Recent Developments in Metal and Ceramic Micro Injection Moulding

V. Piotter, E. Honza, T. Mueller, K. Plewa

Karlsruhe Institute of Technology; Institute for Applied Materials
P.O. Box 3640, 76021 Karlsruhe, Germany
Tel. : +49 0721 6082 6463; Fax: +49 0721 6082 2095
volker.piotter@kit.edu

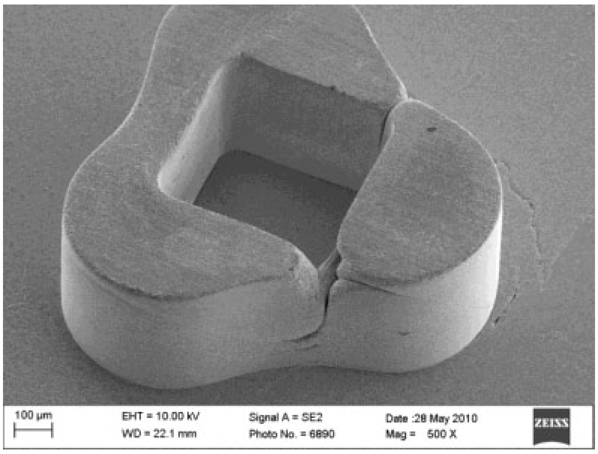
Abstract

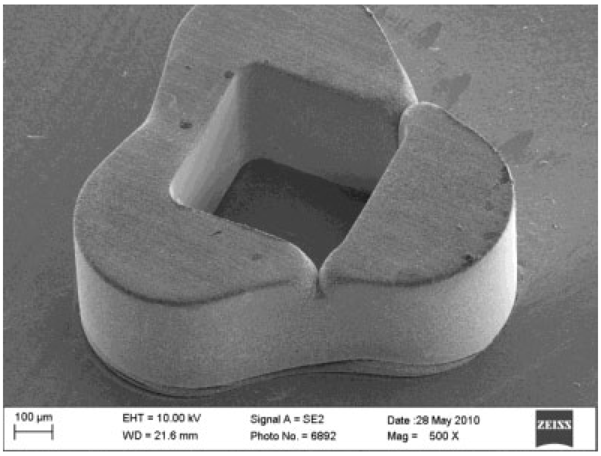
At present, polymer injection moulding has reached an established status as fabrication method for micro components. Additionally, furthered by the growing market demand for metal and/or ceramic miniaturized parts, the micro powder injection moulding (MicroPIM) process reveals considerable progress.
For the reduction of assembly costs and generation of highly integrated products so-called 2C-MicroPIM is under development. Meaningful examples are ceramic shaft-wheel components. Sophisticated feedstock compositions and sintering parameters led to either immovable or movable joints.
As a further variant to create multi-material products micro inmould-labelling combining powder filled tapes with adequate feedstocks offers additional possibilities for functionalized surfaces as well as for application of nano and/or functional powder materials.

1. Introduction

Even today´s demand for metal and ceramic high-precision parts can only be answered by tomorrow´s production technology where medium or large series manufacturing with short process times and reduced mechanical finishing will result in economical production. As chances for a profitable production of such metal and ceramic micro precision parts powder injection moulding seem to be a very good option if the prerequisites for process safety and process profitability have to be established. This necessitates require intensive research and development in machine, tool, and process technology. Using microstructured mould inserts and an enhanced process conduct minimal details of 10µm or even less and replication accuracies down to ±0.1 – ±0.3% can be achieved. Last not least there is also a strong development demand with regard to powder, binder, and feedstock production [Pio08, Pet08, Mor09, Ger10].
Although there had been and are still thorough R+D activities, MicroPIM had already found it´s way into practical application as proven by the growing row of industrial examples. A much more comprehensive description can be found in [Pio11a+b] including a few examples for MicroPIM products having successfully entered the market.

Nevertheless, there are still opportunities for incremental improvements. One concerns the degree of replication performance of complex geometries. In polymer injection moulding the so-called compression injection moulding method enjoys intensive application in such cases. To evaluate the potential for MicroPIM comparative trials have been performed at KIT. To explore the benefits of an additional compression step a challenging tooling was obviously meaningful. Therefore, a LIGA mould insert was chosen and a typical MicroCIM feedstock filled with 50Vol% zirconia powder was used. After determining the interaction of the most important parameters in micro compression PIM (Micro-CPIM) a direct comparison between the test geometries replicated by classical MicroPIM and the enhanced Micro-CPIM process had been performed. It turned out that the replication performance of Micro-CPIM is slightly better than operating the pure MicroPIM procedure. However, differences are small and can only be detected using quite fine sized structures, see Figs. 1 and 1. A more detailed description of the comparative trials can be found in [Hon12].





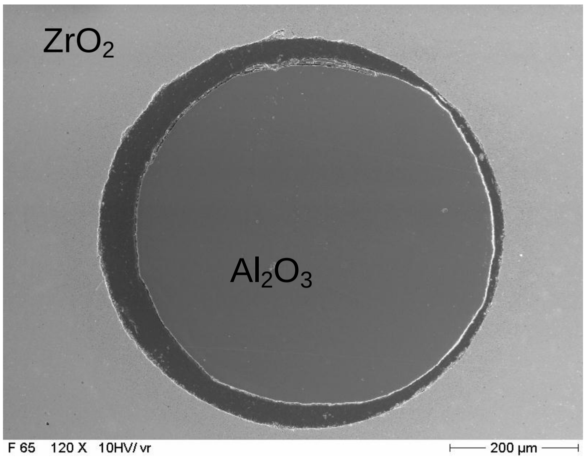
Figs. 1, 2: Sintered ceramic structure (housing for a rotary gear wheel pump). Shaping has been performed by pure MicroPIM process (left) and by Micro-CPIM procedure (right).

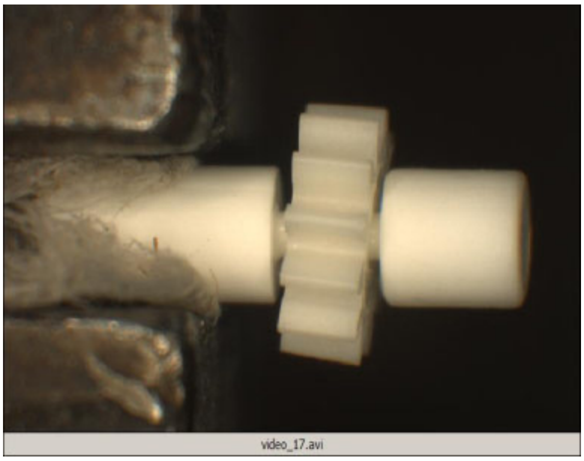
2. Micro Two-Component Powder Injection Moulding (2C-MicroPIM)

Two-component injection moulding has been of major technological significance to the manufacture of multicomponent plastic parts for several years. In addition, as described in chapter 1 fundamental knowledge has been acquired of powder injection moulding of single-component parts. Merging of these two injection moulding variants into one, i.e. into two-component micro injection moulding (2C-MicroPIM), constitutes a particular technical challenge. Additonally, due to the reduced assembly efforts combined with the possibility to create rather new multi-functional products 2C-MicroPIM exhibits a large industrial potential [Alc98, Mae06, Img08, Pet10, Pio10, Sim10].

The possibility of manufacturing two-component ceramic parts by means of 2C-MicroPIM was demonstrated some years ago at KIT (former FZK) by the example of heating needles consisting of a mixture ceramic (Al_2O_3+TiN) with different mixing ratios [Pio04].
Since the then state of knowledge was limited on this particular application, all studies to follow were placing emphasis on thorough scientific 2C-MicroPIM analyses [Ruh08]. The method was investigated by the example of a shaft-to-collar connection made up of two components: A gearwheel consisting of zirconium oxide and a shaft with reinforced shaft collar consisting of aluminum oxide. . One of the major challenges was to show that using that technology, both articulated (movable) and permanent joints can be manufactured. Compared to single-component PIM-parts, partially complex conditions making high demands on 2C-MicroPIM material and process development must be considered when realizing two-component parts. The fact that both components, i.e. different metals or ceramics, must be sintered at a time and, thus, at identical temperatures makes material selection rather difficult and complex.
For sufficient compound strength, permanent joints must have defined joining surfaces between the shaft and gearwheel. At the same time, stresses in the two components must be avoided or be reduced to a minimum. To ensure the latter, the materials and processes must be selected such that the shaft and gearwheel can be sintered simultaneously i.e., such that both parts are characterized by almost identical degrees of shrinkage and sintering kinetics.

For articulated joints, the process parameters and material combinations must be chosen such that the aluminum oxide shaft starts sintering before the zirconium oxide gearwheel does. In addition, the shaft must be characterized by a higher absolute degree of shrinkage. Only then and when using suitable tool designs a gap between the shaft and gearwheel can be formed and enable rotation of the latter, see Figs. 3 and 4.
Besides, the thermal expansion of the respective components must be taken into account with a view to heating and subsequent cooling. The considerable difference between the coefficient of thermal expansion of zirconium oxide ($10\text{-}11 \cdot 10^{-6} K^{-1}$) and that of aluminum oxide ($7\text{-}8 \cdot 10^{-6} K^{-1}$) may cause effects on the detachment or shrinking-on of and the formation of stresses in the permanent and articulated joints and, being another critical point, had to be considered in the selection of materials and process modes.





Figs. 3, 4: Shaft-to-collar connection layed out to create movable joints. Mainly by a reduced powder content of the axis feedstock a clearly visible gap is obtained (left) leading to a tilted but rotable mounting of the gear wheel on the shaft (right).

Due to the considerable potential of 2C-MicroPIM research is not only performed at KIT. Under this respect activities carried out at Fraunhofer IKTS in Dresden [Mor08] and Fraunhofer IFAM in Bremen [Img07] have to be mentioned. While the former deals with 2C-MIM (2-component metal powder injection moulding [Mul10], the latter concentrates on ceramic systems above the micrometer range mainly for the automobile and railroad industries [Mor09b]. To obtain permanent connections between ATZ and ZTA ceramics, intermediate layers of ceramic sheets are inserted thus excessive concentration gradients can be avoided [Man11]. Recently, moreover, interesting findings were obtained on metal-ceramic compounds. Co-metal powder injection moulding is also being researched into at State Key Laboratory of Powder Metallurgy at the Central South Universität in Changsha (China). There, metallic gear wheels with a so-called skin-core structure were manufactured. For better distinction, their core material was enriched with 1 % commercial graphite [He10].

3. Combination of Inmould-labelling and Micro Powder Injection Moulding (IML-MicroPIM)

Due to the apparent attractiveness 2C-MicroPIM is not the only way to perform multi-component replication. A supplementarey alterntive is to use a procedure quite similar to the well-known inmould-labelling process in plastic packaging: a pre-fabricated insert in the form of foil or film is mounted in a tool and subsequently covered by a backwards injection-moulded layer, see Fig. 5. The metal or ceramic foils might be manufactured by e.g. slip casting, foil casting, or rolling processes. Before inserting them into the injection moulding tool, the foils can be printed, punched, embossed or subjected to another preliminary treatment. In this way, it is possible to generate color patterns or lateral structures on the surface of the PIM body. Another benefit is obtained by the fact that submicron powders or nanopowders can be merged into the foils without the usually occurring massive increase in viscosity.

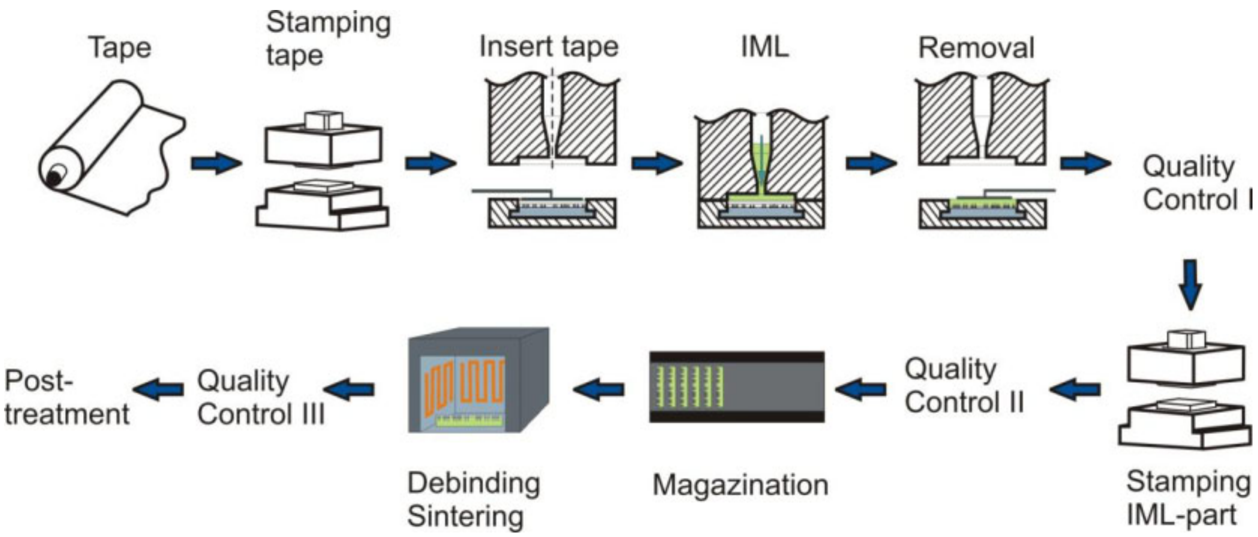
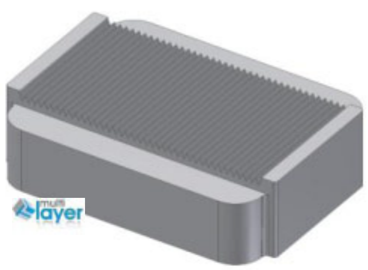
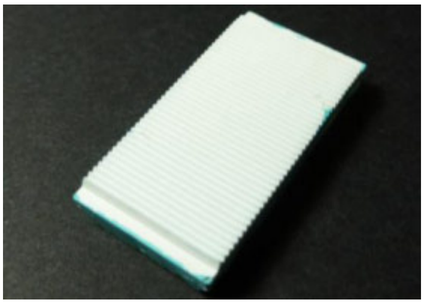
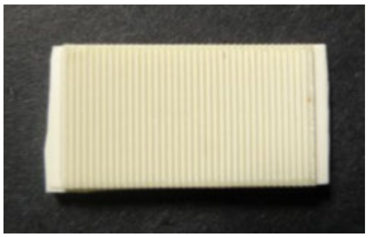
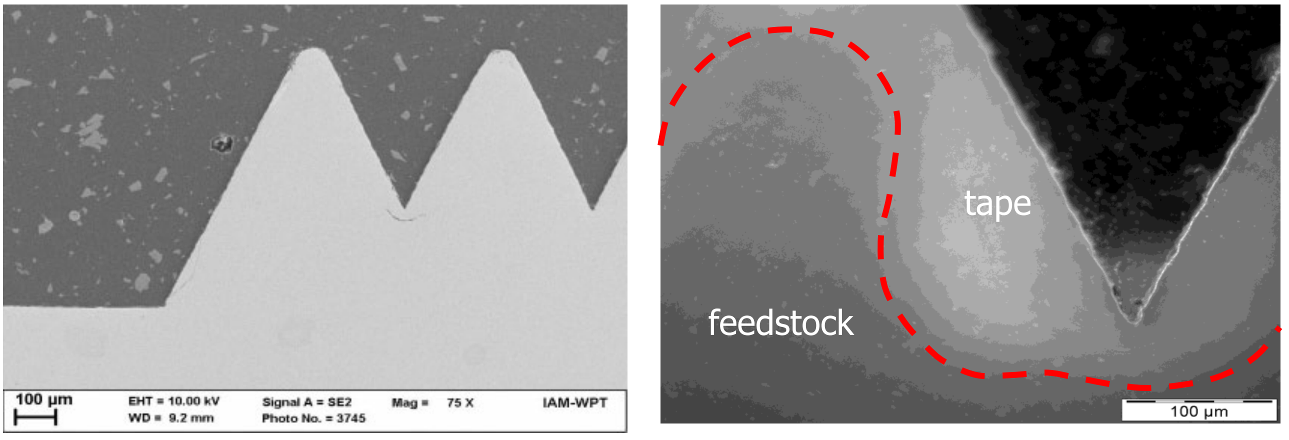


Fig. 5: A schematic drawing of the IML-MicroPIM process principle using the injection pressure (4^{th} picture above) to imprint the tape/foil into the µ-structured mould insert.

The major challenge associated with inmould-labelling combined with PIM is given by the development of an adequate sinter process. The demands are similar to 2C powder injection moulding of fixed joints, i.e. sintering shrinkage and temperature shall be mostly equal. This sinter process has to allow for dense compacts of both partial volumes as well as for a tight interface. The process has already been investigated for macroscopic applications [Bau08] and trials for adaptation to micro systems technology are currently running: Micro inmould labeling by use of PIM feedstocks is presently being developed within the EU Multilayer Large Integrated Project (FP7-NMP4-2007-214122) [Vor10]. An impression of the R+D work is given by Figs. 6-10.

Figs. 6-8: A test mould insert used for the development of IML-MicroPIM, height of the zig-zag structure is approx. 550µm (left); green body after tape insertion, feedstock injection, and demoulding (middle); sintered part, height of the zig-zag structure now is approx. µm (right).



Figs. 9-10: Cut view on the interface of a sintered test specimen, first two rows showing slight delamination at the bottom of the zig-zag structure (left), detailed view with the former interface between tape and feedstock indicated by the red line (right).

4. Outlook

The results presented above lead to the conclusion that micro powder injection moulding is on it´s best way to become an established special variant of PIM-technology. In case of the one-component version improvement of geometrical accuracy and surface quality can be regarded as one of the most challenging topics for future R+D activities.

By multi-component injection moulding (2C-MicroPIM) different metal and ceramic materials can be combined in one compound part. Additionally, simultaneous shaping of the partial sections even in the micrometer range is possible, too. The process allows for fixed as well as movable connections. The latter, however, requires profound adaption of the feedstock recipes and the thermal process conduct.

Micro inmould-labelling using PIM-feedstock (Micro-IMLPIM) offers an additional method to produce multi-material, thus multi-functional devices. Similar to fixed 2C-MicroPIM it requires a sophisticated tuning between feedstock composition and the shaping and sintering parameters. With this challenge becoming more and more solved the process offers a quite economical efficient option to fabricate products with improved and/or functionalized surfaces.

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