Production-Cost-Sensitivity Analysis for Metal Powder Injection Molding

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Abstract

An economic simulation is used to analyze the powder injection molding (PIM) process. The five layer analysis has been verified and provides a consistent means to determine the key drives on component cost, including consideration of tooling, material (powder), component features, economic batch size, and production steps. The model is accurate within 10%. Benchmark parts are used to assess the sensitivity to several factors ranging from complexity, size, tolerances, shape, feature combinations, materials, batch size, and various debinding and sintering technologies. Components from stainless steel at 1, 10 and 100 g mass are used to illustrate the interplay between the adjustable parameters with respect to production cost. The simulation helps the designer understand the sensitivity to various features and to anticipate design options to minimize PIM production costs. Each design differs, but these calculations some typical PIM components. Two approaches are used to show relative contributions to price via pie charts and to show price sensitivities. Analysis of price sensitivity derives from differentiation of the fabrication cost with respect to design criteria - material, mass, complexity, tolerances, and such. The sensitivity analysis ranks case-specific factors such as process yield, labor cost, and furnace loading. For a typical PIM case (8 g stainless steel component with maximum dimension of 25 mm produced at 1 million parts per year via thermal debinding and batch sintering), this analysis shows the lowest cost comes from self-mixing, coring to reduce mass, improved process yields, water atomized powder, and high furnace loading. Attention to these areas results in a 45% savings. Other examples are included in the analysis.

Introduction

Two questions are dominant when designers interact with the PIM production community:

1) Can you make this part?
2) What is the price?

Much previous literature has been devoted to the process, properties, design rules, and other factors relating to the first question [1-3]. The second question is more elusive, and not typically backed with data. Indeed, designers indicate the PIM community is very inconsistent in its pricing. Some reports give an eightfold difference in quoted price between vendors. Even in high profile PIM projects, where multiple vendors are involved, the price varies by at least a factor of two. Several contributing factors to price variation were introduced earlier.

Earlier contributions in this series treated powder injection molding (PIM) cost issues in a sequence that started with the overall model [4], tool costs [5], feedstock costs [6], batch size effects [7], and unit operation costs [8]. This increment examines the price sensitivity price in two steps. First, the model is used to generate pie charts showing relative contributions to overall price, thereby identifying key areas for attention. Second, sensitivity analysis is applied to guide the design and process improvements toward significantly lower prices.

Cost Contributors

PIM costs and prices are variable between sites. Accuracy in the costing calculations comes by subdividing the analysis into many small steps, with cross-industry benchmarks at each step. Other approaches have taken simple routes to estimation of cost using mass or thickness [9]. For this analysis, detailed information is required to generate accurate costs for tooling, feedstock, production steps, finishing steps, including the batch size effect.

These price calculations capture the unit operation costs and distributes those costs over the batch and include profit and other general expenses to calculate a price for each component. The PIM facility is assumed to be busy, thus direct costs are assigned based on the pro rated time for mixing, molding, debinding, and sintering for each component. Accordingly, cost is the product of dwell time in each stage multiplied by the operational costing rate of that stage. For example, if a component is molded in 18 s and the molding step costs $20 per h, then the cost for molding is $0.10 each (18/3600 times 20). Knowing the cost coefficients for each operation and part allows accurate costing by determining the dwell time in each manufacturing step.

For example, several variants exist in PIM production equipment. Low pressure molders tend to have lower capital costs, but are slower in cooling cycles when compared to high pressure molders. Some materials have high heat capacities or low thermal conductivities, so heating and cooling cycles vary between materials. With respect to the component design, thick sections cool slower in the mold and heat slower in the furnace and cost more to produce. If a process is well understood, then time estimates are possible for each production step, allowing calculation of the total production cost based on material, process details, and equipment characteristics.

In this manner, cost is derived from a series of intertwined linear equations. When compiled the cost is marked up to determine the price. The designer probably cares little for the details, but is very concerned with the price.

The first task is to derive equations showing the cost. Price is calculated from the cost by adding additional factors such as risk, taxes, insurance, and profits. Pie charts generated at this point show where cost reduction efforts might be most fruitful. Further, sensitivity analysis is possible based on a first derivative of those equations.

Price analysis provides a quantitative means to evaluate possible design or process changes. This is illustrated by the molding cycle. The time to form a component is often dominated by the cooling time, which depends on the section thickness. To lower cost it is possible to reduce the maximum section thickness without compromising function, say by 10%. The cycle time in molding is calculated as follows:

$$t_C = t_M + t_E + t_W W^2 \qquad (1)$$

t_C is the molding cycle time (units of seconds)
t_M is the empty molding machine cycle time (units of seconds)
t_E is the extra time associated with various tool options (units of seconds)
t_W is the cooling time factor, which depends on mold temperature, feedstock temperature, and feedstock thermal conductivity (units of s/cm^2)
W is the wall thickness (units of cm).

For typical feedstock, the parameter t_M is 7 s and t_T is 30 s/cm^2, for a simple mold the extra time parameter t_E is 3 s. Of the 18 s cycle time, 10 s is independent of the section thickness, but the remaining 8 s would benefit from a thinner wall. The 8 s cooling time corresponds to a wall of 5 mm. A 10% reduction to 4.5 mm reduces the molding cycle time from 18 s to 16 s. At a cost of $20 per h, this reduces the molding cost per part by more than 10%. Unfortunately, molding often is one of the lower cost steps, so this design change cuts the molding cost by 10%, yet may have no meaningful impact on the final price. It is an example of solving the wrong problem.

Figure 1. A cellular telephone and two PIM parts.

Figure 1 shows a popular 2.2 g cellular telephone component from stainless steel as an illustration. When production is more than one million per year, the calculated price is $0.27 each using water atomized powder and batch sintering. Figure 2 is a pie chart showing the price contributions; price is dominated by finishing, profit, and overhead. Curiously none of these are core PIM costs. With respect to PIM, sintering and feedstock costs are the most important factors. A redesign to reduce the wall thickness from 2.1 mm to 1.8 mm with the same mass lowers the price per part by 3%. However, if the wall thickness and mass are decreased by 10%, then the price drops by 8%. Continuous sintering gives a larger savings, and if continuous thermal debinding and sintering are combined, a total 15% price reduction occurs. Hence, nearly 23% price reduction is possible via section thickness and process changes. Finally, if the profit is cut in half, then the price drops to less than $0.18 each, yet is still profitable.

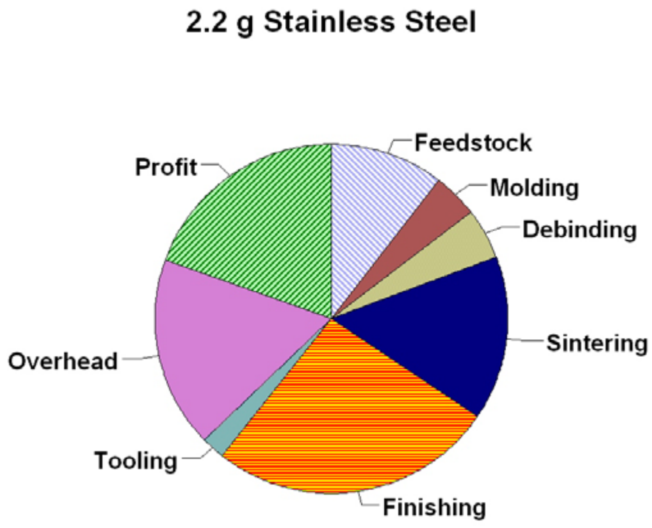

Figure 2. Contributions to the price of the cellular telephone component shown in Figure 1.

This case illustrates that some costs are not important. To attend to the important factors shows that a PIM calculation is needed to first identify the controlling parameters. The first step is to apply the model, determine the sensitivities over the range of practical options, followed by implementation of strategies to meet the design objectives, yet lower price.

Sensitivity Factor

A related tool comes from sensitivity analysis. Each of the cost contributors has a different amplification factor. Small changes to dominant factors provide large gains. For example sintering might have ten times the impact on final cost when compared to molding. Thus, changes in section size to increase molding productivity might be less important when compared to efforts to reduce sintering time. The sensitivity factor F provides a rationalization of various influences,

$$F = (X/C)\ (\Delta C/\Delta X) \qquad (2)$$

where X is an operating parameter such as labor cost, and C is the component price, so this is the normalized change in price ($\Delta C/C$) divided by a normalized change in one of the operating parameters ($\Delta X/X$). This approximates the partial derivative in the price versus parameter space of the cost model. Since many factors are involved, and each component is different, the sensitivity factors change with each component, operation, material, and design.

Table 1. Typical PIM Parameters Used for Cost Calculations

part = 8 g, 316L stainless steel, 7.9 g/cm^3, 1 million per year, 25 mm long, 60 features
tolerance = ±0.1 mm
tool base cost = $1,000
number of side pulls = 1
projected area of part = 500 mm^2
number of surface bumps and depressions = 10
surface finish on tooling = 0.2 µm
lettering on tooling = yes
tool maker hourly rate = $50/h
number of cavities = 4
material = 316L stainless steel
powder = -20 µm water atomized
powder cost = $13.06/kg
binder cost = $4/kg
facility rental rate = $60/m^2 per year
production floor area = 75% of factory
factory labor rate = $8.50/h
benefit rate = 15%
setup engineering cost = $16,000
depreciation schedule = 10 years
maintenance provision = 5%
mixing facility cost new = $195,000
mixing rate = 50 kg/h
molding facility cost new = $90,000
molding cycle time = 30 s
debinding facility cost new = $90,000
debinding furnace volume = 0.25 m^3
debinding furnace loading factor = 10%
debinding cycle time = 18 h
sintering facility cost new =$590,000
sintering furnace volume = 0.42m^3
sintering furnace loading factor = 10%
sintering cycle time = 24 h
electric rate = $0.10/kW-h
cooling water rate = $2.00/h
gas rate = $0.60/m^3
process yield = 95%
operational hours per year = 6000 h
overhead rate = 15%
profit rate = 10%

Typical Component Analysis

Typical PIM components cluster in a design window defined by the following parameters [1,10]:

mass - 80% range between 0.3 g and 60 g
projected area - 80% range between 200 mm^2 and 2500 mm^2
thickness - 80% range between 1 mm and 14 mm
maximum dimension - 80% range between 8 and 80 mm
complexity - 80% range between 20 and 160 features
material - majority contain iron.

The median component has 60 features, 500 mm^2 projected area, 4 mm thickness, a maximum length of 25 mm, and mass of 8 g. All of these do not exist at the same time, yet these statistics help define where PIM is successful. For this analysis, we will use a 316L stainless steel component for the analysis. Figure 3 is a pie chart of price contributions for this component using 4-cavity tooling at one million parts per year. The calculations assume 15% general overhead, 10% profit, and 95% process yield for a factory that is typical in PIM as detained in Table 1

Figure 3. Pie chart showing relative contributions to the production of a typical 8 g, 316L stainless steel PIM component.

The sensitivity analysis considered several factors to determine the price changes with each. The sensitivities are ranked in Figure 4. Other factors considered, but not listed had smaller impact in this case. The decision on purchased feedstock versus self-mixing is the most significant parameter. Efforts to lower the mass, improve process yield, use lower cost raw materials, and improve sintering all promise to improve efficiency.

As demonstrated in Table 2, a few factors have significant impact on the final price, shown here are the benefits from self-mixing, reducing mass 10%, improving process yield to 98%, shifting to water atomized powder, improving furnace loading, and shortening sintering time. The price drops to almost half that initially calculated. These changes are realistic, since coring or section thickness changes can be used to reduce the mass, process yields of 98% are realized in on larger orders, water atomized stainless steel powders are widely used in PIM, changes in the setters and packing of parts can improve furnace loading, and thin substrates, heat exchangers and convective cooling can reduce the sintering cycle time. Curiously, labor rates, capital equipment cost, and facility rental rates were less important factors.

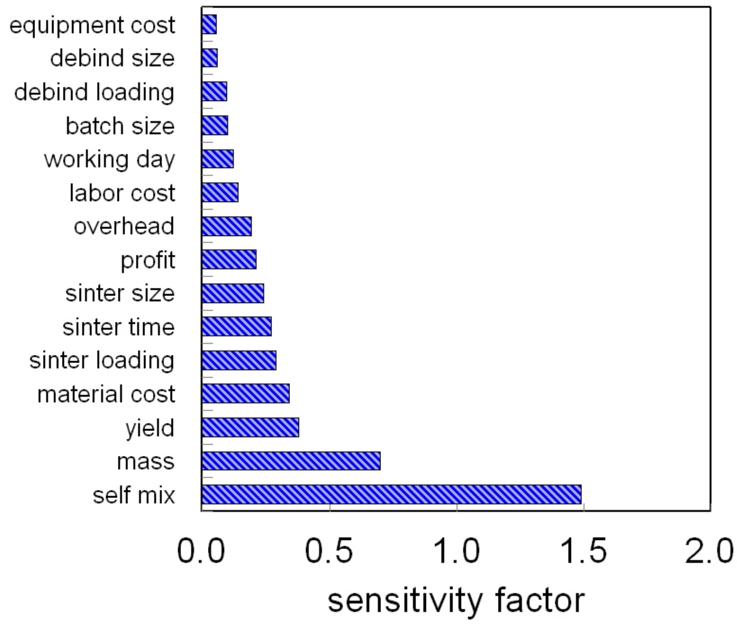

Figure 4. Price sensitivity factors for a typical PIM component, showing the relative impact of various process or design features with respect to the price.

Table 2. Price Reduction for a Typical PIM Component Via Sensitivity Analysis

parameter	**initial setting**	**improved setting**
feedstock	purchased	self-mixed
part mass, g	8	7.2
process yield, %	95	98
powder type	gas atomized	water atomized
furnace loading, %	10	25
sintering cycle time, h	24	18
unit cost, $	0.66	0.36

Component Mass Effects

The above detailed example was for the median 8 g stainless steel component. At the other extremes, 10% of the components are 0.3 g or less and 90% are 60 g or less. Table 3 compares the upper and lower component attributes in comparison with the typical (8 g) component. The larger part would be characteristic of a turbine impeller, pump housing, or solenoid housing, while the smaller part would be characteristic of a fiber optic connector, orthodontic bracket, or surgical biopsy tool [1].

These two cases benchmark the range of PIM products. Figure 5 plots the price contributions from several factors for the three component sizes. The 8 g component was most sensitive to feedstock (mass), yield, and sintering cost reductions. For the larger 60 g component, the comparative plot shows that feedstock cost is even more important, followed by sintering. On the other hand, for the small 0.3 g component, the price is dominated by finishing and tooling costs. From the sensitivity analysis, cost reduction efforts are most fruitful if applied to the major cost contributors.

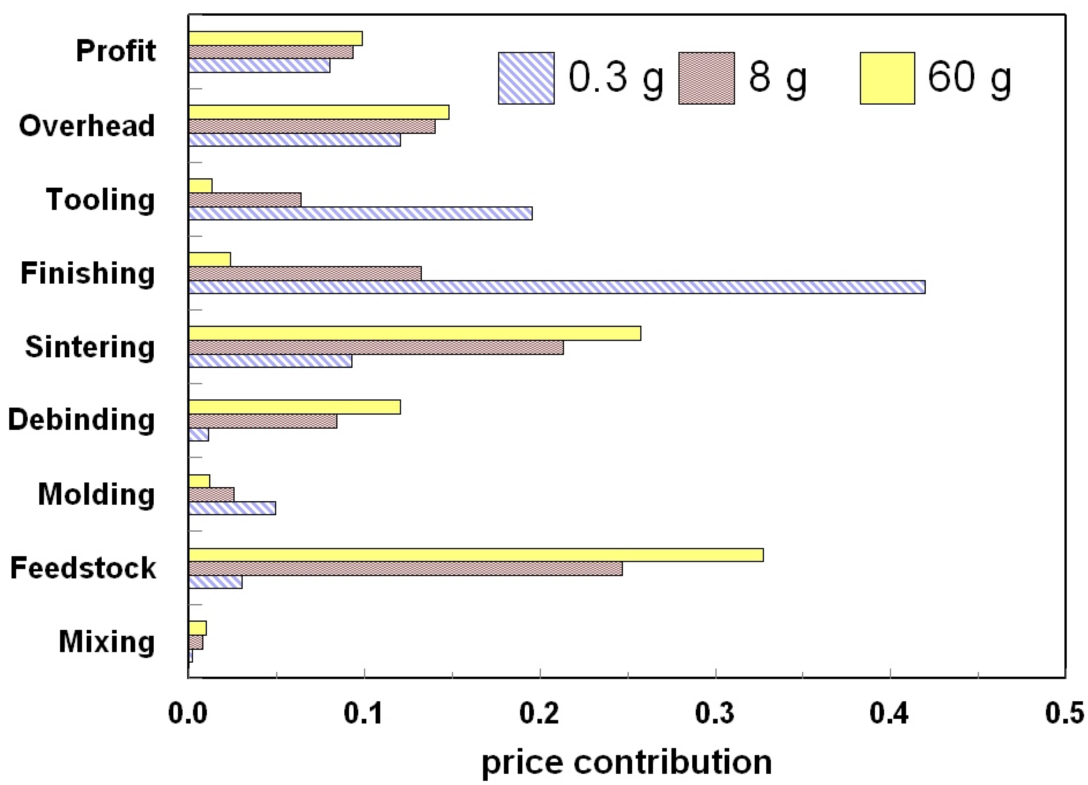

Figure 5. A comparison of price contributions for small, typical, and large PIM components; the small component is most sensitive to tooling and finishing costs, while the large component is most sensitive to feedstock and sintering costs.

Table 3. Parameter Space for PIM Components

cumulative population, %	10	50	90
mass, g	0.3	8	60
number of features	20	60	160
projected area, mm^2	200	500	2,500
thickness, mm	1	4	14
maximum dimension, mm	4	25	80

Golf Clubs

The PIM technology has repeatedly been applied to the fabrication of golf clubs. In this series, previous efforts examined the economic feasibility of producing a sand wedge. The component was introduced in the tooling calculation [5], included in the feedstock analysis [6], and treated in the component cost paper [8]. A single cavity tool was estimated at $25,000. Production was set at 100,000 club heads over a year. The estimated price using self-mixed water atomized 17-4 PH stainless steel feedstock was $9.96 each, assuming the customer purchased the tooling. When titanium was considered, the mass decreased, but the price increased to $17.91 each using hydride-dehydride titanium powder, and increased to $53.23 each using spherical atomized titanium powder.

If we examine the price factors for the stainless steel version, then several small changes are identified to lower the price. For example, custom fixtures would increase furnace loading in debinding and sintering to 20%, while convective gas cooling would reduce sintering time to 18 h. Other realistic changes, such as improving process yield to 98%, would bring the price to an asymptotic level near $6.12 each. This approaches the price currently paid for investment cast golf club heads, so a viable project emerges, but with great effort. For titanium there is little hope for PIM to compete against investment casting, even with low-cost powder.

Summary Comments

There are two questions when the design community interfaces with the PIM parts production community - can you make it and what is the price? Many books, brochures, technical papers, and presentations have answered the first question. Presented here is a definition of pricing rationalized to the PIM design window.

Once a cost model is created, then it is possible to determine what factors are dominant. Pie charts are given for small, typical, and large components. Further, the discussion on golf club production helps capture the reality of PIM for some target applications. Sensitivity analysis provides data on where attention will have the greatest payout. It is demonstrated that a few changes can reduce component price by 30 to 50%. In general, the most fruitful changes are to perform self-mixing (except for very small operations), use coring and other design changes to reduce mass, maximize process yield, rely on lower cost powders, and to push sintering technologies for shorter times and higher loading. For smaller components, price is dominated by tooling and finishing costs, while for larger components the price is most sensitive to feedstock and sintering factors.

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References

1. R. M. German, *Powder Injection Molding Design and Applications*, Innovative Material Solutions, State College, PA, 2003.
2. R. M. German and A. Bose, *Injection Molding of Metals and Ceramics*, Metal Powder Industries Federation, Princeton, NJ, 1997.
3. B. C. Mutsuddy and R. G. Ford, *Ceramic Injection Molding*, Chapman and Hall, London, UK, 1995.
4. R. M. German, "An Economic Model for PIM Component Production," *Proceedings PIM 2003*, (International Powder Injection Molding Symposium, State College, PA), Innovative Material Solutions, State College, PA, 2003.
5. R. M. German, "Engineering Economics of Powder Injection Molding Component Production: Part 1, Tool Costing," *P/M Science and Technology Briefs*, 2003, vol. 5, no. 2, pp. 5-11.
6. R. M. German, "Engineering Economics of Powder Injection Molding Component Production: Part 2, Feedstock Costs," *P/M Science and Technology Briefs*, 2003, vol. 5, no. 3, pp. 11-16.
7. R. M. German, "The Impact of Economic Batch Size on the Cost of Powder Injection Molded (PIM) Products (Part 3 [sic])," *Advances in Powder Metallurgy and Particulate Materials - 2003*, Metal Powder Industries Federation, Princeton, NJ, 2003, part 8, pp. 146-159.
8. R. M. German, "Engineering Economics of Powder Injection Molding Component Production: Part 4, Component Costs," *P/M Science and Technology Briefs*, 2004, vol. 6, in press.
9. T. Pelletiers, unpublished data, Latitude Manufacturing Technologies, Haskettstown, NJ, 2003.
10. B. Smarslok, unpublished data, Center for Innovative Sintered Products, Pennsylvania State University, University Park, PA, 2003.