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Fabrication of Metal Matrix Composites by Metal Injection Molding - A Review

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Abstract

Metal injection molding (MIM) is a near-net shape manufacturing technology that is capable of mass production of complex parts cost-effectively. The unique features of the process make it an attractive route for the fabrication of metal matrix composite materials. In this paper, the status of the research and development in fabricating metal matrix composites by MIM is reviewed, with a major focus on material systems, fabrication methods, resulting material properties and microstructures. Also, limitations and needs of the technique in composite fabrication are presented in the literature. The full potential of MIM process for fabricating metal matrix composites is yet to be explored.

Keywords: Powder injection molding (PIM); Metal injection molding (MIM); Metal matrix composite (MMC)

1. Introduction

Powder injection molding (PIM) is a near-net shape manufacturing technology that combines the shaping efficiency of plastic injection molding with the capability of powder metallurgy for processing metal and ceramic powders [1]. The PIM process normally involves four steps: mixing, injection molding, debinding and sintering, as illustrated in Fig.1. The evolution of the PIM technology has resulted in many variations, reflecting different combinations of powders, binders, molding techniques, debinding routes, and sintering practices. Metal injection molding, commonly known by its acronym MIM, is by far the most widely used PIM process.

Fig.1 Schematic diagram of powder injection molding

The process offers many unique advantages for the mass production of small and complex parts. First, precise and reproducible shapes can be achieved at a notably reduced cost as compared to conventional manufacturing processes. Part quantities varying from 5,000 per year (e.g., specialty firearm sights) to over 100 million per year (e.g., cell phone vibrator weights) can be economically produced by MIM [2, 3]. Second, complex shapes can be fabricated relatively easily with MIM, whereas conventional powder metallurgy methods are limited to the fabrication of parts with simple geometries. Third, the use of very fine powders in the feedstock promotes densification during sintering and hence high-performance parts can be produced with material systems that are difficult to sinter using conventional processes.

The attractive features of the MIM process can be applied advantageously to the fabrication of metal matrix composite (MMC) or ceramic matrix composite (CMC)

parts. Although many MMC or CMC offer unique properties that cannot be normally achieved by monolithic materials, their commercial use is often restricted by the high cost of materials and manufacturing. By applying the MIM process, the cost for commercial use of composite materials can be significantly reduced. In recent years, comprehensive work has been conducted to explore the potential of MIM for the fabrication of metal- and ceramic-based composites and components. Companies have even been established to discover the commercial capacity of the MIM technology for the fabrication of composites [4, 5]. The most widely studied composites by PIM are metal based, including stainless steels, refractory metals, intermetallic compounds, and titanium alloys. Although theoretically the reinforcements in a composite can take either continuous (typically long fibres) or discontinuous (particles and short fibres/whiskers) form, the flow and mould filling requirements of the PIM process determine that it is most applicable for processing feedstock containing particles or short fibres. Consequently, it is not surprising that all of the metallic composites fabricated by MIM to date are strengthened by discontinuous reinforcements.

This paper provides a review of the research activities related to composite fabrication through the MIM route. For completeness, bimetal structures and surface engineered components manufactured by MIM are also included in the metal matrix composites. Furthermore, fabrication of microcomponents by micro metal injection molding will be covered as well in the context even though it is still green at fundamental investigation stage.

2. Metal Matrix Composites (MMCs) by MIM

Based on the matrix materials, the composites fabricated by MIM can be divided into refractory metal matrix, titanium matrix, intermetallic matrix and steel matrix. Bimetal structures are also discussed in this section. The MIM route has enabled the fabrication of MMCs containing ingredient materials that are not compatible in molten state and difficult to fabricate by conventional routes [6].

Refractory Metal Matrix MMCs

Tungsten and molybdenum are two refractory metals that have attracted great interest for high temperature applications in such industries as consumer electronics, aerospace, telecommunications, medical and defence, due to their excellent heat resistance. The high melting temperatures of the metals (3422 °C for tungsten and over 2623 °C for molybdenum), however, make it extremely difficult to process the materials by melting and casting. Conventionally, tungsten and molybdenum based alloys and composites are fabricated by the powder metallurgical method, followed by minor machining or grinding, if necessary. The components manufactured by the conventional powder metallurgy processes are normally limited to simple geometries. The shaping advantage of MIM makes it suitable for producing complex shaped parts from tungsten or molybdenum based materials. Therefore, MIM has been widely explored as an alternative manufacturing route for fabricating refractory metal based materials [7-14]. Currently, the fabrication of such refractory components represents one of the most profitable applications of PM technology [11].

Due to the poor sinterability of the refractory system, ultrafine powders, particle sizes less than 10 micron or even at submicron scale, are commonly used in the fabrication of refractory parts by MIM in order to achieve high sintering density. A homogenous

mixture of the powders should be attained prior to further processes. Mechanical alloying and reduction of oxidized powders have been employed to achieve uniform mixtures of the starting materials [15]. The binder is a critical element in determining the part quality and the productivity of MIM process. New binder systems have been developed, some of which are listed in Table 1. As shown, wax-based binders are extensively used to formulate the MIM feedstock because waxes have low melting temperature, good wetting, short molecular chain length, low viscosity and small volume change during thermal process. After injection molding, the green parts are subjected to debinding process, solvently or thermally, or both. In most cases, the debound refractory composite parts are sintered at over 1200 °C in a pure hydrogen atmosphere. Final density, mechanical, thermal and electrical properties are the key parameters for the product [16].

An important refractory metal based composite is the W-Cu system, which has superior thermal management properties and high microwave absorption capacity. It is predominantly used for heavy-duty electrical contacts and arcing resistant electrodes. W-Cu parts are usually fabricated by infiltrating Cu into W powder compacts or liquid phase sintering of W/Cu powder mixtures. However, conventional techniques are unsuitable for the mass production of small intricate parts. MIM has been practised as an apposite method for mass production of small and delicately shaped W-Cu parts.

Table 1 Binder systems used in the feedstock of refractory composites for MIM

In Yoo's invention [29], MIM is employed to fabricate a tungsten skeleton structure having the porosity in the range of 15-40 % after sintering. Copper infiltration is then carried out by putting a copper plate beneath the tungsten skeleton structure and heating in hydrogen atmosphere. Compared to conventional P/M methods, the method can save energy and sidestep a sudden shrinkage during sintering. Furthermore, Yoo adopted the method for fabricating a hermetically sealed W-Cu package container for microwave device and achieved a strip wire connection with the thermal expansion coefficient similar to that of GaAs without any extra machining process [30]. Knuwer [31] confirmed that using MIM followed by liquid phase sintering was a promising and economical method for the production of housings for integrated HF-circuits. He obtained satisfactory accuracy as well as the mechanical and physical properties. Besides using ultrafine powders, adding a small amount of a third metal such as Co, Ni or Fe into the system was evidenced to improve the sinterability [32]. However, introduction of the additive element compromises the thermal management properties of the composites, as purity and homogeneity control in the W-Cu system is critical for obtaining high thermal conductivity [33, 34]. The use of ultrafine powders, in particular nanosized W/Cu powders, provides an effective solution to the sinterability problem of the W-Cu system. W-Cu composites with nearly full density have been achieved [15-23, 35]. For example, a W-20%Cu composite made of nano-sized particles could be densified to 95 % of theoretical density by sintering at 1150 °C for 2 hrs, and the W particles distributed homogeneously in Cu [15]. To achieve uniform mixing of tungsten and copper powders

and to increase the solid loading of nanosized powders, Kim and colleagues [18-21] adopted low energy ball milling to modify the shape of commercial fine powders. In the course of the low energy ball milling, the tungsten powder exhibited no change in either size or shape, while the ductile Cu powder was deformed to a three-dimensional equiaxial shape with reduced size. The change of the powder shape and size resulted in improved solid loading and better sinterability. Kim's investigation indicated the low energy ball milling could circumvent the agglomerate of nanopowders and prevent potential contaminations encountered in other milling processes. However, iron contamination was detected in the products even when the authors restricted ball milling time to 2 hrs. Undoubtedly, most of this impurity was introduced from the stainless steel vial used for milling and it could be minimized by using vials made from cemented carbides. Besides mixing and milling, reducing mechanically alloyed W-Cu powder at 600 °C for 1 hour in a hydrogen atmosphere can also lead to improvements in the green density and shape stability of the powder compact [19, 20, 36-38]. This effect is mainly attributed to the removal of internal impurities and oxides. In both Meinhardt's and Lee's inventions [39-41], they proposed to take advantage of different processes, such as grinding and reducing oxides in hydrogen, mixing powders with a protecting liquid in an inert atmosphere, to make super fine and pure composite powders for MIM.

Fabrication of W-Ni-Fe composites by MIM has been widely investigated as well [24-28, 42-47] due to the unique combination of high density, high strength, good ductility and corrosion resistance of the materials. The primarily studied W-Ni-Fe system for MIM fabrication is 90W-7Ni-3Fe [24-27, 43-47]. Nano-scale W-Ni-Fe composite powders are commonly fabricated by mechanical milling and mixed with a multi-component binder to

form homogeneous feedstock [25, 27, 43, 46, 47]. Experimental results demonstrated that milling escalated the degree of mixing of the elemental powders, the maximum powder loading, homogeneity of the feedstock, and the final sintering. Fully densified parts with high mechanical properties and negligible distortion were produced by solid state sintering in the temperatures range of 1350 °C to 1450 °C. In order to control the dimensional deviation of the final products, Fan [24] proposed a mathematic model of adjusting the weight deviation of the injected green parts, which was verified by experimental investigation. Furthermore, the role of additives like Mo, Ta and Re on the microstructure and mechanical properties of the W-Ni-Fe system by MIM has been scrutinized by German and Bose [48-50]. Their results show that even a small quantity of Re has remarkable solid solution strengthening and the grain refining capacity. However, the high cost of Re may restrict the addition of the additive to only special applications.

Similar to the W-Cu composite, the Mo-Cu composite has high thermal conductivity and a thermal expansion close match to semiconductor materials. The superiority of Mo-Cu to W-Cu is the lower density at the same weight fraction level. During the fabrication of the composite, poor sinterability is also an inherent problem. While at sintering temperature, there is essentially no solubility of Cu in Mo and only 1-1.5 % solubility of Mo in molten Cu. Utilizing the MIM process to fabricate Mo-Cu composite improves sinterability due to the use of ultra fine particles in the feedstock. Further more, additive elements, having a higher solubility for Mo and forming a continuous solid solution with Cu, will promote densification. Kirk [51] discovered that the addition of Ni to the systems could significantly enhance densification during sintering. However, this was achieved at the cost of coarsening Mo grain size, and abating thermal diffusivity.

Using ultrafine powders seems to be more beneficial because it raises the thermal diffusivity of the composite together with densification. An alternative route to improve thermal diffusivity of the composite is to amplify the high conductivity FCC phase by increasing the volume of Cu [52].

Titanium Matrix MMCs

Titanium alloys are the most promising metallic biomaterials for medical implant applications due to their good biocompatibility, high chemical stability in the physiological environment, and excellent mechanical properties. They are also extensively used in aerospace applications because of their high specific strength and corrosion resistance. The current research on titanium matrix composites through MIM is primarily focused on applications in the biomedical field.

Thian and his colleagues are the leading researchers in exploring the fabrication of titanium-hydroxyapatite (HA) composites for medical implant applications by MIM [53-57]. HA is a calcium phosphate compound $[\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2]$ with a composition similar to the mineral phase in natural bones. It is established as a bioactive material that encourages bone ingrowths when used in implants. HA itself, however, is brittle in nature, and cannot be used in load-bearing applications. The purpose of developing the HA/Ti alloy composite is to combine the superior bioactivity of HA and the excellent mechanical properties of titanium alloys, so as to avoid the brittleness and low fracture toughness problems of HA [58]. To make a homogeneous feedstock, Ti6Al4V and HA powders were first mixed by a slurry approach, using polyvinyl alcohol (PVA) as the carrier [53]. The PVA was removed later by heating, and the powder mixture was

crushed into small particles to obtain Ti6Al4V/HA composite powders with an inner core of Ti6Al4V wrapped with an outer layer of HA. A commercial binder system, PAN-250S, was used in the experiment. To set appropriate molding and debinding temperature, the thermal properties of the multi-component binder was investigated by TGA/DSC. The optimal solid loading of the composite powder in the feedstock for MIM [54] was around 60 vol.%, essentially the same as most other kinds of feedstock for MIM. The molded parts were debound thermally and the heating rate and gas flow rate played an important role in the process [55]. A slow heating rate at the beginning stage of debinding and a higher rate at the later stage, with a high gas flow rate during the whole process, were demonstrated as an effective approach to remove the binder.

During sintering a key challenge in fabricating Ti6Al4V/HA composite is to prevent HA from decomposing during high temperatures sintering. The degree of HA decomposition increases with sintering temperature, and it becomes significant when the sintering temperature reaches 1100 °C [56]. On the other hand, to achieve a high degree of densification of the composites requires a relatively high sintering temperature. Thian et al.'s results showed that for a Ti6Al4V/HA composite with 50 wt.% of Ti and 50 wt.% of HA, a sintering temperature of 1100 °C, a heating rate of 7.5 °C/min and a cooling rate of 5 °C/min produced the highest relative density and microhardness, while higher sintering temperature resulted in higher flexural strength and modulus. Furthermore, an in vitro study of the MIMed Ti6Al4V/HA tensile bars performed in simulated physiological conditions revealed the complete dissolution of the secondary phases such as tricalcium phosphate (TCP), tetracalcium phosphate (TTCP), and CaO after 2 week immersion. Following that, calcium phosphate crystals precipitated after 4 weeks of

immersion. It was also found that the mechanical properties deteriorated during the initial immersion period and then gradually recovered to almost identical the pre-immersion values because of the precipitation of an apatite layer [57].

It should be pointed out that the research on Ti/HA based MMCs by MIM is relatively new. Many issues, such as the sintering mechanisms of the Ti/HA system, the mechanical properties of the composites, and the preventions of the decomposition of HA at high temperatures, need to be elucidated. Given that pure HA could be sintered in controlled conditions to achieve better mechanical properties than that reported for the Ti/HA composite [58], further improvements in the mechanical properties of Ti/HA composites can be reasonably expected. Also, HA based composites with such reinforcers as silver, silica, tantania [59-67] have also been sintered to get attractive mechanical and biological properties. The reported Ti6Al4V/HA composite produced by MIM consisted of 50 wt.% Ti6Al4V and 50 wt.% HA, with HA coated onto the Ti6Al4V powder in the feedstock. During sintering, HA-HA and HA-Ti6Al4V would be bound together, whereas the Ti6Al4V powder actually restricted densification of the composite [57]. That is one of the reasons for the high porosity of the composite (over 50 %) in the study. Therefore, the mechanical properties of the composite are mainly contributed by the sintered HA powders and Ti6Al4V/HA interfaces. Also, sintering in vacuum would cause decomposition of HA at lower temperature [60, 67], especially with the presence of Ti. Altering the composition and revising the sintering conditions will be able to advance the properties of the MIMed composite.

Intermetallics Matrix MMCs

It has been recognized that intermetallic compounds based on aluminium have appealing characteristics of low density, high strength at elevated temperatures, along with good corrosion and oxidation resistance, which are highly desirable for high temperature structural applications as replacement for superalloys. However, the brittleness and poor fabricatability of the compounds limit their applications. Composite strengthening offers a way to improve the mechanical properties.

Among the intermetallic compounds, nickel aluminide Ni_3Al is one of the most widely studied materials and many techniques have been developed to produce the Ni_3Al based composites [68]. What makes this material unique is its anomalous thermal hardening behaviour. Depending on composition, the strength of Ni_3Al increases with temperature up to approximately 600 °C to 900 °C. Bose and German may be among the first to investigate the feasibility of fabricating a Ni_3Al based composite by MIM [69-73]. Both prealloyed and elemental powders were used in the experiment. The preferential alignment of the fibers in the matrix was attained by a modified form of MIM, where the feedstock was extruded through a special nozzle. After debinding, the consolidation was attained by reactive sintering of elemental powders under an imposed external stress via hot isostatic compaction (HIP). Full densification was possible by appropriate selection of particle sizes, composition, thermal procedure, pressure. As evidenced by the investigation, it is of general applicability to use relatively inexpensive elemental powder to fabricate hard-forming compounds

Alman and Stoloff further explored the adaptability of MIM for the production of other intermetallic matrix (NiAl , MoSi_2 and TaTiAl_2) composites [74-82]. The Al_2O_3 fibres were chopped and dispersed into the powders by mixing in alcohol. MIM was used to

form the shape and the consolidation of the composites was conducted by reactive synthesis followed by hot isostatic pressing. Results indicated superior alignment was achieved with small spherical powders after injection molding. Microhardness tests revealed that the Al_2O_3 fibers would strengthen the substrate, especially when aligned by MIM [82].

MoSi_2 is another attractive high-temperature structural material due to its high melting point (2030°C), excellent oxidation resistance and low density. Its extreme brittleness at temperature below 1000°C and the low creep resistance, however, hamper the manufacture and application of this material. Adding 20 vol.% of chopped Al_2O_3 fibres to the MoSi_2 PIM feedstock produced a MoSi_2 - Al_2O_3 composite with much improved fracture resistance and hardness [77, 83].

A distinct advantage of PIM in fabricating short-fibre reinforced composites is the capability of controlling the orientation of the fibres. Research results show that expanding the flow of the feedstock tend to align the fibres perpendicular to the flow direction, while contracting flow will produce a fibre alignment parallel to the flow direction, as schematically shown in Fig.2 [84]. By properly controlling the flow of the feedstock during injection molding, the mechanical properties along a certain direction can thus be tailored according to performance requirements. The key to successful alignment has been confirmed to be the size of the starting powder while the morphology of the powders has little effect on the degree of alignment [74]. However, this method suffers from several obstacles, including the need for fine spherical powders, proper selection of reinforcement and binder, and complete binder removal. Nevertheless, the

process has demonstrated the potential for near-net shape processing of intermetallic composites.

Fig. 2 Alignment of the fibres during injection molding

Steel-Matrix MMCs

Steel matrix composites seem to be of much less interest to the research society as compared to the other metal matrix composites described in the previous sections. This is because steels can be processed relatively easily using the conventional fabrication processes, and the properties of steels can be controlled in a wide range by simply varying alloy compositions and heat treatments. Therefore, few publications could be found on the research of steel-matrix composites.

The main purpose of fabricating ferrous composites by MIM is to improve the wear-resistance of the steel, coupled with the unique shaping advantage of MIM. Fine TiN and TiC powders, with an average diameter less than 10micron, are commonly added as the reinforcement. The amount of the addition is controlled to below 5 wt.%, to avoid compromising the densification and potential damage to the injection molding machine. The steel powders and the additive powders are mixed together to create uniform starting materials before adding the binder. Wax-based binder systems are predominantly employed in the fabrication of the steel-matrix as well. Table 2 represents some of the binders successfully applied in labs. The sintering is usually processed in reduction atmosphere and the temperature is subjected to the steel matrix, usually achieving over 90 % theoretical density in the range of 1200 °C to 1400 °C.

Table.2 Binder systems used in steel-matrix MMC fabrication

Turker et al [85] examined the rheological properties of mechanically alloyed composite powder prepared by two different instruments: a high energy attritor and a three-dimensional turbula mixer. It was found that the composite powders milled by an attritor showed more favourable rheological properties than those by turbula mixing. This was attributed to the fact that mechanical alloying in a high-energy attritor produced nearly spherical or ellipsoidal particles, whereas milling the powder in a ball-containing turbula mixer produced flake-like particles. Spherical particles are more desirable because of their better flowability and elevated packing density, which can result in high solid loading, improved compact strength and little dimensional change during sintering. In addition, powders mechanically alloyed by the high energy attritor are easy to densify during sintering due to the high strain energy stored in the powders. Although the high energy attritor mill is an effective instrument for preparing MIM feedstock, special care is needed to minimize contamination during the mixing process. The milling container and milling balls are potential sources of the impurities. Selecting the container and milling balls made from the same materials as the powders is an preferred way to minimize the contamination.

MMCs composed of gas atomized 316L stainless steel and TiC powders were fabricated by Loh et al with MIM [86]. By optimizing powder loading, the concentration of TiC in the composites, and the debinding and sintering process parameters, it was shown that MMC parts with about 98 % full density could be produced. The addition of TiC significantly increased the microhardness of the sintered parts. Khakbiz [87]

investigated the rheological behaviour and stability of the 316L/TiC composite feedstock. It was identified that the addition of TiC powders had different effects on the viscosity of the stainless steel feedstock at low shear rates ($<500 \text{ s}^{-1}$) and high shear rates ($>500 \text{ s}^{-1}$), owing to the competition between higher packing efficiency and deagglomeration caused by hydrodynamic stress with increasing shear rate. For stability, the results indicated that the addition of a secondary powder degrades the rheological behaviour and elevates the instability indexes. The studies show that TiC is an effective reinforcement to be added into stainless steel. By Through adjusting the rheological properties and processing parameters, defect free composite parts with improved hardness and wear resistance can be produced by MIM.

A major challenge in the sintering of steel matrix MMC is the precise control of carbon content in the steel matrix. This can be achieved by selecting the binder and controlling the CO partial gas pressure in the debinding and sintering atmosphere, often by a trial and error approach [88-90]. For steel based composites, a relative density of 95-99 % can be achieved with 3-5 wt.% ceramic addition [86,87]. Within this density range, the wear resistance of the steel based MMCs can be substantially improved. For example, a MIM composite with a 4140 steel matrix and 3 wt.% TiN particles showed 10 times lower wear mass loss as compared to the matrix material without reinforcements [88].

Bimetal Structures

Metallic components are often operated under severe conditions and aggressive environments. A bimetal structure with two different material layers bonded together can offer performance advantages for such applications. A traditional way of making the bimetal structure is to weld or bond the two selected materials together. In addition to the

high cost associated with the secondary operations, the conventional joining approach also has the disadvantage of requiring the use of a third material (e.g., weld-fillers, adhesives, etc) that frequently becomes the vulnerable locations on the components and hence impairs the component performance. Press fit or shrink fit can also be used for the fabrication of bimetal structures, but this approach can only be applied to parts with certain specific shapes [91]. MIM provides an alternative solution. By molding two metallic materials of different chemistries and properties together and sintering them to produce a finished bimetal part can overcome these problems. Bimetal structures produced by MIM are sometime regarded as continuously reinforced MMCs [91-101]. This is true only in the macro scale and is accepted in this paper as well.

Based on the application of the composites, different combinations of materials can be manufactured into bimetal composites. Wear resistant pieces with a core of stainless steel and a covering of tool steel or heavy metal, and electronic parts of a non-magnetic center surrounded by magnetic ring were fabricated [91-94]. Actually, various combinations of materials can be manufactured into bimetal composites if similar sintering kinetics and thermal expansion of the compositions can be achieved. In practice, wax-based binder systems are widely used as well. By modifying the solid loading of the component powder, the sintering behaviour of the different materials can be adjusted.

A bimetal part can be molded in two ways. The first is molding with two single-barrel injection-molding machines. By this method, one material is injected into the mould with one or several cavities in a single-barrel machine, and then the molded part is transferred to another tooling in another single-barrel machine, where the second material is injected in [91-94]. The second method is molding with a twin-barrel injection molding machine,

as illustrated in Fig.3. The cavity is filled by the first material from a barrel, then the whole mould is modified by rotation or subsection and the second material is injected around or adjacent to the insert [95,96]. The second method has apparent advantages in comparison with the first one. The procedure for the first method involves logistic and quality challenges because the first material must be placed exactly into the second mould, where the first material must be cooled to room temperature. This step may induce thermo-mechanical stresses between the two components after the second molding operation. In contrast, the second method does not require the transfer of an insert since it remains in the same mould. The second material is injected immediately after the first injection, and the two materials cool together without inducing the stress caused by the temperature difference. Based on above ideas, diversified methods were derived and patented [97, 98]. In [97], different powder materials are each mixed with a binder system and granulated to form feedstocks. The feedstocks are melted and concurrently or sequentially injected into a mold and allowed to solidify as the green part. A patent [98] describes the second composition which is molded by injecting the second feedstock into the cavity where the first MIMed compact is arranged to let the second material flow parallel to the joining surface. As a result, the second composition can contact the first with neglectable temperature gradient.

Fig.3 A schematic diagram of co-injection molding

To produce strong bonding between the co-injected materials during sintering, it is required that the two materials have similar thermal expansion and densification behaviour along with chemical compatibility. Choosing component materials with good

metallurgical compatibility, suitable particle shape, size distribution and tap density are essential for suitable bonding [91-93, 102].

Investigations on composite material of iron/iron-silicon, iron/316L, iron-silicon/316L and a low alloy steel/tungsten carbide heavy metal were presented and discussed by Pischang [94]. The shrinkage behaviours of the ingredient materials, and the sintering behaviours of two different shaped composites, layered sample and coated sample, were studied. The results confirmed that distortion and cracks could initiate along the phase boundaries of different materials if the ingredient materials are not properly selected. Therefore, it is important to ensure that the ingredient powders will be densified at the same temperature with similar shrinkage. The formation of intermetallic phases along the interface would deteriorate the composite mechanical properties.

The co-injection route can realize the production of wear resistant tool steel using a low alloy steel or stainless steel substrate, where the low alloy steel or stainless steel can impart toughness, corrosion resistance and cost preference as compared to a component that is fabricated of 100 % tool steel. Pest et al. [99, 100] showed that a bimetal composite of M4 tool steel and Fe-2Ni could be molded and thermally processed. The feedstock of both materials was produced in a twin-screw mixer. Fe₂Ni1B green parts were molded first and then cut in the middle. One half was placed into the cavity, and then M4 feedstock was injected into the cavity. After debinding, the parts were sintered in hydrogen with graphite as the carbon source. Matching the densification behaviour of the ingredient powders was realized by altering the particle characteristics and alloy chemistry of the powders. In this experiment, M4 powder was milled to promote solid state sintering at low temperature and boron was admixed with the Fe-2Ni to form a

liquid phase at the sintering stage [99]. Heaney successfully molded and sintered M2 tool steel with 316L stainless steel as a bimetal composite [101]. In his study, two material systems were selected by detecting the shrinkage rate of the component with a dilatometer. The sintering behaviours of M2, Fe-10Cr-0.5B, 4340-0.5B, 316L-0.5B and Fe-2Ni-0.5B (wt.%) were investigated. These powders were admixed with 2 wt.% paraffin wax and pressed into cylindrical compacts. After thermally debinding in a flowing hydrogen atmosphere, the samples were sintered at 1400 °C in a 95/5 vol.% argon/hydrogen atmosphere. By comparing the shrinkage of the different materials with M2, it was found 316L-0.5B stainless steel had the best sintering compatibility with M2. The final sintered products displayed sound metallurgical bonding between the ingredient materials, resulting in a defect-free, functionally graded MIMed bimetal composite component.

Furthermore, the co-injection molding method presents a new way for surface engineering. It is particularly advantageous when small parts with complex geometries require relatively thick coating. By injecting a layer of desired materials onto an inexpensive solid core, a high-performance bimetal composite with an engineered surface can be formed after sintering [103, 104]. Howell et al. [104] has demonstrated that Stellite 3 cobalt alloy powder can be injection molded onto a 1090-wrought steel core to fabricate a composite cotton picking spindle part. The combination of superior ductility and toughness of the 1090 steel core combined with the magnificent wear resistance of the Stellite material has resulted in an economical part with greatly improved wear resistant. Because of the high sintering temperature involved in the densification of PIM parts, the bimetal composites fabricated by molding powder to a solid core will normally

produce a core material in the annealed condition, which can sometimes compromise the strength of the core.

3. MMC by Micro-MIM

Miniaturization offers the conspicuous advantage of a higher functional integration and a wider range of new application fields associated with portable products [105]. Therefore, microsystem technology (MST) has been regarded as one of the leading technologies in the engineering world and it is predicted that the MST will become as significant for innovative products in nearly all branches as microelectronics is today [106]. In the last decade, microdevices and microcomponents with dimensions ranging from nanometers to millimeters have been applied in various areas, e.g., biomedical and biotechnology, automotive industry, telecommunication, and electronics [107-109]. However, commercialized microsystem products are mainly limited to polymeric and silicon materials so far. Metallic microsystems offer specific properties which could not be attained by polymers or silicon materials. Furthermore, existing microfabrication methods, such as X-ray lithography, electro-forming and excimer laser ablation, have the drawbacks of either low productivity and high production cost or constrained material availability. To overcome these disadvantages, micro metal injection molding (μ MIM) has been established as a promising route to the mass production of metallic microcomponents [110-112].

Micro metal injection molding (μ MIM) is the miniaturization of the conventional metal injection molding process (MIM) and it inherits the features of conventional MIM such as low production cost, geometric complexity, near net-shape, good tolerance and reproducibility [113]. As in conventional MIM, the four major processing steps of μ MIM

are: formulation of the feedstock, molding to achieve design geometry, debinding to remove the binder and sintering to obtain desired properties. As can be expected, the requirements for the powders, binders, facilities are much more stringent for μ MIM because the structure dimensions are reduced to micron scale.

To date, most μ MIM work was focused on the fabrication of micro components using single materials. The exploration of μ MIM for the fabrication of composites has just started. W-Cu composite fabricated by μ MIM was reported by Kim [114] and WC-Co composite by μ MIM was mentioned in [113]. Kim prepared the nanocomposite powder of W-30%Cu by mechanical alloying in a stainless steel container for 50hrs and produced irregularly-shaped W-Cu agglomerates with a mean particle size less than 100nm. The binder system for μ MIM was a wax-based multicomponent system, adapted from their previous study on conventional MIM [18]. Micromolded PMMA was used as the mold insert. The tiny flow channels used in the micro moulds have created significant resistance to the flow of the feedstock. Complete filling of the micromold could be achieved only upon prior evacuation of the cavity by a vacuum pump. The sintering behaviour of the nanocomposite powder was examined by dilatometric analysis to modify the processing parameters. Due to the use of extremely fine powders in the feedstock, W-Cu microparts of full densification without distortion were achieved by solid state sintering at 1050 °C for 5 hrs with a heating rate of 3 °C/min. The sintering temperature was much lower than the one used in conventional sintering.

As the conventional MIM, μ MIM can also be applied to fabricate the bimetal structures. Based on the dilatometric study of the materials during sintering, a considerable number of parts made from different metals and alloys have already been

manufactured [115]. Depending on the specific application, materials with different mechanical and/or physical properties might be joined with each other. In the process, the feedstocks of different materials are co-injected into the mould in order to obtain a bimetal composite without additional operations. Fig.4 exhibits an encoder fabricated by IFAM, with the combination of a non-magnetic steel (316L) and ferromagnetic steel (17-4PH Stainless steel) fabricated by μ MIM.

Fig.4 Micro-MIMed Encoder composited by a non-magnetic steel (316L) and a ferromagnetic steel (17-4PH)

(a) Green and sintered parts (b) Microstructure of the bimetal composite; Interface area about $850 \times 850 \mu\text{m}^2$
(Courtesy of Philipp Imgrund, IFAM, German)

As encountered in [114], incomplete mold filling often occurs in the injection molding of microcomponents with commercially available feedstock or feedstock with convention binder system because of the high viscosity or the insufficient stability in the micron scale [110]. Three methods are generally applied to avoid the filling problem, i.e., using high injection pressure and holding pressure, elevating the mold temperature and applying vacuum to the mold cavities [116, 117]. Rota [113] solved the poor filling of WC-Co due to the high heat conductivity by heating the mold to the feedstock temperature.

Although studies have already demonstrated the feasibility of fabricating composites using μ MIM, the R&D in this area is still at its embryonic stage and quite a lot problems

need to be addressed. Even for monolithic materials fabricated by μ MIM, reproducibility as well as quality assurance, standardized measuring systems are still pending for successful commercialization [118]. Compared with conventional MIM, μ MIM has inherent challenges due to submicron powders used and micron scale accuracy. Since submicron powders tend to be pyrophoric and prone to contamination, it is essential to avoid any oxidation and impurity during processing. Handling of such fine powders and formulating the feedstock usually takes place in a glove box under argon [119]. Furthermore, the thermal stresses in the microcomponents induced during debinding and sintering are much higher than conventional components because of the tiny particle size. In addition, uniformity in micron scale in the course of every step is laborious to achieve with conventional facilities, which would result in the deviation of the properties and dimensions of the products. It is expected that the above problems would be more difficult for composites, comprising of two or more different submicron particles. Advances in automation and control, together with enhanced tooling accuracy, will positively minimize the deviation of the final products and problems arising from production, in the future.

4. Summary

MIM provides a promising way of fabricating MMC materials and components. It is particularly cost-effective for the fabrication of small, complex parts due to its shaping capabilities. The nature of the MIM process determines that it is suited mainly for the fabrication of composites with discontinuous reinforcements, typically particles or short fibres/whiskers. It can also be used to fabricate bimetal or surface engineered

components, which are considered composites with continuous reinforcements in a wider sense.

The composite materials fabricated by MIM so far include steel, refractory metal, intermetallic compounds, and titanium alloys with various types and forms of reinforcements. Bimetal composite structures can be produced by MIM through co-injection of different types of feedstock or molding a powder over a solid core as well. Furthermore the micro MIM has shown the capacity of manufacturing composites at micron scale. Limitations and needs of the technique in composite fabrication are also presented in the literature. Previous research has demonstrated the feasibility of fabricating advanced composites and components using the MIM approach. The full potential of MIM process for fabricating metal matrix composites is yet to be explored.

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Fig.1 Schematic diagram of powder injection molding

Fig. 2 Alignment of the fibres during injection molding

Fig.3 A schematic diagram of co-injection molding

Fig.4 Micro-MIMed encoder composited by a non-magnetic steel (316L) and a ferromagnetic steel (17-4PH)

(a) Green and sintered parts (b) Microstructure of the bimetal composite; Interface area about $850 \times 850 \mu\text{m}^2$

(Courtesy of Philipp Imgrund, IFAM, German)

Table 1 Binder systems used in the feedstock of refractory composites for MIM

Ref.	Composition	Molding temperature	Solid loading (vol.%)	Debinding method	Powder
Moon [15,17] Kim [18,19] Ryu[20] Kim[21]	45% PW, 15% Bee wax 30%PE, 10% SA	120-130	NA	Thermal	W-Cu
Yang [22]	35% PP, 60%PW, 5%SA	NA	52	Solvent + Thermal	W-Cu
Yang [23]	40%PP, 55%PW, 5%SA	NA	54	Solvent + Thermal	W-Cu
Fan[24]	PS, PP, EVA, PW., Oil, SA, DOP	140-160	51	Solvent+ Thermal	W-Ni-Fe
Suri [25]	PW, PP	170	60	NA	97W-2Ni-1Fe
Fan [26] Huang [27]	74%PW, 20%EVA, 5%HDPE, 1%SA	135	57	NA	90W-7Ni-3Fe
Li[28]	50%Polystyren, 30%PP, 20%VO	185	47	Solvent+ Thermal	97W-2Ni-1Fe

Table.2 Binder systems used in steel-matrix MMC fabrication

Ref.	Composition	Molding temperature	Solid loading (vol.%)	Debinding method	Powder
Turker [85]	60%PW, 35%PP, 5%SA	175	50	NA	Fe-Cr-Al ₂ O ₃ -Ti-Y ₂ O ₃
Loh [86]	PAN31 (Adeka Fina Chemical)	60-70	53	Thermal	316L-3%TiC
Khakbiz [87]	53% PP, 30%EVA, 15% CW, 2%SA	60-80	55-60	Solvent + Thermal	316L-3-5%TiC
Miura [88]	69% PW, 20% PP, 10% Carnauba wax, 1% SA	NA	68	Thermal	SCM440-3%TiN

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