QUALIFICATION METHOD FOR POWDER INJECTION MOLDED COMPONENTS

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ABSTRACT

The PIM process produces net-shape or near net-shape parts at a reduced manufacturing cost; however, significant process and product qualification is required to ensure that the final product is acceptable. The level of qualification depends upon the end use of the product. It could be as simple as making a prototype part or as complicated as characterizing and controlling the entire process. As a rule, medical and aerospace products require the greatest amount of qualification and less critical products such as tools and consumer products require the least. In this paper, a guideline is presented to qualify a PIM process that meets a final specification at a minimum cost. A rationale for choosing only the most critical process control methods is presented.

INTRODUCTION

Powder injection molding (PIM) is a process that allows the formation of net shape or near-net shape parts at a reduced manufacturing cost as compared to machining and at a higher precision level than other forming technologies such as casting. Example PIM parts are shown in Figure 1. However, the process is fairly complicated, requiring knowledge from various disciplines to ensure that quality product is manufactured. Knowledge of powder handling, powder sintering, injection molding, powder/polymer rheology, polymer degradation, metallurgy, etc. must be understood and used to ensure a stable process and a quality product.

Based on the complexity of the PIM process, an engineer can get lost in all the possible variables that could be implemented to attain a controlled process, and most importantly, a quality product. Often, a high level of process control is required and other times it is not. In this paper, a program is presented for a design engineer to easily determine the proper material for an application, to qualify a component vendor, and finally to have a design engineer understand the PIM process well enough to make intelligent decisions with regards to the use of PIM in their applications.

THE POWDER INJECTION MOLDING PROCESS

To use and to validate the PIM process, a design engineer must have a basic understanding of the process. The process must be divided into its sub process categories. The number of process steps can be as many as 9. The number of steps depends upon the particular technology and the amount of processing that a manufacturer performs. For example, whether the manufacturer purchases feedstock or manufactures the feedstock in-house. The PIM process is schematically represented in Figure 2. The process steps are as follows:

I. Raw Material Selecting and Monitoring
II. Material Blending
III. Feedstock Compounding
IV. Injection Molding
V. Solvent or Catalytic Debinding
VI. Thermal Debinding
VII. Sintering
VIII. Secondary Operations (HIP, machining, heat treating, grinding, etc.)
IX. Inspection and Packaging

Figure 1. *Example of PIM parts after sintering.*

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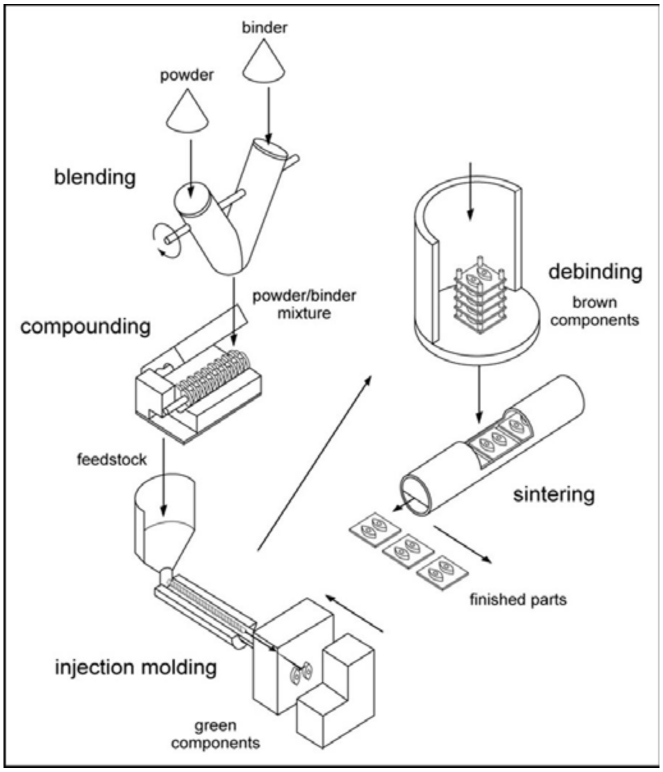

Figure 2. A schematic representation of the metal injection molding process

Each process step produces a product that feeds the next step. Thus, controls can be performed on the individual processes and also on the product of each step to ensure that the entire process is in control. Table I lists a PIM process sequence and the inputs and output of each sub process.

PRODUCT QUALIFICATION METHOD

The first question that must be asked is whether PIM can be used for an application. This is a two-sided question. First, is it technically feasible, and second, is it economically feasible. With this in mind, one must determine the economics of using the PIM process versus the current fabrication technique or conventional method for an application. If the economic exercise is successful, the next step is to determine the required application properties and critical dimensions on the component. Prototype mold fabrication is then performed and candidate materials are selected. This is followed by near net shape part fabrication and application testing. Figure 3 shows a logic diagram that can be followed to get a PIM part fabricated and qualified.

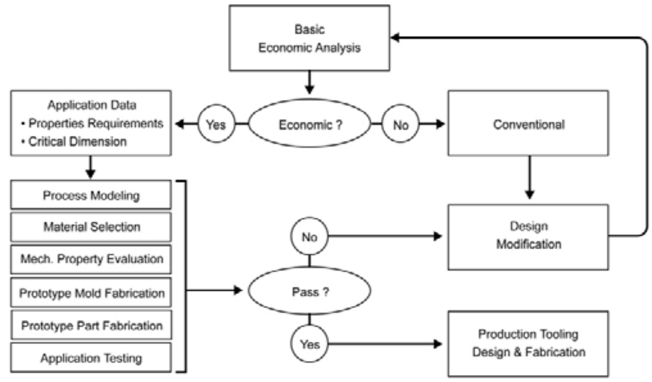

Figure 3. Logic diagram to go from concept to production for PIM

The first step in qualifying PIM for an application is to do the economic analysis. If the economics look undesirable, one must return to a conventional manufacturing technique or make design modifications in material type or part size to make the project economical. Often the size of the part will dictate whether PIM can be used, not only from a technical point of view for removal of the binder, but also because of the powder cost. Typically, parts greater than 300 grams cannot be fabricated economically using contemporary PIM technology. After a successful economic analysis, the next step is to look at the technical aspects of the component – specifically the application data such as property requirements and critical dimensions. After these have been defined, the proper material or group of materials is selected for evaluation. These materials are then injection molded and evaluated for properties, such as tensile strength and/or corrosion resistance. Property evaluation can be skipped if a vendor has defined these data in previous work. Satisfactory results for properties justify the fabrication of a prototype mold. "Prototype" is emphasized since these parts are

Table I. Process Input and Output Products for Comprehension and Process Control

Process Step	Process Input	Process Output
Blending	Powder & Binder	Powder/Binder Mixture
Compounding	Powder/Binder Mixture	Feedstock
Molding	Feedstock	Green Part
Debinding	Green Part	Brown Part
Sintering	Brown Part	Finished Part*

* may require secondary operation

produced using low cost tooling. More detail on prototype molds is presented in the following section on "PIM Prototype Methodology". The prototype parts might require secondary operations that would not be required while using production tooling. Application testing is the final test to validate that PIM can be utilized for an application. If application testing is unsuccessful, the development cycle starts again with design modifications and economic analysis, provided management continues support.

The above methodology is a philosophy. Variations to this technique may exist for different applications, different amounts of available capital, and also considering time to market for a product. For example, one may choose to go directly to production tooling fabrication and do the development on the production tool.

PIM PROTOTYPE METHODOLOGY

Following the economic analysis, the first step for any potential PIM application is the evaluation of mechanical properties of potential materials and the production of prototype parts. The production of test samples (tensile, fatigue, wear discs) or actual prototypes is done to test a new material for a particular application with the minimum of cost. Property evaluation can be as simple as locating property values in the MPIF standards manual, a PIM part supplier's specifications, or from other literature that pertains to a specific material. Special and new materials may need to be evaluated independently, since PIM is a relatively new technology and not all data are available. Also, mechanical properties can be PIM part supplier dependent, since all suppliers use different processing methods and raw materials. For example, vacuum sintering of stainless steels may reduce its corrosion resistance or the feedstock binder may leave a carbon residue that could compromise properties or corrosion resistance of the sintered metal.

Material Selection:

Selection of the proper material for a particular application often decides the success of a PIM project. Table II lists some available metal alloy and ceramic systems and potential applications. The specific features are as compared within the family of material. From this, a design engineer can obtain an approximate idea of the proper material for an application. Sometimes, multiple materials are evaluated for an application and a decision is made based on performance, cost, and input from a PIM part supplier or expert.

Table II. Materials Selection Guide

Material Family	Applications	Specific Alloys	Specific Feature
Stainless Steel	Medical, Electronic, Tools, Sporting Goods, Aerospace, Consumer Products	17-4PH	Strength, heat treatable, processability
		316L	Corrosion resistance, elongation, processability
		410L, 420L, 440C	Hardness, wear resistance, heat treatable
		430L	Magnetic response
Low Alloy Steels (heat treatable)	Tools, Bearings, Races, Consumer Goods	2200	Magnetic
		2700	High nickel
		4605	
		8620	Case hardenable
		4140	
		52100	
Tool Steels (heat treatable)	Wood and Metal Cutting Tools	M2	Low cost
		M4	Processability
		T15	High speed, processability
		M42	High speed, processability
		H13	
Titanium	Medical, Aerospace, Consumer Products	Ti	Light weight
		Ti-6Al-4V	Light weight, high strength
Copper	Electronic, Thermal Management	Cu	High thermal and electrical conductivity
		W-Cu, Mo-Cu	High thermal conductivity, low thermal expansion
Magnetic	Electronic, solenoids, armatures, relays	Fe-3%Si[1]	
		Fe-50%Ni[1]	
		Fe-50%Co[1]	
Hardmetals	Cutting and Wear Applications	WC-5Co	Higher hardness
		WC-10Co	Higher toughness
Refractory Metals	High Temperature, High Density, Electronic	Ta	Electronic
		W-Ni-Cu, W-Ni-Fe	High density
Ceramics	Wear applications, Nozzles, Ferules	Alumina	Low cost
		Zirconia	High wear resistance
		Silicon Carbide	High wear resistance
		Silicon Nitride	High performance

There are other materials available and these can be custom made by a talented PIM parts supplier. As a general rule, if a material is available in a fine powder form, it can be powder injection molded. Some exceptions are materials that have high strength at high temperatures, since these materials are difficult to sinter. A good vendor or PIM design engineer should be able to work with you to select the proper material once you have determined the family of materials that is appropriate for your application.

Prototype Production:

A PIM prototype is a PIM part that has been fabricated using the PIM process; however, the tooling that is used is much less in cost than production tooling. A prototype tool will cost less than one quarter the cost of a production tool, since expensive mold components such as slides and cams are not used. Difficult features are machined in as secondary operations, since fewer than 1,000 prototype parts are typically produced. The tooling is also made with easy to machine metals such as P20 and unhardened H13. Aluminum can also be used, however, this metal is easily dinged and mauled during prototype development. It is often valuable to have your mold shop work with materials that they are accustomed to machining. Examples of prototype tooling are shown in Figure 4.

PROCESS CONTROL

Once a PIM prototype part has passed initial qualifications for use, the next step is to ensure that a process is sufficiently in control for a particular application. Minimum process control is required if the specifications are broad and a significant amount of process control is required if the specifications are narrow. This section breaks down the PIM process to allow one to determine what are the needs for a specific PIM process to achieve the required specifications at the minimum of cost.

Figure 4. *Example of Prototype tooling. No details requiring slides or cams are on the part*

To analyze the PIM process for process control, the process must be divided into its sub process categories. Each of these sub processes can be controlled to ensure a more repeatable process; however, the more you monitor, the more costly is the overall process. Therefore, an engineer must balance between cost and control to ensure that the PIM process is profitable for a particular application. For example, if a company is doing aerospace or medical parts, where the cost of a catastrophic failure is high, there must be a high level of process documentation and control. A company that manufactures products that have less financial exposure for catastrophic failure would require less. The general concept is to produce the best possible product with the least amount of process monitoring.

Table III lists each of the process steps for powder injection molding, and also the parameters that could be controlled for that process step. Although there are many potential parameters to control in the PIM process, not all need to be controlled. Application and process type define the required control. Table IV lists a comparison of process control auditing for two levels of control. One process control would be considered minimum in both cost and effort whereas the other provides precise control for precision and high performance components.

CONTROL PARAMETER UNDERSTANDING

The following section is devoted to describing the different process controls and the reason for their use. These can also be used in the process setup and qualification stage to ensure a stable process and reviewed periodically or when a problem arises.

(1) Powder Characteristics

Chemistry: Chemistry monitoring is most critical for materials that are sensitive to carbon level and oxygen level, however, other elements such as chromium for stainless steels may be important to monitor. Carbon level is required for materials where it is important for properties and heat treatment. The most common being tool steels, low alloy steels, and martensitic stainless steel. In these materials, it affects dimensional stability, sintered density, and mechanical properties. Also, materials sensitive to carbon embrittlement, such as titanium, should have the carbon monitored. Oxygen monitoring is important for materials such as titanium since it effects the elongation. Also, oxygen in combination with silicon in stainless steels

Table III. Potential Parameters to Control for the PIM Process

Process Step	Process Attribute	Measurable Attribute	Monitor Method
Raw Materials	Powder	Chemistry	Specification sheets Chemistry analyzer
		Powder Size	Specification sheets PSD analysis
		Powder Size Distribution	PSD analysis
		Density	Pycnometry
		Tap Density	Tap Density
		Moisture level (ceramic)	Hydrometer
	Binder	**Moisture Level**	Hydrometer
		Viscosity	Capillary Rheometry
Compounding	Feedstock	Density (powder/binder ratio)	Pycnometer
		Viscosity Stability	Capillary Rheometry
		Viscosity vs. Shear Rate	Capillary Rheometry
Injection Molding	Switch-over Pressure	Switch-over Pressure Stability	Machine
	Screw Return Torque	Screw Return Torque Stability	Machine
	Part	Part Mass	Scale
	Defects	Blisters, Voids, Cracks, Powder/Binder Separation, Knit Lines	Visual, X-ray
Solvent Debinding	Part	Mass Loss	Scale
	Defects	Cracks, Blisters	Visual
Thermal Debinding	Part	Mass Loss	Scale
	Part	Shrinkage	Linear Measurement
	Defects	Cracks, Blisters	Visual
Sintering	Maximum Temperature	Max Temp Stability	Thermocouple
	Temp. Uniformity	Temp Uniformity Stability	Thermocouple
	Defects	Voids, Cracks	Visual, X-ray
	Part	Shrinkage, Final Dimensions	Linear Measurement
	Part	Surface Finish	Profilometer
	Part	Corrosion Resistance	Salt spray, poteniodynamic scans
	Part	Properties	Application testing
Inspection	Part	Dimensions	Linear Measurement
	Gauging	Dimensions	Linear Measurement

may effect the elongation by the formation of silica particles.

Powder Size and Size Distribution: Powder size and size distribution affects mixture viscosity and injection molding. As particle size increases, mixture viscosity decreases. This affects the molding process consistency. Also, sintered density and mechanical properties are affected by the powder size. As particle size decreases, the sintering response increases. Therefore, variability in particle size affects the part dimensions, part density, and mechanical properties.

(2) *Feedstock Behavior*

Pycnometer Density: Pycnometer density is a direct measure of the ratio between the powder and the binder. Improper pycnometer density effects sintered size, mixing viscosity, and molding.

Feedstock Viscosity: Improper feedstock viscosity will result in variability during molding and part quality. It also can be an indication of improper raw materials, degraded raw materials, degraded feedstock, and poorly mixed feedstock.

(3) *Injection Molding*

Part Mass: A variation in part mass will result in a variation in dimensions in a sintered part. The part mass variability may be the result of the feedstock preparation step or of barrel temperature variability. Variability in the switchover position or hold pressure can cause mass variability and final part dimensional variability.

Table IV. Process Auditing Comparison for Minimum and Precision Process Control

Attribute	Minimum Control	Precision Control
Feedstock	• As-molded part mass auditing	• As-molded part mass auditing • Pycnometer density auditing • Viscosity stability auditing
Injection Molding	• Part mass auditing • Position switch-over and monitor switchover pressure	Part pycnometer density Part dimension . Cavity pressure switch-over and monitor switchover position, closed-loop control on hold pressure
Solvent Debinding	. Weight loss studies	Weight loss studies . Weight loss auditing
Thermal Debinding		I. Weight loss studies II. Weight loss auditing
Sintering	• Select part dimension auditing • Part mass auditing	• Select part dimensions • Part mass • Chemistry analysis • X-ray • Crack detection • Microstructure • Mechanical Testing

(4) *Debinding*

Weight loss: Understanding the amount of binder in your part and the rate at which it is removed is critical for defect free parts. Also, if the binder is not removed correctly, there is a chance that "ash" will form in the part, put excess carbon in the part, and affect the final mechanical properties of the parts.

(5) Sintering

Select part dimensions: Dimensional variability shows the most effect after sintering. As the temperature in the furnace varies, so do the dimensions. Therefore, knowledge of the dimensions and how they vary are important to understand the sintering process and to maintain a controlled process. The variability of all the previous process steps will be exasperated in the sintering step and show up as part dimension variability.

Part mass: After sintering, the mass of a component can change if there is an alloying element that vaporizes in the furnace. For example, the loss of chromium in stainless steel during vacuum sintering is well documented.

Chemistry analysis: Material evaporation or contamination from the furnace or process gas can be detected to high accuracies using chemistry analysis.

X-ray: Voids and cracks are easy to detect using X-ray equipment. This could be used for the setup of critical parts for medical or aerospace applications.

Crack detection: Many methods exist for the detection of cracks. These can range from acoustics to visual detection.

Microstructure: The evaluation of microstructure can be extremely valuable. The detection of oversintered or undersintered microstructure is simple using this method. Also, many other characteristics of the part can be detected from the microstructure. These include carbide formation, phase ratios, etc.

Mechanical testing: Often, the components can be put through function testing for strength or evaluated for hardness on the actual part. Another method to monitor the sintering process is to have test specimens sintered with the parts and evaluate the test samples for strength, elongation, or some other test.

CONCLUSION

A method to qualify powder injection molding for an application was presented. This was done for both product and process. A thorough evaluation of process controls and monitoring that can be done on a PIM process was laid out. Also, a rational for the selection of the best process control for a particular application has been presented. In general, one should monitor only the most critical parameters that are dependent upon the application and its specifications.

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