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Extrusion Based Additive Manufacturing of Metal Parts

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Abstract: AM (additive manufacturing) of metal parts becomes increasingly important in many industrial fields. However, currently used AM processes like laser melting or electron beam melting are quite complex and expensive. The extrusion based AM technology for dense metal components (Composite Extrusion Modelling-CEM), is characterised by an easy handling and cost efficiency in comparison to powder based processes. The CEM process contains two steps, the additive manufacturing of the green parts and the consecutive sintering. The additive manufacturing of green parts is carried out in a thermally controlled extrusion process. The standard metal injection moulding material with a high proportion of metal and thermoplastic binder is deposited in layers by a heated nozzle. In this way overhangs and bridge structures can be realised. The quality of the green parts that were manufactured with the specifically developed extruder corresponds to typical Fused Deposition Modelling parts. In case the surfaces need to be smooth the green parts can be mechanically post-processed before going through the debinding and sintering process.

Key words: Additive manufacturing, metal, metal injection moulding.

1. Introduction

AM (additive manufacturing) or commonly called 3D-printing no longer just concerns research institutions and large enterprises; it has already found its way into the private user area. One important reason was the development of low-cost 3D-printing kits based on the FDM (fused deposition modelling) process. The process was initially developed by S. Scott Crump, Stratasys Inc., Eden Prairie, USA and protected by the patent US 5121329 A [1], which expired in October 2009. The FDM process is based on a layer by layer fusing of volume elements, like all AM processes. In this special case the volume elements are extruded thermoplastic threads. According to Gebhardt [2] AM processes can be categorized according to the state of aggregate of the source material. In this context FDM is one of the processes with a solid source material. In contrast to other additive processes, which also use solid source material like for example SLS (selective laser sintering) or 3DP (3D powder bed printing), the part is not built into a powder bed, but on an empty plate. This requires the use of supporting structures for overhangs and large self-supporting constructions. The source material is usually available as a filament, familiar to the wire for plastic welding and is limited to thermoplastic polymers. Occasionally additives are composited to the thermoplastic base material, to adapt the material properties in terms of elasticity, optic and haptic characteristics or conduction. There are thermoplastic elastomers, wood-, sand- or even metal filled filaments. Especially the metal filled filaments do not increase the mechanical strength of the material. They rather decrease it in terms of brittleness by the added particles in the thermoplastic matrix. The success and the popularity of the FDM process are based on the cost efficient system concept, the manageable material and not least because of the achievements made by the open source community that have gained access to AM. Nevertheless the industrial use of AM increasingly requires processes that can build metal parts like it is shown in the Wohlers Report 2014 (76% growth of metal AM systems sale) [3]. Distributed representatives are beam based powder bed processes like SLM (selective laser melting), EBM (electron beam melting) and SLS. These methods are based on the layer wise applying of

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fine metal powders to a building plate and the selective fusing of the particles by use of energetic beams (laser or electron beams). Because of the high costs and the risks in terms of material handling (powder explosions/metal fire, contamination of powder, inhalation) the application of these AM methods are primary reserved to large companies and research institutions at present. The implementation of the AM of metal parts via a FDM related process could result in a dissemination of AM in small and medium-sized enterprises and industry in general, like it occurred in the private section with FDM. A well-known combination of thermoplastic extrusion and metal part manufacturing is represented by the MIM (metal injection moulding). With the use of a feedstock consisting of 40-45 vol% thermoplastic binder and 55-60 vol% metal powder green parts can be produced by injection moulding. Consecutively the green parts are debinded and sintered. In regard to the processing of standard MIM materials the development of an additive extrusion technology was carried out. A two phase combination of an additive manufacturing of green parts and a subsequently debinding and sintering in an industrial process were developed, named CEM (composite extrusion modelling). Similar approaches were already made with the use of customised ceramic feedstocks [4-6]. The manufacturing of near shaped green parts accomplishes the processing of materials that are difficult for machining (cutting, drilling and turning) like ceramics and hard metals. However the aim of this study is the development of the extrusion technology and the processing of industrial standard MIM materials as well as the evaluation of the results. In this manner the suitability for rapid prototyping applications and direct manufacturing of custom parts in the field of MIM can be estimated.

2. Materials and Methods

2.1 Composite Extrusion Modeling

According to the CEM process a granule shaped material is processed in an additive extrusion system. As seen in Fig. 1, after this first step the green part is taken from the build plate and put into an industrial oven. Through thermal cracking and pyrolysis the polymer binders are solved and the metal particles are free. By reaching the melt temperature of the lowest alloy component the sinter process is initiated and a solid metal part is the result.

With the use of a secondary extruder a thermoplastic support material can be added, which will then be pyrolysed in the post-processing. Due to the debinding process certain shrinkage can be anticipated, which has to be determined. The resulting microstructure of the metal inside the component should be comparable to the structure of components that were manufactured by MIM. Furthermore the relative density of the sintered CEM components should be nearly as high as sintered MIM components. With a selective insertion of macroscopic porosities and inner infill structures material properties can be adjusted accordingly. In contrast to powder bed based processes fully closed hollow structures can be realised.

2.2 Extrusion and Printing Setup

For the CEM-process a compact and moveable granule extruder was developed that can be positioned three dimensionally via an x y z gantry. The CEM extruder has overall dimensions of 160 mm × 60 mm × 80 mm, a nozzle diameter of 0.5 mm and is driven by a 0.5 Nm stepper motor as seen in Fig. 2.

The positioning of the extruder controlled by the automatic generated tool paths yet was realised by the open source platform Reprap Mendel. An assembly kit

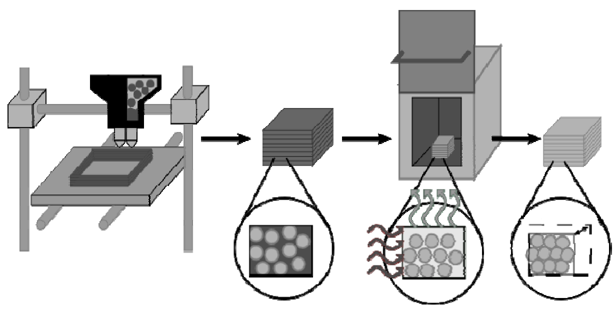

Fig. 1 CEM process chain.

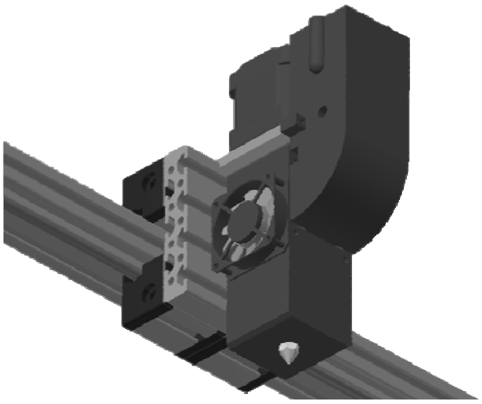

Fig. 2 Moveable CEM extruder on x axis (CAD image).

FDM printer could simply be customized for the processed investigations.

2.3 Material and Post-Processing

The material is a conventional MIM material, which is available as granulate with a grain size of 3 mm. The thermoplastic binder input has a proportion of 45 vol% and is responsible for the fluidity and the formability of the feedstock. This thermoplastic matrix carries the stainless steel powder 1.4542, which is steel with a chrome proportion of up to 17.5%, which is among others used in space and aviation applications and for medical instruments. Due to the high chrome proportion a reducing pure hydrogen atmosphere is necessary during the sinter cycle. To gain comparability to the industrial MIM process the green parts were depended and sintered in accordance with the manufacturer process information. Concerning this, the green parts were inserted into a continuous working industrial oven batch per batch. The debinding process was carried out at a temperature of 450 °C. A complete pyrolysis of the remaining binder was reached at 600 °C. Subsequently the sintering process was initiated at 1,365 °C. Due to the continuous procedure of the oven, the debinding and sintering process amounted to 14 h. The sintering could be followed by a hardening process, which is recommended for final applications, yet the following investigations were made without any hardening.

2.4 Print Tests and Validation

Since the developed extruder is a custom device and the material is usually processed in industrial injection moulding systems, the standard process information for the extrusion of granulate has to be examined and adjusted. In a first step barrel temperature, screw speed and flow rate have to be aligned to reach a maximum melt flow. Furthermore the maximum melt flow limits the possible print speed (movement speed of the extruder while extruding) which has to be determined. In further proceeding the three dimensional fusing of structures has to be investigated. Critical factors are minimal layer heights, adhesion between layers and realization of overhangs. For this purpose cylindrical samples for visual inspections and measurements were designed. Due to the loss of binder during the sintering process there should be a significant shrinkage. This has to be determined by measurements of the height and diameter of the green parts and the sintered parts. In this manner a tactile digital calliper (resolution 0.01 mm, accuracy +/- 0.02 mm) and the CLSM (confocal laser scanning microscope) LEXT OLS 4,000 (Olympus, Japan) were used. Furthermore the sintered parts were cut, smoothed and polished to determine the porosity with the CLSM. According to the fact that the layer by layer extrusion does not have any counter-pressure like it is given in the injection moulding process by the mould, it is anticipated, that the density of the CEM components falls short of the value for a full material 1.4542 steel with 7.8 g/cm³ [7].

3. Results and Discussion

3.1 Extrusion and Print Quality

According to the extrusion tests an ideal nozzle temperature of 210 °C could be determined. At this point the extruded string was smooth and continuous and a maximum flow rate of 2.9 mm³/s could be reached. Considering the cylindrical form of the extruded string and the 0.5 mm diameter of the nozzle, the maximum print speed is 15 mm/s. Subsequently processed three dimensional printing tests with print speeds between 5 mm/s and 15 mm/s indicated a good adhesion between the layers in the field of 0.1 mm to 0.25 mm layer height. Certainly, the adhesion slightly decreases with increasing print speed, which could lead to print failures. Infill structures, consisting of one-stringed grid patterns were printable as well as overhang structures. The 3D components show kind of wobbly shell surfaces. During the printing tests a significant oscillation of the whole printer could be recognized. Induced by the higher mass of the extruder, compared to custom FDM-extruder, this leads to a loss of repeat accuracy. Hence, a shifting from layer to layer was observed. Geometrical measurements of the green parts show a clear visible shrinkage in x-y direction and a slightly lower shrinkage in z. This is explained by the layer wise contraction of the printed layers and the interpolation of the component height by an integral multiple of the layer height.

3.2 Sintering Shrinkage and Density

The components could be sintered successfully without any deformations, cracks or other failures except for the shrinkage by the loss of the binder volume. Fig. 3 shows the green part and the corresponding sintered part of a pulley, the shrinkage is clearly visible.

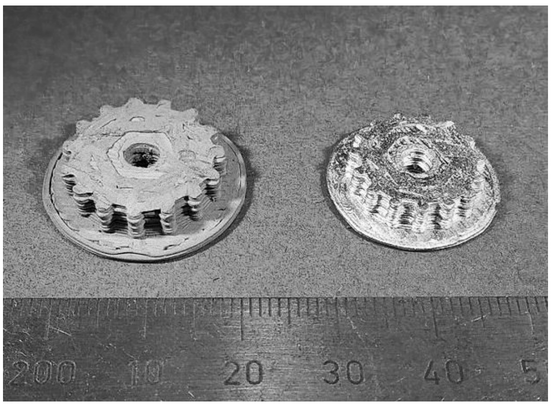

Fig. 3 Green part (left) and sintered part (right) of a pulley.

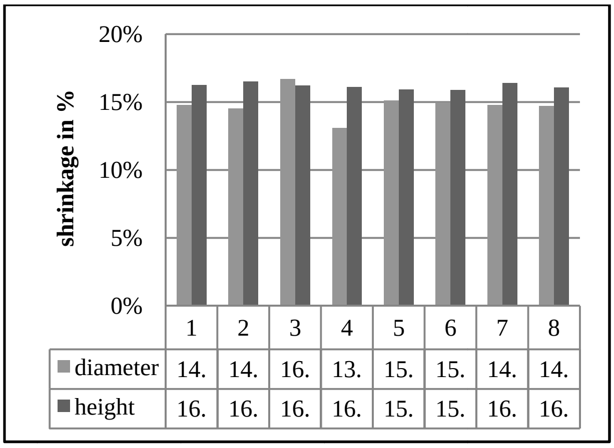

Fig. 4 Geometrical shrinkage of cylinders due to sintering.

Furthermore also components with overhangs could be sintered successfully. Obviously the exact thresholds for realizable overhangs have to be determined in following works. The shrinkage due to binder loss is shown in Fig. 4 separated in shrinkage of the samples height (z direction) and shrinkage of the samples diameter (x-y direction).

The shrinkage in z is with an average value of 15.8% slightly higher than the shrinkage in x-y direction with an average value of 14.49%. This difference is induced by gravity, but small enough to work with an average scaling factor of 15% to produce near shape components. The measured sintering density reached an average value of 7.49 g/cm³ with a standard deviation of 0.16 g/cm³. This leads to a relative sintering density of 96.03% compared to the bulk material. The good results in terms of material connection and density can also be confirmed by SEM investigations.

As shown in Fig. 5 the single layers are clearly visible on the outside of the part. However there is a dense surface of the single threads and a very good connection between the layers.

4. Conclusions

The processing of standard industrial material in an additive manufacturing could be approved in example of the MIM material with the CEM-process. The results concerning the sintering density, the

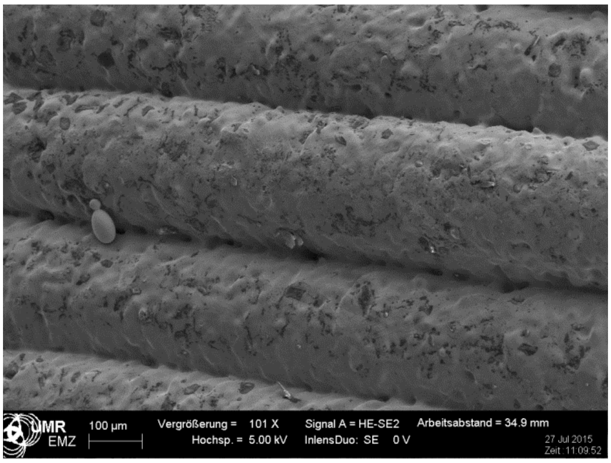

Fig. 5 SEM image of a printed an sintered cylinder.

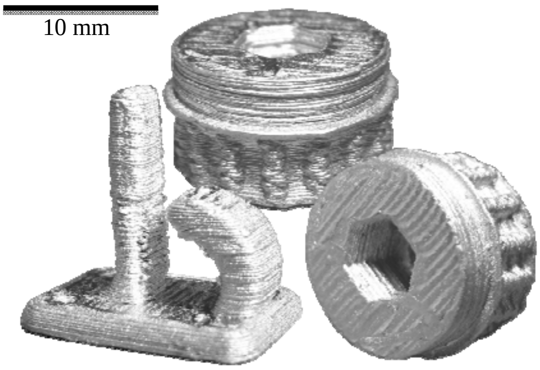

Fig. 6 Different sintered components.

microstructure and the shrinkage are comparable to values delivered by standard MIM processes. Furthermore the creation of overhangs as seen in Fig. 6 and also closed hollow parts could be approached. In further investigation an optimization of the extrusion process, concerning the print speed and -quality, will be carried out. Also there will be further investigations of the mechanical strength. Specifically tensile strength tests, notched bar impact tests and tests for the exact dependence of infill proportion and build direction will be made. Potential applications could lay in the field of rapid prototyping for MIM products, but also in small batch production or custom components for special applications. The possibility to build fully closed hollow metal components in a cost efficient process could bring benefits for space and aviation application and also for the production in small and medium sized enterprises.

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