RAPID PROTOTYPING OF FUNCTIONAL METAL AND CERAMIC COMPONENTS BY THE MULTIPHASE JET SOLIDIFICATION (MJS) PROCESS

Donald Kupp and Harald Eifert
Fraunhofer Resource Center-Delaware
1 Innovation Way, Suite 301
Newark, DE 19711

Matthias Greul and Matthias Künstner
Fraunhofer-Institute for Applied Materials Research
Lesumer Heerstr. 36
28717 Bremen, Germany

Abstract

The need to generate high-quality conceptual models of manufacturing components and limited application functional components has driven the development of Rapid Prototyping (RP) in the last fifteen years. Recently, however, it has become increasingly obvious that an RP system that can produce fully functional components in materials other than polymers would be beneficial. In order to fulfill the requirements for the direct production of metallic and ceramic components for functional testing and application, the development of new processes and materials are key development areas at the Fraunhofer Institute for Applied Materials Research (IFAM) and the Fraunhofer Resource Center-Delaware (FRC-DE). For the free-form fabrication of ceramic and metal parts, the Multiphase Jet Solidification (MJS) process has been developed for producing metal and ceramic components. The MJS process extrudes metal and ceramic based binder systems (such as Al_2O_3, SiC, stainless steel, and Ti), forming the desired component layer by layer. As in powder injection molding, after a part is formed by MJS, the binder phase is removed chemically or thermally and the remaining powder compact is sintered to final density. This paper presents the MJS technique and outlines a variety of potential applications.

Introduction

Commercial rapid prototyping has matured tremendously in the last five years to include a wide range of process techniques and materials. Based on a 3D CAD description of the desired geometry, these advanced processes now represent rapid and economical methods for producing manufacturing models and prototypes. However, for the free-form fabrication of functional prototypes, only a few materials systems and deposition techniques currently exist. For example, for metallic prototypes, a second step of investment casting or infiltration of the rapid prototyped part is commonly needed to produce a dense, fully functional piece. This method presents limitations in terms of the compositions that can be produced and in the process time reductions that are normally achievable through rapid prototyping.

As the rapid prototyping technologies mature and materials availability broadens, the need to produce truly functional ceramic or metal components through rapid prototyping has become more apparent. In order to meet increasingly stringent requirements, several new approaches based on powder metallurgical techniques have evolved. One such process, Multiphase Jet Solidification (MJS), has been developed to produce free-form metallic or ceramic components from powder/binder mixtures.

Working Principles of the MJS Process

The working principle of the MJS system is shown in Figure 1. A mixture of metal or ceramic powder and a suitable polymer-based binder system (i.e. feedstock) is held for delivery in the heated chamber. The feedstock is heated to the desired temperature to achieve a suitable viscosity then extruded through the nozzle by a pumping system. As the feedstock is extruded, the extrusion nozzle is rastered in the x-y plane to deposit the molten feedstock. The feedstock solidifies as it contacts the substrate (first deposition layer) or previously deposited layers due to the temperature and pressure decrease and heat transfer to the part and surrounding environment. Since the extruded material is in the liquid state, it partially remelts the previously deposited layer, forming a well bonded, continuous structure. After each cross section or "slice" is completed, the extrusion head is incremented in the z direction in step sizes of 0.1 mm to 0.5 mm and the next layer is begun. This process is repeated until the part has been fabricated to its final extension.

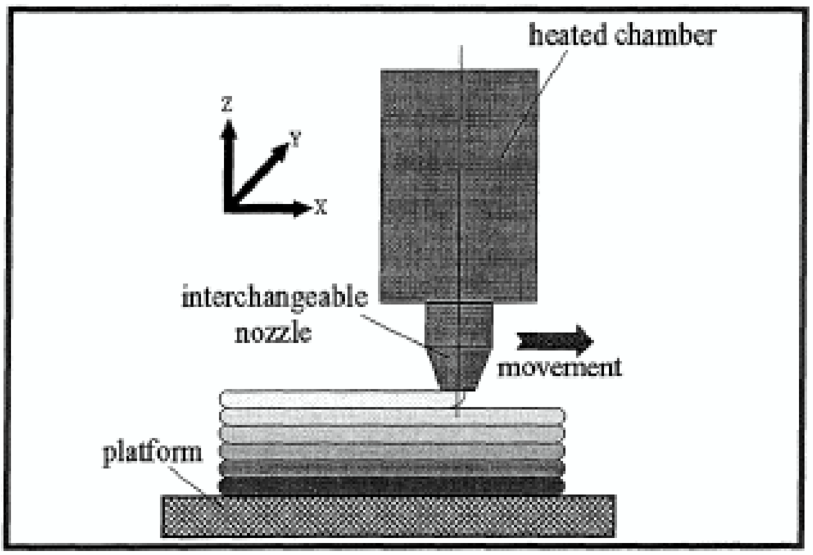

Figure 1. A schematic representation of the working principle of the Multiphase Jet Solidification System.

Components are fabricated on the basis of a 3D CAD model. From this description, STL files are generated to produce a numerical control code which drives the extrusion head. Process parameters such as positioning speed and material extrusion rate are added and the control file for the machine is generated [1].

Based on the MJS technique, the RP Jet-200 System was developed and constructed in collaboration with the German manufacturer, Logeto GmbH. A heated extrusion chamber with a stability of ±1°C (up to 200°C) can accept feedstock in powder, granulate, bar or rod form. Various extrusion tip geometries from 0.02 in (0.5 mm) to 0.08 in (2.0 mm) have been successfully used. A computer is used to control the x-y-z positioning system with a precision of ± 0.0004 in (0.01 mm) and a total work volume of 10 x 10 x 7 in (250 x 250 x 175 mm). Figures 2 and 3 show the system installed at the FRC-DE.

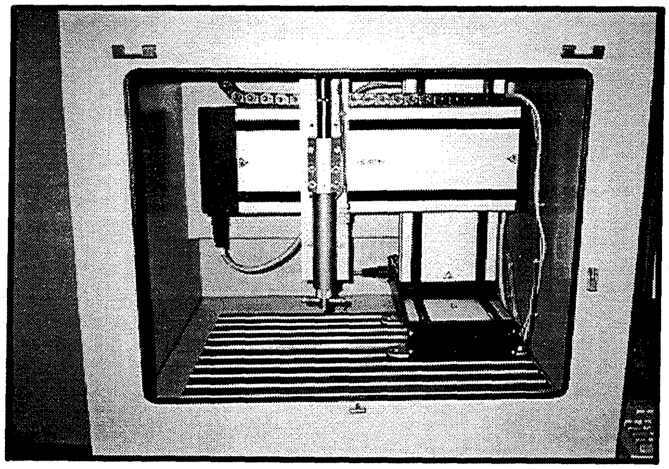

Figure 2. Extrusion head and translation system of the RP Jet-200 MJS machine.

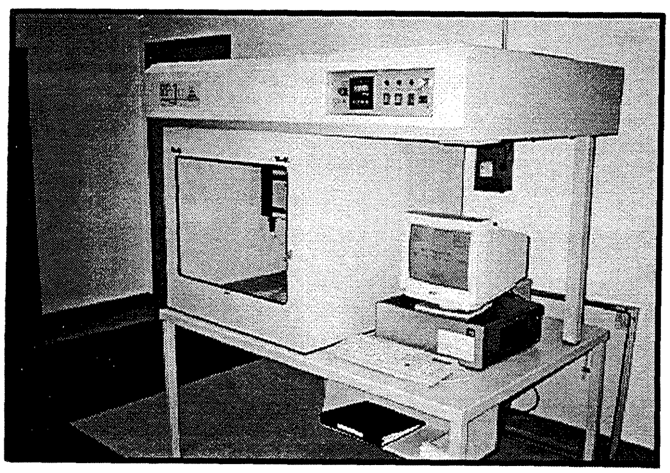

Figure 3. The RP Jet-200 MJS system from Logeto, GmbH. showing the deposition chamber and computer control station.

While the suitability of any feedstock system for use in the MJS process must be determined individually, the RP Jet-200 MJS system was developed specifically to accommodate the general rheological behavior and processability of PIM materials. Based on the use of such PIM feedstock materials, the fabrication of metal or ceramic components is carried out in three basic steps:

- The first step is to fabricate the component, comprised of metal or ceramic powder in a polymeric matrix. This "green" component is similar to that produced through powder injection molding except that the geometry has been developed without the use of any restrictive fixtures or molds. The feedstock and therefore, the "green " component is composed of up to 50-70 volume percent solid material (balance of polymer). This solids loading level can usually be modified somewhat depending upon the related processing criteria and ultimate performance characteristics of the finished part.
- After the part has been formed, the polymer matrix must be removed so that only metal or ceramic material remains prior to heat treatment to its final composition and microstructure. Depending on the type of polymer binder system used, different techniques for binder depletion can be implemented. Most commonly, a form of standard powder metallurgy or PIM methods involving chemical dissolution and/or thermal decomposition are used to produce a "brown" part (also known as debound or debindered part).
- This "brown" part, comprised of only metal or ceramic material, can now be heat treated or sintered to its final, desired density.

Figure 4 shows sample feedstock and prototype "green" and sintered components fabricated with the MJS process using an EVA copolymer/paraffin wax binder system.

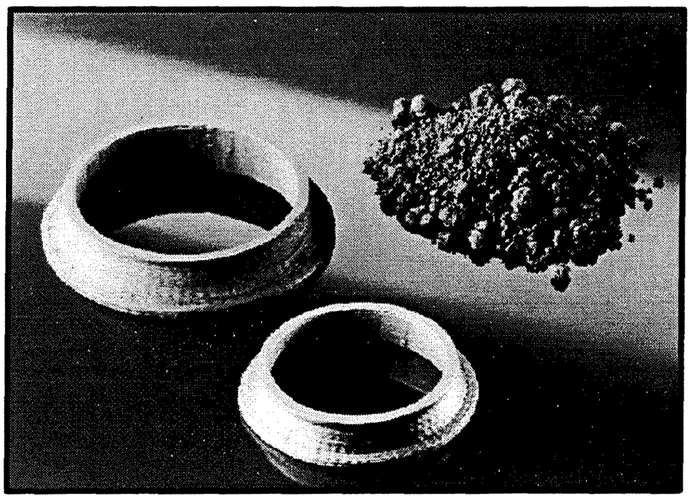

Figure 4. Feedstock for use in the MJS process (right) and "green" (left) and sintered (foreground) parts produced by Multiphase Jet Solidification.

Manufacturing Capabilities and Materials

A prime feature of the MJS technique is its ability to produce fully functional metal or ceramic components using commercially available feedstock material. Many types of feedstock systems are readily available for use in powder and polymer injection molding (PIM) and even low temperature alloys. The broad range of these systems allows the user to select the appropriate feedstock to meet specific criteria in component fabrication including such things as part complexity, binder removal technique, and most importantly, base material composition. Ceramic-based feedstock systems such as aluminum oxide, silicon nitride, silicon carbide, and zirconium oxide are currently available. Metal-based systems such as carbonyl iron, various stainless steels, magnetic materials and titanium are even more widely known and distributed.

MJS is closely related to the PIM process with the primary difference being that MJS enables fabrication of parts without the use of a mold. Table 1 shows some examples of typical PIM materials in different groups. Representative samples of each group have been successfully processed with the MJS system preparing tensile test bars and other testing shapes. Comparison of PIM and MJS processing is shown in Figure 5 [2].

Material Group	Examples for Typical MIM Materials in this Group	Successfully Tested with MJS
Stainless Steels	AISI 316L, 410, 430	316L
Heat Treatable Steels	17-4-PH, $Fe_2Ni0.5C$, Fe7Ni,0.9C	not tested
High Speed Steels	D2, CPM 9V/10V	M4T2
Magnetic Materials	FeNi, FeCo, FeSi, FeNdB, AlNiCo	FeNi
Lightweight Materials	Ti, TiAl6V4	Ti
Special alloys	WFeNi, WCu, NiAlCr, silicides, Stellites	Stellite (Co-Cr-Mo)
Ceramics and Carbides	Al_2O3, SiC, WC-Co, ZrO_2	SiC

Table 1. Examples of different material groups and typical MIM alloys.

The material most widely produced by PIM is 316L stainless steel. A comparison of typical MIM parts of 316L stainless steel to those fabricated using the MJS process can be seen in Table 2.

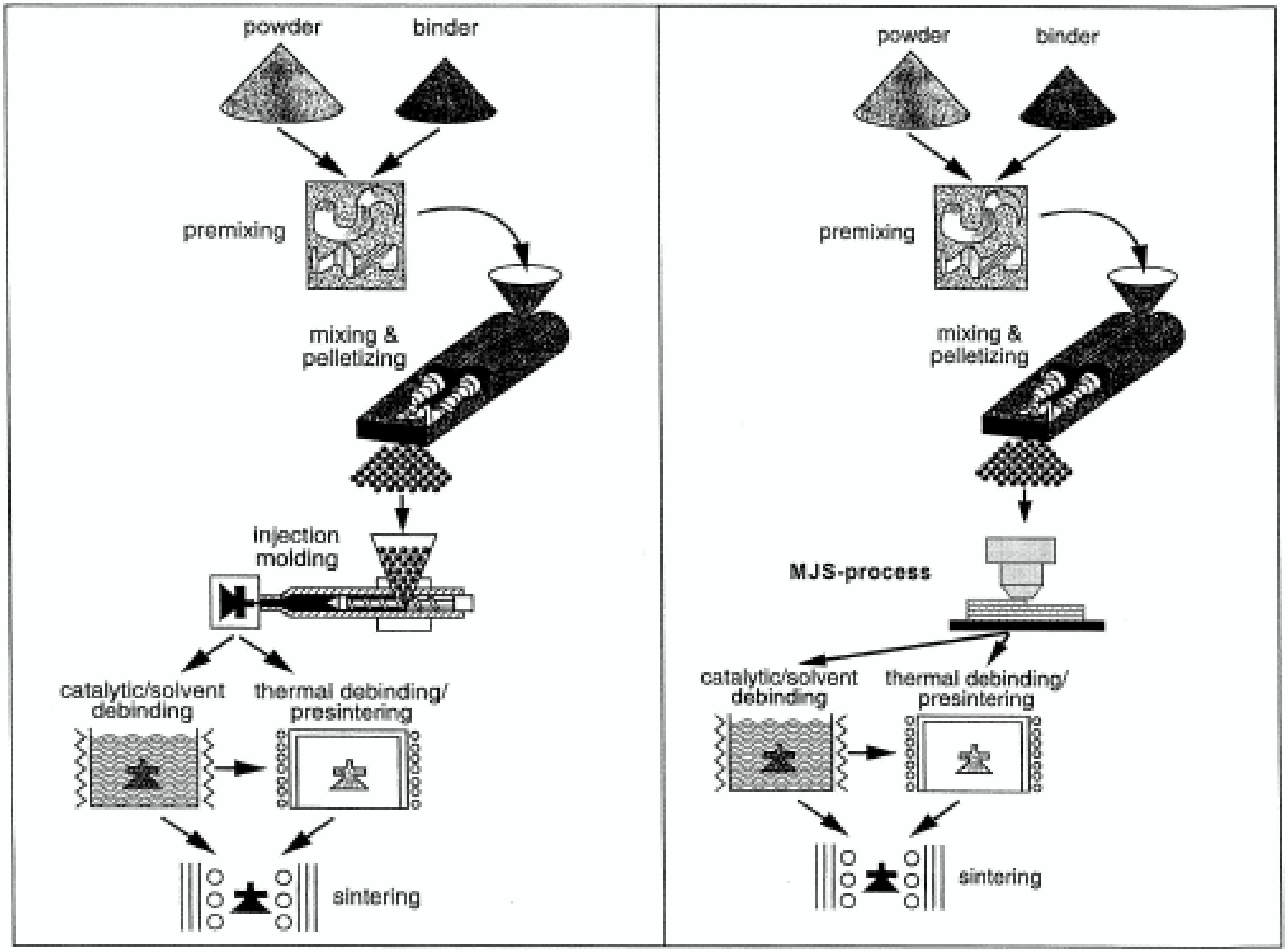

Figure 5. Comparison of PIM (left) and MJS (right) component fabrication routes [2].

Process and Material	Density (% of theoretical)	Ultimate Tensile Strength (MPa)
MIM 316L, typical values [2]	95-99.8	450-520
MJS 316L	97-99.3	480

Table 2. Mechanical properties of 316L stainless steel (Fe-17Cr-12Ni-2Mo-2Mn) prepared by metal injection molding and MJS.

Summary

Generally, the MJS technique can process any materials that can be processed via PIM. Currently, the only limitations are that the feedstock viscosity should be in the range of 10 to 200 Pa·s with a binder melting temperature below 200°C These process boundaries can likely be exceeded with minor hardware modifications. All material systems mentioned previously have been successfully processed via MJS with other materials such as tool steels, hard alloys, and ultrafine materials under development. Also, highly filled polymer systems such as carbon-black based feedstock for conductive polymers are suitable for MJS deposition.

Since the MJS process produces fully functional parts, it is useful not only as a rapid prototyping technique for producing demonstration and visualization components, but also as an agile manufacturing process which can produce limited production runs of specialty items for real applications and performance trials. Also, by using MJS in combination with PIM feedstocks, the materials development for injection molding (shrinkage, debinding, and sintering behavior) can be completed without using expensive tooling.

Rapid prototyping systems commercially available today do not satisfy the requirements of manufacturers in need of functional metallic or ceramic prototypes. Compared to Selective Laser Sintering [3] or 3D printing [4], the MJS process has the prime advantage of utilizing a broad range of materials in a process closely related to powder injection molding, an existing and already successful technology. Due to the variety of developed applications for PIM, many material systems or feedstocks suitable for MJS are already commercially available. The ability of MJS to form components using materials with high melting points combined with the relative simplicity of the deposition apparatus further enhances the usefulness of such a technique.

Common to all RP techniques, the development of new materials systems and optimization of the deposition technology in areas such as accuracy, surface finish and production times are on-going developmental issues. Further development in areas such as feedstock rheology, deposition mechanics, and hardware and software design will lead to the production of more complex geometries with improved accuracy and repeatability.

References

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