

Additive manufacturing techniques for WC–Co cemented carbides: Principle, progress, and perspective

Zhan-he LIU ^a, Ke-chao ZHOU ^b, Kai-hua SHI ^c, Xiao-zan WU ^a, He XIAO ^d, Chao-qun PENG ^a, Ri-chu WANG ^a, Xiao-feng WANG ^{a,b,*}

^a School of Materials Science and Engineering, Central South University, Changsha 410083, China;

^b State Key Laboratory of Powder Metallurgy, Central South University, Changsha 410083, China;

^c China Tungsten and Hightech Materials Co., Ltd., Zhuzhou 412000, China;

^d Zhuzhou Cemented Carbide Cutting Tools Co., Ltd., Zhuzhou 412000, China

Abstract: Additive manufacturing (AM) technology has emerged as a viable solution for manufacturing complex-shaped WC–Co cemented carbide products, thereby expanding their applications in industries such as resource mining, equipment manufacturing, and electronic information. This review provides a comprehensive summary of the progress of AM technology in WC–Co cemented carbides. The fundamental principles and classification of AM techniques are introduced, followed by a categorization and evaluation of the AM techniques for WC–Co cemented carbides. These techniques are classified as either direct AM technology (DAM) or indirect AM technology (IDAM), depending on their inclusion of post-processes like de-binding and sintering. Through an analysis of microstructure features, the most suitable AM route for WC–Co cemented carbide products with controllable microstructure is identified as the indirect AM technology, such as binder jet printing (BJP), which integrates AM with conventional powder metallurgy.

Keywords: cemented carbides; additive manufacturing; WC–Co; direct additive manufacturing; indirect additive manufacturing; microstructure; complex shapes

1 Introduction

Cemented carbides, also named as hard alloy, are composite materials primarily composed of refractory metal carbides (reinforcement phase) and binder metals (binder phase) [1]. Among these, WC–Co cemented carbide, first invented by SCHRÖTER in 1923, consists of WC as the hard phase and cobalt as the binding phase, playing a transformative and crucial role in the industrial development of modern times [2,3]. This material has found widespread applications in various fields such as metal cutting, petroleum drilling, and geological exploration and is used for

manufacturing cutting tools [4], drill bits [5] and wear-resistant components [6] due to its favorable properties, such as high hardness, wear resistance and elastic modulus.

Currently, the manufacturing of WC–Co cemented carbides components is mainly achieved via injection molding, extrusion molding, and powder metallurgy (PM) [7]. Powder metallurgy and extrusion molding technologies have matured and stabilized, enabling the fabrication of cemented carbides with high hardness and without the η phase [8,9]. However, these methods are limited to simple shapes and cannot handle complex geometries. The molds for PM must be tailored to the product's shape, extending development cycles, especially for

Corresponding author: *Xiao-feng WANG, Tel: +86-13467516329, E-mail: 13467516329@163.com
[https://doi.org/10.1016/S1003-6326\(25\)66946-9](https://doi.org/10.1016/S1003-6326(25)66946-9)

Received 7 April 2024; accepted 24 March 2025

1003-6326/© 2026 The Nonferrous Metals Society of China. Published by Elsevier Ltd & Science Press

This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>)

intricate designs. Creating complex molds for cemented carbide components is often challenging or impossible. The emergence of the additive manufacturing (AM) technology provides a solution for the manufacturing of complex-shaped WC–Co cemented carbide products. AM is a novel manufacturing technique that uses CAD models to fabricate complex parts layer-by-layer. It offers rapid prototyping and mold-free shaping, overcoming traditional cemented carbide preparation limitations [10]. More and more researchers have conducted studies on WC–Co cemented carbides additive manufacturing using various AM technologies, achieving significant research progress [11–18]. Up to now, several AM processes are being applied in the manufacturing of WC–Co cemented carbide components, including selective laser melting (SLM)/selective laser sintering (SLS) [18–31], binder jet printing (BJP) [11–13,32–36], fused deposition modeling (FDM) [16,37,38], and 3D gel-printing (3DGP) [39], etc.

For instance, to improve surface quality, researchers have made efforts to reduce defects by modifying process parameters such as laser power [40], working distance [41], and powder properties [31]. To enhance the relative density of WC–Co cemented carbide components, researchers have proposed post-processing methods such as post-infiltration with Co [36], or the use of hot isostatic pressing (HIP) [12]. Recently, research conducted by ENNETI et al [12] reported that they fabricated WC–12Co cemented carbide products with a relative density of 96.65 % and a hardness of HV₃₀ 1256 using the BJP technology, which are already close to those of the microcrystalline cemented carbides produced by powder metallurgy methods. The lifespan of the cemented carbides wire drawing pellets manufactured by SANDVIK is 20 times that of traditional wear-resistant steel [42].

In recent years, additive manufacturing of WC–Co cemented carbides has garnered extensive attention from companies such as Kennametal, Global Tungsten & Powder Corp, SANDVIK, International Metalworking Companies, Seed Technology, and Huarui Precision, with multiple patents related to WC–Co cemented carbide additive manufacturing [42–49]. SANDVIK acquired BEAMIT group shares in 2019 and built a solid industrial partnership [50]. KENNAMETAL

has established a strategic partnership with General Electric and joined GE Additive's beta partnership program. Together, they are collaborating on the development of BJP cemented carbides to achieve high-volume production of hundreds of cemented carbide components annually [51]. It is evident that research on cemented carbide additive manufacturing technology is transitioning from the feasibility verification stage [52,53] to the industrial utilization stage. Therefore, it is necessary to systematically summarize and analyze the research and development of cemented carbide additive manufacturing technology.

This work begins by explaining the fundamental principles of additive manufacturing technology, then delving into the principle and process specific to cemented carbide additive manufacturing, which provides a comprehensive overview of the distinctive characteristics exhibited by WC–Co cemented carbide additive manufacturing technology. The research status and current applications of WC–Co cemented carbide additive manufacturing technology are summarized, followed by an analysis of compatibility with the process and microstructure of cemented carbides. Lastly, the existing challenges are identified and potential solutions are proposed.

2 Principles and classification of additive manufacturing

According to the American Society for Testing and Materials (ASTM) definition [54], additive manufacturing technology, also known as 3D printing technology, uses a method that differs from traditional subtractive manufacturing. It fabricates parts possessing specific shapes layer-by-layer with the control of the computer. The process starts by using software like Computer-Aided Design (CAD) to “slice” the digital model into a 2D representation. Then, a computer controls the manufacturing movement, guiding the layer-by-layer deposition on a 3D platform. Various materials, such as photosensitive resin [55], plastic [56], metal powder [57,58], ceramic powder [59], and even cell tissue [60], can be combined to form a three-dimensional object by AM. Figure 1 illustrates cemented carbide components manufactured using additive manufacturing technology [16–18]. Figure 2(a)

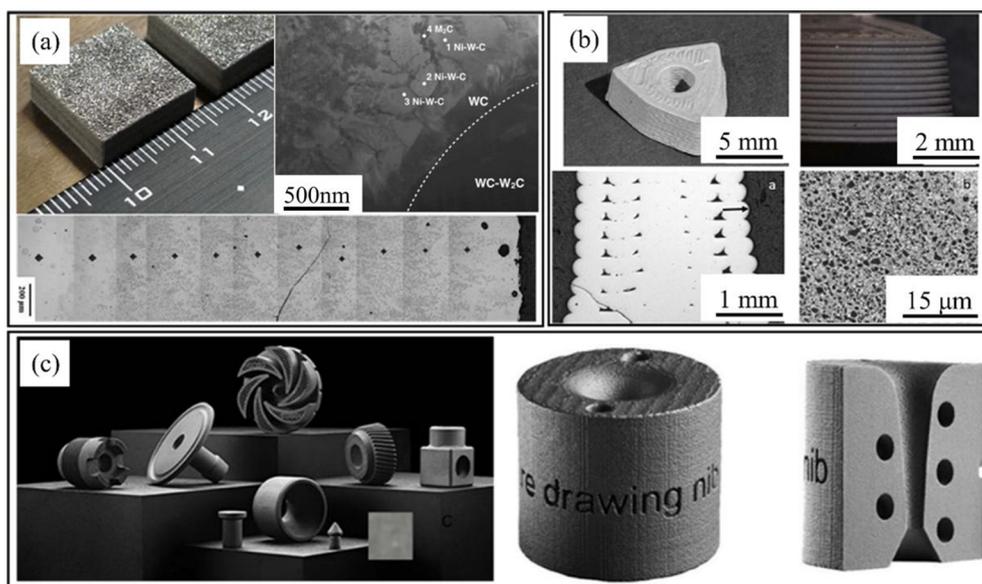


Fig. 1 Cemented carbides fabricated by additive manufacturing technology: (a) Sample fabricated by SLS [18]; (b) Samples fabricated by FDM [16]; (c) Samples fabricated by BJP [53]

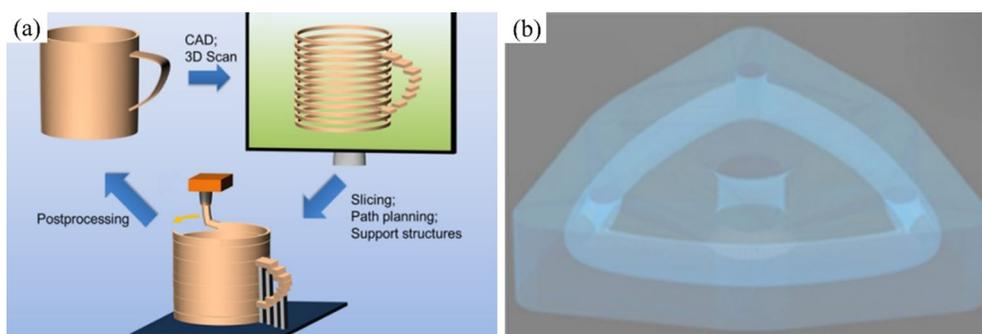


Fig. 2 (a) Demonstration diagram of additive manufacturing [61]; (b) Models with complex voids [16]

illustrates the technological process of additive manufacturing technology. Compared to the conventional methods like powder metallurgy, 3D printing offers the advantages of direct manufacturing and rapid production of intricate structures. Figure 2(b) depicts an example of a cemented carbide part with complex internal cavities fabricated using additive manufacturing techniques.

The ASTM International Committee 2972 [62] standards classify additive manufacturing technologies into seven distinct categories. These categories include powder bed fusion (PBF), direct energy deposition (DED), material extrusion (MEX), material jetting (MJ), binder jetting (BJ), sheet lamination, and vat polymerization (VP).

DED and PBF are additive manufacturing technologies with high energy heat resources. DED melts material directly at the nozzle using a

high-energy heat source, deposited on the platform to form a molten pool. PBF selectively melts the powder bed with a high-energy heat source while the platform descends randomly. Both create parts layer by layer. The techniques used for the application of WC–Co cemented carbides in DED and PBF include laser engineering net shaping (LENS or L-DED), SLS/SLM, and selective electronic beam melting (SEBM) (as depicted in Fig. 3).

MEX [65] uses molten or semi-molten polymers, slurries, polymer solutions, or dispersions. These materials are extruded through nozzles and deposited on the printing platform, following the path defined by the CAD slice model. Layer-by-layer deposition results in the fabrication of the desired sample [66]. This technology can be divided into wax-based MEX and water-based MEX according to different raw materials. Among

them, the wax-based MEX that has been applied in fabrication of WC–Co cemented carbides includes fused deposition modeling (FDM) and thermoplastic 3D printing (T3DP), and the water-based methods that have been applied in fabrication of WC–Co cemented carbides include 3D gel-Printing (3DGP).

Material jetting and binder jetting are AM technologies based on injection molding principles. Material jetting directly injects material for accumulation and shaping [67], while binder jetting sprays adhesive to form a 3D entity on the powder

bed [52]. Figure 4(b) illustrates the 3D powder bonding technique. Currently, the binder jetting printing (BJP) has been applied to the additive manufacturing of cemented carbides.

Sheet lamination, or laminated object manufacturing (LOM) [68,69], uses synthetic polymer or paper sheets laminated, cut, and stacked layer by layer to construct objects. This technology combines additive and subtractive manufacturing advantages. Figure 4(c) schematically illustrates sheet lamination. There is currently no application of this technology in the field of cemented carbide.

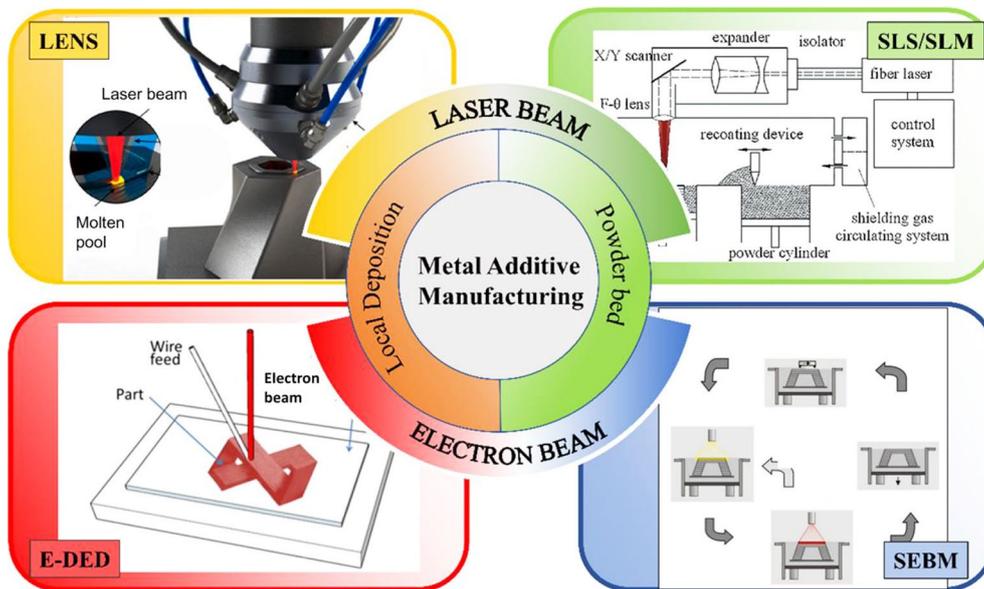


Fig. 3 Classification of DED and PBF, including LENS, SLS/SLM, E-DED [63], and SEBM [64]

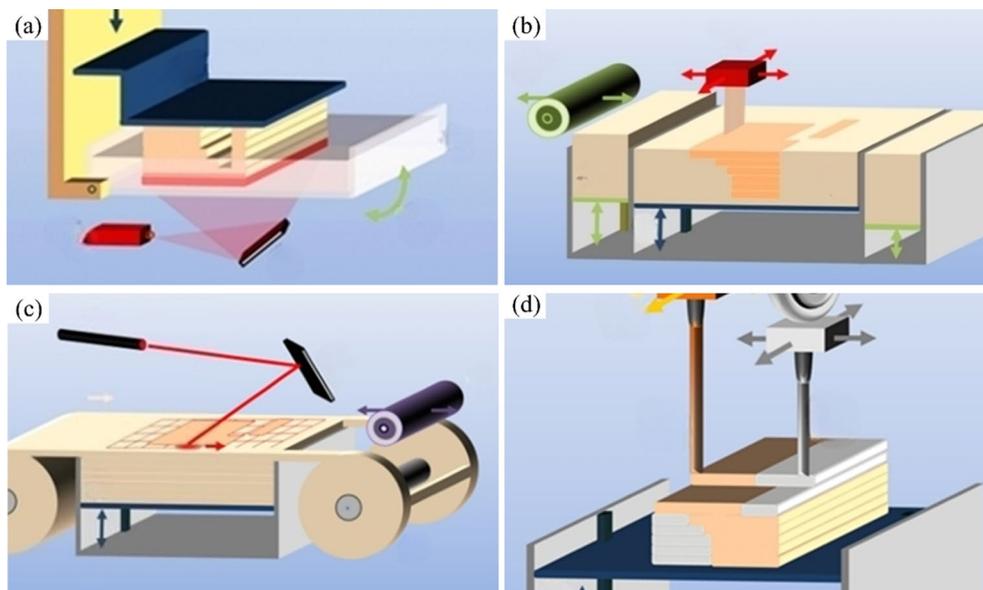


Fig. 4 Schematic diagrams of four additive manufacturing [61]: (a) VP technology; (b) 3D powder bonding technology; (c) Sheet lamination; (d) Fused deposition modeling

Vat polymerization (VP) is an AM technique using the photopolymerization reaction, originating in the 1980s [70]. It is widely applied in various fields. The fundamental principle involves UV light scanning photosensitive resin along a path, curing each layer to stack and create the molded sample. Already applied in WC–Co cemented carbides, VP technology is digital light processing (DLP) [71]. Figure 4(a) schematically shows stereolithography. Compared to other AM technologies, VP can produce high-resolution and intricately structured components [72,73].

3 Additive manufacturing techniques in cemented carbides

In 1999, YOO et al were among the first to utilize selective laser sintering technique for the production of WC–9Co cemented carbides [22]. Since then, various additive manufacturing

technologies have been employed in the field of cemented carbides, including SLS/SLM [19–23, 25,26,28,29,31,40,74,75], LENS [15,41,76–79], SEBM [80], BJP [11–13,32–36], FDM [16,37,38, 81–83], 3DGP [39], and DLP [84,85], etc. A comparison of additive manufacturing technologies is provided in Table 1. Based on whether these post processes like de-binder process and sintering are carried out, the additive manufacturing of WC–Co cemented carbides can be categorized as direct additive manufacturing (DAM) technique or indirect additive manufacturing (IAM) technique for WC–Co cemented carbides, as illustrated in Fig. 5.

3.1 Direct additive manufacturing for cemented carbides

Currently, DAM technologies applied in the study of WC–Co cemented carbides include SLS/SLM [18–21,23,24,27–29,31,40], SEBM [63,80],

Table 1 Advantages and disadvantages of techniques in cemented carbides

Technique	Method	Advantage	Disadvantage	Ref.
Selective laser melting and selective laser sintering	Laser powder bed fusion (L-PBF)	One-step shaping, high relative density and hardness, and low dimensional distortion	Uneven composition, high residual stress, and existing brittle η phase	[28,31,57,74]
Selective electron beam melting	Electron beam powder bed fusion (E-PBF)	Low residual stress, high build speed, high degrees of freedom and less support compared to SLM	Low surface accuracy, presence of brittle η phase, and high power consumption	[63,80,86,87]
Laser engineer net shaping	Laser directed energy deposition (L-DED)	High solidification rate and hardness decreasing with increase in height compared to SLM	Uneven composition, low degree of freedom, and presence of brittle η phase	[15,78,88–90]
Binder jet printing	–	No η phase generation, uniform grain size, high mechanical strength, and high relative density	Large shrinkage and complicated processes	[11,12,33,36,91]
Fused deposition modeling	Fused filament fabrication (FFF)	Low cost, uniform composition, and no η phase generation	Large shrinkage, low mechanical properties, large void ratio, and low surface accuracy	[16,37]
3D gel-printing	Direct ink writing	Low residual stress, uniform microstructure, low powder requirement, and no raw material loss	Large dimensional shrinkage, low surface accuracy, and limited printing time	[39]
Stereolithography	–	Low residual stress, uniform microstructure, and high resolution	Large shrinkage size, and low mechanical properties	[92]

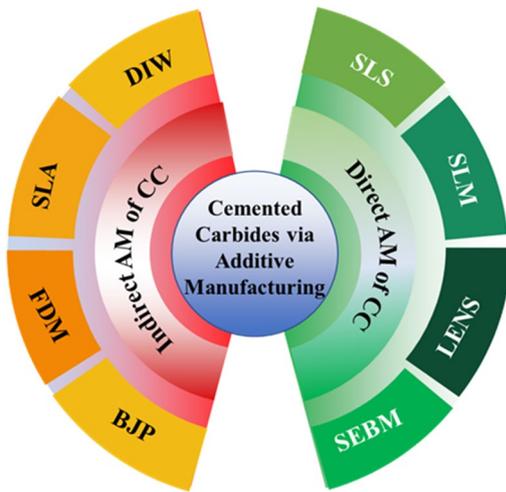


Fig. 5 DAM and IAM techniques for cemented carbides

and LENS [14,15,41,76–79,89,93], etc. Characteristics and product properties of cemented carbides prepared using DAM technology are listed in Table 2.

3.1.1 Selective laser sintering (SLS)/selective laser melting (SLM)

SLS and SLM belong to the category of PBF technology. Both methods utilize high-energy lasers as heat sources to achieve the layer-by-layer powder deposition, sintering/melting, and rapid solidification of the molten pool, as depicted in Fig. 6(a). SLS [80] was developed by Professor DECKARD at the University of Texas [44] and subsequently further developed by the Fraunhofer Institute for Laser Research in Germany [96]. SLM, an enhancement of SLS, utilizes a higher-energy laser beam to fully melt the powder, addressing the issue of inadequate powder cohesion in SLS. Compared to other metal additive manufacturing technologies, SLS and SLM offer advantages such as a simplified process, wide material compatibility,

cost-effectiveness, and high relative density of products [97,98]. These techniques have found extensive applications in additive manufacturing across various materials, including titanium alloys, aluminum alloys, cobalt–nickel alloys, and stainless steel.

In 2002, WANG et al [40] utilized SLS technology to prepare WC–Co cemented carbides and conducted a systematic study on the influence of different parameters on the microstructure and properties of the samples. Their work revealed that the laser energy was absorbed by the cemented carbide powder bed within 0.4 mm of the surface layer, resulting in defects like cracks and delamination. CHEN et al [31] employed SLM to prepare WC–20Co cemented carbides and observed a distinct layered structure in the vertical section (Figs. 6(b, c)). KUMAR [28] employed SLS to prepare WC–17Co and conducted a comprehensive study on the SLS production process. They found that the difference in melting point and the mismatch of thermal expansion coefficient between carbides and binder phase inevitably led to cracks and the formation of η phases.

Currently, the research on utilizing SLS/SLM for manufacturing cemented carbides primarily focuses on controlling and reducing defects through process parameter optimization and post-treatments. Studies have shown the following results:

(1) Adjusting process parameters and selecting appropriate raw materials can effectively control defects and improve product performance. WANG et al [40] discovered that reducing laser power (from 8 to 18 W) and choosing slower scanning speeds (10–15 mm/s) appeared to reduce thermal deformation and achieve better surface quality.

Table 2 Characteristics of DAM techniques in cemented carbides

Technique	Characteristics	Composition	Hardness	Density/(g·cm ⁻³)	Ref.
SLM/ SLS	Simple steps, high relative density and hardness, and low dimensional distortion	WC–12Co	HRA 81	14.2	[26]
		WC–17Co	HV (1722±13)	12.85	[74]
		WC–17Co	HRC 60 (HV 697)	–	[20]
SEBM	Low residual stress, high build speed, high degrees of freedom and less support	WC–13Co	9–9.5 GPa (HV 918–969)	14.1	[80]
LENS	High solidification rate and hardness decreasing with increasing products' height	WC–10Co	HV (1326±111)	12.9	[15]
		WC–12Co	HV (1436±19)	–	[83]
L-DED	High solidification rate and hardness decreasing with increasing products' height	WC–12Co	HV (1373±68)	–	[94]
		WC–12Co	HV 1000	–	[95]

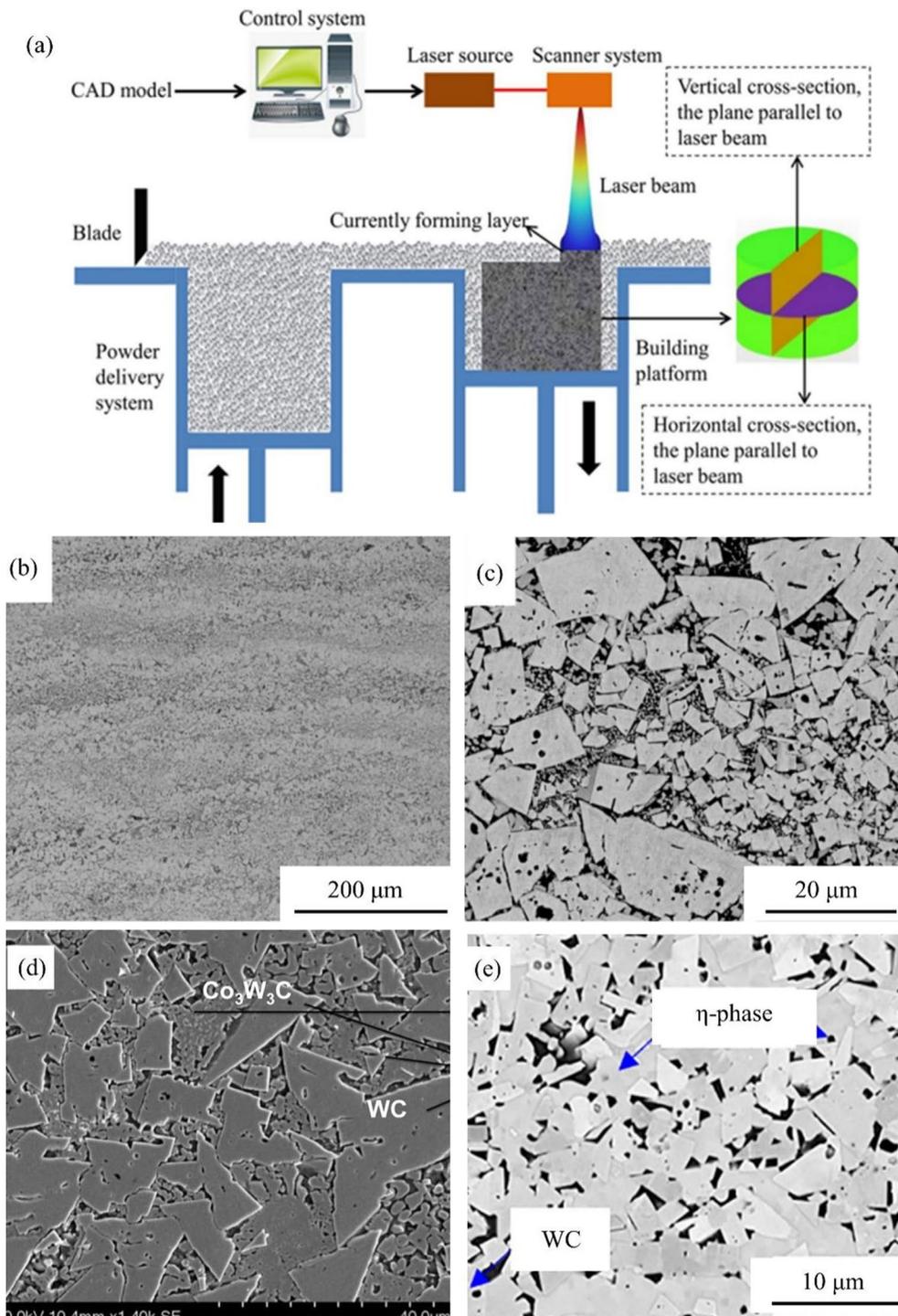


Fig. 6 Preparation of cemented carbides by SLS/SLM: (a) Schematic diagram of SLS/SLM [74]; (b, c) Cross-sectional lamellar structures of carbide [31]; (d) SEM image of sample fabricated at energy density 185 J/mm^3 [20]; (e) SEM image of cemented carbides and precipitation [99]

CHEN et al [31] conducted a systematic study on the influence of process parameters and powder quality on the microstructure and mechanical properties of cemented carbides produced by SLM. They found that using spherical powders resulted in fewer pores, voids, cracks, and higher final density,

which could be increased from 86% to 96%. ZHAO et al [26] conducted a comprehensive investigation of the process parameters in additive manufacturing and reported that an appropriate scanning speed could produce samples with a relative density exceeding 99%. AGYAPONG et al [100] studied

the impact of process parameters on the performance of WC–17Co cemented carbides produced by SLM method. They observed that the sample with a scan spacing of 0.04 mm exhibited the lowest porosity, and the sample density was the highest, which can reach 98% of theoretical density, when the energy density ranged from 170 to 210 J/mm³.

(2) In enhancing the performance of WC–Co cemented carbide samples, the composition of raw materials plays a crucial role. Some researchers mix other elements into the raw materials to enhance the performance of WC–Co cemented carbides. LIU et al [74] conducted a study on impact of cobalt content during SLM printing process of cemented carbides. The results showed that increasing the cobalt content from 12 to 32 wt.% led to improved sintering densification, resulting in a higher relative density of 93%–97%. AGYAPONG et al [75] utilized SLM to prepare WC–17Co cemented carbides and found that the addition of 3 vol.% (h-BN) enhanced the sample's hardness by 28.7%. Furthermore, the sample with 5 vol.% h-BN exhibited the best fracture toughness, measuring at 6.97 MPa·m^{1/2}.

(3) Applying proper pretreatment or post-treatment methods can effectively address the issue of porosity in SLM/SLS products and minimize the occurrence of cracks. KUMAR and CZEKANSKI [20] investigated the impact of heat treatment on the performance of cemented carbides produced by SLM method, and observed that the sample after heat treatment at 600 °C yielded the highest hardness of HRC 64.4 and improved toughness and the sample after heat treatment at 400 °C exhibited the best wear resistance, with a mass loss of 0.00012 g. The SEM image of samples is shown in Fig. 6(d). BRÍCIN et al [23] conducted hot isostatic pressing on SLM cemented carbides, leading to the decomposition and transformation of W₂C and high-temperature η -phase into hexagonal WC phase due to carbon diffusion. The relative density of the product increased from 85% to 96% after hot isostatic pressing. Furthermore, FRIES et al [99] studied the effects of sintering–hot isostatic pressing and hot isostatic pressing on the performance of cemented carbides produced by SLM technique. Their research demonstrated that hot isostatic pressing significantly reduced residual stress from 917 to 281 MPa. Moreover, the

combination of sintering and hot isostatic pressing increased the fracture strength of SLM-made samples almost threefold, from 416 to 1138 MPa. The SEM image of sample is shown in Fig. 6(e).

3.1.2 Selective electron beam melting (SEBM)

SEBM utilizes an electron beam as a heating source, which is controlled by a computer, to melt materials and form desired samples layer-by-layer in a vacuum. SEBM shares similarities with other DAM technologies, such as a simplified process, minimal dimensional deformation, and excellent mechanical properties. Compared with SLM, SEBM presents distinct features: (1) SEBM possesses faster construction speed and higher energy of heat source than SLM/SLS, while loses its dominant position at the expense of surface finish, dimensional tolerances, and feature resolution [101]. (2) SEBM employs preheating treatment temperatures exceeding 1000 °C to enhance the density of the powder, resulting in lower residual stress within the part and a more uniform microstructure [101]. (3) Through pre-sintering, SEBM achieves an even distribution of cobalt without the occurrence of cobalt pools [62]. (4) SEBM provides greater degrees of freedom in design and requires relatively fewer support structures [64,102]. Compare to SLM/SLS, the cost of SEBM is higher, and the surface roughness of its sample is worse.

PENG et al [86] utilized SEBM to fabricate nickel-based cemented carbides and discovered that the mechanical properties of the sample were inconsistent, with poor edge hardness measuring HRC (54±1), significantly lower than that of commercial cemented carbides. KONYASHIN et al [80] used SEBM to produce WC–13Co cemented carbides, revealing unsatisfactory surface quality of samples with roughness values of 4.4 μm (R_a) and 22.8 μm (R_z) at the top surface. Phenomena like delamination and the presence of the η phase were observed. However, by optimizing process parameters, it is possible to obtain high-density samples free from η phases (see Fig. 7(b)). The mechanical properties exhibit anisotropy, with Vickers hardness ranging from 9.0 to 9.5 GPa, and average fracture toughness values of 13 MPa·m^{1/2} (the transverse direction) and 20 MPa·m^{1/2} (the longitudinal direction). WANG et al [87] utilized SEBM to fabricate WC–12Co cemented carbides and investigated the impact of heat treatment on

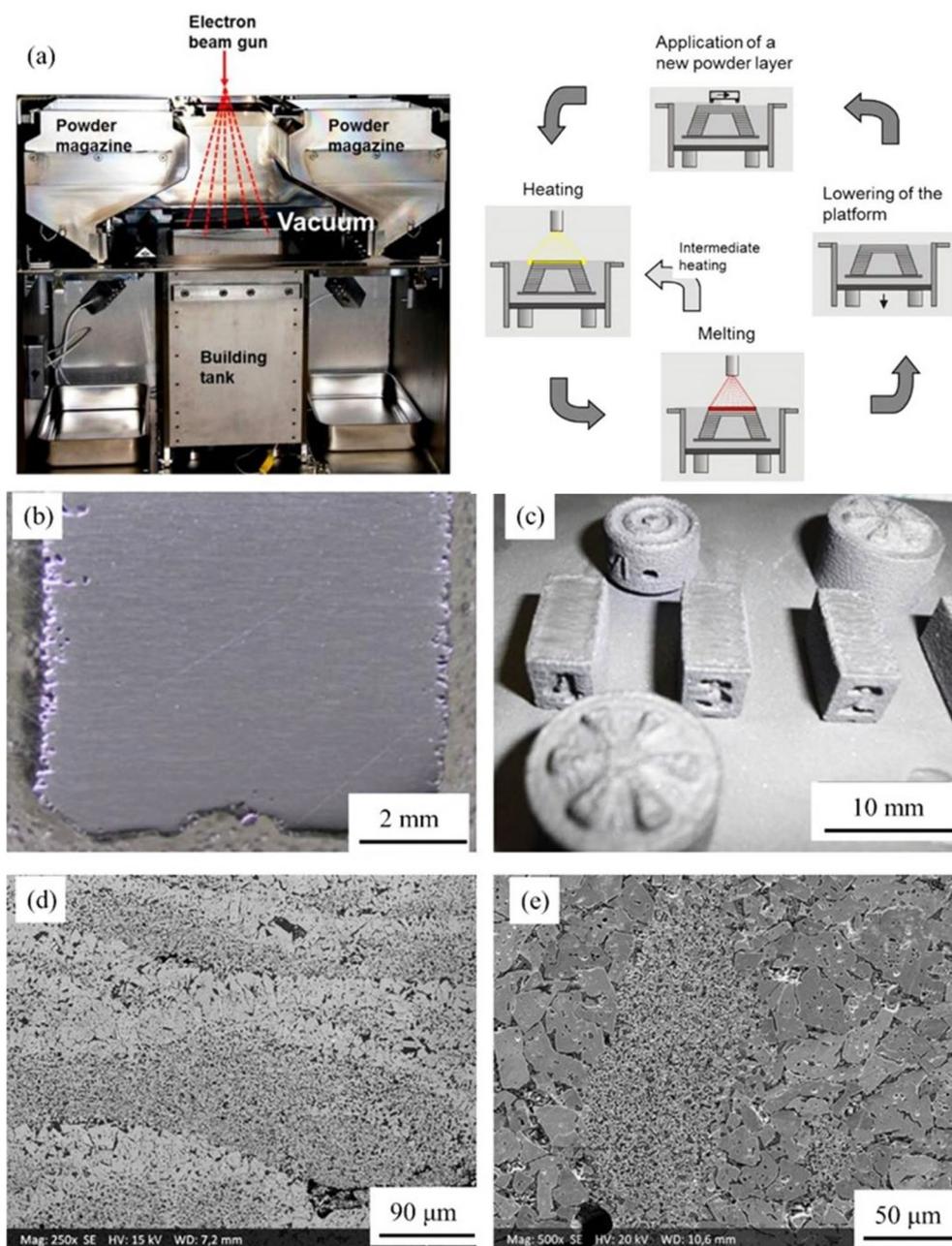


Fig. 7 Preparation of cemented carbides by SEBM: (a) Schematic diagram of SEBM equipment and principle [63]; (b) Appearance of cemented carbide sample obtained at current of 10 mA and scan rate of 800 mm/s [80]; (c) Appearance of cemented carbide particles obtained by SEBM; (d) HRSEM image of sample obtained at current of 5 mA and scan rate of 1500 mm/s; (e) HRSEM image of sample obtained at current of 10 mA and scan rate of 800 mm/s

microstructure, phase composition, and mechanical properties. They found that heat treatment resulted in reduced porosity, enhanced compressive strength, and improved relative density. The mechanical properties also exhibited anisotropy, with hardness values of 16.63 and 15.28 GPa for the cross-section and longitudinal section, respectively. Additionally, Seed Technologies Corp., Ltd. [49] utilizes SEBM to develop products like WC–Co cemented carbides

PDC (polycrystalline diamond compact) drill bits for oil drilling. Although SEBM technology has made significant advancements compared to SLM/SLS, challenges still remain in the production of cemented carbide products.

3.1.3 Laser engineering net shaping (LENS)

LENS, also known as L-DED and LMD, utilizes a high-energy laser as a heat source and uses laser cladding technology to layer-by-layer

melt metal powder or wire, allowing for the rapid solidification and deposition of the entire cemented carbide part on a metal platform [76,103]. LENS is an extension of rapid prototyping (RP) technology specifically designed for manufacturing alloy parts. Developed at Sandia National Laboratories in the United States during the 1990s, LENS has several advantages such as improved material structure and thermal stability, controllable grain growth, enhanced processing efficiency [15,104], and reduced processing costs. Figure 8(a) presents a schematic diagram illustrating the LENS process. Furthermore, LENS can be utilized as a surface treatment process, in addition to fabricating complex structural parts [62]. This technique finds applicability across a wide range of metallic materials, including stainless steels, nickel-based superalloys, copper alloys, titanium alloys, and functional composites with enhanced physical and mechanical properties [105–107].

XIONG et al [15] utilized LENS method to fabricate WC-based cemented carbides and discovered various defects within the samples, such as the presence of carbon-deficient phase W_2C , η phase, and delamination with uneven grain sizes.

Similar to SLM, these defects are attributed to the high-energy heat source, leading to cobalt evaporation and generating high residual stresses. Furthermore, XIONG et al [41] conducted a study on the influence of process parameters and observed that adjusting the working distance significantly improved the occurrence of delamination and suppressed abnormal growth of WC grains. Particularly utilizing a working distance of 4 mm resulted in nearly defect-free microstructure (Fig. 8(b)), with a relative density of 96% and a hardness of HV (1304±57). BALLA et al [83] investigated the microstructure and wear resistance of WC–12Co cemented carbides coatings deposited on stainless steel substrates using LENS. Their findings revealed that laser energy affected the coating thickness, in which lower power corresponded to decreased hardness and increased wear coefficient.

KIM et al [94] used the L-DED technique to fabricate WC–12Co cemented carbides and observed numerous defects, including irregular coarse pores, melt pools, layering phenomena, cracks, and decarburization. The sintered components exhibited anisotropic hardness, with a

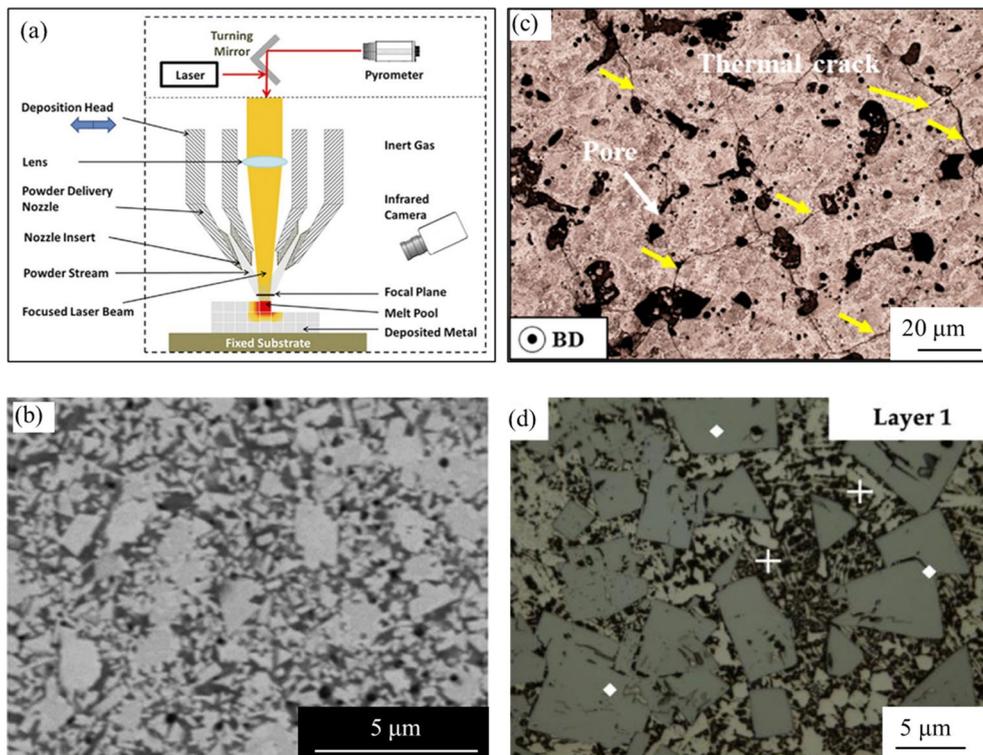


Fig. 8 Preparation of cemented carbides by LENS: (a) Principle and schematic diagram of LENS [79]; (b) Undamaged carbide surface at working distance of 4 mm [41]; (c) OM micrograph of cross-section of WC–12Co cemented carbides in building direction [94]; (d) OM micrograph of cross-section of sample in as-built condition [95]

hardness on top surface of HV (1373±68) and a hardness on side surface of HV (1352±62). The wear resistance of the samples was good, possibly due to the uneven microstructure leading to the simultaneous presence of coarse and fine particles on the sample surface. The average wear rate of the samples was $1.673 \times 10^{-8} \text{ mm}^3/(\text{N} \cdot \text{m})$. The OM micrograph of the cross-section of the sample in building direction is shown in Fig. 8(c). MORALES et al [95] also utilized L-DED to fabricate WC–12Co cemented carbides and used post-processing at different temperatures to optimize the property of samples. The SEM image revealed the presence of numerous coarse pores and cracks in the samples prepared by L-DED, which was attributed to residual stresses induced by the high-energy heat source. The OM micrograph of the cross-section of the sample in as-built condition is shown in Fig. 8(d). The samples also show the η phases and uneven microstructure. Additionally, it was found that heat treatment did not change the performance of cemented carbides fabricated by L-DED but could only modify the size and morphology of the η phase in the matrix.

The manufacturing of cemented carbides through DAM technology encounters several challenges. Firstly, these challenges are inherent to the molding method employed. When a high-energy laser serves as the heat source, the rapid scanning speed of the beam results in higher energy absorption per unit area of the powder bed, leading to instantaneous powder temperatures exceeding 2000 °C [24]. Consequently, the excessive energy absorbed within the shallow depth creates a significant energy gradient, causing higher sintering temperatures in the upper part of the powder bed compared to the lower part. Moreover, the overlapping region between layers undergoes double liquid-phase sintering processes [31,108], resulting in abnormal grain growth in this area [18].

Secondly, the challenges occur due to the complex multi-phase structure of cemented carbide materials. The high instantaneous temperature during the manufacturing process leads to carbon loss in the hard phase carbides [20]. Additionally, the substantial difference in melting points between the hard phase and binder phase contributes to the evaporation of the low melting point binder phase [24]. The instantaneous laser irradiation induces a brief period of liquid phase sintering, limiting the

sufficient diffusion of each component element [18]. Furthermore, thermal expansion coefficient mismatches between the hard phase and binder phase [18] exacerbate the inhomogeneity of the matrix.

These combined factors, including energy distribution and multi-phase material complexities, contribute to the difficulties encountered during the manufacture of cemented carbides using DAM technology.

3.2 Indirect additive manufacturing for cemented carbides

As aforementioned, IAM technology follows the shaping–debinding–sintering (SDS) principle, which aligns with powder metallurgy techniques. This involves forming a green body that matches the shape and size of the desired part firstly. Subsequently, through the degreasing process, the organic content is removed, and finally, the green bodies are sintered to fabricate dense parts. Currently, various IAM technologies are applied to WC–Co cemented carbide production, including binder jet printing (BJP) [11–13,32–36], digital light processing (DLP) [85], fused deposition modeling (FDM) [16,37], T3DP, and 3D gel-printing (3DGP) [39]. Table 3 provides an overview of the characteristics and properties of cemented carbides manufactured using IAM technology.

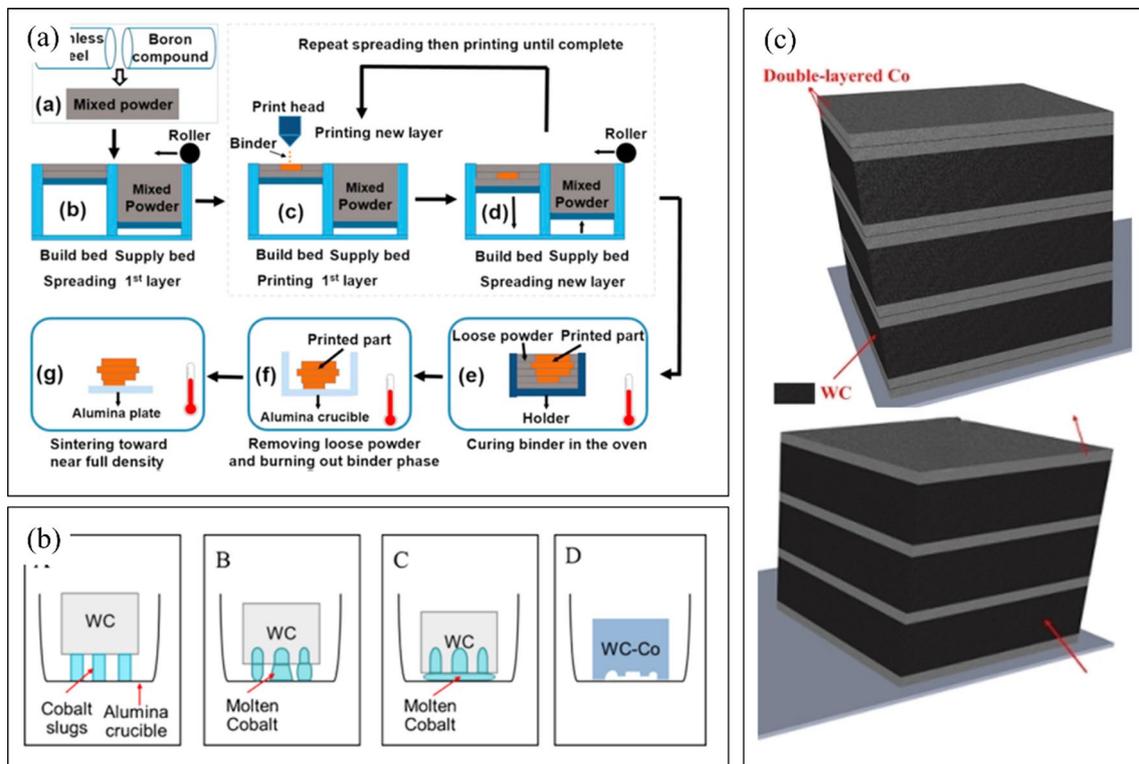
3.2.1 Binder jet printing (BJP)

BJP is one of AM techniques involving spraying the binder into the powder bed to bond the powder particles and form a green body. Subsequently, the green body undergoes degreasing and sintering processes to achieve a dense three-dimensional structure. The technological process of BJP is shown in Fig. 9(a). BJP enables the formation of green bodies at low temperatures, without melting powder. Additionally, almost all unformed powder can be recycled and reused, making BJP a cost-effective manufacturing method [36].

ENNETI et al [12] were the first to utilize BJP method for the preparation of WC–12Co cemented carbides. They investigated the influence of different sintering processes on the properties of cemented carbides manufactured by BJP. The obtained samples exhibited poor mechanical properties, with hardness ranging from HRA 83.1 to

Table 3 Characteristics of IAM techniques for cemented carbides

Technique	Characteristic	Content	Hardness	Density/(g·cm ⁻³)	Ref.
BJP	No η phase generation, uniform grain size, but large size shrinkage	WC–23Co	11.5 GPa (HV 1173)	13.0	[12]
		WC–12Co	HV ₃₀ (1211±8)	14.2	[109]
		WC–12Co	HV ₃₀ 1306	14.2	[110]
FDM (FFF)	Low cost, homogeneous structure but many pores, poor mechanical properties	WC–13Co	HRA 88	–	[16]
MEX	Low cost, homogeneous structure but many pores, poor mechanical properties	WC–8Co	HV ₃₀ 1312–1326	14.7	[111]
3D gel-printing	Low residual stress, homogeneous microstructure, no raw material loss, but strict time requirement	WC–20Co	HRA 87.7	13.55	[39]
DLP	Uniform grain size, and good sample surface quality	WC–6Co	–	–	[112]
		WC–12Co	HV ₁₀ (1157±59)	13.0	[71]

**Fig. 9** Preparation of cemented carbides by BJP: (a) BJP technology process [113]; (b) Pressure-less fusion infiltration of Co into WC prepared by BJP [36]; (c) Two ways of stacking WC layers with Co layers [91]

85 and relative density ranging from 92% to 94% at 20% shrinkage rate. MARIANI et al [11] studied the microstructure, phase composition, and mechanical properties of WC–12Co cemented carbides prepared by BJP. They observed a uniform phase structure and microstructure in the cemented carbides. However, the green body experienced significant shrinkage during sintering, with a maximum shrinkage rate of 26%. WOLFE et al [110] employed BJP to produce medium-grain and

coarse-grain cemented carbides and found that the performance of the medium-grain cemented carbides matched that of traditionally manufactured medium-grain cemented carbides. However, the sample exhibited a high shrinkage rate of 28%. BERGER et al [109] utilized BJP to fabricate WC–12Co cemented carbides and found that the shrinkage rate of sample ranges from 28% to 32%; the sintered parts have high relative density, from 98.7% to 99.4%, and do not exist η phase and free

carbon in matrix.

To mitigate the sintering shrinkage of BJP green bodies, CRAMER et al [36] implemented pressure-less infiltration of Co into the WC–Co cemented carbides. They investigated the influence of the Co infiltration amount on the performance and microstructure of the samples. Figure 9(b) illustrates the schematic diagram of the Co infiltration process. The findings revealed that pressure-less cobalt infiltration effectively addressed the dimensional shrinkage issue in cemented carbides manufactured by BJP, reducing the shrinkage rate from 26% to 14%. Furthermore, the density of the infiltrated samples significantly increased, reaching 97.6%. TANG et al [87] made improvements based on CRAMER's Co infiltration approach and introduced one step that alternates stack of WC and Co layers in the Z-axis direction, followed by infiltration in high temperature, as depicted in Fig. 9(c). This method allowed for the production of WC–Co cemented carbides with low shrinkage and high shape retention. The shrinkage rate was reduced to 3%, and the relative density reached 96.65%. The mechanical properties of the obtained cemented carbides were comparable to SANDVIK's traditional grade cemented carbides, with a hardness of 11.5 GPa and a fracture

toughness of $23.5 \text{ MPa}\cdot\text{m}^{1/2}$.

The problem of low mechanical properties in cemented carbides prepared by BJP can be effectively addressed through post-treatments. ENNETI et al [12] enhanced the properties of BJP-manufactured cemented carbides through pressure sintering. The results demonstrated that, at the same temperature, the hardness of pressure-sintered samples was 8% higher than that of vacuum-sintered samples, reaching HRA 88.6–88.9. This level of hardness is comparable to some PM-made cemented carbide materials (as depicted in Fig. 10(b)). Furthermore, pressure sintering led to the elimination of most pores and cracks (see Figs. 10(c, d)), resulting in a relative density of 99% (see Fig. 10(a)). MARIANI et al [11] investigated the impact of hot isostatic pressing (HIP) on the performance of cemented carbides produced by BJP. The findings revealed that HIP treatment effectively closed most internal pores and improved the density of cemented carbides. Moreover, SANDVIK developed a new type of cemented carbide powder and utilized the BJP technology to manufacture wire drawing grains, whose service life was increased by over 20 times compared to steel knife grains [42]. KENNAMETAL [51] and SANDVIK [46] also

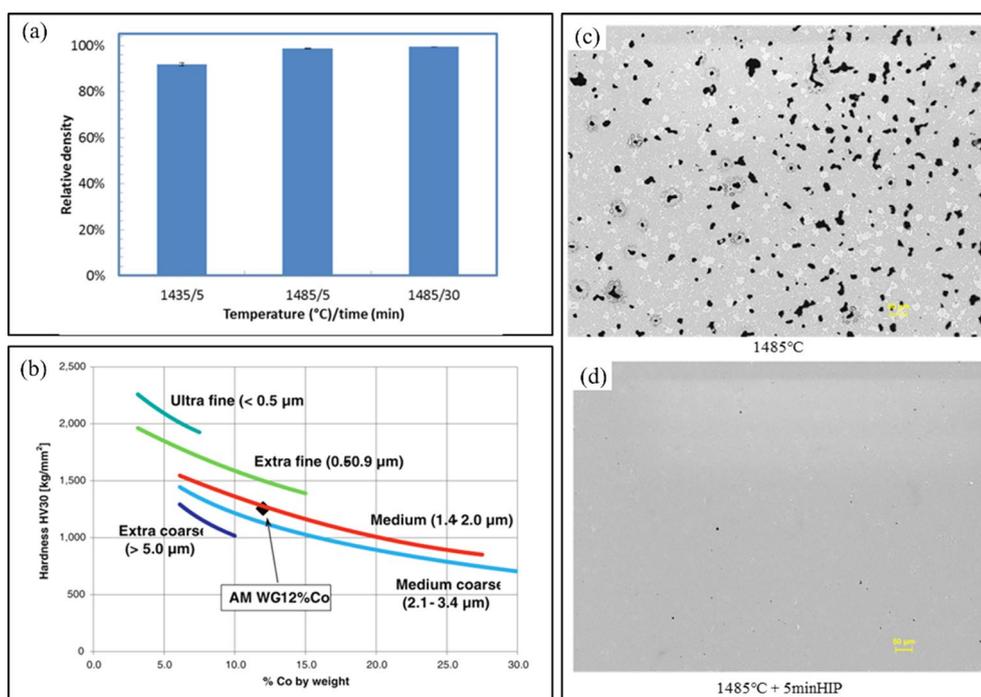


Fig. 10 (a) Variation of sample density with time in pressure sintering [12]; (b) Typical hardness of samples compared to powder metallurgy produced cemented carbides [12]; (c) Microscopic morphologies of sample vacuum sintered at 1485 °C [12]; (d) Microscopic morphologies of sample hot isostatically pressed at 1485 °C [12]

utilized BJP to fabricate WC–Co cemented carbide cutters, nozzles, and other components with closed-loop spiral cooling channels.

3.2.2 Fused deposition modeling (FDM) and thermoplastic 3D printing (T3DP)

FDM and T3DP both belong to the category of wax-based MEX technologies. FDM heats and melts materials consisting of polymer and powder by a heater. The molten material is then extruded through a nozzle and then deposited layer by layer on the platform following a specific path to produce three-dimensional part [114,115]. Similar to FDM, T3DP utilizes a thermoplastic bonding system to prepare materials with high solid content. However, T3DP employs materials with a relatively lower melting temperature (100 °C) and lower viscosity compared to FDM [116]. The material can be extruded through the nozzle as fine filaments and, uniquely, can also be dispensed in a discontinuous liquid droplet form through micro-dispensing technology. These droplets rapidly cool in the air and undergo solidification during the descent process. Since the patent for fused deposition modeling was proposed in 1989 [115], FDM-based 3D printers have undergone continuous development, found applications in various fields, and matured over time. Figure 11(a) provides a schematic diagram of the FDM process. In recent

years, researchers have explored mixing powders with thermoplastic polymers to create wire or granular masterbatches. FDM is then employed to shape green bodies, which are subsequently degreased and sintered into ceramic or metal parts, including alumina, zirconia, titanium alloys, and tungsten alloys [81]. The major advantage of FDM and T3DP is their low manufacturing cost.

LENGAURER et al [16] utilized FDM to fabricate WC–10Co cemented carbides and investigated the influence of process parameters on the sample properties. The findings revealed that the FDM-produced samples exhibited more voids and noticeable layering (as depicted in Fig. 11(b)), resulting in lower mechanical strength and significant shrinkage. However, by optimizing the printing strategy, the voids could be reduced, as shown in Figs. 11(c, d). In a study by LEE et al [37], FDM and SLM were employed to prepare WC–20Co cemented carbides, and a comparison was made between the two kinds of samples. The research indicated that, in comparison to SLM, FDM allowed for better control of porosity and phase content, due to the carbon loss and high residual stress introduced by high energy resource. The WC–Co cemented carbides fabricated by FDM possess a high relative density of 96.3% and a hardness of HRA 89.06.

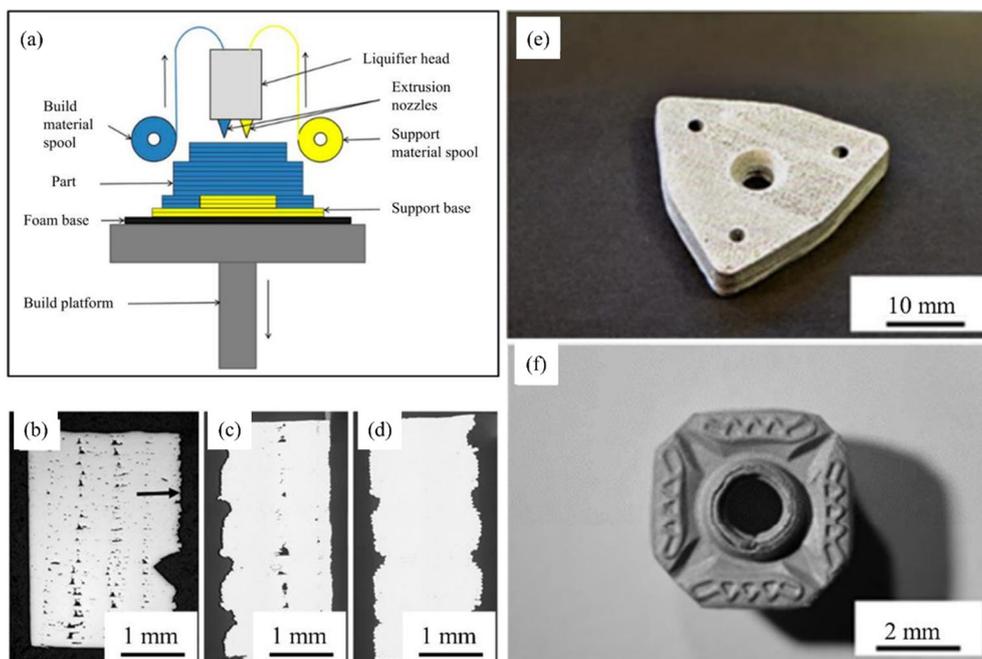


Fig. 11 Preparation of cemented carbides by FDM: (a) Schematic diagram of FDM [81]; (b) Cross-section of sample with large numbers of laminar pores [16]; (c) Cross-section of sample before using optimized strategy [16]; (d) Cross-section of sample after using optimized strategy [16]; (e) Prototype of printed indexable insert (WC–Co cemented carbides) with looped cooling channel [16]; (f) Printed parts with imprint of indexable insert [16]

ZHAO et al [111] utilized MEX to prepare WC–8Co cemented carbides and found that the samples exhibited a high relative density, approximately around 99%. Sintered samples do not contain η phase but showed a small number of pores and uncombined carbon, and some linear defects. They attributed these findings to the unevenness of the raw materials or nozzle blockages, leading to the inability to achieve a continuous and satisfactory extrusion of the material. Also, the sintered samples demonstrated higher hardness, ranging from HV₃₀1313 to HV₃₀1362. SCHEITHAUER et al [117] employed T3DP technology to fabricate WC–Co cemented carbides. They observed that the sintered samples achieved a relative density of 100%, with fine grains and almost no defects. However, the corresponding mechanical behavior characterization was not reported.

3.2.3 3D gel-printing (3DGP)

3DGP is an extrusion-based IAM technique [118]. This method involves extruding a suspension slurry, consisting of powder, solvent, dispersant and other organics, through a nozzle into a linear shape using a pinhole, and layer-by-layer deposition to form a three-dimensional structure. Unlike FDM, the 3DGP nozzle does not require heating, as the slurry undergoes a gel-status transition or a crosslinking reaction and solidifies within a limited time frame [39]. Figure 12(a) illustrates the schematic diagram of 3DGP equipment. The advantages of 3DGP technology include the use of simple raw materials, low production costs, and the

ability to mold at room temperature.

ZHANG et al [39] utilized 3D gel-printing to prepare WC–Co cemented carbides using a toluene-hydroxyethyl methacrylate gel system. They successfully formed and sintered a sample with a high relative density (99.93 %) and a density of 13.55 g/cm³. The resulting WC–Co cemented carbides exhibited a hardness of HRA 87.7 and a transverse rupture strength of 2612.8 MPa. However, the surface roughness was relatively high, necessitating further finishing or post-treatment processes.

3.2.4 Digital light processing (DLP)

DLP utilizes a digital light source to expose liquid photosensitive resin materials in a surface exposure method, leading to photoinitiated polymerization and layer-by-layer solidification, ultimately forming a three-dimensional structure [72]. This technology offers significant advantages in terms of printing speed, resolution, and accuracy. Unlike other additive manufacturing methods that utilize path scanning, DLP directly scans the photosensitive resin using a specific digital micromirror device (DMD) [72]. Consequently, DLP technology excels in printing speed, resolution, and accuracy. Figure 12(b) depicts a schematic diagram of DLP [84].

RIEGER et al [71] utilized the DLP method to prepare WC–12Co cemented carbides and observed numerous voids and defects within the sintered body. The relative density of the sintered body was found to be 90%, with an average porosity of 9%, and the maximum pore size reaching 167 μm .

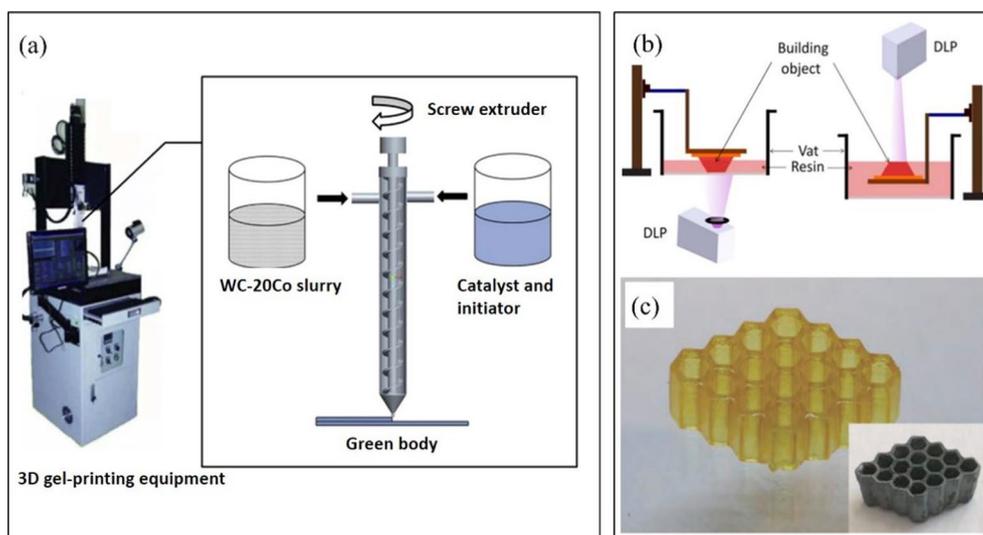


Fig. 12 Preparation of cemented carbides by 3DGP and DLP: (a) Schematic diagram of 3DGP [39]; (b) Schematic diagram of two structures of DLP [84]; (c) Cemented carbide green body and sintered parts prepared by DLP [112]

The hardness after sintering was relatively low, measuring $HV_{10}(1157\pm 59)$. At present, a collaborative effort between Central South University, Zigong Cemented Carbides Co., Ltd., and The Hebrew University of Jerusalem introduced a method for preparing cemented carbides using DLP technology. The approach involves combining monomer polymerization in organic chemistry with metal carbonization in inorganic chemistry [112]. Tungsten salts, cobalt salts, and acrylic monomers serve as raw materials to produce high-salt-concentration “inks”, which are then used to form cemented carbide precursor blanks through DLP. Subsequently, the WC–Co cemented carbides are densified through high-temperature carbonization/reduction and sintering processes [92]. Figure 12(c) shows the cemented carbide precursor body and sintered body prepared using this method. Furthermore, this approach has also been utilized for the additive manufacturing of porous tungsten materials [85]. The method offers advantages such as low manufacturing cost, high product fineness, and good surface quality. However, it is worth noting that the precursor body exhibits significant shrinkage and relatively low strength.

4 What AM technique is suitable for WC–Co cemented carbides?

The high hardness and wear resistance of WC–Co cemented carbides stem from their unique microstructure. Figure 13 illustrates the microstructure of a typical WC–Co cemented carbides prepared by powder metallurgy, which exhibits particular features. It can be observed that the typical cemented carbide possesses high density without graphite phase precipitated by excess carbon content, abnormally grain growth and substoichiometric carbide phase called η -phase (Co_3W_3C and Co_6W_6C). The binder phase, Co, and the hard phase, WC, are evenly distributed in the matrix [119]. These characteristics above depend on the properties of raw materials and the fabrication processes used.

WC, as hard phase in cemented carbides, belongs to the hexagonal crystal system with a melting point of $2860\text{ }^\circ\text{C}$. In the microstructure, it appears as step-like prisms [120], contributing to the wear resistance and hardness. The binder phase consists of the γ phase, which dissolved tungsten and carbon and has a melting point of $1495\text{ }^\circ\text{C}$. In

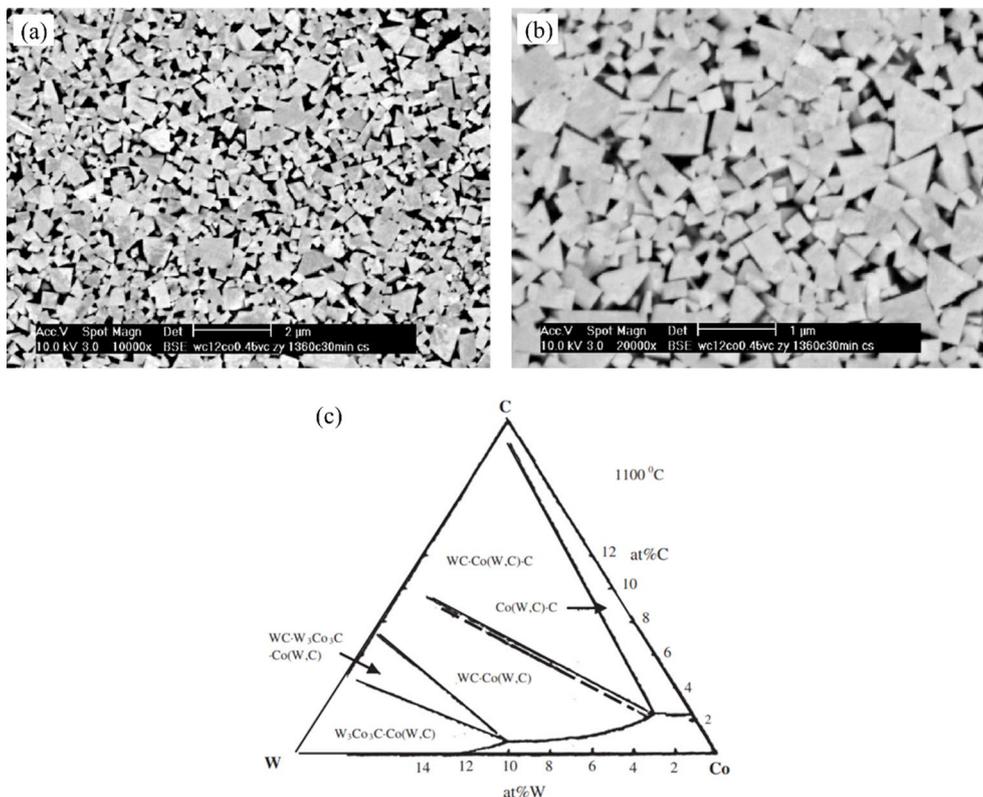


Fig. 13 (a, b) SEM images of ultrafine cemented carbides [120]; (c) W–C–Co ternary phase diagram [119]

the grain structure, it exists as separate γ grains at grain boundaries or as isolated γ domains within the matrix, contributing to the toughness of cemented carbides. According to the powder metallurgy sintering theory [119,121], the densification process of WC–Co cemented carbides during sintering can be divided into three stages [122–124]:

(1) Initial shrinkage: Increasing temperature causes solid state, surface, and bulk diffusion in powder particles, leading to sintered body shrinkage and strength increase.

(2) Significant shrinkage: Approaching the WC–Co eutectic point, Co binder metal undergoes viscous flow, altering particle contact and causing notable shrinkage.

(3) Densification: Co binder transforms into a liquid phase at its melting temperature, enabling typical liquid-phase sintering.

The dissolution–precipitation mechanism, driven by surface tension, dissolves WC at contact points and precipitates elsewhere, reducing particle distance and achieving shrinkage and densification. It is evident that the formation of the microstructure in WC–Co cemented carbides is a dynamic process that requires time for shrinkage and densification to occur. It is important to note that the carbon content has a significant impact on the properties of WC–Co cemented carbides. In the W–C–Co ternary phase diagram, there is a single-phase region of γ phase with W and C dissolved in cobalt. Along the Co–WC line, the cross-section can be divided into two regions. The upper-right region mainly consists of the three-phase region γ , WC, and C, while the lower-left region consists of the multiphase region composed of γ , WC, WC₂, W, and the ternary compound η phase. It can be observed that the range of the γ +WC two-phase region is narrow. When the carbon content exceeds the upper limit, graphite phases separate from the matrix, resulting in porosity. When the carbon content is below the lower limit, brittle phases such as the η phase (Co₃W₃C and Co₆W₆C) are formed, deteriorating the properties of WC–Co cemented carbides. Therefore, the carbon content of the sintered samples must be kept within narrow limits, in which neither η -phase nor graphite precipitates. In conclusion, the fabrication of cemented carbides using powder metallurgy techniques is a complex process that involves multiple solid-phase reactions and liquid-phase sintering mechanisms. Under the

influence of numerous interconnected factors, the sintered body undergoes dynamic shrinkage and densification, resulting in the formation of the microstructure of composite material.

Apparently, there are significant differences between PM and direct additive manufacturing of cemented carbides. DAM of cemented carbides is characterized by high cooling rates [20], high thermal gradients, and local liquid-phase sintering [31]. These characteristics lead to phenomena such as the re-melting of cobalt layers, evaporation of binder metals, generation of η -phases [18], and incomplete melting of powders. As a result, the microstructure of the composite material becomes inhomogeneous, with a decrease in toughness and the presence of defects such as pores and cracks. Researchers have attempted to address these issues by utilizing heat treatments [23,28], using powders with spherical shapes and smaller initial pore sizes [40] to eliminate porosity, preheating the powder bed to reduce residual stresses [27], selecting lower power heat sources to minimize thermal deformation [40], or adjusting the working distance [41] to eliminate layering effects. However, the inherent defect of non-uniform microstructure and lack of carbon and binder metal in DAM of cemented carbides have not been completely resolved.

Compared to DAM techniques, IAM of cemented carbides does not involve high temperatures and avoids issues such as volatilization of binder phases, carbon loss from hard phases, and uneven powder melting. The resulting microstructure of the prepared cemented carbides is uniform without normal grain growth and layer-liked structure, which is close to that of powder metallurgy products. In fact, IAM techniques have high consistency with the principles of the SDS (shape–debinding–sintering) method and are more suitable for cemented carbides. By drawing upon the well-established theories and technologies of powder metallurgy developed for large-scale industrial applications, IAM techniques can be further advanced. The proven techniques and approaches in powder metallurgy can also be applied in achieving industrial-scale implementation of IAM.

Some treatments in AM have been invented in the PM technique. For instance, CRAMER et al [36] and TANG et al [91] reduce the shrinkage of

samples after sintering by backfilling with cobalt via pressure-less infiltration, as well as SANDVIK's researchers utilize HIP to improve relative density. However, it should be noted that IAM still faces challenges such as complicated technological processes, excessive carbon content in the debinding process, and high shrinkage rates of the sintered sample. These issues need to be addressed through optimizing of process parameters, simplifying the process, or developing new AM techniques. Based on the discussion above, IAM techniques are prone to the fabrication of cemented carbides.

In summary, compared with DAM techniques, IAM techniques should be better for the fabrication of cemented carbides with controllable microstructure. As well-known, the unique microstructure of cemented carbides which determines their excellent properties is influenced by their fabrication processes. The rapid heating and cooling processes involved in DAM make it difficult to achieve a uniform and dense microstructure of cemented carbides, resulting in inherent defects such as porosity, η -phase, and high residual stresses. IAM, on the other hand, is closer to powder metallurgy techniques, making it easier to obtain microstructural characteristics, performance, and macroscopic dimensional accuracy similar to those achieved through traditional processes by adjusting process parameters.

5 Perspective and conclusions

Additive manufacturing technologies with features such as rapid prototyping and mold-free production have been successful in fabricating WC–Co cemented carbides known for their high hardness and strength. After years of development, components manufactured through the additive manufacturing show significant improvements in various aspects. Industrializing WC–Co cemented carbides manufacturing technology and making it a key focus in the future of the cemented carbides industry will be of great importance. The future challenges and development directions of WC–Co cemented carbide additive manufacturing can be summarized as follows.

Direct additive manufacturing (DAM) can fabricate any complex-structured WC–Co cemented carbides without post-processing, saving costs and

processing time. However, it still faces many defects that are difficult to address. The biggest challenge of DAM technology is to eliminate the inherent defects of pores, cracks, brittle η phase, and layer-like microstructure. Overcoming this issue completely needs to establish a model to simulate the actual variations in carbon–cobalt content during high energy sintering and design an appropriate surplus of carbon–cobalt based on this issue. Furthermore, optimizing powder forming processes and investigating residual stress mechanisms are equally crucial. At present, extensive simulation work has been conducted in metal AM, using some models like continuum heat conduction model and stress field model to analyze temperature and stress distributions, explore molten pool dynamics, and model residual stresses. These models are also expected to guide the additive manufacturing of WC–Co cemented carbides and decrease the inherent defects.

Indirect additive manufacturing (IAM) aligns harmoniously with powder metallurgy by combining green-body additive manufacturing technology and sintering principles employed in powder metallurgy. Though samples prepared by IAM possess the characteristics of complex geometry, high relative density, and excellent mechanic properties, it still faces challenges such as long process chains, high shrinkage rate, and carbon residue issues. Therefore, it is necessary to optimize the process chain and conduct systematic research on the debinding process and organic systems. Subsequently, it is essential to summarize the sintering densification behavior of cemented carbides green body via IAM. As for the defect of green body, in-situ sensing and process monitoring should be taken in account in the process of indirect additive manufacturing. These methods utilize a variety of detection and sensor technologies to continuously monitor the manufacturing process, enhancing the property of green body.

There is a need for systematic exploration of the post-treatment technologies associated with additive manufacturing techniques in cemented carbides, which contain re-densification, reshaping, polishing, and so on. These strategies certainly influence material properties. Establishing these technologies requires a deeper understanding of each additive manufacturing technology, followed by analysis and summarization to derive empirical

formulas that can facilitate the technological evolution of additive manufacturing of cemented carbides.

The emergence of additive manufacturing (AM) offers limitless possibilities for fabricating geometrically complex components of high-performance WC–Co cemented carbides. However, the application domains for AM-produced hard alloys remain unclear and need further discussion. Firstly, for complex and high-precision parts that are challenging to produce using existing technologies, a combination of recently developed techniques with cemented carbides production can be employed to broaden its application. Furthermore, AM technologies has the potential to achieve the capability of directly programming and manufacturing precise microstructure at the microscopic scale with further development, such as the direct fabrication of gradient hard alloys with excellent performance through multi-material printing. Lastly, expanding the application of cemented carbides involves incorporating them into existing complex components with low strength. Simultaneously, the development of corresponding policies and quality standards is equally important, along with expediting the industrialization of additive manufacturing for cemented carbides.

CRediT authorship contribution statement

Zhan-he LIU: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – Original draft; **Ke-chao ZHOU:** Supervision, Formal analysis, Writing – Review and editing; **Kai-hua SHI:** Methodology, Resources, Formal analysis; **Xiao-zan WU:** Resources, Data curation; **He XIAO:** Investigation, Data curation, Formal analysis; **Chao-qun PENG:** Resources, Supervision, Writing – Review and editing; **Ri-chu WANG:** Resources, Supervision; **Xiao-feng WANG:** Resources, Supervision, Conceptualization, Methodology, Writing – Review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by Major Science and Technology Projects in Fujian Province, China (No. 2023HZ021005), State Key Laboratory of Powder

Metallurgy, Central South University, China, and Fujian Key Laboratory of Rare-earth Functional Materials, China.

References

- [1] CHANG S H, CHEN Song-ling. Characterization and properties of sintered WC–Co and WC–Ni–Fe hard metal alloys [J]. *Journal of Alloys and Compounds*, 2014, 585: 407–413.
- [2] GENGA R M, CORNISH L A, AKDOGAN G. Effect of Mo₂C additions on the properties of SPS manufactured WC–TiC–Ni cemented carbides [J]. *International Journal of Refractory Metals and Hard Materials*, 2013, 41: 12–21.
- [3] LIU Xue-mei, WANG Hai-bin, SONG Xiao-yan, MOSCATELLI R. Elastic modulus of nanocrystalline cemented carbide [J]. *Transactions of Nonferrous Metals Society of China*, 2018, 28(5): 966–973.
- [4] ZHANG Wei-bin, DU Yong, PENG Ying-biao. Effect of TaC and NbC addition on the microstructure and hardness in graded cemented carbides: Simulations and experiments [J]. *Ceramics International*, 2016, 42(1): 428–435.
- [5] HU Jian, SUN Yu-shuang, ZHANG Hui, CHEN Zhen. Research on the structure of ultra small cemented carbide micro drill with ultra high aspect ratio and coating technology [J]. *Cemented Carbides*, 2022, 39: 409–417. (in Chinese)
- [6] SUN Hua-xin, XU Shu-bo, LI Hui, ZHENG Jun-zi. Effect of Ni content on mechanical properties and corrosion resistance of WC–Co–Ni cemented carbides [J]. *Rare Metals and Cemented Carbides*, 2022, 50: 77–82. (in Chinese)
- [7] LI Na, ZHANG Wei-bin, PENG Ying-biao, DU Yong, DERBY B. Effect of the cubic phase distribution on ultrafine WC–10Co–0.5Cr–xTa cemented carbide [J]. *Journal of the American Ceramic Society*, 2015, 99(3): 1047–1054.
- [8] ZHOU Ji-cheng, HUANG Bai-yun, WU En-xi. Extrusion moulding of hard-metal powder using a novel binder system [J]. *Journal of Materials Processing Technology*, 2003, 137(1/2/3): 21–24.
- [9] SU Wei, SUN Ye-xi, WANG Hui-feng, ZHANG Xian-qi, RUAN Jian-ming. Preparation and sintering of WC–Co composite powders for coarse grained WC–8Co hardmetals [J]. *International Journal of Refractory Metals and Hard Materials*, 2014, 45: 80–85.
- [10] MA Bei-yue, ZHANG Bo-wen, YU Jing-kun, QU Xuan-hui. Research progress on 3D printing technologies and advanced applications [J]. *Materials Research and Application*, 2016, 10: 233–237. (in Chinese)
- [11] MARIANI M, GONCHAROV I, MARIANI D, DE GAUDENZI G P, POPOVICH A, LECIS N, VEDANI M. Mechanical and microstructural characterization of WC–Co consolidated by binder jetting additive manufacturing [J]. *International Journal of Refractory Metals and Hard Materials*, 2021, 100: 105639.
- [12] ENNETI R K, PROUGH K C, WOLFE T A, KLEIN A, STUDLEY N, TRASORRAS J L. Sintering of WC–12%Co processed by binder jet 3D printing (BJ3DP) technology [J]. *International Journal of Refractory Metals and Hard*

- Materials, 2018, 71: 28–35.
- [13] CRAMER C L, AGUIRRE T G, WIEBER N R, LOWDEN R A, TROFIMOV A A, WANG H, YAN J, PARANTHAMAN M P, ELLIOTT A M. Binder jet printed WC infiltrated with pre-made melt of WC and Co [J]. *International Journal of Refractory Metals and Hard Materials*, 2020, 87: 105137.
- [14] DAVOREN B, SACKS N, THERON M. Microstructure characterization of WC–9.2wt.%Monel 400 fabricated using laser engineered net shaping [J]. *Progress in Additive Manufacturing*, 2021, 6(3): 431–443.
- [15] XIONG Y H, SMUGERESKY J E, AJDELSZTAJN L, SCHOENUNG J M. Fabrication of WC–Co cermets by laser engineered net shaping [J]. *Materials Science and Engineering A*, 2008, 493: 261–266.
- [16] LENGAUER W, DURETEK I, FÜRST M, SCHWARZ V, GONZALEZ-GUTIERREZ J, SCHUSCHNIGG S, KUKLA C, KITZMANTEL M, NEUBAUER E, LIEBERWIRTH C, MORRISON V. Fabrication and properties of extrusion-based 3D-printed hardmetal and cermet components [J]. *International Journal of Refractory Metals and Hard Materials*, 2019, 82: 141–149.
- [17] CHEN Cai, HUANG Bo-yun, LIU Zu-ming, LI Yong-xia, ZOU Dan, LIU Tao, CHANG Yi-ming. Additive manufacturing of WC–Co cemented carbides: Process, microstructure, and mechanical properties [J]. *Additive Manufacturing*, 2023, 63: 103410.
- [18] LI Chen-wei, CHANG Kai-chun, YEH An-chou, YEH Jien-wei, LIN Su-jien. Microstructure characterization of cemented carbide fabricated by selective laser melting process [J]. *International Journal of Refractory Metals and Hard Materials*, 2018, 75: 225–233.
- [19] KHYMYROV R S, SAFRONOV V A, GUSAROV A V. Obtaining crack-free WC–Co alloys by selective laser melting [J]. *Physics Procedia*, 2016, 83: 874–881.
- [20] KUMAR S, CZEKANSKI A. Optimization of parameters for SLS of WC–Co [J]. *Rapid Prototyping Journal*, 2017, 23(6): 1202–1211.
- [21] LIU Jin-yang, CHEN Jian, LIU Bing-yao, LU Yang, WU Shang-hua, DENG Xin, LU Zhong-liang, XIE Zhi-peng, LIU Wei, LIU Jian-ye, WANG Zhong-ping, QU Zhi. Microstructure evolution of WC–20Co cemented carbide during direct selective laser melting [J]. *Powder Metallurgy*, 2020, 63(5): 359–366.
- [22] YOO S H, SUDARSHAN T S, SETHURAM K, SUBHASH G, DOWDING R J. Short note Dynamic compression behaviour of tungsten powders consolidated by plasma pressure compaction [J]. *Powder Metallurgy*, 2013, 42(2): 181–182.
- [23] BRICÍN D, ACKERMANN M, JANSÁ Z, KUBÁTOVÁ D, KŘÍŽ A, ŠPIRIT Z, ŠAFKA J. Development of the structure of cemented carbides during their processing by SLM and HIP [J]. *Metals*, 2020, 10(11): 1477.
- [24] LU L, FUH J Y H, CHEN Z D, LEONG C C, WONG Y S. In situ formation of TiC composite using selective laser melting [J]. *Materials Research Bulletin*, 2000, 35(9): 1555–1561.
- [25] SON S, PARK J M, PARK S H, YU J-H, KWON H, KIM H S. Correlation between microstructural heterogeneity and mechanical properties of WC–Co composite additively manufactured by selective laser melting [J]. *Materials Letters*, 2021, 293: 129683.
- [26] ZHAO Y X, WANG H, ZHANG L, LI X F, GUO Z, ZHANG J F, YI D H, LIU B, BAI P K. Study on the microstructure and properties of WC–12Co cemented carbide fabricated by selective laser melting [J]. *Journal of Materials Research and Technology*, 2022, 20: 3512–3521.
- [27] ZHAO Yu-xia, WANG Hang, ZHANG Li, LI Xiao-feng, GUO Ziao, ZHANG Jin-fang, YI Deng-hao, LIU Bin, BAI Pei-kang. Effect of high-temperature preheating on the selective laser melting of yttria-stabilized zirconia ceramic [J]. *Journal of Materials Processing Technology*, 2015, 222: 61–74.
- [28] KUMAR S. Process chain development for additive manufacturing of cemented carbide [J]. *Journal of Manufacturing Processes*, 2018, 34: 121–130.
- [29] LI Yu-xin, BAI Pei-kang, WANG Yao-min, HU Jian-dong, GUO Zuo-xing. Effect of Ni contents on the microstructure and mechanical properties of TiC–Ni cermets obtained by direct laser fabrication [J]. *International Journal of Refractory Metals and Hard Materials*, 2009, 27: 552–555.
- [30] HU Zi-jian, ZHAO Zhe, DENG Xin, LU Zhong-liang, LIU Jian-ye, QU Zhi, JIN Feng. Microstructure and mechanical behavior of cemented carbide with Al alloy binder fabricated by selective laser melting [J]. *International Journal of Refractory Metals and Hard Materials*, 2022, 108: 105916.
- [31] CHEN Jian, HUANG Miao-jun, FANG Zak Zhi-gang, KOOPMAN M, LIU Wei, DENG Xin, ZHAO Zhe, CHEN Shao-hua, WU Shang-hua, LIU Jian-ye, QI Wen-jun, WANG Zhong-ping. Microstructure analysis of high density WC–Co composite prepared by one step selective laser melting [J]. *International Journal of Refractory Metals and Hard Materials*, 2019, 84: 104980.
- [32] XU Z K, MEENASHISUNDARAM G K, NG F L. High-density WC–45Cr–18Ni cemented hard metal fabricated with binder jetting additive manufacturing [J]. *Virtual and Physical Prototyping*, 2021, 17(1): 92–104.
- [33] ENNETI R K, PROUGH K C. Wear properties of sintered WC–12%Co processed via Binder Jet 3D Printing (BJ3DP) [J]. *International Journal of Refractory Metals and Hard Materials*, 2019, 78: 228–232.
- [34] MOSTAFAEI A, de VECCHIS P R, KIMES K A, ELHASSID D, CHMIELUS M. Effect of binder saturation and drying time on microstructure and resulting properties of sinter-HIP binder-jet 3D-printed WC–Co composites [J]. *Additive Manufacturing*, 2021, 46: 102128.
- [35] CRAMER C L, WIEBER N R, AGUIRRE T G, LOWDEN R A, ELLIOTT A M. Shape retention and infiltration height in complex WC–Co parts made via binder jet of WC with subsequent Co melt infiltration [J]. *Additive Manufacturing*, 2019, 29: 100828.
- [36] CRAMER C L, NANDWANA P, LOWDEN R A, ELLIOTT A M. Infiltration studies of additive manufacture of WC with Co using binder jetting and pressureless melt method [J]. *Additive Manufacturing*, 2019, 28: 333–343.
- [37] LEE S W, KIM Y W, JANG K M, LEE J W, PARK M S, KOO H Y, HA G H, KANG Y C. Phase control of WC–Co hardmetal using additive manufacturing technologies [J]. *Powder Metallurgy*, 2021, 65(1): 13–21.

- [38] DEMOLY A, LENGAUER W, VEITSCH C, RABITSCH K. Effect of submicron Ti(C,N) on the microstructure and the mechanical properties of Ti(C,N)-based cermets [J]. *International Journal of Refractory Metals and Hard Materials*, 2011, 29: 716–723.
- [39] ZHANG Xin-yue, GUO Zhi-meng, CHEN Cun-guang, YANG Wei-wei. Additive manufacturing of WC–20Co components by 3D gel-printing [J]. *International Journal of Refractory Metals and Hard Materials*, 2018, 70: 215–223.
- [40] WANG X C, LAOUI T, BONSE J, KRUTH J P, LAUWERS B, FROYEN L. Direct selective laser sintering of hard metal powders: Experimental study and simulation [J]. *The International Journal of Advanced Manufacturing Technology*, 2002, 19(5): 351–357.
- [41] XIONG Y H, SMUGERESKY J E, SCHOENUNG J M. The influence of working distance on laser deposited WC–Co [J]. *Journal of Materials Processing Technology*, 2009, 209(10): 4935–4941.
- [42] GYLLENFLYKT T. Method of making a powder for additive manufacturing: WO 2023274818A1 [P]. 2023–01–05.
- [43] BOOKHEIMER A J, SEMNISKY L M. Compound cutting tool: DE 102022117021A1 [P]. 2023–01–19.
- [44] DECKARD C R. Method and apparatus for producing parts by selective sintering: US 4863538A [P]. 1989–09–05.
- [45] KONYASHIN I Y, RIER B H, HINNERS H. Method of manufacturing a cemented carbide material: US 10946445B2 [P]. 2021–03–16.
- [46] MADERUD C J, SUNDSTRÖM J, MAGNUS E. A method of making cermet or cemented carbide powder: US 20220288683A1 [P]. 2015–12–17.
- [47] POETSCHKE J. Sintered cemented carbide granulate and its use: US 20190185972A1 [P]. 2019–06–20.
- [48] STOYANOV P. Cutting tool made by additive manufacturing: US 11123801B2 [P]. 2018–05–22.
- [49] XU Yue-hua, YUAN Yuan. Metal-based composite material and material additive manufacturing method thereof: CN 105458256A [P]. 2016–04–06.
- [50] SANDVIK. Sandvik acquires stake in BEAMIT, a leading Additive Manufacturing service provider [EB/OL]. [2022–12–27]. <https://www.additive.sandvik/en/news-trends/archive/2019/07/sandvik-acquires-stake-in-beam-it-a-leading-additive-manufacturing-service-provider/>.
- [51] 3D SCIENCE VALLEY. Kennametal becomes GE additive beta partner to advance binder jet capabilities in tungsten carbide [EB/OL]. [2022–12–27]. <http://en.51shape.com/?p=4269>.
- [52] ZHOU Xiang-kui, XU Zhi-feng, WANG Kai, LI Guo-jian, LIU Tie, WANG Qiang, HE Ji-cheng. One-step Sinter-HIP method for preparation of functionally graded cemented carbide with ultrafine grains [J]. *Ceramics International*, 2016, 42(4): 5362–5367.
- [53] SANDVIK. Materials authority Sandvik introduces 3D printed components in cemented carbide-enabled by patented process [EB/OL]. [2022–12–27]. <https://www.additive.sandvik/en/>.
- [54] GUO Nan-nan, LEU M C. Additive manufacturing: Technology, applications and research needs [J]. *Frontiers of Mechanical Engineering*, 2013, 8(3): 215–243.
- [55] TAKI K, WATANABE Y, TANABE T, ITO H, OHSHIMA M. Oxygen concentration and conversion distributions in a layer-by-layer UV-cured film used as a simplified model of a 3D UV inkjet printing system [J]. *Chemical Engineering Science*, 2017, 158: 569–579.
- [56] CHACÓN J M, CAMINERO M A, GARCÍA-PLAZA E, NÚÑEZ P J. Additive manufacturing of PLA structures using fused deposition modelling: Effect of process parameters on mechanical properties and their optimal selection [J]. *Materials & Design*, 2017, 124: 143–157.
- [57] ARAMIAN A, RAZAVI N, SADEGHIAN Z, BERTO F. A review of additive manufacturing of cermets [J]. *Additive Manufacturing*, 2020, 33: 101130.
- [58] YU A H, WEI X, XIN L, TAMADDON M, LIU B W, TIAN S W, ZHANG C, MUGHAL M A, ZHANG J Z, LIU C Z. Development and characterizations of graded porous titanium scaffolds via selective laser melting for orthopedics applications [J]. *Transactions of Nonferrous Metals Society of China*, 2023, 33(6): 1755–1767.
- [59] SUN Chang-ning, TIAN Xiao-yong, WANG Ling, LIU Ya-xiong, WIRTH C M, GÜNSTER J, LI Di-chen, JIN Zhong-min. Effect of particle size gradation on the performance of glass-ceramic 3D printing process [J]. *Ceramics International*, 2017, 43(1): 578–584.
- [60] LIAN Qin, ZHUANG Pei, LI Chang-hai, JIN Zhong-min, LI Di-chen. Mechanical properties of polylactic acid/beta-tricalcium phosphate composite scaffold with double channels based on three-dimensional printing technique [J]. *Chinese Journal of Reparative and Reconstructive Surgery*, 2014, 28(3): 309–13.
- [61] LIGON S C, LISKA R, STAMPFL J, GURR M, MULHAUPT R. Polymers for 3D printing and customized additive manufacturing [J]. *Chemical Reviews*, 2017, 117(15): 10212–10290.
- [62] SANAEI N, FATEMI A. Defects in additive manufactured metals and their effect on fatigue performance: A state-of-the-art review [J]. *Progress in Materials Science*, 2021, 117: 100724.
- [63] DEBROY T, WEI H L, ZUBACK J S, MUKHERJEE T, ELMER J W, MILEWSKI J O, BEESE A M, WILSON-HEID A, DE A, ZHANG W. Additive manufacturing of metallic components—Process, structure and properties [J]. *Progress in Materials Science*, 2018, 92: 112–224.
- [64] KÖRNER C. Additive manufacturing of metallic components by selective electron beam melting—A review [J]. *International Materials Reviews*, 2016, 61(5): 361–377.
- [65] GOH G D, YAP Y L, TAN H K J, SING S L, GOH G L, YEONG W Y. Process–structure–properties in polymer additive manufacturing via material extrusion: A review [J]. *Critical Reviews in Solid State and Materials Sciences*, 2019, 45(2): 113–133.
- [66] NATHAN-WALLESER T, LAZAR I M, FABRITIUS M, TÖLLE F J, XIA Q, BRUCHMANN B, VENKATARAMAN S S, SCHWAB M G, MÜLHAUPT R. 3D micro-extrusion of graphene-based active electrodes: Towards high-rate AC line filtering performance electrochemical capacitors [J]. *Advanced Functional Materials*, 2014, 24(29): 4706–4716.
- [67] REVILLA-LEON M, OZCAN M. Additive manufacturing technologies used for processing polymers: Current status

- and potential application in prosthetic dentistry [J]. *J Prosthodont*, 2019, 28(2): 146–158.
- [68] DERMEIK B, TRAVITZKY N. Laminated object manufacturing of ceramic-based materials [J]. *Advanced Engineering Materials*, 2020, 22(9): 2000256.
- [69] TAN L J, ZHU W, ZHOU K. Recent progress on polymer materials for additive manufacturing [J]. *Advanced Functional Materials*, 2020, 30(43): 2003062.
- [70] KODAMA H. Automatic method for fabricating a three-dimensional plastic model with photo-hardening polymer [J]. *Review of Scientific Instruments*, 1981, 52(11): 1770–1773.
- [71] RIEGER T, SCHUBERT T, SCHURR J, KOPP A, SCHWENKEL M, SELLMER D, WOLFF A, MEESE-MARKTSCHEFFEL J, BERNTHALER T, SCHNEIDER G. Vat photopolymerization of cemented carbide specimen [J]. *Materials (Basel)*, 2021, 14(24): 7631.
- [72] ZAKERI S, VIPPOLA M, LEVÄNEN E. A comprehensive review of the photopolymerization of ceramic resins used in stereolithography [J]. *Additive Manufacturing*, 2020, 35: 101177.
- [73] LIU Zhan-he, LIU Zi-ruì, ZHOU Ke-chao, CHEN Zi-hang, SHI Kai-hua, WANG Xin-yu, PENG Chao-qun, WANG Ri-chu, MAGDASSI S, HE Jin, WANG Xiao-feng. Vat photopolymerization additive manufacturing of WC–Co hardmetals enabled by in situ polymerization-induced microencapsulation [J]. *ACS Applied Materials & Interfaces*, 2025, 17(4): 7190–7200.
- [74] LIU Jin-yang, CHEN Jian, ZHOU Li, LIU Bing-yao, LU Yang, WU Shang-hua, DENG Xin, LU Zhong-liang, XIE Zhi-peng, LIU Wei, LIU Jian-ye, QU Zhi. Role of Co content on densification and microstructure of WC–Co cemented carbides prepared by selective laser melting [J]. *Acta Metallurgica Sinica (English Letters)*, 2021, 34(9): 1245–1254.
- [75] AGYAPONG J, DUNTU S H, CZEKANSKI A, YIADOM S B. Microstructural evolution and properties of cemented carbides alloyed with hexagonal boron nitride (h-BN) using selective laser melting [J]. *The International Journal of Advanced Manufacturing Technology*, 2022, 122(9/10): 3647–3666.
- [76] XIONG Y H. Investigation of the laser engineered net shaping process for nanostructured cermets [M]. Davis: University of California, 2009: 1–3.
- [77] XIONG Y H, HOFMEISTER W H, CHENG Z, SMUGERESKY J E, LAVERNIA E J, SCHOENUNG J M. In situ thermal imaging and three-dimensional finite element modeling of tungsten carbide–cobalt during laser deposition [J]. *Acta Materialia*, 2009, 57: 5419–5429.
- [78] XIONG Y, SCHOENUNG J M. Process cost comparison for conventional and near-net-shape cermet fabrication [J]. *Advanced Engineering Materials*, 2010, 12(3): 235–241.
- [79] IZADI M, FARZANEH A, MOHAMMED M, GIBSON I, ROLFE B. A review of laser engineered net shaping (LENS) build and process parameters of metallic parts [J]. *Rapid Prototyping Journal*, 2020, 26(6): 1059–1078.
- [80] KONYASHIN I, HINNERS H, RIES B, KIRCHNER A, KLOEDEN B, KIEBACK B, NILEN R, SIDORENKO D. Additive manufacturing of WC–13%Co by selective electron beam melting: Achievements and challenges [J]. *International Journal of Refractory Metals and Hard Materials*, 2019, 84: 105028.
- [81] MOHAN N, SENTHIL P, VINODH S, JAYANTH N. A review on composite materials and process parameters optimisation for the fused deposition modelling process [J]. *Virtual and Physical Prototyping*, 2017, 12(1): 47–59.
- [82] ROSHCHUPKIN S, KOLESOV A, TARAKHOVSKIY A, TISHCHENKO I. A brief review of main ideas of metal fused filament fabrication [J]. *Materials Today: Proceedings*, 2021, 38: 2063–2067.
- [83] BALLA V K, BOSE S, BANDYOPADHYAY A. Microstructure and wear properties of laser deposited WC–12%Co composites [J]. *Materials Science and Engineering A*, 2010, 527: 6677–6682.
- [84] CHAUDHARY R, FABBRI P, LEONI E, MAZZANTI F, AKBARI R, ANTONINI C. Additive manufacturing by digital light processing: A review [J]. *Progress in Additive Manufacturing*, 2022, 8(2): 331–351.
- [85] ZAN Xiu-qi, WANG Xin-yu, SHI Kai-hua, FENG Yan, SHU Jun, LIAO Jun, WANG Ri-chu, PENG Chao-qun, MAGDASSI S, WANG Xiao-feng. Three-dimensional porous tungsten via DLP 3D printing from transparent ink [J]. *Journal of Physics D: Applied Physics*, 2022, 55(44): 444004. (in Chinese)
- [86] PENG Hui, LIU Chang, GUO Hong-bo, YUAN Yuan, GONG Sheng-kai, XU Hui-bin. Fabrication of WC_p/NiBSi metal matrix composite by electron beam melting [J]. *Materials Science and Engineering A*, 2016, 666: 320–323.
- [87] WANG Jian-hong, HAN Yu-long, ZHAO Yu-xia, LI Xiao-feng, YI Deng-hao, GUO Ziao, CAO Yuan-kui, LIU Bin, TANG H P. Microstructure and properties of WC–12Co cemented carbide fabricated via selective electron beam melting [J]. *International Journal of Refractory Metals and Hard Materials*, 2022, 106: 105847.
- [88] SING S L, AN J, YEONG W Y, WIRIA F E. Laser and electron-beam powder-bed additive manufacturing of metallic implants: A review on processes, materials and designs [J]. *Journal of Orthopaedic Research*, 2016, 34(3): 369–85.
- [89] KUNIMINE T, MIYAZAKI R, YAMASHITA Y, FUNADA Y, SATO Y, TSUKAMOTO M. Cladding of stellite-6/WC composites coatings by laser metal deposition [J]. *Materials Science Forum*, 2018, 941: 1645–1650.
- [90] XIONG Y H, SMUGERESKY J E, LAVERNIA E J, SCHOENUNG J M. Processing and Microstructure of WC–CO cermets by laser engineering net shaping [C]//2008 International Solid Freeform Fabrication Symposium. Austin: University of Texas Libraries, 2008: 116–127.
- [91] TANG Jun-yu, LUO Lai-ma, LIU Zhen, ZAN Xiang, WU Yu-cheng. Shape retention of cemented carbide prepared by Co melt infiltration into un-sintered WC green parts made via BJ3DP [J]. *International Journal of Refractory Metals and Hard Materials*, 2022, 107: 105904.
- [92] SHI K H, ZAN X Q, ZHANG L, WANG X F, SHU J. Research status and prospects of 3D printing cemented carbides [J]. *Cemented Carbides*, 2020, 37(1): 19–29.
- [93] DAVOREN B, SACKS N, THERON M. Laser engineered net shaping of WC–9.2wt.%Ni alloys: A feasibility study [J].

- International Journal of Refractory Metals and Hard Materials, 2020, 86: 105136.
- [94] KIM K W, KALE A B, CHO Y H, PARK S H, LEE K A. Microstructural and wear properties of WC–12Co cemented carbide fabricated by direct energy deposition [J]. *Wear*, 2023, 518: 204653.
- [95] MORALES C, FORTINI A, SOFFRITTI C, MERLIN M. Effect of post-fabrication heat treatments on the microstructure of WC–12Co direct energy depositions [J]. *Coatings*, 2023, 13(8): 1459.
- [96] MEINERS W, WISSENBACH K, GASSER A. Shaped body especially prototype or replacement part production: DE 19649865C1 [P]. 1998–12–02.
- [97] HAN Xiao, KANG Nan, JIAO Jian-chao, WANG Chao. Surface characteristics of selective laser melted AlSi10Mg mirrors [J]. *Journal of Central South University (Science and Technology)*, 2020, 51(11): 3088–3092. (in Chinese)
- [98] YAO Cong, LI Rui-di, YUAN Tie-chui, NIU Peng-da. Microstructure and properties of Fe–Mn–Si based shape memory alloy by powder feeding laser additive manufacturing [J]. *Journal of Central South University (Science and Technology)*, 2020, 51(11): 3081–3087. (in Chinese)
- [99] FRIES S, VOGELPOTH A, KALETSCH A, BROECKMANN C. Influence of post heat treatment on microstructure and fracture strength of cemented carbides manufactured using laser-based additive manufacturing [J]. *International Journal of Refractory Metals and Hard Materials*, 2023: 111: 106085.
- [100] AGYAPONG J, CZEKANSKI A, BOAKYE-YIADOM S. Effect of process parameters on part quality, microstructure, and mechanical properties of a WC–Co-hexagonal boron nitride alloy prepared by laser power bed fusion process [J]. *Journal of Materials Engineering and Performance*, 2024, 33(1): 410–426.
- [101] REKEDAL K D, LIU D. Investigation of the high-cycle fatigue life of selective laser melted and hot isostatically pressed Ti–6Al–4V [M]//*Additive Manufacturing Handbook*. CRC Press, 2017: 569–574.
- [102] CHAUDHARY V, MANTRI S, RAMANUJAN R, BANERJEE R. Additive manufacturing of magnetic materials [J]. *Progress in Materials Science*, 2020, 114: 100688.
- [103] ZHANG An-feng, LI Di-chen, LIANG Shao-duan, WANG Tan, YAN Shen-ping. Development of laser additive manufacturing of high-performance metal part [J]. *Aeronautical Manufacturing Technology*, 2016, 517: 16–22. (in Chinese)
- [104] XIONG Y, SMUGERESKY J, LAVERNIA E, SCHOENUNG J. Processing and microstructure of WC–CO cermets by laser engineered net shaping [C]//19th Annu Int Solid Free Fabr Symp. SFF, 2008.
- [105] GRIFFITH M L, ENSZ M T, PUSKAR J D, ROBINO C V, BROOKS J A, PHILLIBER J A, SMUGERESKY J E, HOFMEISTER W H. Understanding the microstructure and properties of components fabricated by laser engineered net shaping (LENS) [J]. *MRS Online Proceedings Library (OPL)*, 2000, 625: 9.
- [106] HOFMEISTER W, GRIFFITH M. Solidification in direct metal deposition by LENS processing [J]. *JOM*, 2001, 53: 30–34.
- [107] LEWIS G K, SCHLIENGER E. Practical considerations and capabilities for laser assisted direct metal deposition [J]. *Materials & Design*, 2000, 21: 417–423.
- [108] PAN Shuai-hang, YAO Gong-cheng, CUI Yi-nan, MENG Fan-shi, LUO Chuan, ZHENG Tian-qi, SINGH G. Additive manufacturing of tungsten, tungsten-based alloys, and tungsten matrix composites [J]. *Tungsten*, 2023, 5(1): 1–31.
- [109] BERGER C, PÖTSCHKE J, SCHEITHAUER U, MICHAELIS A. Correlation of different cemented carbide starting powders with the resulting properties of components manufactured via binder jetting [J]. *Metals*, 2023, 13(11): 1848.
- [110] WOLFE T A, SHAH R M, PROUGH K C, TRASORRAS J L. Binder jetting 3D printed cemented carbide: Mechanical and wear properties of medium and coarse grades [J]. *International Journal of Refractory Metals and Hard Materials*, 2023, 113: 106197.
- [111] ZHAO Zai, LIU Ru-tie, CHEN Jie, XIONG Xiang. Carbon control and densification of WC–8%Co fabricated by extrusion-based additive manufacturing under pressureless sintering [J]. *Materials Today Communications*, 2023, 36: 106866.
- [112] WANG Xin-yu, FENG Yan, ZAN Xiu-qi, SHI Kai-hua, SHU Jun, LIAO Jun, PENG Chao-qun, WANG Ri-chu, MAGDASSI S, WANG Xiao-feng. 3D printed cemented carbide: Indirect preparation of precursors by photocuring printing [J]. *The Chinese Journal of Nonferrous Metals*, 2023, 33(4): 1063–1073. (in Chinese)
- [113] DO T, KWON P, SHIN C S. Process development toward full-density stainless steel parts with binder jetting printing [J]. *International Journal of Machine Tools and Manufacture*, 2017, 121: 50–60.
- [114] CAI Jia-wei, ZHANG Bai-cheng, ZHANG Mao-hang, WEN Yao-jie, QU Xuan-hui. Indirect 3D printed ceramic: A literature review [J]. *Journal of Central South University*, 2021, 28(4): 983–1002.
- [115] AWASTHI P, BANERJEE S S. Fused deposition modeling of thermoplastic elastomeric materials: Challenges and opportunities [J]. *Additive Manufacturing*, 2021, 46: 102177.
- [116] SCHEITHAUER U, SCHWARZER E, RICHTER H J, MORITZ T. Thermoplastic 3D printing — An additive manufacturing method for producing dense ceramics [J]. *International Journal of Applied Ceramic Technology*, 2015, 12(1): 26–31.
- [117] SCHEITHAUER U, PÖTSCHKE J, WEINGARTEN S, SCHWARZER E, VORNBERGER A, MORITZ T, MICHAELIS A. Droplet-based additive manufacturing of hard metal components by thermoplastic 3D printing (T3DP) [J]. *J Ceram Sci Technol*, 2017, 8(1): 155–160.
- [118] REN Xiang-yuan, SHAO Hui-ping, LIN Tao, ZHENG Hang. 3D gel-printing—An additive manufacturing method for producing complex shape parts [J]. *Materials & Design*, 2016, 101: 80–87.
- [119] FERNANDES C M, SENOS A M R. Cemented carbide phase diagrams: A review [J]. *International Journal of Refractory Metals and Hard Materials*, 2011, 29: 405–418.
- [120] XIE Hai-gen, YI Dan-qing, HUANG Dao-yuan, LI Jian.

- Preparation of ultra-fine grained hard metals [J]. Rare Metals and Cemented Carbides, 2007, 171(4): 14–17. (in Chinese)
- [121] GARCÍA J, COLLADO CIPRÉS V, BLOMQVIST A, KAPLAN B. Cemented carbide microstructures: A review [J]. International Journal of Refractory Metals and Hard Materials, 2019, 80: 40–68.
- [122] MCHUGH P E, RIEDEL H. A liquid phase sintering model: Application to Si_3N_4 and WC-Co [J]. Acta Materialia, 1997, 45: 2995–3003.
- [123] GERMAN R M, SURI P, PARK S J. Review: Liquid phase sintering [J]. Journal of Materials Science, 2009, 44(1): 1–39.
- [124] UPADHYAYA G S. Materials science of cemented carbides—An overview [J]. Materials & Design, 2001, 22: 483–489.

WC-Co 硬质合金增材制造技术：原理、进展和观点

刘展赫¹, 周科朝², 时凯华³, 伍晓赞¹, 肖和⁴, 彭超群¹, 王日初¹, 王小锋^{1,2}

1. 中南大学 材料科学与工程学院, 长沙 410083;
2. 中南大学 粉末冶金国家重点实验室, 长沙 410083;
3. 中钨高新材料股份有限公司, 株洲 412000;
4. 株洲钻石切削刀具股份有限公司, 株洲 412000

摘要: 增材制造(AM)技术已成为制造复杂形状 WC-Co 硬质合金产品的可行解决方案, 从而扩大了硬质合金产品在资源开采、设备制造和电子信息等领域的应用。全面总结了增材制造技术在 WC-Co 硬质合金中的研究进展, 介绍了增材制造技术的基本原理和分类, 评述了 WC-Co 硬质合金的增材制造技术并进行分类。根据是否包含脱脂和烧结等后处理, 将这些技术划分为直接增材制造技术(DAM)和间接增材制造技术(IDAM)。通过分析微观结构特征, 确定间接增材制造技术更适合于制备微观结构可控的 WC-Co 硬质合金产品。该类技术, 如粘结剂喷射打印(BJP), 可以将增材制造与传统粉末冶金相结合。

关键词: 硬质合金; 增材制造; WC-Co; 直接增材制造; 间接增材制造; 微观结构; 复杂形状

(Edited by Bing YANG)