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Process chain development for additive manufacturing of cemented carbide

Sanjay Kumar

Department of Mechanical Engineering, York University, Toronto, Canada

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ABSTRACT

Cemented carbide is a difficult material to be processed by Additive Manufacturing (AM) necessitating the need for process chain development to overcome the limitations of AM. Selective Laser Sintering (SLS) is proven to be the best AM process for making a complex product, and has potential to help produce a defect-free cemented carbide product. Consequently, in the present work, SLS is selected for process chain development study. Optimized SLS parameters are obtained to process WC-17Co (cemented carbide), which are able to furnish products of appreciable dimensional accuracy containing various fine features. In order to further improve product properties and remove any deficiencies, heat treatment is selected as a post-processing, which is accomplished in a furnace by heating samples at various temperatures (400, 600, 800 and 1000 °C) for a fixed duration of 3 h and by letting them cool inside the furnace. Samples are subsequently characterized to determine their hardness, fracture toughness, microstructure, wear resistance, composition of various phases and types of compounds formed. It is found that a moderate heat treatment has beneficial effects as the treatment at 600 °C furnished better hardness and fracture toughness while at 400 °C gave the best wear resistance. It is concluded that the heat treatment can be included as a complementary processing technique for producing cemented carbides as it has helped achieve products having better mechanical and wear properties.

Introduction

Additive manufacturing (AM) is a generic name for processes which make a product by adding a number of layers of various shapes and thicknesses as per CAD file of the product. In an ideal case, these processes are known to make a fast, inexpensive, complex and strong product, and are quite successful in making complex metallic and polymer products. However, for processing ceramic-dominated materials such as cemented carbides, these processes encounter myriad problems such as high porosity, a number of cracks, lack of mechanical strength and lack of complexity in shape. A number of AM processes such as Ink Jet Printing (IJP), Binder Jet 3D Printing (BJ3DP), Directed Energy Deposition (DED), Selective Laser Sintering (SLS) and Selective Laser Melting (SLM) have been employed to process cemented carbides. An early attempt was made to fabricate a mold from cemented carbides using a process similar to AM (a combined process of layer manufacturing and milling) [1].

IJP and BJ3DP take help of organic binders to shape cemented carbide products. These binders pose limitations to the maximum strength that could be achieved by a product. The strength can be improved by the removal of binders and subsequent infiltration. However, these post-processing techniques are not feasible for all geometries and sizes. Benichou and Laufer developed a tungsten carbide-cobalt ink composition to make micro parts using IJP [2]. Instead of depositing ink, it is experimentally demonstrated that a slurry containing WC-20Co, solvent, monomer and cross-linking agent can be deposited to form an end-use product (bevel milling cutter) [3]. Kernan et al. fabricated a WC-10Co part from a slurry containing WC, cobalt oxide and binder using BJ3DP [4]. The parts after sintering at a furnace reached to almost theoretical density but did not impart high strength. Recently, Enneti et al. achieved high density and fracture toughness using WC-12Co powder [5]. It is possible to make stronger cemented carbide products using DED but there is difficulty in making overhang structures. Xiong et al. used DED to make simple 3D blocks from WC-Co, but there is no further attempt made to use DED for fabricating complex cemented carbide parts [6]. Majority of works on this material has been done by SLS and SLM as these processes have an edge over other AM processes for making complex parts from high melting point materials. Kumar attempted to solve various manufacturing problems for making cemented carbide parts and conducted wear analysis on fabricated molds. However, parts needed to be infiltrated with bronze for increasing densification and strength [7]. Gu and Shen mixed nano WC-10Co particle and Cu powder to make a WC-Co/Cu composite. However, the amount of WC was not high (36 wt.%) and the final product was porous [8]. Gu and Meiners fabricated in-situ WC using a composition of W-Ni-graphite. It furnished a composite comprising of WC/Ni_2W_4C, W and Ni containing a low amount of WC [9]. In another case of the formation of metal matrix composites comprising WC, the wear resistance of a Ni-based alloy was improved by adding 25 wt. % WC [10]. Khymrov et al. were able to make crack-free WC-Co parts but the percentage of WC was low (25%) and fabricated parts were smaller. In this case, by increasing amount of WC to 50%, formation of cracks

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could not be avoided [11,12]. Uhlmann et al. could made WC-17Co parts comprising of cooling channels, but fine micro-cracks were observed in all samples [13]. Transverse rupture strength of these parts containing high amount of retained Co was significantly improved by application of hot isostatic pressing (HIP) as post-processing [14]. Past works show that making a WC-Co part by AM is easy if the amount of WC is low [11,12], shape of the part is simple and the size is small.

Kumar and Czekanski were able to make a complex WC-17Co part consisting of various micro-features such as thin walls tilted at various angles, cylindrical pins and holes of various diameters [15]. Their superior wear test results in comparison to maraging steel MS1 (the best available commercial SLM tool materials) indicated that SLS cemented carbide holds promise to deliver a superior tool material [16]. In most of the cases mentioned above, either a mixture of powders is taken or a composite powder is used. Cavaleiro et al. instead used a steel-coated WC powder which gave them an advantage of causing uniform distribution of steel in WC-steel matrix. However, due to poor wetting between WC and steel, structures were turned out to be mainly porous [17]. Davydova et al. used SLM to make a composite of Boron carbide and Co, but the resulting product was found to be porous [18]. These works establish that a material combination of WC and Co rather than a combination of any carbides and metals has higher possibility to furnish non-porous products using SLS/SLM.

Majority of the laser based powder bed fusion systems are not equipped with heaters to apply pre-heating more than 200 °C which limits the successful processing of high melting point materials (i.e. WC). This is the reason why there has not been as much progress in the processing of cemented carbides as in case of metals, polymers and other materials [19], though manufacturing problems for processing cemented carbides was attempted a decade back [7]. The present work is an attempt to overcome this limitation of SLS equipment by performing post heat treatments at various temperatures. This will help develop process chain for materials which are not yet processable by powder bed fusion systems. Unlike conventional sintering, SLS furnishes non-equilibrium microstructures, inhomogeneous melting and inhomogeneous distribution of pores [20]. This fact has a scope to shape greater role for post-processing in SLS. In the present work, WC-Co samples fabricated by an SLS system are undergone various heat treatments, and their effect thereafter are observed and analyzed. There has been a number of works reported on heat treatments of WC-Co coatings [21,22] and claddings [23] but there is no such work on heat treatments of additive manufactured cemented carbides. The present work will fulfill this gap.

Experimental

A composite powder (size from 15 to 45 μm) consisted of 83 wt. % WC and 17 wt. % Co is selected for experimentation. In order to produce the composite powder, WC powder (average size from 2 to 5 μm), cobalt powder and organic binders are agglomerated by milling. With the help of spray drying, the milled mixture is converted into spherical shape, which is further treated in a furnace to remove the binder and to strengthen it by sintering. The resulting powder has a minimum apparent density of 4.3 g/cc and is of near-spherical shape as shown in Fig. 1. Each powder comprises of several WC grains of maximum size 5 μm A composite powder is preferred over a mixture of constituents as it allows uniform distribution of binder (Co) during deposition and subsequent processing which helps achieve maximum densification using minimum amount of Co.

An AM system EOS M 280 [24], made for processing customized metals is used for processing powders. Before processing, its chamber is vacuumed and filled up with nitrogen gas. In order to use small area of powder bed platform for making parts, adaptive plates are used. The plate is made up of 1045 cold rolled steel of thickness 6 mm and size 10 mm × 10 mm and is acted as a substrate on which parts are built. By varying process parameters [15] such as laser power, scan speed, layer thickness, hatch spacing and preheating, a number of samples are fabricated which are analyzed to find optimized parameters (as shown in Table 1). These parameters are used to make a model of thickness 2 mm and area 20 × 70 mm (as shown in Fig. 2) consisting of following microfeatures: 1) holes of diameter 2, 4 mm and each of depth 2 mm, 2) cylindrical pins of diameter 0.5, 1, 2, 4 mm and each of height 5 mm, 3) thin walls of height 10 mm, thickness 2 mm and bent at angles 90°, 75°, 60°, 45°, 30° on a substrate plane [15].

For further experiments, the model is cut into five pieces: four of area 20 × 15 mm and one of area 20 × 10 mm. Samples are then heated in a furnace at room atmosphere for three hours at 400, 600, 800 and 1000 °C respectively at a heating rate of 150 K/h. They are then left in the furnace for ten to twenty hours to cool at maximum cooling rate of 50 K/h and to attain room temperature. The difference in the cooling rates does not influence the phases formed [25]. These samples are henceforth named as 400 °C sample, 600 °C sample, 800 °C sample and 1000 °C sample respectively while the sample without heat treatment is named as 0 °C sample.

Samples are polished using following steps in sequence: 20 min

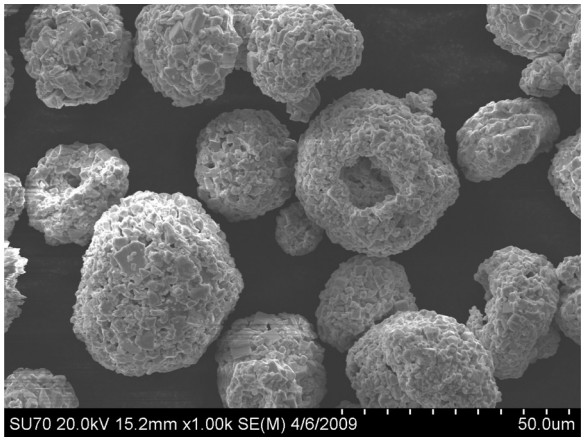

Fig. 1. Image of WC/Co powder.

Table 1
Values for optimized parameters.

Process parameter	Value
Laser power (W)	270
Scan speed (mm/s)	500
Layer thickness (mm)	0.04
Hatch spacing (mm)	0.04
Preheating (°C)	200

Fig. 2. Image of a model consisting of various micro features.