The production and evaluation of alumina sinter supports for Metal Injection Moulding by ceramic Additive Manufacturing

In this article, Dr Samuel von Karsa-Wilberforce, Emery Oleochemicals GmbH, Germany, and co-authors report on the production and evaluation of sinter supports for Metal Injection Moulding produced by the Additive Manufacturing of highly filled alumina feedstock filaments. The alumina filaments are based on Emery Oleochemicals' established PIM binder system and processed by Material Extrusion (MEX). Partners in the study include CMG Technologies, UK, 3DGence Sp. z o.o, Poland, Spectrum Filaments, Poland, SiCeram GmbH, Germany, and Ingenieur-Buero Jaeckel, Germany.

Material Extrusion (MEX), the ISO category for AM processes that are also known as Fused Filament Fabrication (FFF) or Fused Deposition Modelling (FDM), is evolving into a very cost-efficient technology for the production of metal and ceramic parts using sinterable filaments. This is particularly the case when compared with more widely known metal AM processes such as Laser Beam Powder Bed Fusion (LB-PBF) where, apart from the cost-efficiency advantage of additively manufacturing with sinterable feedstock filaments, the processing of ceramic materials using a process such as LB-PBF is simply not possible. Additionally, standard sinterable powders can be used in sinter-based AM processes as powder flow properties are not as critical as in LB-PBF. As with any other AM process, the selection of the right application is crucial to the successful use of sinterable feedstock filaments.

This study seeks to compare the performance of additively manufactured alumina sinter supports produced by MEX with state-of-the-art sinter supports manufactured by Ceramic Injection Moulding (CIM). Sinter supports, produced by the extrusion of sinterable feedstock filaments, have the potential to be used for small series runs of components usually manufactured by Metal Injection Moulding (MIM) (Fig. 1).

Fig. 1 Schematic of sinter support and MIM component

Material Extrusion process overview

Material Extrusion has been used for the processing of thermoplastic polymeric materials for a number of decades. One of the first main applications of MEX was in rapid prototyping, where it offered the

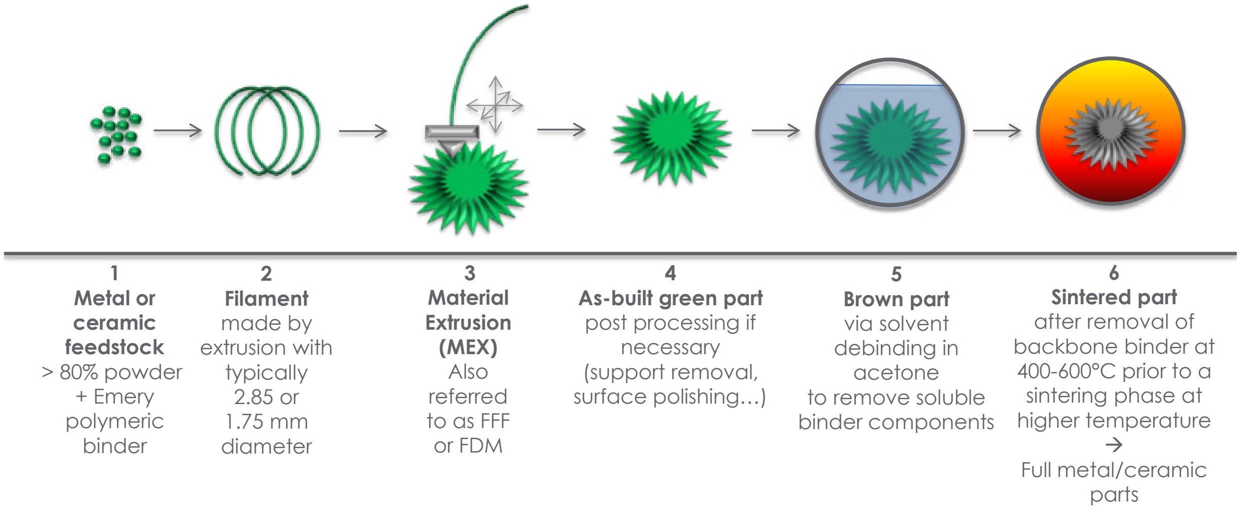

Fig. 2 Illustration of AM process used, from raw material to sintered part

benefits of reduced cost as well as faster time-to-market. Across all material types, MEX is today the most widely used of all AM technologies, due to its suitability for commercial and home use, as well as the ease of operation of MEX machines compared with other AM technologies [1]. The result of this is the increasing availability of new materials for MEX, including high-performance polymers such as polyetheretherketone (PEEK), as well as, more recently, highly filled polymeric filaments containing metal or ceramic powders, typically up to > 80 wt.%. Within the filament, the powder particles are held together by a thermoplastic binder. Such a 'feedstock filament' is an evolution of conventional Powder Injection Moulding feedstock, which is used in a granulated form.

These highly filled feedstock filaments can be processed in the same way as conventional thermoplastic filaments. However, after a build, the additively manufactured part, known as a 'green' part, is not yet functional and has to go through post-processing steps to achieve its final form as a metal or ceramic part. The complete process is outlined in Fig. 2. It is worth mentioning that although a solvent debinding system is used in this example, catalytic or thermal debinding systems also exist.

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The promising technological attributes of extrusion-based metal and ceramic AM, such as user-friendliness, the simplicity of the technology and the abillty to use standard sinterable PIM powders as flow properties are not critical, led to the adaptation of the well-established PIM binder system from Emery Oleochemicals for metal and ceramic filaments. Metal and ceramic parts produced with filaments based on the Emery binder system typically have very high green part strength, allowing them to be handled and transported with ease, as well as the ability to apply processes such as polishing.

Despite the promising use of metal and ceramic based filaments, the selection of the right application is key to the realisation of the full potential of the technology, as well as for customer satisfaction. Others have investigated the use of metal and ceramic feedstock extrusion for cutting tools and magnetic material applications [3]. This article will therefore focus on the Additive Manufacturing of sinter supports for MIM components, employing ceramic feedstock filament based on Emery Oleochemicals' binder technology.

The production of MIM sinter supports via current processes, most commonly machining and Ceramic Injection Moulding, can result in long lead times for the production of MIM components. Delivery times for the moulds to make the supports by CIM, as well as the time required for mould optimisation, may be in the region of eight weeks. Hence, the Additive Manufacturing of sinter supports using ceramic feedstock filaments enables the rapid and on-demand production of sinter supports, leading to short lead times and a shorter time to market. It should also be considered that current production methods for ceramic sinter supports add a significant overhead cost to MIM component production [4]; therefore, a more efficient way to manufacture sinter supports will be advantageous for the MIM industry.

The alumina sinter supports produced for this case study were used for a commercially manufactured MIM component produced by CMG Technologies, a well-established MIM company based in the UK. The digital file from which the sinter supports were built was provided by CMG, which also tested the finished sintered alumina sinter supports with the corresponding MIM parts and CIM sinter supports as reference.

Production of alumina feedstock filament

The alumina feedstock granules were compounded by SiCeram GmbH, Jena, Germany, using 99.7% pure alumina powder with a particle size D50 of approximately 0.6 µm and the binder system from Emery Oleochemicals. The binder system mainly consisted of the LOXIOL® 2472 plasticiser produced exclusively by Emery Oleochemicals and a polyamide copolymer. The compounded alumina feedstock granules contained approximately 80 wt.% alumina powder. The feedstock granules were then supplied to Spectrum Filaments, Poland, to produce the alumina feedstock filaments. Spectrum Filaments, an established manufacturer of filaments for Additive Manufacturing, extruded the 2.85 mm diameter feedstock filaments using a single screw system (Fig. 3). The green density of the alumina feedstock filament was 2.53 g/cm^3.

Fig. 3 A spool with aluminium oxide filament, 2.85 mm thickness

During filament production, the diameter was measured every 1 mm in 2 axes with ± 0.8 µm accuracy. To be sure that the measurement results are reliable, Spectrum Filaments uses certified laser measuring devices. In the final step, the collected data are digitally stored by Spectrum Filaments, enabling customers and end-users to check the filament diameter online.

Additive Manufacturing of alumina MIM sinter supports

CMG Technologies supplied the STL file for the sinter support. In order to obtain near-final dimensions of the sinter supports after the final post-processing step, the STL file of the sinter support was modified using Cura Additive Manufacturing software to compensate for shrinkage after sintering of approximately 19–21% in xyz directions. After this, the input file for the AM machine, known as the g-code file, was generated. The g-code file tells the AM machine what actions to perform to build the part. Two different machines were used to build the sinter supports, with the first being a BCN3D Sigma r19 machine from BCN3D Technologies, Spain. This is a standard filament system available on the open market and suitable for developmental work and proof of concepts. The second system was a high-performance machine with a modified print head from 3DGence, Poland, for the processing of sinterable feedstock filaments and designed for small series production. The build parameters used on both machines were as follows:

- Build temperature of between 160–170°C
- Build speed of between 20–50 mm/s,
- Extrusion head nozzle diameter of between 0.4–0.6 mm
- Layer height of 0.1 mm
- Infill density of 30%

A total of approximately twenty sinter supports were built for post-processing and application testing (Fig. 4). Sinter-supports with both opened-bottom grid structure and closed-bottom grid structure were built to investigate the effect on their application as MIM sinter supports (Fig. 5).

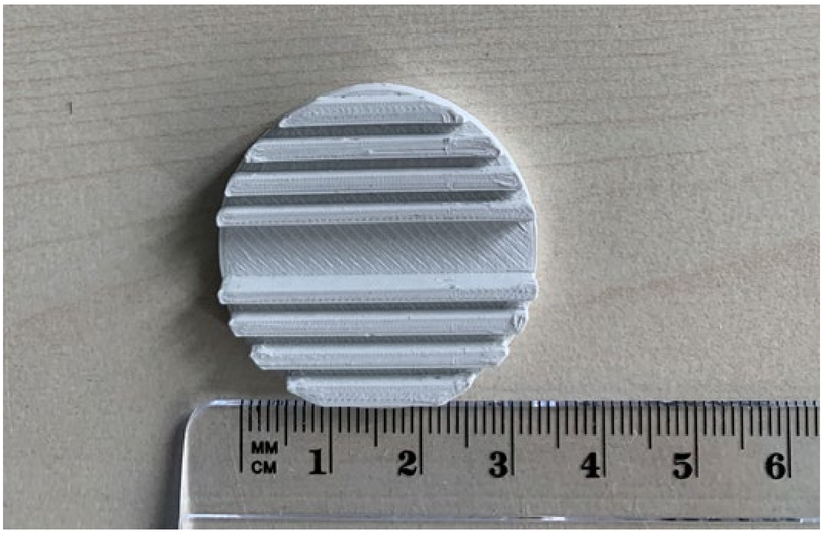

Fig. 4 An example of an additively manufactured green alumina sinter support with 30% infill density

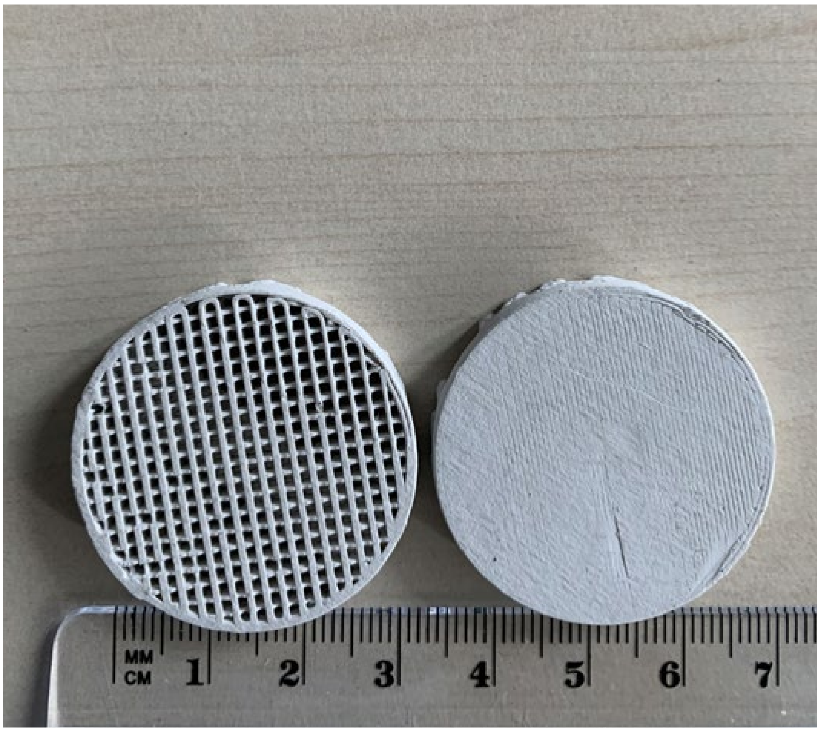

Fig. 5 Examples of green AM alumina sinter supports with opened-bottom grid base and closed-bottom base but with grid infill structure. Both supports have infill density of 30%

Post-processing of alumina sinter supports

The solvent debinding and sintering of the green sinter supports were carried out by SiCeram GmbH. Solvent debinding of the sinter supports was carried out in acetone at 42°C for approximately twenty-four hours, followed by a 3–5 hour drying time at room temperature to remove the residual acetone. The remaining backbone polymeric binder component was removed at 500–600°C during pre-sintering at 1250°C in air to obtain partially sintered supports. The pre-sintering of the sinter supports allowed for a much better control of part deformation and twisting that might occur during sintering. The final sintering of the supports was carried out at 1540°C in air to obtain the fully sintered alumina supports (Fig. 6).

Application testing of final sinter supports with MIM component

The flatness, surface roughness, height and diameter of the fully sintered sinter supports are crucial for the successful use of the supports. The flatness of the supports was determined via the so-called rock test using a digital height gauge. The rock test flatness values were all below 0.1 mm, indicating good flatness for use as sinter supports. Typically, rock test flatness values of sinter supports above 0.15 mm render them unusable.

The average surface roughness of the additively manufactured sinter supports was measured to be between 2.0–2.5 µm Ra and this was higher than that of sinter supports manufactured by CIM, which had a surface roughness of approximately 0.3 µm Ra. The surface roughness value of the AM sinter supports was, however, well below the 5 µm Ra maximum surface roughness for such an application. Sinter supports with a surface roughness above 5 µm will most likely cause markings on the surface of the MIM components, rendering them unusable.

The average final dimensions of height and diameter of the AM sinter supports were measured to be approximately 4.33 mm and 28.54 mm, respectively. The height and diameter measurements were close enough to the theoretical dimensions of height and diameter (4.5 mm and 29 mm, respectively), indicating sufficient accuracy to produce sinter supports for MIM applications.

It is worth mentioning that this is an initial proof of concept for the accuracy of the MEX process for the production of alumina sinter supports. The flatness, roughness and dimensional accuracy can still be further optimised to meet the needs of the user.

The AM alumina sinter supports were then tested in use as supports for the specific MIM application at CMG, with the MIM parts positioned on the AM sinter supports and sintered at 1300°C (Fig. 7). The results showed that the AM alumina sinter supports performed as well as the CIM alumina sinter supports.

In addition, high-performance lightweight alumina sinter supports could be produced by AM with an infill density of 30%, leading to material savings, lower production costs and energy savings during sintering. For the sinter support geometry and size considered in this case study, the base structure (whether opened-based grid or closed-based grid) had no effect on the function as sinter supports. Nonetheless, having an opened-base grid structure could lead to quicker solvent debinding when manufacturing the supports.

The reuse attributes of the sinter supports were also investigated for approximately seven days, based on two sintering cycles a day at 1300°C. After approximately fourteen sintering cycles, the sinter supports showed no visual surface, structural or material degradation, confirming their durability (Fig. 8). The strength of the supports also appeared to be unchanged after the fourteen runs.

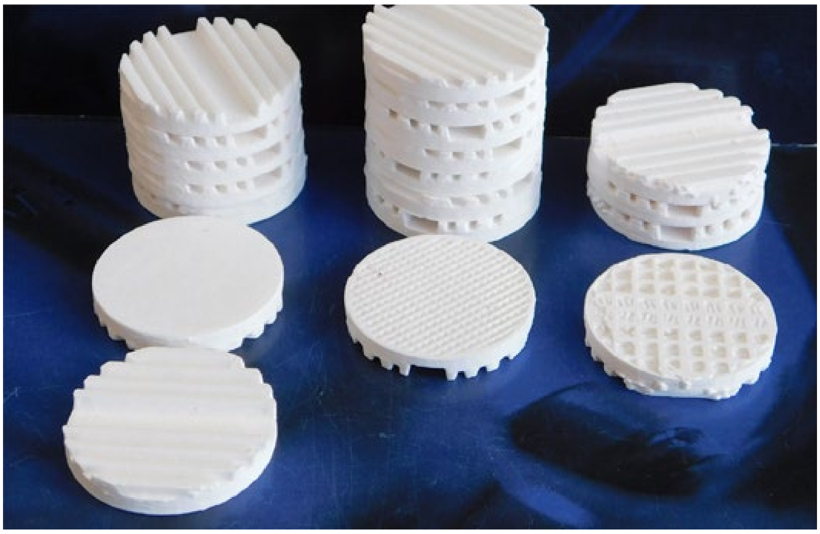

Fig. 6 Fully sintered AM alumina sinter supports. Full sintering was carried out at 1540°C in air

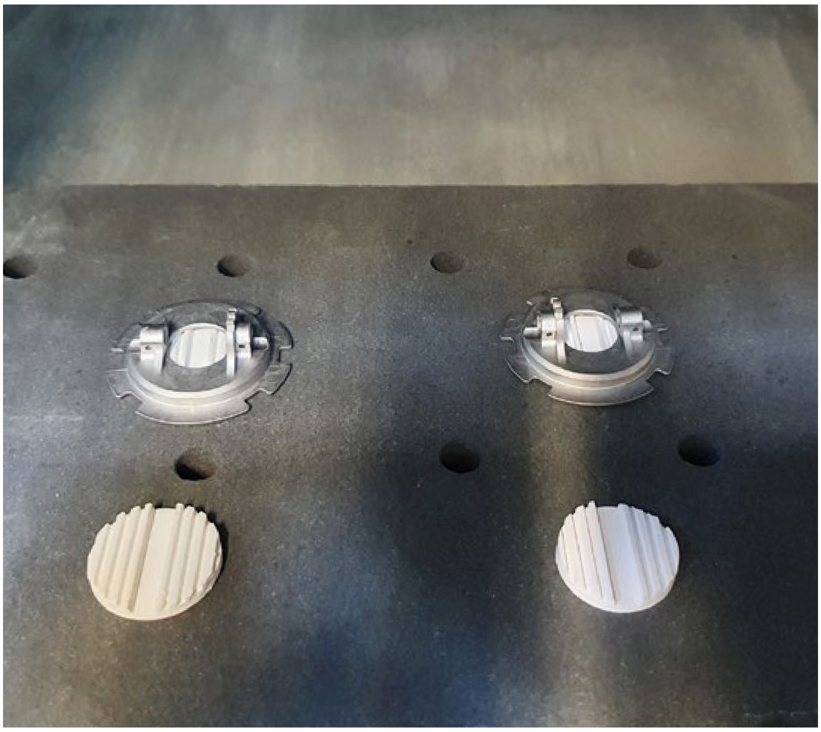

Fig. 7 Photo of MIM components sitting on an AM sinter support (left) and Ceramic Injection Moulded sinter support (right) in a sintering furnace

Conclusion

In this study, ceramic feedstock filaments were employed to produce high-performance MIM sinter supports with excellent reuse attributes. The targeted control of the infill density at 30% of the AM alumina sinter supports allowed the production of lightweight high-performance MIM sinter supports with excellent durability and shock resistance, which is sometimes poor with fully dense supports. Moreover, as a result of targeted control of the infill density of the sinter supports, savings on material, production time and costs were achieved. The production of MIM sinter supports via filament-based Additive Manufacturing provides a cost-effective solution to the challenge of producing sinter supports on-demand, reducing time-to-customer and time-to-market.

Additionally, production of sinter supports via this process is ideal for small series component production where a new mould is needed

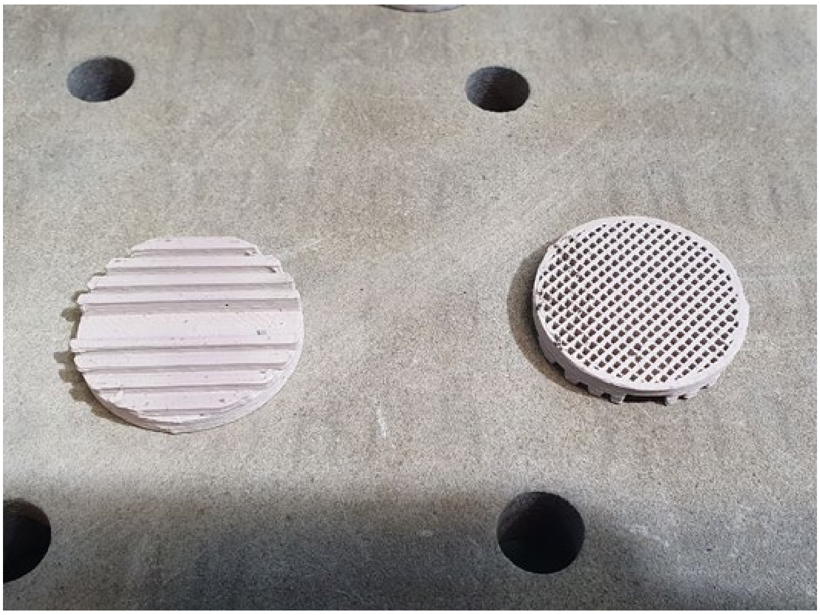

Fig. 8 Sinter supports after approximately fourteen sintering cycles at 1300°C. No visual degradation to surface, structure or material was observed

for each small series component, leading to significantly higher overall production costs. Furthermore, the outsourcing of sinter support moulding could result in lead times of up to eight weeks, leading to delay in final MIM component production.

Whilst it was shown that the AM sinter supports could be reused over a limited period, the long-term reuse attributes of the AM alumina sinter supports need to be further investigated. Furthermore, other MIM sinter support geometries, as well as supports with larger dimensions, need to be manufactured and tested. This will enable the evaluation of the impact of using MEX technology to manufacture different support geometries and sizes.

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