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Powder Injection Molding (PIM) for Low Cost Manufacturing of Intricate Parts to Net-Shape

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ABSTRACT

Powder Injection Molding (PIM) is a low cost manufacturing process that produces very complex parts to net-shape in a wide variety of materials and unique alloys, including superalloys, stainless steels and carbides, resulting in minimal secondary and assembly operations. PIM offers significant cost savings, increased design and materials flexibility, increased possibility of miniaturization, high mechanical properties, good surface finish and high speed production. The activities and expertise in powder metallurgy as well as in process numerical modeling related to powder injection molding at the Industrial Materials Institute of the National Research Council of Canada (NRC-IMI) and at Maetta Sciences, a company that has research and development facilities at the NRC-IMI, will be presented. Selected solutions and examples realized by NRC-IMI and by Maetta Sciences using respectively their high pressure and their scalable PIM platforms will be presented and described. Potential applications for the military, transportation and aerospace sectors will be highlighted.

1.0 INTRODUCTION

Injection molding is a low cost, productive and widely used shaping technology for plastics. The knowledge base for this technology is highly developed and the most recent innovations are around new formulations of polymers. Powder Injection Molding inherited from this development. PIM is also a low cost manufacturing process that produces very complex parts to net-shape in a wide variety of materials and unique alloys, including superalloys, stainless steels and carbides, resulting in minimal secondary and assembly operations. PIM is a young but established technology with world annual sales of more than $1,200M and a sustained growth rate between 10 and 25%. This paper presents the general PIM process implementation, design aspects and some case studies related to communication, transportation and aerospace sectors. Also, the activities conducted at NRC-IMI are presented focussing around numerical modeling and new material formulations. Finally, an innovative approach to integrate PIM in all the steps of a product development lifecycle is discussed. The vision is to scale the PIM process to the required production volume with minimal detrimental impact on the production cost.

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2.0 POWDER INJECTION MOLDING PROCESS

Powder injection molding combines the qualities of plastic injection molding, such as form complexity and high productivity, to the specific properties of ceramic, metallic or carbide materials. The basis of the process is to use a semi-solid mixture, made of fine powder and melted polymeric binders, to fill the mold cavity by injection under pressure. The polymers are then extracted and the porous structure of loosely packed powder is sintered into a dense solid to obtain the strength which characterizes the dense material. The typical implementation of PIM process is described below. As illustrated in Figure 1, there are four primary steps in the PIM process.

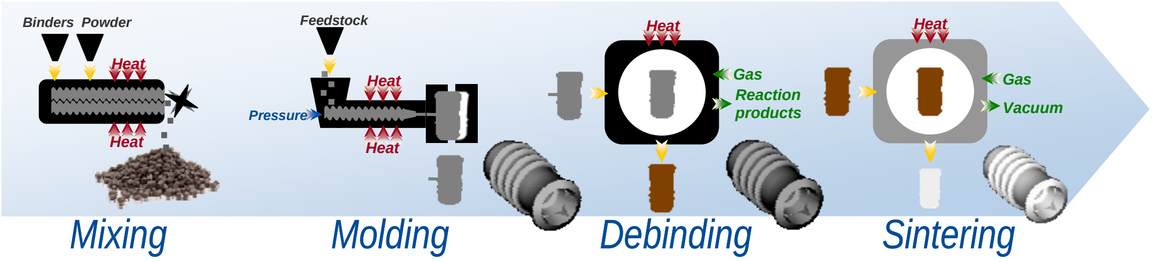


Figure 1 : Typical PIM process chain

2.1 Process Implementation

The first step of the process, the mixing, is critical since all the details must be considered in order to obtain homogenous and predictable feedstock with the desirable rheological behaviour. Fine metallic, ceramic or carbide powders, of less than 25 µm, are hot mixed together with melted polymeric binders using a continuous or a batch mixer, then cooled and granulated to form the feed material for the injection molding machine. Spherical powder is the best candidate since it helps in increasing the maximum solid loading of the feedstock and, therefore, offers a better control of the final dimensions. The usual solid loading is between 60 and 65 vol.%. Several binder systems have been proposed in the literature and consist in mixtures of polymers, waxes, dispersants and surfactants. Typical polymers are polyethylene, polyethylene glycol, polymethyl methacrylate, polypropylene, and typical wax is paraffin wax.

The feedstock is converted into a defined shape using a molding machine similar to the one used for plastic injection molding. The feedstock granules are melted into a heated barrel with an internal screw for compressing, dosing and injecting the powder suspension into a closed cavity. The injection pressure ranges from 1.5 to 60 MPa. The mold filling takes place in less than a second and the pressure is still maintained during the final cooling to prevent void or crack formation due to contraction. The total cycle time between 10 to 30 seconds is normally achieved. The mold is designed to compensate the final shrinkage that occurs during sintering. The typical shrinkage is between 12 and 18% depending on the solid loading of the feedstock and the level of densification achieved during sintering.

The multi-components binder system is then eliminated during the debinding step. The main goal of this step is to remove the binder without distorting the part. Thermal debinding is the most common technique where the parts are heated in an oven under controlled atmosphere. The first binder component is eliminated at lower temperature while a second component, the backbone polymer, maintains the powder particles in place. The porous network formed during the first stage of the debinding step helps in the evacuation of the degradation residues from the backbone polymer and reduces the internal pressure that could deform the part. Alternative debinding routes are also available where solvent can be used to remove the first component while the backbone polymer is thermally removed. Organic solvents are normally used to dissolve the polymer but water can also be used for water soluble polymer such as polyethylene glycol. The final thermal debinding stage where the backbone is removed is often coupled with the sintering step in order to avoid any damage to the debound part.

The final sintering step is to densify the part by removing the voids left behind by the binder extraction. The sintering occurs at temperature lower but close to the melting temperature of the metallic, ceramic or carbides powder material. A diffusion assisted mechanism helps the filling of the pores which leads to a shrinkage of the part. The final density is normally more than 97% and can reach up to 99.5%. The mechanical, physical and chemical properties are comparable to wrought material.

2.2 Component Design Aspects

The understanding of the capabilities of the PIM process in the early stage of the design of a component is a means to improve quality, increase functionality and reduce the cost. Complex net-shape components from metals, ceramics, cemented carbides, and cermets can be produced by PIM. The process offers the possibility of increasing the production volume to amortize the cost of the tooling. The part selection criteria are based on four main considerations: annual volume, part complexity, part dimensions and material. The typical decision tree illustrated in Figure 2 might be useful for the early part selection for PIM.

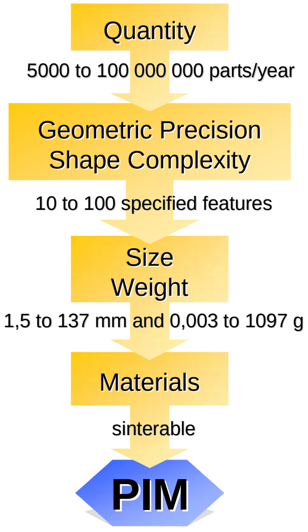


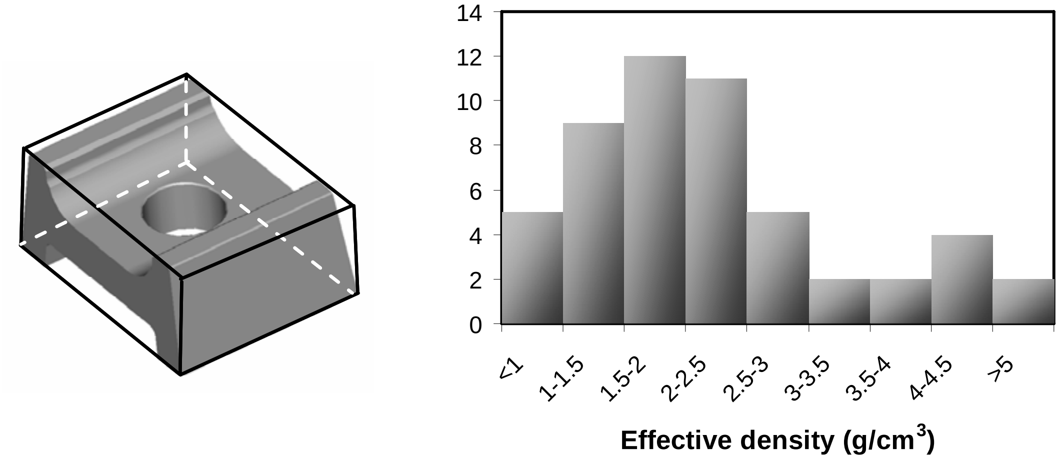
Figure 2 : PIM decision tree

This simplified decision tree should be supported by more specific knowledge of the advantages and limitations of PIM to eventually adapt the component design to the characteristics of PIM process. The past experience offers significant information regarding the PIM process capabilities as summarized in Table 1. Several design guides are available and give excellent advices on design considerations [1][2][3][4].

Table 1: Range of PIM process capabilities

	Minimum	Maximum	Typical
Component Mass (g)	**0.003**	**1097**	**32**
Largest dimension (mm)	**1.5**	**137**	**34**
Wall thickness (mm)	**0.1**	**10**	**5.0**
Tolerances (1σ, %)	**0.03**	**2**	**0.3**
Specified features	**10**	**100**	**40**
Cost per part ($)	**0.06**	**400.00**	**1.00**
Annual production (units/year)	**2000**	**100,000,000**	**300,000**

German [1] introduced the effective density concept to illustrate the success of PIM over machining. The effective density is the mass of the component divided by the outer envelope volume from which machining would start. The concept is illustrated in Figure 3a. He studied more than 50 case stories of PIM steel and stainless steel component. As illustrated in Figure 3b, the compiled data show that most PIM component production is applied to shape with a low effective density in the range of 25% of the bulk density meaning that PIM has avoided 75% mass loss in machining.



(a) **(b)**

Figure 3 : (a) Effective density concept and (b) the effective density distribution of 50 PIM steel components [1]

The effective density concept is certainly an excellent criterion to select a part based on its relative complexity. The design features that can be made by PIM are similar to those made by conventional plastic injection molding or die-casting. However, some specific features are desirable to take advantage of PIM or to avoid its limitations. One of the key features is the use of uniform wall thickness in order to avoid sink mark, voids, internal stresses and distortion problem during debinding and sintering. By removing material in locations where it is not needed and by using ribs and webs to reinforce specific area, uniform wall thickness can be obtained. In addition, the use of cores and holes reduces material usage and improve the efficiency of debinding by reducing the mean travel path of the binder residues. One major advantage of PIM is the ability of integrating non-circular holes on many different axes in the part design. In addition, external and internal threads, surface features (knurled surface, letters and logos) can be molded using PIM process. Despite the increased complexity introduced by some specific design constrains, acceptable tolerances on specified features are obtained. Table 2 summarized the minimum and typical tolerances possible with PIM process without secondary operation [5].

Table 2: Current dimensional tolerance limits of PIM process [5]

Feature	Best Possible	Typical
Angle	0.1°	2°
Density	0.2%	1%
Weight	0.1%	0.4%
Dimension	0.05%	0.3%
Absolute dimension	0.04mm	0.1mm
Hole diameter	0.04%	0.1%
Hole location	0.1%	0.3%
Flatness	0.1%	0.2%
Parallelism	0.2%	0.3%
Roundness	0.3%	0.3%
Perpendicularity	0.1% or 0.1°	0.2% or 0.3°
Average roughness	0.4µm	10µm

The PIM tolerance limits are constantly improving. A recent study from German and Heaney proposed the trend in the improvement of the tolerances [6]. Their prognosis for 2005 is that 50% of the industry has dimensional tolerance of ±0.17mm (3σ) while the typical claims are ±0.075mm (3σ) and the best performance is ±0.010mm (3σ). Their projection for 2010 is that 5% of the industry will be capable of ±0.03mm (3σ) but only the most recent PIM producers using the best practices will have this capability.

3.0 CASE STUDIES

Figure 5 shows the segmentation of the market served by PIM industry and the relative growth of the various segments [1]. The largest market segment for PIM is the production of casting cores. These are ceramics components (alumina, silica or zirconia) with intricate geometries that are inserted into casting cavities for internal features. Several examples can be found in the literature, such as the use of casting cores to form cooling passages in turbine blades. This segment is still showing a moderate growth due to the expansion of land turbine, power generation equipment and jet engines.

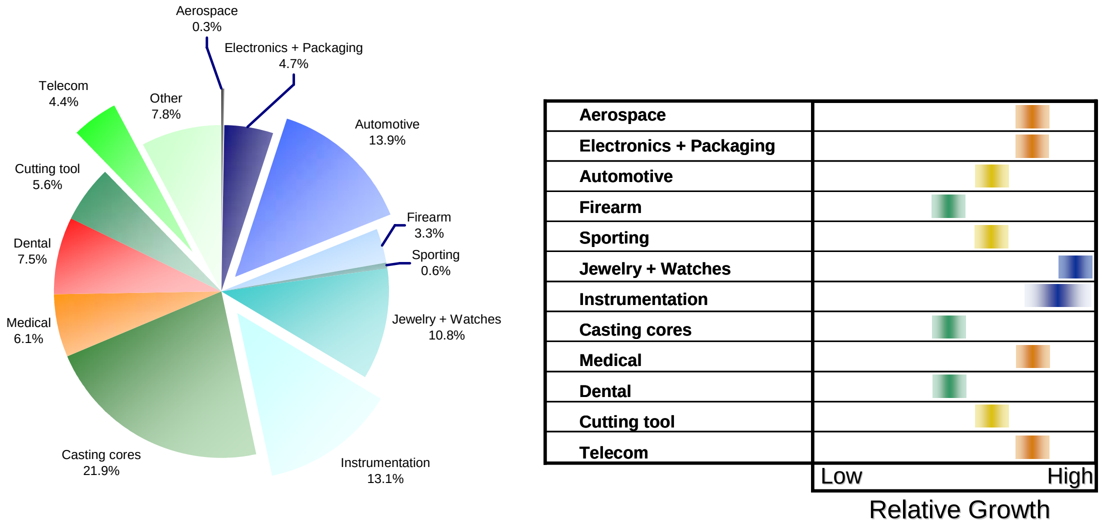


Figure 4 : Relative partitioning and relative growth of the sales by market segments[1]

For the aerospace sector, PIM is a solution to support the "buy-to-fly" philosophy. The net-shape capability and the recycling of the molding process artefacts (runners and gates) are certainly attracting for this segment. However, the stringent product specifications limit the penetration of PIM in this market. But, there are still a lot of R&D activities around nickel-based or cobalt-based superalloys and titanium alloys produced by PIM. Turbine engines contain thousands of small intricately shaped parts that require extensive machining and finishing operations when made from wrought materials. The cost effective advantages of net-shape manufacturing methods such as PIM were shown for intricate turbine engine components, such as a 17-4PH stainless steel vane actuator arm for the V-22Osprey T-406 engine and an Inconel 718 sidewall nozzle segment for the Joint Strike Fighter engine. Respectively 30% and 80% reduction in manufacturing cost over wrought alloy methods were obtained [7]. PIM was also explored for the manufacturing of a butterfly valve housing (or a flow body) weighing approximately 1000 grams. Large flow bodies in IN718 were successfully molded and sintered. Tensile and fatigue properties were shown to exceed those of investment cast IN718 [8].

Electronics/packaging, telecom and instrumentation are the segments where PIM show the highest market penetration. Numerous examples of PIM parts can be found in the consumer goods (cellular phones hinges, vibrator weight, connector bodies and various types of housing). Significant R&D efforts were put in the processing of low thermal expansion materials (Fe/Ni, Kovar or Fe54Ni31Co15, W-Cu and Mo-Cu) for microelectronic packaging via PIM. The increased demand for high-frequency-modules for communication network and automotive sensors is the main driver for this development. Hermetic glass-metal seal electronic packages are now commercially produced from Kovar [1][9]. Other applications are thermal management devices where mechanical strength, high thermal conductivity and low thermal expansion coefficient adjustable to GaAs are required. These requirements are met by tungsten- or molybdenum-pseudoalloys, which can be net-shape manufactured only by PIM because of the tight dimension tolerances needed for the final sealing of the electronic package [10].

PIM is also very attractive for materials that are difficult to fabricate and/or are very expensive raw materials. Rhenium metal, for instance, which costs about US$ 800 /lb, offers the advantage of a high melting point. It can maintain reasonable strength at temperature of 2,000°C or above and it is immune to thermal shock. Such high temperature materials find applications in tubes, valves and thrusters of solid fluid propeller systems. Production of these components is however both expensive and difficult, as rhenium cannot be worked at room temperature. PIM overcomes these difficulties and enables the production at lower cost of small and complex shapes. Recent examples of components for solid propellant divert and attitude control system have been demonstrated. The cost saving associated with the development of a rhenium PIM manufacturing process is between 25 to 80%. In addition, the PIM process significantly reduce the lead-time when compare to the old processing route [11].

PIM offers increased manufacturing freedom for new materials formulation by using elemental powder blends or specific additives to pre-alloyed powder in order to obtain new alloys formulations, composite materials, and materials which are difficult to shape with other manufacturing technologies. Some of the latest developments target these specific challenges and demonstrate the flexibility of PIM over other manufacturing routes.

4.0 DEVELOPMENT AT NRC-IMI AND MAETTA SCIENCES

NRC is composed of over 20 institutes and national programs, spanning a wide variety of disciplines and offering a broad array of services. NRC is present in every province in Canada and plays a major role in stimulating community-based innovation. NRC institutes and programs are organized into five (5) key areas: Life Sciences, Physical Sciences, Engineering, Technology and Industry Support, Corporate Services.

NRC-IMI offers the most important R&D platform on powder metallurgy and particulate materials in Canada. With expertise in the formulation of polymers, polymer composites and powders, NRC-IMI has the knowledge required to design formulations specific to PIM. In addition, the available equipment at NRC-IMI allows the production and the control of the rheology and homogeneity of the formulations produced in both low and industrial volumes. NRC-IMI has been involved for the last 10 years in various aspects of the process. The early developments were related to the formulation of a partially water-soluble binder system containing a low molecular weight polyethylene glycol. The binder system was loaded with 45% by volume of submicrometer stabilized zirconia powder. The water-soluble constituent was removed by dissolution in hot water and the remaining backbone polymer, an oxidized high density polyethylene, was removed using a thermal treatment up to 500°C [12].

More recently to support powder injection molding activities, NRC-IMI has also developed parallel finite element computation modeling software to simulate the process in 3D and so predict the behaviour of the formulation during the mold filling, compacting and cooling phases. The simulation for a metal injection molding compound, which is strongly influenced by thermal effects, predicted several observed flow patterns: initial annular free surface flow (or jetting), bypass and folding flow to form surface defects and the transition from uniform (axisymmetric) flow to nonuniform (nonaxisymmetric flow) with increasing fill time and lower temperature [13]. Joint activities with Honeywell International led to some mold filling optimization work which is illustrated in Figures 5 and 6. The flow patterns for 17-4PH PIM feedstock were observed using short shots and simulated for mold filling through a diaphragm gate over a range of filling time and melt-mold interface temperatures. Simulation predicted the observed free annular jet and the internal voids in the molded part and also predicted a thicker gate would eliminate jetting and reduce voids and surface defects [14]. Based on 34 experimental observations and 64 simulations, a boundary was established between regions of stable and unstable flow in term of dimensionless Graetz number (Gz, ratio of heat conduction time to fill time) and B, a dimensionless ratio indicating the sensitivity of viscosity to the temperature difference in the mold.

The injection presses available at NRC-IMI cover a wide range of parts volumes and an extensive range of injection pressures (0.5 to 250 MPa). New functionalities may also be obtained using two-component molding. For instance, it is possible to mix magnetic and non-magnetic materials or dense and porous materials during molding and so minimize machining and assembly steps. Very high precision miniature components with volumes of less than 1 cm^3 may be obtained by powder injection micromolding at a high production rate for applications in micromechanics and microfluidics. NRC-IMI's expertise in molding and modeling helps with the optimization of the cavities shape and molding conditions before the mold is made, among other advantages.

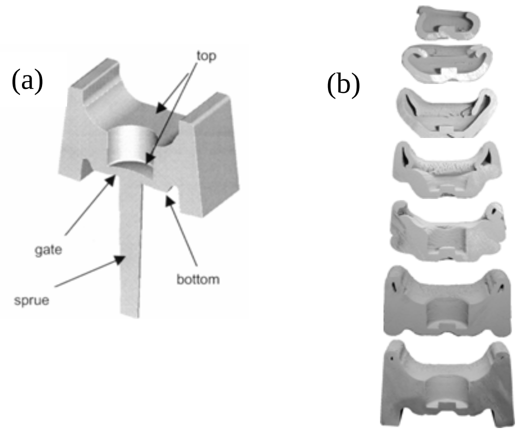


Figure 5 : Cross section of the part including the sprue and the diaphragm gate (a) and cross sections of short shots for uniform flow at mold/melt temperature of 36/82°C and nominal fill time of 2 sec (b).

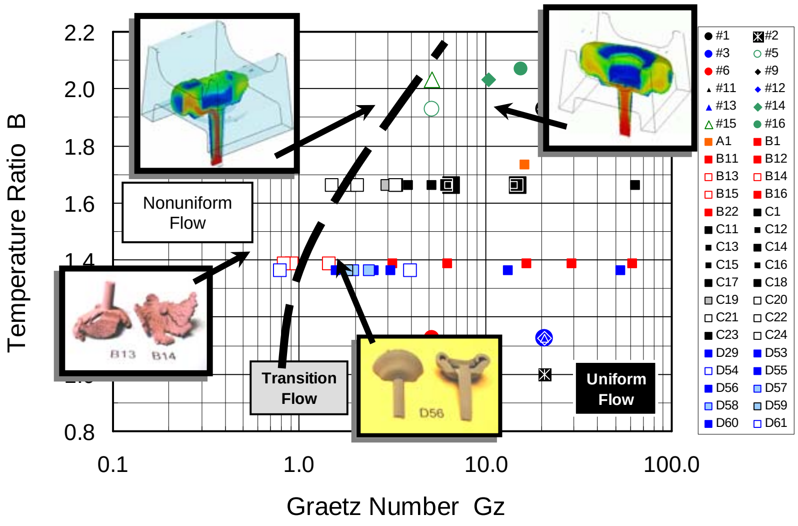


Figure 6 : Flow stability diagram of B vs. Gz based on experimental measurement and simulation.

The development of binders that degrade without any residue and of adapted sintering procedures for reactive metals is at the very heart of NRC-IMI activities. Some of the most recent activities at NRC-IMI targets to PIM processing of titanium and Ti6Al4V alloy to match the most stringent specifications for biomedical and aerospace applications. In this context, the control of the interstitial elements (C, O, N and H) content is important and, therefore, the selection of a suitable debinding method (solvent, catalytic and thermal), the binder system constituents and the starting titanium powder are critical. The global objective of this initiative is to define a PIM processing route to maintain the oxygen content below 0.13wt. % and carbon below 0.08 wt. %. Table 3 shows the actual stage of the optimization process using a commercial binder system and a Ti6Al4V powder containing 0.105wt.% of oxygen and 0.014wt.% of carbon (see Figure 7).

Table 3: Interstitial contents of a PIM Ti6Al4V component

	O wt.%	C wt.%
Final contents	**0.246**	**0.066**
Increase related to PIM	**0.141**	**0.052**

(a) (b) (c)

Figure 7 : Ti6Al4V PIM component (a) initial powder, (b) shrinkage of the feedstock with 60% in volume of solid loading and (c) the microstructure of the as-sintered component.

The vast range of expertise available to NRC-IMI combined with a full complement of powder injection molding and micromolding production tools makes this facility a unique platform in Canada. It allows NRC-IMI researchers and their R&D partners to produce components in small and medium lots, and therefore to rapidly validate their concepts, the fabrication technology and potential markets. Access to the equipment and expertise available at NRC-IMI makes it possible to:

- Design, produce and form metals and alloys, ceramic materials and composite materials that cannot be obtained by machining;
- Develop high function integration components through the development of two-component injection and composite materials;
- Reduce medium and large volume manufacturing costs for complex metallic and ceramic parts.

In parallel to these R&D activities, Maetta Sciences, a company that has research and development facilities at NRC-IMI, is developing a new scalable manufacturing process based on PIM. The Maetta system offers efficient prototyping and low production costs with regards to small production volumes. The main goal is to introduce PIM technology in the early stages of a product's lifecycle. On a regular basis, several manufacturing processes are used at the various phases of a product's life in order to comply with the cost and production volume requirements (see Figure 8). This approach has some limitations with various aspects of the design, product certification and procurement of the raw material which results in extra costs. These limitations can be alleviated with a scalable process based solely on PIM such as the one proposed by Maetta (see Figure 9).

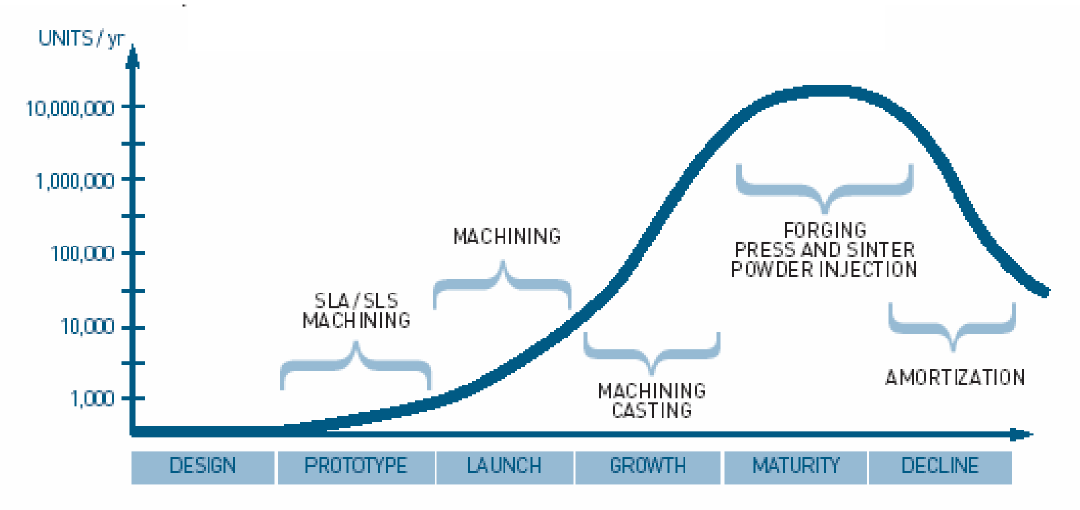
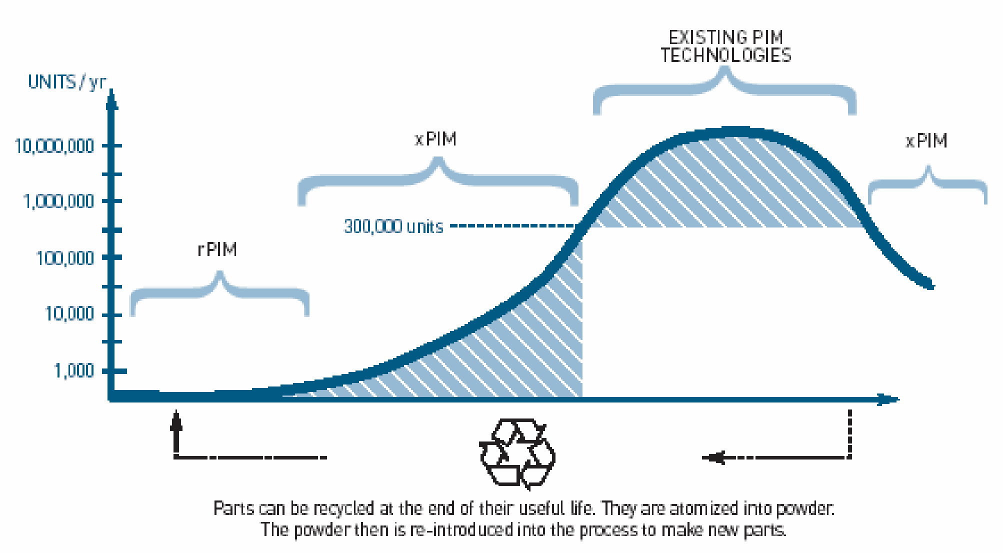


Figure 8 : The current parts manufacturing sequence for the lifecycle of any product (SLA : Stereolithography and SLS : Selective Laser Sintering).

The PIM system developed by Maetta offers the ability of prototyping by using lower pressure molding with lower cost mold system. This prototyping solution, also called rPIM in figure 9, has an annual capacity of 5,000 parts and typical batch size of 1 to 100 parts. It offers the flexibility required for the design and prototyping stages. After the prototyping stage, the launch and growth phases can be achieved using a scalable process for mass production where automation, hard molds, larger production batches offer annual capacity between 5,000 and 300,000 units (see xPIM in Figure 9). Beyond 300,000 units per year, in the maturity stage of the product's lifecycle, conventional PIM process, as described in previous pages, would be selected for it cost effectiveness at larger production volumes. This integrated process, which reduces both cost and time to market, relies on one basic process – PIM. The selection of the raw material, the development of the processing route (mixing, molding, debinding and sintering) can be transported over the whole product's lifecycle with the related benefits.



Parts can be recycled at the end of their useful life. They are atomized into powder.
The powder then is re-introduced into the process to make new parts.

Figure 9 : Maetta scalable manufacturing process based on PIM.

5.0 CONCLUSIONS

PIM is a young and viable technology with many opportunities in both traditional and emerging industries. It is still in the rapid growth phase of its lifecycle not ready yet for maturation.

PIM gives access to intricate, net shape components with a high level of functional integration from conventional ceramic and metallic materials but also from material that could not be shaped with conventional processes. Several applications were commercially successful especially in the electronic packaging/telecom/consumer goods segment. Foreseen innovations are in the field of titanium based materials, low-thermal expansion coefficient and thermal management materials, composites and functional material (magnetic, electrical ceramics). The targets for future development will be in improved tolerances, wider range of materials and reduced production cost.

The introduction of PIM in all the steps of the product development lifecycle, from design to the mature high volume production, will contribute to the reduction of the cost and time to market.

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MEETING DISCUSSION – PAPER NO: 7

Author: E. Baril

Discusser: W. Voice

Question: Ti-6-4 oxygen content: How much is derived from the sintering in vacuum process?

Response: Based on the comparative study between as debound and as sintered, the contribution in oxygen is lower than 0.01%. However, this sintering needs to be done on non-oxide setters such as BN. We compared sintering under high vacuum and purified argon and obtained same oxygen contents.