Processing and properties of bi-material parts by micro metal injection moulding

Ph. Imgrund, Dr. A. Rota, L. Kramer

Fraunhofer Institute for Manufacturing and Advanced Materials (IFAM), D-28215 Bremen, Germany

Abstract

Several metals and alloys can be used to enhance mechanical and physical properties of micro parts and components for micromechanical, -chemical or sensor applications. Such parts can be produced in series by the powder metallurgical process of micro metal injection moulding (µ-MIM) that has been developed at IFAM in recent years.

A micro system is usually obtained by assembling a number of parts with different functions, i.e. materials, in difficult packaging or joining operations. This paper describes a novel manufacturing route for metallic multi-material micro components, bi-material micro metal injection moulding (2K-µ-MIM). Similar to "two-colour" injection moulding of plastics, the process allows the integration of multiple functions in a micro part by simultaneously injecting and joining two materials in one mould. Net-shape parts with well-defined, solid material interfaces are obtained. In this paper, the 2K-µ-MIM process is exemplified for the combination of different non-magnetic (316L) and ferromagnetic (17-4PH, Fe) metals. It is shown that intact material interfaces of less than 1x1mm² can be achieved by careful selection and tailoring of metal powders (powder particle size, chemical composition), injection moulding and co-sintering parameters.

Keywords: Micro-MIM, Bi-material processing, Magnetic properties

1. Introduction

The process of micro metal injection moulding (µ-MIM) has been developed in recent years with the objective of making metals and alloys available for the mass production of micro parts and micro-structured surfaces. As competing manufacturing technologies are often limited concerning material choice and / or large scale production capability, µ-MIM significantly enhances the availability of metals and alloys for micro applications, thereby introducing new material properties like high-temperature stability, strength and toughness, but also heat conductivity and magnetic properties to micro applications.

Moreover, comparable to micro injection moulding of plastics, bi-material processing has been developed for µ-MIM. This allows in-process joining of two different metallic materials within the injection moulding step. Multifunctional micro parts can be designed and manufactured without difficult assembly and joining operations.

2. Micro Metal Injection Moulding (µ-MIM)

2.1 Process

The µ-MIM process is depicted in Figure 1. In a first step, a metal powder is blended with an organic binder at elevated temperatures to make up a mouldable powder-binder-mixture, the so-called feedstock. The feedstock can be processed on a conventional or micro injection moulding machine. Subsequently, the binder is extracted from the part by a solvent and / or thermal process (debinding) and the part is sintered to full density.

Compared to the standard MIM process widely used in industry, some process specialities have to be considered for µ-MIM. These include powder particle size, which is significantly reduced compared to standard MIM, and binder composition, which needs to be adjusted for safe ejection of small structures. Due to these variations, debinding and sintering routes also have to be adjusted accordingly. These influences of the variations on processing routes and material properties are presented in more detail elsewhere [1].

Figure 1: The µ-MIM process

2.2 Applications of µ-MIM parts

Due to an increasing demand for micro parts with high mechanical strength, plastic micro parts may be replaced by ferrous materials in some micro mechanical applications. Figure 2(a) shows micro gears and impellers manufactured by µ-MIM of 316L stainless steel. As can be seen from Figure 2(b), smooth surface quality and sharp edges are obtained after sintering. Outer diameters of the parts shown here are about 1mm. Yet, the smallest parts that were achieved by µ-MIM so far had outer dimensions of just 350µm after...
sintering. When using very fine metal powders (mean particle size 2-3µm), roughness values $R_a$ of 0.4µm and $R_z$ of 3µm were achieved.

Figure 2: (a) 316L micro gears and impellers; (b) detail of micro gear (co-operation with Scholz GmbH, Germany)

Stainless steel provides good chemical and corrosion resistance, which makes the material interesting for applications in micro reaction technology. Compared to larger reactors, critical chemical reactions may be conducted in a more controlled environment due to the lower volumes of reacting agents involved. Large quantities of reaction products can be attained by “numbering up” of the micro reactors instead of “scaling up” a reactor. Figure 3(a) shows an example micro mixer manufactured by surface structuring through µ-MIM. Figure 3(b) depicts a photo catalytic reactor with a TiO$_2$ coating designed for the sterilisation of water. Channel widths are about 500µm and 250µm, respectively.

Figure 3 (a) Micro reactor and (b) photo catalytic reactor by µ-MIM of stainless steel

3. Bi-Metal processing

Beyond single micro parts or structures, a micro system is usually obtained by assembling several parts made of different materials for special functionality. Therefore, to set up a micro system, a number of packaging or joining operations is needed. In order to reduce the amount of such operations, a 2K-µ-MIM process was developed to allow the integration of different materials and therefore functions in one part within the injection moulding step. Micro components consisting of a ferromagnetic and a non-magnetic part were designed and fabricated.

3.1 Feedstock preparation

Powders of 316L, 17-4PH and iron were used to produce feedstock suitable for µ-MIM. The powder characteristics are given in Table 1.

The binder used for the experiments was wax-polymer based with a polymer content of 50wt.-%. This formula was used because the outer dimensions of the parts to be moulded were less than 1x1 mm$^2$ at the material interface and therefore, high green strength had to be assured.

Table 1: Particle size and chemical composition (wt.-%) of the powders used

<table>
<thead>
<tr>
<th>Powder</th>
<th>$D_{50}$ [µm]</th>
<th>$D_{90}$ [µm]</th>
<th>Fe</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu</th>
<th>Mo</th>
<th>Mn</th>
<th>Nb</th>
<th>Si</th>
<th>N</th>
<th>O</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>316L</td>
<td>3.6</td>
<td>5.8</td>
<td>Bal.</td>
<td>17.2</td>
<td>11.2</td>
<td>2.6</td>
<td>1.8</td>
<td>2.76</td>
<td>0.025</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17-4PH</td>
<td>3.3</td>
<td>5.1</td>
<td>Bal.</td>
<td>16.7</td>
<td>4.9</td>
<td>0.17</td>
<td>0.63</td>
<td>0.3</td>
<td>0.59</td>
<td>0.11</td>
<td>0.077</td>
<td>0.038</td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>6.6</td>
<td>14.3</td>
<td>Bal.</td>
<td>0.01</td>
<td>0.2</td>
<td>0.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2 Adjustment of Co-Sintering parameters

It has been known for some time that similar sintering temperature and shrinkage is essential to avoid stresses and cracking at the interface during co-sintering of two materials [2]. More recently, a new approach was set up to quantify the differences in sintering behaviour that are acceptable for successful co-sintering [3]. Both approaches are based on data obtained by sinter dilatometry. Thus, sinter dilatometry was also used to compare and adjust the sintering behaviour of the different feedstocks in the experiments presented here.

Figure 4: Sinter Dilatometry of 316L, 17-4PH and Fe feedstocks

As can be seen from figure 4, there was a good compatibility of the sintering behaviour of the 316L and 17-4PH prealloyed powders. So, good bonding and intact material interfaces could be expected. For carbonyl iron powder, sintering was much less in accordance with the prealloyed 316L. Adjustment of sintering behaviour was done by using a so-called 316L master alloy (MA) in which carbonyl iron was mixed with the other alloying elements so that the final alloy composition was formed during sintering. This lead to an earlier start of the sintering process and thus to a better accordance in the sintering of 316L and iron, at least up to the $\alpha-\gamma$-transition temperature of iron of 911°C.

3.3 Influence of moulding conditions

In order to evaluate the influence of moulding conditions on interface quality, different parameters were investigated for the system 316L and 17-4PH. In the first step, a test part was moulded with the first component. This test part was cut in two pieces and one part was placed back into the mould as an insert. Then the second component was injected into the same mould to obtain a composite with a well-defined narrow interface. The experiments were done using a laboratory injection moulding machine. The interface
area of the samples was 10x1.5mm².

Experiments with an unheated mould resulted in a number of compounds with cracks at the interface, see Figure 5(a). By increasing mould and feedstock temperature, the quality of the green compound could be improved, as indicated in Figure 5(b). The higher temperature lowered the viscosity of the feedstock during moulding and improved wetting of the interface. This resulted in a better adhesion and, therefore, fewer cracks in the compounds.

Figure 5(a) Feedstock temperature 90°C: cracks at the interface; (b) Feedstock temperature 120°C: solid bonding

A quantification of the interface quality as function of mould and feedstock temperature is given in Figure 6. For a low feedstock temperature of 90°C, it was observed that mould temperature and preheating time had a positive influence on interface quality, but still, just 40% of the samples tested showed good bonding. Similar results were obtained for a higher mould temperature of 110°C, though no significant influence of preheating time was detected. Best results were obtained for 120°C feedstock temperature while injecting in a mould preheated to 50°C.

Figure 6: Influence of moulding conditions on interface quality.

In further investigations, it was found that interfacial cracks apparent after moulding tended to grow in the subsequent debinding and sintering steps. On the contrary, a crack-free bond in the green compound between the two materials and good co-sintering compatibility resulted in sintered parts with solid bonding at the interfaces. To exemplify, figure 7 shows micrographs of co-sintered parts of the 316L / 17-4PH and 316L master alloy / Fe combinations.

4. Manufacturing of magnetic-nonmagnetic parts

For showing the feasibility and functionality of 2K-µ-MIM, two demonstration parts were designed and manufactured. The first part was a magnetic positioning encoder consisting of a non-magnetic bar (316L) with two ferromagnetic cubes at the end (17-4PH or Fe). These cubes were moulded first and used as inserts before injecting the 316L material as second component. Figure 8 shows the mould inserts used for manufacturing as well as the green and sintered parts. In the sintered state, the interface area was about 850x850µm². When moving the parts in front of a hall sensor, a change in the magnetic field was detected that could be transferred to a change in position relative to the sensor.

Figure 8: Mould inserts and sintered part of magnetic positioning encoder; the circle indicates the 17-4PH or Fe material

The second demonstration part, a miniature tachometer, was moulded on a “two-colour” injection moulding machine. The mould cavity manufactured for this purpose is shown in Figure 9. One of the five wings of this part was separated from the rest of the cavity by a gate during injection of the non-magnetic 316L feedstock. After the first moulding step, the gate was opened automatically and the last wing was moulded from 17-4PH material. Thus, handling of inserts to achieve the two-material part was avoided.

Figure 9: Mould cavity of miniature tachometer
Figure 10(a) shows some of the green and sintered parts obtained. In the sintered state, the interface area was 1x1mm². A micrograph of the interface is presented in Figure 10(b). A solid bond of the material interface was obtained, though the shape and position of the interface can be improved by variation of injection moulding conditions.

Figure 10: (a) green and sintered miniature tachometer parts; (b) Interface 316L / 17-4PH after sintering

5. Magnetic properties of 17-4PH

Due to the chemical composition of 17-4PH stainless steel, a change in the material microstructure during the sintering process could be used to adjust the magnetic properties without a subsequent heat treatment. As 316L was non-magnetic regardless of the sintering temperature, no significant change occurred for this material. Figure 11 shows that an increase in sintering temperature from 1050 to 1300°C lead to a significant drop in coercivity $H_c$. This was related to a change from a semi-austenitic to a martensitic microstructure in this temperature field.

Figure 11: Coercivity of 17-4PH as a function of sintering temperature

6. Summary

With µ-MIM, a wide range of metallic materials can be made available for micro engineering. Possible areas of application are micro chemical engineering, micro medical devices and micromechanical systems. With 2K-µ-MIM, multifunctional micro parts can be produced by adjusting co-injection moulding and co-sintering parameters. This can help to avoid difficult handling and joining operations. Above this, magnetic properties of the co-injection moulded parts presented here are adjustable with controlling the co-sintering route. This is a promising outcome for manufacturing of micro-bimetallic parts by the micro co-injection moulding process. The development of new material combinations processable with this manufacturing process will further enhance the use of multifunctional metallic parts in micro engineering.

References

