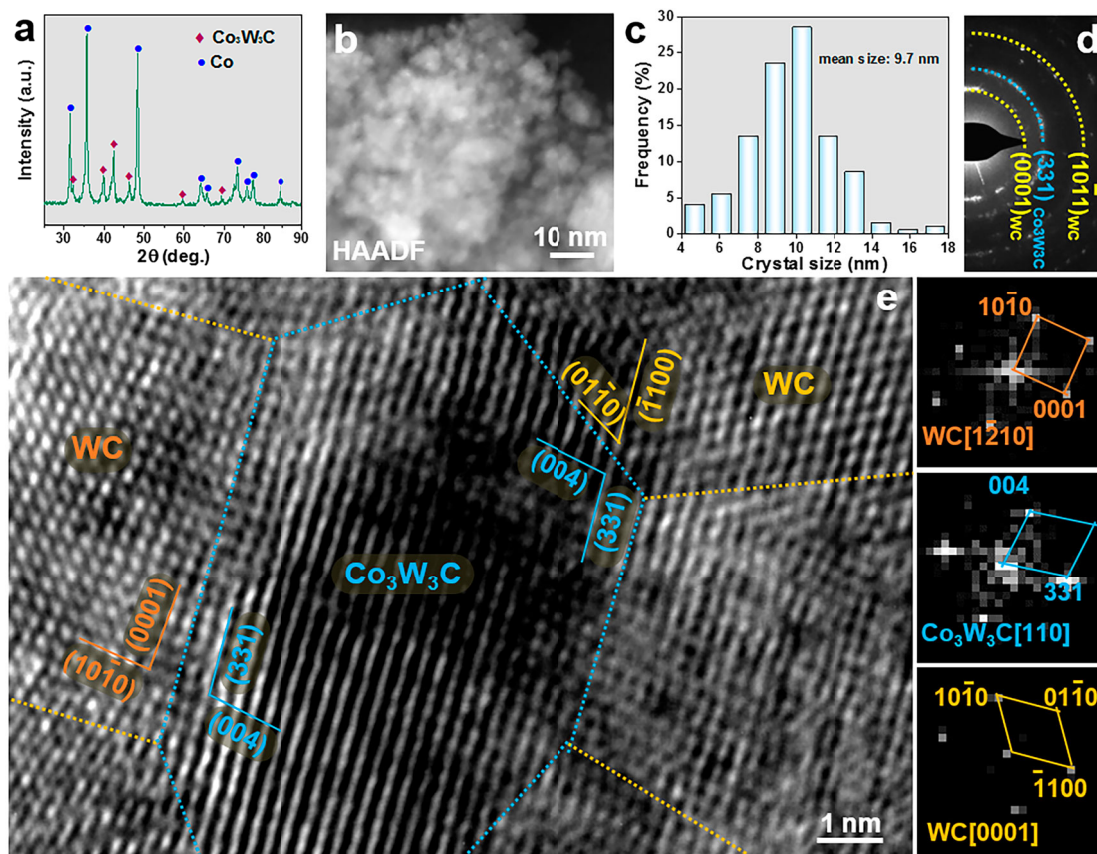


Figure 3. Characterizations of the amorphous powder mixture after heat-treatment at 800 °C for 2 h; (a) Phase constitution; (b) HAADF-STEM image; (c) Grain size distribution; (d) SAED pattern of the observed area in (b); (e) Coherent interface relationship between $\text{Co}_3\text{W}_3\text{C}$ and WC.

The formation mechanism of the Co-rich nanoparticles with a dispersed distribution in WC grains is illustrated in Figure 4. During the crystallization process, the nanocrystals of $\text{Co}_3\text{W}_3\text{C}$ and WC precipitate from the amorphous Co-W-C matrix while the free carbon is randomly distributed among these nanograins (Figure 4a). As the temperature rises, the $\text{Co}_3\text{W}_3\text{C}$ phase reacts with carbon according to the equation: $\text{Co}_3\text{W}_3\text{C} + 2\text{C} = 3\text{WC} + 3\text{Co}$, resulting in the growth of the previously crystallized WC grains and the formation of Co. Owing to the presence of the coherent interfaces between the crystallized $\text{Co}_3\text{W}_3\text{C}$ and WC phases (Figure 4(b)), there is a low energy barrier for the atomic reconstruction of $\text{WC}\{10\bar{1}0\}$ plane from the cubic $\text{Co}_3\text{W}_3\text{C}\{331\}$ plane. As a result, the growth of WC grains is very fast and the simultaneously formed Co is caught inside the WC grains. Due to the extremely low solubility of Co in WC lattice, the newly formed Co transits into Co-rich nanoparticles within WC grains. With the continuous growth of WC grains, the Co-rich nanoparticles initially formed at the edge migrate towards the center of WC grains (Figure 4c). Nonetheless, the sizes of the

Co-rich particles are restricted to nanoscale due to the strong constraint from the ceramic WC matrix.

The mechanical properties of the fabricated WC-Co composite bulk with a cobalt content of 13.62 wt.%, together with those of the counterparts reported in the literature, are shown in Figure 5(a) and (b). It is evident that the present WC-Co composite exhibits a superior balance of hardness and fracture toughness in comparison to its counterparts [26–33]. Particularly, the fracture toughness obtained in this work is as high as $18.9 \pm 1.4 \text{ MPa}\cdot\text{m}^{1/2}$ while maintaining a hardness of $1618 \pm 80 \text{ kgf/mm}^2$, which is rarely reported for WC-Co composites. The compressive strength of the prepared WC-Co composite is 3518 MPa, as determined from the stress-strain curve shown in Figure 5(b).

The TEM microstructures of the WC-Co alloy in the deformation region after the compressive fracture strength test are shown in Figure 5(c) and (d). In this region, a typical WC grain and its internal features are observed. There is a high density of dislocations and stacking faults within the WC grain. The stacking faults resulting from dislocation slip traversed the entire WC

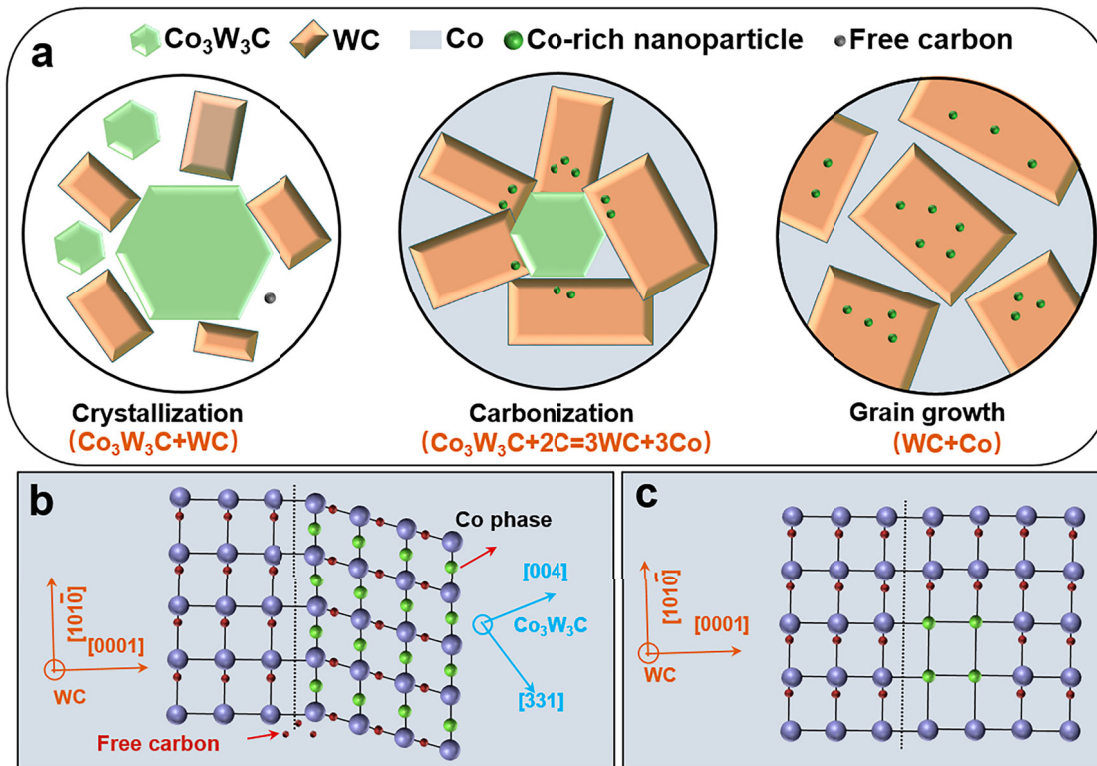


Figure 4. Formation mechanism of Co-rich nanoparticles within WC grains: (a) schematic diagram showing the formation process of the Co-rich nanoparticles; (b,c) evolution of coherent interfaces between the Co-rich particles and WC matrix.

grain. When these stacking faults encountered the dispersed Co-rich nanoparticles, two scenarios emerged. In one case, the internal Co-rich nanoparticles resulted in the cross-slip of partial dislocations on the crystal plane of WC(10 $\bar{1}0$) (indicated by the green arrow). In another case, the stacking faults terminated within the Co-rich phase (marked by the red arrow), while others directly cut through the nanoparticles, which dominated the slip process. Notably, around the Co-rich nanoparticles, no significant accumulation or entanglement of dislocations is observed. Figure 5(d) shows the HRTEM microstructure of the framed area in Figure 5(c). It was found that the width of the stacking fault decreased significantly after crossing the nanoparticles. This suggested that the lattice distortion caused by the stacking fault was mitigated due to the presence of the Co-rich nanophase.

Though the fracture mode of the composite prepared by the present method is primarily intergranular fracture, transgranular fracture of WC grains also accounts for a relatively high proportion. The presence of Co-rich particles effectively hinders the motion of dislocations and stacking faults within WC grains. Moreover, the coherent interfaces between the Co-rich nanoparticles and WC matrix contributed to the stress coordination, thereby minimizing stress concentration and postponing

the emergence of microcracks. This, in turn, results in the inhibition of crack propagation within WC grains, and ultimately the strengthening and toughening of the composite.

4. Conclusions

In this study, a novel approach of incorporating Co-rich nanoparticles into ceramic WC matrix by crystallization of amorphous $\text{Co}_2\text{W}_4\text{C}$ powder and subsequent in situ reaction with carbon was proposed. The mechanisms for the formation of Co-rich nanoparticles within WC grains and their contribution to toughening the WC-Co composite were disclosed. The following conclusions can be drawn.

- (1) Under optimized processing conditions, the synthesized $\text{Co}_2\text{W}_4\text{C}$ powder can turn into amorphous state. During its subsequent crystallization and in situ reaction with carbon, the $\text{Co}_3\text{W}_3\text{C}$ nanocrystals nucleate and gradually evolve into WC phase, concurrently resulting in the formation of Co-rich nanoparticles inside WC grains.
- (2) The Co-rich nanoparticles formed by in situ reaction between $\text{Co}_3\text{W}_3\text{C}$ and carbon predominantly have coherent interfaces with the WC matrix. This

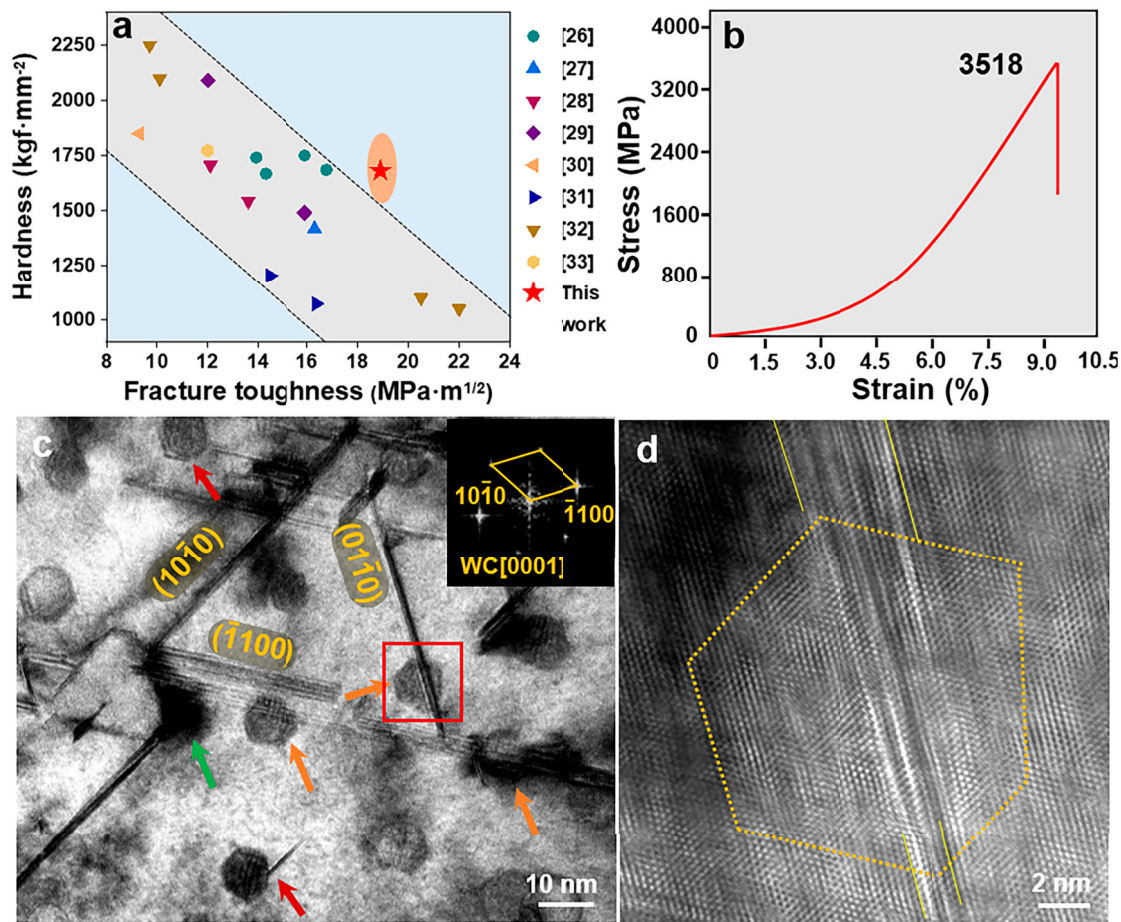


Figure 5. The mechanical properties and featured sub-grain microstructure of the prepared WC-Co composite: (a) hardness and fracture toughness of the present WC-Co sample in comparison to those of the counterparts with various Co contents (8–15 wt.%) and similar WC grain size reported in the literature; (b) compressive stress-strain curve of the present sample; (c) interactions between stacking faults and dislocations, and the Co-rich nanoparticles in a typical WC grain in the deformation region after compressive fracture strength test; (d) enlargement of the framed area in c showing the shearing behavior of stack faults.

specific interfacial relationship is retained in the final consolidated WC-Co composite bulk material.

- (3) The fabricated WC-Co composite has a high hardness of 1618 ± 80 kgf/mm² and an exceptional fracture toughness of 18.9 ± 1.4 MPa·m^{1/2}, which are superior to the mechanical properties of the counterparts reported in the literature.
- (4) The presence of the high-fraction Co-rich nanoparticles with coherent relationship with WC matrix is the key to toughening the WC-Co composite. These nanoparticles effectively hinder the motion of dislocations and stacking faults in the WC grains, yet not cause stress concentration, resulting in delayed micro-crack formation hence enhanced resistance against WC fracture.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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References

- [1] Chang YW, Yao XY, Chen YY, et al. Review on ceramic-based composite phase change materials: preparation, characterization and application. *Compos Part B-Eng.* 2023;254:110584. doi:10.1016/j.compositesb.2023.110584
- [2] Lou M, Chen X, Xu K, et al. Temperature-induced wear transition in ceramic-metal composites. *Acta Mater.* 2021;205:116545. doi:10.1016/j.actamat.2020.116545
- [3] Syed K, Xu MJ, Kok KKOD, et al. Correlations of grain boundary segregation to sintering techniques in a three-phase ceramic. *Materialia.* 2020;14:100890. doi:10.1016/j.mtl.2020.100890

- [4] Zhu QQ, Ji W, Zou J, et al. Strengthening $\text{Hf}_{0.95}\text{Ta}_{0.05}\text{B}_2$ ceramic with ultrafine grains and high-density dislocations. *J Eur Ceram Soc.* 2023;43(14):6599–6605. doi:10.1016/j.jeurceramsoc.2023.05.026
- [5] Zhao C, Lu H, Wang HB, et al. Solid-solution hardening of WC by rhenium. *J Eur Ceram Soc.* 2020;40(2):333–340. doi:10.1016/j.jeurceramsoc.2019.09.050
- [6] Jing KF, Guo ZX, Hua T, et al. Strengthening mechanism of cemented carbide containing Re. *Mat Sci Eng A-Struct.* 2022;838:142803. doi:10.1016/j.msea.2022.142803
- [7] Wang YY, Dong S, Li XT, et al. Synthesis, properties, and multifarious applications of SiC nanoparticles: A review. *Ceram Int.* 2022;48(7):8882–8913. doi:10.1016/j.ceramint.2021.12.208
- [8] Lu TW, Yao N, Chen HY, et al. Exceptional strength-ductility combination of additively manufactured high-entropy alloy matrix composites reinforced with TiC nanoparticles at room and cryogenic temperatures. *Addit Manuf.* 2022;56:102918. doi:10.1016/j.addma.2022.102918
- [9] Wang LJ, Wang L, Zhou SC, et al. Precipitation and micromechanical behavior of the coherent ordered nanoprecipitation strengthened Al-Cr-Fe-Ni-V high entropy alloy. *Acta Mater.* 2021;216(5):117121. doi:10.1016/j.actamat.2021.117121
- [10] Dong LR, Zhang J, Li YZ, et al. Borrowed dislocations for ductility in ceramics. *Science.* 2024;385:422–427. doi:10.1126/science.adp0559
- [11] Xu L, Guo W, Zou J, et al. Low-temperature densification of high entropy diboride based composites with fine grains and excellent mechanical properties. *Compos Part B-Eng.* 2022;247:110331. doi:10.1016/j.compositesb.2022.110331
- [12] Qi Y, Zhang H, Yang X, et al. Achieving superior high-temperature mechanical properties in Al-Cu-Li-Sc-Zr alloy with nano-scale microstructure via laser additive manufacturing. *Mater Res Lett.* 2023;12(1):17–25. doi:10.1080/21663831.2023.2285388
- [13] Jiang HL, Su FY, Yang YT, et al. Coprecipitation of Co and La_2O_3 coprecipitation on WC for tailoring the grain distribution and boundary of high-performance coarse-grained WC-10Co cemented carbide. *Int J Refract Met H.* 2023;115:106303. doi:10.1016/j.ijrmhm.2023.106303
- [14] Zhao C, Lu H, Liu XW, et al. Strengthening cemented carbides by activated nano TaC. *Int J Refract Met H.* 2021;95:105449. doi:10.1016/j.ijrmhm.2020.105449
- [15] Östberg G, Buss K, Christensen M, et al. Effect of TaC on plastic deformation of WC-Co and Ti(C,N)-WC-Co. *Int J Refract Met H.* 2006;24(1–2):145–154. doi:10.1016/j.ijrmhm.2005.04.010
- [16] Wittmann B, Schubert WD, Lux B. WC grain growth and grain growth inhibition in nickel and iron binder hardmetals. *Int J Refract Met H.* 2002;20(1):51–60. doi:10.1016/S0263-4368(01)00070-1
- [17] Hu HX, Liu XM, Lu H, et al. Ultra-coarse cemented tungsten carbide with (Zr,W)Cx precipitates in ceramic phase. *Int J Refract Met H.* 2023;115:106294. doi:10.1016/j.ijrmhm.2023.106294
- [18] Liu XW, Song XY, Wang HB, et al. Complexions in WC-Co cemented carbides. *Acta Mater.* 2018;149:164–178. doi:10.1016/j.actamat.2018.02.018
- [19] Ghasali E, Ebadzadeh T, Alizadeh M, et al. Spark plasma sintering of WC-based cermets/titanium and vanadium added composites: A comparative study on the microstructure and mechanical properties. *Ceram Int.* 2018;44:10646–10656. doi:10.1016/j.ceramint.2018.03.093
- [20] Ghasali E, Ebadzadeh T, Alizadeh M, et al. Unexpected SiC nanowires growth during spark plasma sintering of WC-10Si: a comparative study on phase formation and microstructure properties against WC-10Co cermet. *J Alloys Compd.* 2019;786:938–952. doi:10.1016/j.jallcom.2019.02.059
- [21] Ming KS, Gu C, Su Q, et al. Strength and plasticity of amorphous ceramics with self-patterned nanoheterogeneities. *Int J Plasticity.* 2020;134:102837. doi:10.1016/j.iplas.2020.102837
- [22] Song XY, Zhang JX, Yue M, et al. Technique for preparing ultrafine nanocrystalline bulk material of pure rare-earth metals. *Adv Mater.* 2006;18(9):1210–1215. doi:10.1002/adma.200502619
- [23] Peng Y, Wang HB, Zhao C, et al. Nanocrystalline WC-Co composite with ultrahigh hardness and toughness. *Compos Part B-Eng.* 2020;197:108161. doi:10.1016/j.compositesb.2020.108161
- [24] Xu MB, Liu XM, Lu H, et al. Increase of specific interfacial coherence in nanocrystalline ceramic-metal composites. *Compos Part B-Eng.* 2023;263:110873. doi:10.1016/j.compositesb.2023.110873
- [25] Yang C, Hu CZ, Xiang CY, et al. Interfacial superstructures and chemical bonding transitions at metal-ceramic interfaces. *Sci Adv.* 2021;7(11):eabf6667. doi:10.1126/sciadv.abf6667
- [26] Lu ZC, Wang W, Zeng MQ, et al. Breaking the hardness-toughness trade-off in WC-Co hardmetals: introduction of dual-scale plate-like WC and modification of prediction models. *Int J Refract Met H.* 2022;108:105910. doi:10.1016/j.ijrmhm.2022.105910
- [27] Zhou B, Wang HB, Lu H, et al. WC-Co-TiNbZr composite with simultaneously high hardness and fracture toughness. *Int J Refract Met H.* 2023; 116:106332. doi:10.1016/j.ijrmhm.2023.106332
- [28] Wei CB, Song XY, Fu J, et al. Microstructure and properties of ultrafine cemented carbides-differences in spark plasma sintering and sinter-HIP. *Mat Sci Eng A-Struct.* 2012;552:427–433. doi:10.1016/j.msea.2012.05.065
- [29] Mukhopadhyay A, Basu B. Recent developments on WC-based bulk composites. *J Mat Sci.* 2011;46(3):571–589. doi:10.1007/s10853-010-5046-7
- [30] Bonache V, Salvador MD, Rocha VG, et al. Microstructural control of ultrafine and nanocrystalline WC-12Co-VC/Cr₃C₂ mixture by spark plasma sintering. *Ceram Int.* 2011;37(3):1139–1142. doi:10.1016/j.ceramint.2010.11.026
- [31] Chen C, Guo ZX, Li SH, et al. Microstructure and properties of WC-17Co cermets prepared using different processing routes. *Ceram Int.* 2019;45(7):9203–9210. doi:10.1016/j.ceramint.2019.01.265
- [32] Chychko A, García J, Ciprés VC, et al. HV-KIC property charts of cemented carbides: A comprehensive data collection. *Int J Refract Met H.* 2022;103:105763. doi:10.1016/j.ijrmhm.2021.105763
- [33] Lee JH, Oh IH, Jang JH, et al. Mechanical properties and microstructural evolution of WC-binderless and WC-Co hard materials by the heat treatment process. *J Alloys Compd.* 2019;786:1–10. doi:10.1016/j.jallcom.2019.01.282