The Impact of Economic Batch Size on the Cost of Powder Injection Molded (PIM) Products

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ABSTRACT

A new costing simulation has been created for the powder injection molding (PIM) process. The five-layer analysis consists of definition of the tooling, selection of the material, consideration of the part, collection of data on the economic climate (depreciation, interest), and finally determination of the production process. This model has proven accurate (within 10%) for the prediction of tool and part costs in many applications. As a consequence, the simulation provides some simple guides to help designers understand PIM production costs. For example, the model allows for self-mixed versus purchased feedstock, automation versus manual parts handling, optimization of the number of tool cavities, and even choice of equipment type (batch versus continuous furnace) to help isolate lowest costs. An optimization is provided for the number of tool cavities versus the economic batch size, showing a single-cavity tool is often the best solution up to 100,000 parts. It becomes evident that costs are highly variable between production sites. Further, depending on the economic batch size, the lowest cost will shift between different types of operations and even net-shape forming technologies. For several components, PIM unit costs level out only when the production quantity reaches about 300,000 per year. For components below about 10 g in mass, powder cost is less of a concern. However, as the component mass increases, the cost of small PIM powder becomes a problem. Indeed, the barrier to large component production by PIM is economic, not technical. This study shows PIM is most attractive for lower-mass components or materials that are hard to machine.

INTRODUCTION

This paper is the third in a sequence analyzing the cost factors involved in powder injection
molding (sometimes termed metal powder injection molding or MIM). Earlier installments have covered the cost of tooling [1] and the cost of raw materials [2]. Here the focus is on the batch size, namely the number of parts being produced as it affects piece cost and price. These two words are defined as follows:

- manufacturing cost is the cumulative expense incurred in the production of a product; it includes the direct purchases of raw materials, the expenditures for energy and labor, and pro rated items such as maintenance, depreciation, insurance, and taxes.

- sale price reflects the value of the component to the user; it is the amount of money exchanged for the fabricated component and normally includes the manufacturing cost and allocations for a return on investment and risk.

Ideally, cost and price should be related, but early in a technology that is not the case. During the 1980s, PIM products were selling at a price that sometimes was just 25% of the manufacturing cost, and bankruptcy was common. Today, the cost is below the price and PIM is profitable.

**COMPONENT COSTING**

Engineering analysis for production costs is a widely discussed topic and the subject of much analysis. The framework for conducting a cost analysis for net-shape production is generally accepted, but the constituent costs are richly debated [3-10]. Figure 1 illustrates a generic unit process and the elements involved in determining the cost of each step in a manufacturing scheme. For PIM the unit processes are feedstock preparation (or purchase), molding, debinding, sintering (note the debind and sinter steps are combined in some operations), and secondary operations (including inspection and packaging). Cost analysis for PIM is a newer activity, but early reports show PIM component fabrication costs differ between sites due to differences in productivity, capacity, equipment, technology, and raw materials consumption [11-22].

Unfortunately, many PIM operations do not have accurate means to analyze cost, so they rely on estimation procedures similar to plastic injection molding (such as two or three times raw material cost) [23]. However, for accurate PIM costing calculations, considerable information is required, including details that are elusive without experience. The standard unit manufacturing cost program [24] includes factors such as rework rates, cycle times, loading factors, capacities, vacation policies, benefit packages, tool maintenance costs, and depreciation schedules.

Figure 1 - A generic unit operation and the flow of mass through the operation with the accumulation of expenses from a variety of contributing factors.
Accordingly, if price variability is common in business transactions, then it should be no surprise that PIM component production cost estimates are variable. A recent PIM medical device quotation for 20,000 parts per year gave the results summarized in Table 1. The ratio between the highest and lowest price is more than a factor of 4. Did the low bidder make a mistake? Is the high bidder too busy? These are possible factors that contribute to the price variability. Further, differences in staffing, labor, and regional costs, such as electricity, impact the final price.

**Table 1. Comparison of Bids for PIM Production of a Medical Device**

<table>
<thead>
<tr>
<th>metric</th>
<th>per part</th>
<th>tooling</th>
<th>total project</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>$2.95</td>
<td>$16,392</td>
<td>$75,368</td>
</tr>
<tr>
<td>median</td>
<td>$2.04</td>
<td>$17,027</td>
<td>$56,743</td>
</tr>
<tr>
<td>deviation</td>
<td>$2.02</td>
<td>$7,408</td>
<td>$45,821</td>
</tr>
<tr>
<td>lowest bid</td>
<td>$1.55</td>
<td>$7,600</td>
<td>$42,600</td>
</tr>
<tr>
<td>highest bid</td>
<td>$8.00</td>
<td>$31,000</td>
<td>$191,000</td>
</tr>
<tr>
<td>high/low ratio</td>
<td>5.2</td>
<td>4.1</td>
<td>4.5</td>
</tr>
</tbody>
</table>

This PIM engineering economic analysis is based on a direct allocation of charges against a project, assuming there is an abundance of projects, so only that proportion of the facility used for any given production run is assigned to the cost calculation. (Idle shops are more expensive and shops running at capacity encounter high overtime or outsourcing expenses.) Ideally, PIM should be like a hotel: the charges in a hotel depend on the number of nights you stay, not on the hotel’s occupancy rate. However, like airlines, even hotels are repricing as demand increases to maximize profits. So far the opposite philosophy seems to be at work in PIM. If the PIM shop is not very busy, then it allocates the cost for idle time (for example equipment depreciation and rent) to fewer active jobs, leading to increasing prices as business declines. One attribute of this approach is that shops that are busier than planned produce higher profits.

To analyze the economic batch size impact on costs and prices requires first a sound PIM economic model, which has not been created [25]. This costing calculation is composed of stages. The first is associated with the material from which the component will be fabricated. The second stage is associated with the operating environment. The third stage is associated with unit operations and the determination of cost allocation per piece at each step. Finally, risk and production balancing are discussed. These are treated in sequence, assuming parallel tool cost calculations, as covered earlier.

**Optimization of Multiple-Cavity Tooling**

Tool cost increases with the complexity of the component and the number of cavities. One advantage of multiple-cavity tooling is the shortened molding time with concomitant cost savings. However, tool construction costs increase with the number of cavities [26] and for PIM that costing increase is proportionate to the number of cavities raised to approximately an
exponent of 3/4. So on one hand tool costs increase with the number of cavities, but molding costs decrease. It is possible to optimize the economic benefit to the customer based on the tradeoff. Letting $N_C$ represent the number of cavities, it is possible to consider the tradeoff between more cavities (with an increase in machining cost) and the reduced molding time. The calculation of the molding rate per hour $M_R$ is covered later, but assume such a value is known (say in the $30/h$ range). Then the benefit from shorter molding time with multiple cavities is calculated with respect to the cost of machining the multiple cavities, giving

$$C_M = C_S N_C^K + (N_P / N_C)(M_H / M_R)$$

1

$C_M$ is the total cost of molding (units of $\$$)
$C_S$ is the cost of a single tool cavity (units of $\$$)
$K$ is the tool cost scaling factor (dimensionless)
$N_C$ is the number of tool cavities (integer)
$N_P$ is the production number or number of parts in a production batch per year (integer)
$M_H$ is the molding machine cost per hour (units of $\$/h$)
$M_R$ is the average molding rate given as the cycles per hour (units of 1/h).

A minimum molding cost occurs when the first derivative of total molding cost $C_M$ with respect to the number of cavities $N_C$ equals zero. With a little calculus and rearrangement of terms, this gives the optimal number of mold cavities $N_{Co}$ as follows:

$$N_{Co} = [N_P M_H / (M_H K C_S)]^{1/(1-K)}$$

2

Normally, Equation 2 is rounded down to an even number, so beyond 1 cavity, the normal progression is 2, 4, and on up to 32 cavities. Two barriers show up in this optimization. The first is from the molding machine - either the clamp force or the shot size might not be able to handle the optimized number of cavities. For example, the peak molding pressure times the projected area of each part times the number of cavities must be below the machine clamping force. The second barrier is associated with the space required for mold actions, with fewer cavities being possible as the number of unscrewing, lifting, or side pulls increases per cavity. Two cavities might be possible with two motions, but only one is possible with three or more motions.

**OPERATIONAL CHARACTERISTICS**

A major impact on component production cost comes from the operational context, which goes beyond the raw material cost [27-31]. Included in this are interest rates, building rental rates, employee benefits, capital equipment depreciation schedules or lease rates, and financial policies. These affect the unit operations of mixing, molding, debinding, and sintering. For example, assume the equipment depreciation time $Y_D$ is known (years). Then each production unit can be assessed an annual depreciation cost based on initial purchase price and age. In turn, as that operation is used for some portion of the year, then the active time is used to collect the depreciation. Similar strategies might be used to accumulate any number of other costs. Thus, for each unit operation there is rate $H_D$ for capital equipment depreciation computed as follows:
\[ H_D = \frac{C_E}{(t_U Y_D)} \] (3)

- \( H_D \): is the hourly rate for capital equipment (units of $/h)
- \( C_E \): is the equipment capital cost (in $)
- \( t_U \): is the hours of time the equipment is used per year.

The use time depends on the number of hours the device is operating each day, number of days per week, and weeks per year; it typically ranges from 4000 to 7000 hours per year for full-scale operations. Such a factor includes everything from lunch breaks to holidays, vacations, and weekends. Note a sensitivity to the utilization rate, implying that a device that is used only part time has a higher use rate, to the point where if it is used only once a year there is a singular, yet high, cost.

The cost for rental of the facility is likewise pro rated over the equipment by first determining the calculated cost per unit time per unit area for the space,

\[ C_R = \frac{R_F A}{t_U} \] (4)

- \( C_R \): is the rental cost per unit area per unit time (units of $/(\text{h} \cdot \text{m}^2))
- \( R_F \): is the facility rental rate per year (units of $/\text{m}^2)
- \( A \): is the approximate area required for each device (units of \text{m}^2)
- \( t_U \): is the use time (units of \text{h}).

Note idle space in the facility creates a burden on each unit operation, since the facility area must equal the sum of the allocation to each device. This calculation is repeated for each unit operation, and if the equipment occupies a large area the costs grow.

Next come the allocations for utilities, maintenance, and labor. These are calculated based on electricity, gas, compressed air, water, and other resource rates gathered on an hourly basis,

\[ C_U = \sum C_i \] (5)

- \( C_U \): is the total hourly burden for each operating device (units $/h)
- \( C_i \): is the individual contributions to the hourly burden, such as electricity use per hour (units $/h)

For example, if the material is abrasive, then maintenance will be high and that cost needs to be captured on a pro rated use basis. Depending on automation, the labor allocation to each unit process will differ. As automation is added, the depreciation expense on capital equipment increases about as fast as the labor expense decreases. However, since labor can be easily varied with the workload, while capital equipment depreciation must be recaptured independent of the annual use, this leads to the lower risk solution - use of manual labor in low labor rate regions. This skews PIM toward manufacturing in low labor rate regions [32] with little automation.
Table 2. Typical Powder Prices in $/kg for PIM Powders and Commercial Feedstock

<table>
<thead>
<tr>
<th>material</th>
<th>production route</th>
<th>powder price range $/kg</th>
<th>feedstock price range $/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>alumina (Al₂O₃)</td>
<td>calcined, tabular</td>
<td>1 to 40</td>
<td>12 to 33</td>
</tr>
<tr>
<td>bronze (Cu-10Sn)</td>
<td>water atomized</td>
<td>8</td>
<td>---</td>
</tr>
<tr>
<td>cemented carbide (WC-10Co)</td>
<td>attritor milled</td>
<td>16 to 50</td>
<td>88 to 110</td>
</tr>
<tr>
<td>cobalt-chromium (Co-28Cr)</td>
<td>gas atomization</td>
<td>75</td>
<td>---</td>
</tr>
<tr>
<td>iron (Fe)</td>
<td>carboxyl decomposition</td>
<td>7 to 10</td>
<td>20 to 29</td>
</tr>
<tr>
<td>iron-silicon (Fe-3Si)</td>
<td>gas atomization</td>
<td>12 to 18</td>
<td>---</td>
</tr>
<tr>
<td>Kovar (Fe-Ni-Co)</td>
<td>water atomization</td>
<td>22 to 32</td>
<td>---</td>
</tr>
<tr>
<td>nickel (Ni)</td>
<td>carboxyl decomposition</td>
<td>14</td>
<td>---</td>
</tr>
<tr>
<td>silicon nitride (Si₃N₄)</td>
<td>carbothermal reduction</td>
<td>55 to 150</td>
<td>121 to 132</td>
</tr>
<tr>
<td>stainless steel (17-4 PH)</td>
<td>water atomization</td>
<td>7 to 20</td>
<td>13 to 33</td>
</tr>
<tr>
<td>stainless steel (316L)</td>
<td>gas atomization</td>
<td>12 to 50</td>
<td>24 to 55</td>
</tr>
<tr>
<td>steel (Fe-2Ni-0.5Mo-0.4C)</td>
<td>water atomization</td>
<td>6 to 12</td>
<td>12 to 18</td>
</tr>
<tr>
<td>superalloy (Ni-base)</td>
<td>gas atomization</td>
<td>20 to 80</td>
<td>---</td>
</tr>
<tr>
<td>titanium (Ti)</td>
<td>gas atomization</td>
<td>75 to 650</td>
<td>175</td>
</tr>
<tr>
<td>tool steel (M2)</td>
<td>gas atomization</td>
<td>25 to 45</td>
<td>44</td>
</tr>
<tr>
<td>tungsten-copper (W-10Cu)</td>
<td>oxidized and reduced</td>
<td>75 to 110</td>
<td>---</td>
</tr>
<tr>
<td>zirconia (ZrO₂)</td>
<td>precipitated, milled</td>
<td>120</td>
<td>132 to 143</td>
</tr>
</tbody>
</table>

CONTRIBUTIONS TO UNIT COST

Powder or Feedstock Cost

Feedstock cost can be up to 50% of the manufacturing cost. Compositions that are popular tend to have lower powder prices. As with most manufacturing, price decreases as consumption increases. For example, 15 micrometer stainless steel powder by water atomization goes from $27/kg at 100 kg to $11/kg at 10,000 kg, and even falls under $8/kg in long-term contracts.

Table 2 provides an estimate of the powder and feedstock price ranges for some popular chemistries. Over the past 10 years, the average sale price for stainless steel powder has declined 30%. This is the largest use segment in PIM, accounting for 50% of the metallic component sales, so it provides the greatest price competition. For a stainless steel, the raw ingredients (iron,
nickel, and chromium) cost less than $2/kg, and atomization costs about $1.50/kg, so the difference reflects a combination of atomization yield, overhead, and profit.

**Molding Costs**

Molding costs depend on the cycle time and number of cavities. There is a setup cost to install tooling, but once installed the internal operating cost per hour for a molder is a standard rate - say $25 per hour, while toll molding has an average of $45 per hour. This is the result of a combination of factors - depreciation, rental, electricity, labor, overhead, and profit. It is desirable to use multiple cavities to improve productivity at the expense of machining the tooling. Molds with up to 40 cavities have been used to fabricate ceramic insulators and cemented carbide abrasive jets.

![Graph showing tooling cost and total project cost plotted versus number of tool cavities for a cell phone component produced by PIM.](image)

**Figure 2 - Tooling cost (right) and total project cost (left) plotted versus number of tool cavities for a cell phone component produced by PIM.**

Most PIM components are generated in tool sets with up to eight cavities. As the number of cavities increases, the molding cost decreases, but as illustrated in Figure 2 the tool cost increases. This plot shows the tool cost and total project cost versus the number of cavities for a stainless steel cell phone component. For this case, the lowest total cost to the customer comes with an eight-cavity mold.

As shown in Figure 3, the economic transition from single-cavity to multiple-cavity tooling is often in the range of 100,000 to 300,000 pieces per year. Four cavities usually are called for with 1 million parts per year. Most operations can produce 1 to 2 million shots per molding machine per year; hence multiple-cavity tooling allows more output. Currently 7 million parts per month are produced on a single machine with a 32-cavity mold operating 24 hours per day.

To lower the molding cost, an obvious step is to create faster cycles via improved cooling. Faster cooling allows for a shorter molding cycle or more parts per hour, so there is less molding cost per part. Because of heat transfer, the cooling time scales with the square of the section thickness; hence, thin sections are attractive. For one component with a 125 mm (5 inch) wall thickness, the cooling time was 5 minutes. This slow molding cycle accumulates a cost of $2 per part and is one reason why thick parts are not often fabricated using PIM.

**Debinding Costs**
The cost of debinding ranges from expensive options, such as vacuum debinding and immersion in chlorinated hydrocarbon solvents, to water drying, which is least costly. This is largely a result of the equipment cost and dwell time in the equipment. Thermal debinding costs depend on the atmosphere and this is the dominant process. In contrast, catalytic debinding relies on expensive equipment with high operating costs associated with the protective atmosphere and environmental (emission) controls. Capital equipment costs vary by a factor of 10 between the debinding technologies. For example, if aggressive solvents are used, then the capital expense for an environmentally approved low emission system is in excess of $450,000, but if debinding occurs with a water-soluble binder, then the cost is dramatically lower, near $20,000. Retort furnaces for thermal debinding are capable of 300 kg of parts per day, and can be purchased for $40,000 to $70,000. Catalytic debinding stations start at $25,000 for small units capable of 50 kg per day. For small PIM components, production debinding costs usually range near $2.5 per kg for a common cycle that takes about 8 hours.

**Sintering Costs**

In production PIM operations, sintering costs are in the $30 to $85 per hour range [26,33,34]. The cost per part then depends on the load in the furnace, cycle time, and other factors that hinder generalizations. Nominally, costs are typically in the $6/kg range, but can vary by a factor of five (low of near $1/kg to high of $30/kg). If pressure-assisted sintering is used, as is common in the carbide industry, then costs tend toward the $10/kg and higher range.

The furnace design depends on the intended production quantity, materials to be sintered, operating costs, type of atmosphere, and post-sintering cooling rate. Production PIM batch sintering furnaces exist for loads ranging from less than 1 kg to 300 kg. Routine continuous sintering can reach levels up to 100 kg/h. In PIM the larger batch furnaces are about 2 to 3 m in diameter and typically operate on cycles lasting from 12 to 36 hours. On the other hand, large pusher furnaces operate on entry-to-exit times ranging from 6 to 24 hours. These tend to be lower in operating cost, near $3 per kg, but are less flexible. Thus, they are used only for sintering similar components - such as watch cases. Batch furnaces result in higher sintering costs, near $6 per kg. Also, large components require slower heating and larger furnaces, thereby incurring even
higher sintering expenses. If a special cycle or special furnace is required, then the sintering cost can jump by a factor of five, especially for higher sintering temperatures. Thus, the actual sintering cost depends on many details, including the component size and shape, furnace load, peak temperature, hold time at the peak temperature, process atmosphere, heating rate, and any special fixtures for sintering.

As an example of sintering costs, a 6 g tool steel piece that must be individually staged and vacuum sintered has a sintering cost of $0.10, but an 8 g stainless steel component has a sintering cost of $0.05. Finally, a 25 g steel component is sintered in a continuous furnace in a nitrogen-based atmosphere for just $0.02.

Secondary, Inspection, and Packaging Costs

Often overlooked, but still contributors to the overall production cost calculation, are the final steps required just prior to shipping. Secondary treatments can be expensive, and in some PIM components contribute more to the cost than all of the PIM steps. Machining steps, heat treatments, electroplating (especially gold plating), and other secondary operations add considerable value, but also consume valuable resources.

Packaging is usually negotiated with the customer. It can range from a paper barrel to individually encapsulated parts ready for automated assembly. Again, this adds to the production cost. Inspection is another of the final costs. Options range from 100% proof testing to periodic checks of dimensions. Every time the component is handled, there is an accumulated cost. Hence, it is desirable to have random samples pulled to establish statistical profiles without doing 100% inspection. Since this area is ill-defined, the customer needs to discuss the cost implications on any requirements.

PER PIECE COSTING

This cost model is really an accounting schedule that has unit costs per time, with input on raw material costs and any subcontracted secondary costs (for example, heat treatment). Now the attention turns to the specific component and its production quantity and production rate. High intensity projects require multiple molders and multiple tool sets. Often, lower costs are associated with moderate production volumes (say from 300,000 to 1,500,000 per year). Once the production demands increase, then additional tool sets and molders are required, sometimes giving an increase in part price. Now attention turns to how many parts can pass through each step per hour. The unit operating cost is then allocated to each part as follows:

\[ P_C = C_T / U \]  

(6)

| U is the average number of parts produced per hour (units of 1/h) |
| P_C is the cost per piece (units of $) |
| C_T is the operating cost (depreciation, rent, labor, benefits, and so on) per unit time (units of $/h) |

These calculations are repeated for each unit operation and the values are summed to estimate the...
A price penalty is incurred when a piece creates a production balance problem. The production equipment comes in simple integers and facility sizing might rely on a formula such as one mixer, eight molder, eight debinders, and four furnaces to make up a manufacturing cell. Depending on the cycle times for each step, it is possible for production to be out of balance. If there is sufficient business, then the spare devices are shifted to other products (but can then overload downstream devices). For example, a spindly component might have very thin sections that allow fast molding, but give low part density packing in the debinding and sintering devices. Consequently, molding will be out of balance from the other operations. If the molder sits idle, then there is a cost for idle time that needs to be accounted for in the pricing, otherwise target financial performance still suffers. This is termed capacity balance cost and is calculated based on the characteristics of the part and the production facility. Some facilities are better suited for certain sizes or shapes; thus, the capacity balance cost depends on the equipment. Typically this cost is distributed over the quoted production quantity, and might amount to a few cents per part in some cases.

**BATCH SIZE EFFECTS**

Powder injection molding could fabricate a single component. However, the cost would be exceptionally high. In general, unit costs tend to stabilize when the production quantity exceeds 300,000 per year. Note this is for a single order. If this is broken into 12 orders of 25,000 per month, the piece cost is higher. The difference reflects the need to set up and run for, say, one week out of every month. For example, a tool change in a molding machine requires a few hours. This cost must be amortized over the production run. Smaller batch sizes have a larger burden per part; alternatively a larger lot size has a smaller setup burden per piece. Hence, PIM prices are sensitive to the batch size, not just the total order size.

For smaller components there is a greater sensitivity to batch size. The approximate point of stabilization is termed the economic batch size. Each shaping technology has a characteristic number where piece price approaches an asymptotic value with increasing quantity. The concept is illustrated in Figure 4 by contrasting machining, investment casting followed by machining, and PIM for a disk drive component. A plateau point is evident for each technology where periodic expenses arise to offset further gains from amortized setup costs. So the order size impacts unit cost through several aspects, including repair, maintenance, setup, design, and tool
wear. For example, a tool change in a molding machine requires a few hours. This cost (for discussion purposes let’s assume it is $400) must be amortized over the production run. If it is a single component, then that component has a large burden to carry (all $400 from tool setup). However, if the lot size is 1000 pieces at a time, then the burden on each is $0.40, while if the tool set successfully runs for 10,000 pieces, then the setup burden is just $0.04 each. With higher-volume products, PIM tools have successfully fabricated up to 2 million parts, lowering the tool setup cost per part to just $0.0002.

Other factors related to production quantity impact the unit cost. Schematic curves showing relative cost versus production volume are given in Figure 5 using a log-log scale. The relative cost is given for three stainless steel components (100 g, 20 g, and 5 g). At a volume of 1 million each, these cost $3.25, $0.55, and $0.30 each; the actual values depend on the design and process details, yet this plot shows the cost reduction that occurs with larger orders. Note the smaller component enjoys a much steeper and longer price decline, since the material cost is small, while for the larger component cost is dominated by raw materials and there is relatively less price decrease with increasing volume. As another example of the volume impact on cost, 85 g silicon nitride turbochargers cost $20 each to produce at a quantity of 250,000 per year, but the cost declines to $4 each at 3 million per year.

CONCLUSIONS

An economic model has been created for PIM component production. The model requires estimates of 130 parameters. Although this might seem complex, the outputs have proven very accurate with respect to PIM.
The success of the economic model helps create an analysis tool to enable evaluation of design alternatives with respect to costs. This effort has demonstrated how the economic batch size is a key parameter in PIM. For small production quantities, the tool and setup costs make PIM noncompetitive for most shapes and materials (exceptions are hard-to-machine ceramics and cemented carbides). As the economic batch size increases over 100,000, then PIM production in a single-cavity tool becomes attractive. The smaller the mass the better.

PIM excels at components below 10 g, but is applied to nonmetallic structures with masses up to 17 kg or more. For metallic structures, PIM thrives on complexity, low mass, and high production quantities. This analysis shows that for most PIM components, only single-cavity tooling is justified for batch sizes below 100,000, and at one million parts 2- or 4-cavity tooling is justified. The higher the component mass, the lower the number of cavities. The model includes consideration of an imbalanced operation, creating a cost for idle capacity in molding, debinding, or sintering. Smaller components (in the 5 to 20 g range) should see significant cost reductions as the economic batch size reaches one million units, but the cost of producing larger components (in the 100 g range) is essentially insensitive to the economic batch size once 100,000 units are fabricated.

ACKNOWLEDGMENTS

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