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Micro-powder injection molding of cemented tungsten carbide: feedstock preparation and properties

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Abstract

Micro-powder injection molding (μPIM) is an advanced net-shaping process for manufacturing metal, ceramic and carbide complex micro-components. The hardmetal ceramic-metal composite cemented tungsten carbide (WC–Co) is known for its high hardness, reasonable toughness, and high abrasion and wear resistance in various applications. This study focused on the characterization and evaluation of WC–Co powder as a feedstock through μPIM. A WC–10 wt.% Co powder was mixed with a paraffin wax (PW) and low density polyethylene (LDPE) binder to obtain the feedstock. The powder-binder mixture was prepared in 49–51 vol.% powder loadings to investigate the effects of the powder content on the feedstock properties. Differential scanning calorimetry and thermogravimetric analysis were conducted to determine the mixing, injection molding, and de–molding stage temperatures. The flow behaviors of the feedstock were evaluated using a capillary rheometer. Finally, the mechanical properties and density of the molded and sintered components were evaluated. This experimental work reveals that the as-received WC powder requires de-agglomeration using sufficient ball milling to achieve an acceptable level of powder loading. The green parts were successfully molded using feedstocks with 49 and 50 vol.% powder loadings. The results indicate that the WC–10 wt.% Co feedstock with a 50 vol.% powder loading provides a sufficient compromise between moldability, green density and stiffness. After debinding and sintering, the findings indicate that a micro part can be successfully fabricated through the μPIM process using the WC–10 wt.% Co feedstock.

Keywords: Injection molding; Carbides; Composites; Thermal properties.

1. Introduction

Powder injection molding (PIM) is a process used to fabricate components and offers several advantages such as shape complexity, low cost, and high performance [1]. Micro-powder injection molding (μPIM) is a cost-effective material processing technique used to produce metallic and ceramic micro-components for micro applications [2–4]. Micro-components are classified into three types: micro parts, micro-structured parts and micro precision parts. Micro parts typically have outer dimensions of a few millimeters and features in the sub-millimeter range. Micro-structured parts range in size between several millimeters and a few centimeters and have three-dimensional microstructures located on one or several surfaces. Micro precision parts have dimensions or features in the range of a few centimeters with tolerances in the micron range [5].

The four main steps in fabricating micro parts through μPIM are mixing, injection molding, debinding and sintering. During mixing, a fine powder is kneaded with an organic binder to yield a homogenized feedstock. The feedstock is heated and then injected at low or high pressure into a small cavity mold to form the desired shape (known as the green part). The binder is removed from the molded part during the debinding step according to the appropriate technique. Finally, the debound part is sintered to obtain high-density components [6].

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The powder and binder specifications for μPIM are considerably more important than those for PIM. To manufacture micro parts, the particle size of the powder should be sufficiently fine to fabricate the micro-components with good tolerance and high-quality surface finishing [4,7]. Small particles increase the time required to achieve a homogeneous feedstock while reducing the critical solid loading. This increased time is attributed to the high tendency of fine powders to aggregate, a problem commonly encountered with fine particles that is called agglomeration [1,8,9]. If agglomeration from the initial powder remains in the powder-binder mixture, it can cause defects in the sintered parts and reduce the mechanical properties of the final components [10]. Therefore, de-agglomeration of the powder is recommended during PIM obtain the desired physical and mechanical properties [9–11].

Feedstock fabrication is important because the subsequent PIM steps rely on the characteristics of the feedstock [12]. During μPIM, the binder system provides fluidity for the feedstock to easily fill the small cavity mold through injection. The binder keeps the powder particles together and maintains the shape of the molded part. An ideal binder should decompose easily during the debinding stage [13]. High powder loading can render mixing more difficult and increase the viscosity of the feedstock. In contrast, low powder content in the feedstock results in high shrinkage of the sintered parts. Therefore, optimizing the powder content in the powder-binder mixture provides sufficient viscosity for injection molding, few defects and good mechanical properties in the debound and sintered parts [14]. During injection molding, the feedstock specifications should be consistent to reduce defects in the micro parts. The thermal properties of the feedstock affect the mixing, injection molding and debinding steps of the μPIM process [7].

Although several studies have detailed the characterization and μPIM fabrication of metal and ceramic parts such as stainless steels [13], tungsten [9], alumina [15], silicon nitride [3] and zirconia [4], data for the μPIM of WC–Co remain insufficient. The WC–Co composite consists of ceramic-like tungsten carbide (WC) grains embedded in a cobalt (Co) binder phase. The WC–Co composite has long been known for its high hardness, wear resistance and strength. Machining of hardmetal is typically difficult and expensive. Hence, μPIM has the potential for manufacturing complex micro WC–Co parts without requiring subsequent finishing processes [16–18]. Few researchers [17] have attempted to fabricate micro WC–Co components using PIM and have obtained final densities 88–92% of the theoretical value after sintering in an argon atmosphere. Merz et al. [17] reported that further investigations into powder and feedstock characteristics are needed to obtain good physical and mechanical properties. In addition, the challenges of manufacturing WC–Co through PIM have been investigated by many researchers [11,19,20], but few reports can be found in the literature that provide details regarding the μPIM of WC–Co, such as powder properties, feedstock characteristics, injection molding data, and debinding and sintering specifications. Therefore, research into the μPIM of WC–Co is still needed. The present study attempted to fill these research gaps by investigating the properties of a submicron WC–Co powder and by fabricating a high-quality feedstock. The main challenges, which occur during the mixing step, are described in this article. The thermal and rheological characteristics of the WC–Co feedstock, which are important during μPIM, are also evaluated. Finally, the properties of the molded and sintered parts are discussed.

2. Experimental

2.1. Materials

A WC–10 wt.% Co powder was used for this work. The powder mixture was prepared by milling WC (99.5% mass fraction) and Co (99.8% mass fraction) powders with mean particle sizes smaller than 1 μm and 1.6 μm, respectively. A vanadium carbide (99% mass fraction) powder with an average particle size of 2.5 μm was doped into the powder mixture at 0.8 wt.%. The powder mixture was prepared through milling on a Fritsch Pulverisette–6 planetary mono mill. A hardmetal vial and ball were used to prevent contamination, and ethanol was used as the milling medium. The powder mixture was milled for 6 h at a rotational speed of 100 rpm. After wet milling, the powder was dried in a vacuum oven at 100 °C for 24 h. The distribution and morphology of the powder mixture were investigated using a Zetasizer ZS laser diffraction particle size analyzer and a Philips transmission electron microscope (TEM). A wax-based multi-component binder system was selected for this study. The binder contained paraffin wax (PW) as a major component to improve its rheological properties and wettability [13], a low-density polyethylene (LDPE) as a backbone polymer to increase the strength of green parts [21], and stearic acid (SA) as a surfactant to reduce the contact angle of the powder and binder interface [1,3]. The binder was designed to contain 65 wt.% PW, 30 wt.% LDPE and 5 wt.% SA. The characteristics of the binder components are presented in Table 1.

2.2. Experimental procedures

In this work, the critical powder volume concentration (CPVC) was measured using the oil absorption technique [22]. The WC–10 wt.% Co powder and binder components were mixed using a Brabender mixer (W50 EHT) at a roller blade speed of 30 rpm using over three powder loadings.

Table 1
Material characteristics of the binder components.

Binders	Chemical formula	Melting point (°C)	Decomposition temperature rang (°C)	Supplier
Paraffin wax (PW)	C_nH_{2n+2}	62.42	200–370	SYSTERM Co.
Low density polyethylene (LDPE)	$(C_2H_4)_n$	124.70	420–500	TITANEX
Stearic acid (SA)	$C_{18}H_{36}O_2$	60.64	160–310	SYSTERM Co.