Best Practices in Powder Injection Molding

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ABSTRACT

The terms “best” and “leading” are associated with a perception of quality, often tempered by cost and performance. In the area of powder injection molding (PIM), the identification of best practices is important to strategic planning. Further, road mapping exercises are a means to establish priorities for the future. To identify best PIM firms requires that we understand the diverse frames of reference for the question that might include financial performance, sales and customer service, product quality, mechanical properties, manufacturing productivity, and so on. The leading operations are those we deem most desirable for partnerships, whether it is as a supplier, customer, investor, or employee. A survey of best practices in PIM has been initiated to profile the industry. This benchmarking provides an objective evaluation basis for any firm to establish their relative placement on the continuum of PIM activities. It also helps management identify areas where specific actions might provide immediate gains by addressing deficiencies.

INTRODUCTION

What is the best? Who is the leader? Today these are frequent questions as powder injection molding (PIM) gains widespread notice. Often confusion occurs when such questions are presented. Part of the problem comes from the several different ways to measure and rank performance.

Formally, best is associated with excelling all others, implying the highest productivity. Leaders are the ones that set the pace for the future and also rank first, especially as we move to a global economy. In many cases, the terms “best” and “leading” are associated with a perception of quality, tempered by cost and performance. As customers, we seek the best value as measured by quality per unit cost. From a financial view one looks at return on investment as a measure of performance. And as prospective employees, we might want to look at stability, growth, and opportunities for personal
development. We are attracted to the leaders because they set the metrics for success. Benchmarking efforts include a contrast and comparison with the leaders. Further, a properly executed benchmarking exercise maps the changes needed to become a leading firm. However, we must be cautious since the leaders will not be idle, so actions taken to catch or imitate the leaders must consider the simultaneous changes that will occur in the leading operations. It is appropriate to overestimate these changes and the upgrades in operating practices needed to join the world-class leaders in PIM.

Important implications are associated with being designated as a leader. My first entry into this area was from a ceramic injection molder that desired to upgrade technology to better mimic the tolerances seen in metal powder injection molding. In several case, the question arose as licenses and companies were purchased, especially when a large company seeks to buy into the industry and desires to purchase an industry leader. Another situation occurs when a large customer, frustrated with its current vendor, sought a stable source. A similar situation arises when investors are seeking out options for participation in the industry. Finally, a common request comes from working with engineers from large corporations in automotive, consumer products, sporting equipment, hand tools, hardware, diesel engines, medical devices, and dental tools that seek to find quality vendors and call upon this database to select candidate vendors.

Thus, over the years, these questions on best firms in PIM keep reappearing in several forms - as part of acquisition and investment decisions, benchmarking exercises, employment decisions, technology licensing decisions, and when large firms are looking for a quality vendor. Such simple questions require a proper context for an adequate response.

In PIM, the identification of best practices is important to several strategic decisions as part of long-term planning. Identification of the best PIM firm requires an understanding of the diverse frames of reference that financial performance, customer service, product quality, manufacturing productivity, and employee satisfaction. The leading, world-class operations will be those most desirable for partnerships, whether it is as a supplier, customer, investor, or employer. This survey enables an inspection of current practices to evaluate a PIM operation over a broad spectrum of activities. The analysis provides one broad metric for identification of the leading PIM firms.

**PIM INDUSTRY STRUCTURE AND BREAKDOWN**

Over the past two decades, the author has visited many of the world’s top PIM production operations and countless research sites and pilot facilities. Each has a special twist on the PIM process. Unfortunately, several of the pilot efforts are now defunct. Others have grown to be large and profitable leaders, while others remain small. This unique perspective, spanning the first 20 years of commercial PIM operations, enables identification of the best practices across the industry. One important benefit is the early identification of characteristics that will allow a start-up to succeed and grow, since only about half of the start-ups survive. No single firm has all of the attributes detailed in this report, but it is clear some operations are far ahead and represent industry leaders.

An overview of key attributes is presented later in this document. With many competitive binders, molding techniques, debinding and sintering concepts, it is impossible to identify a clearly leading technology. Thus, technology is only an ingredient, but is not the determinant of being a leader. It
is most evident that the **systems management** perspective is the discriminator between operations. The best firms have already worked through and set up sophisticated systems that address a wide array of issues. In other words, world-class firms that we label as the “best” have learned to manage the total system via business practices, and customer and vendor relations. Further, these PIM operations are experts at knowledge management, and have developed plans and procedures with respect to protecting intellectual property, including patents, copyrights, employment agreements, employee training, industry knowledge, and supplier-vendor relations.

In any PIM organization there are five fundamental segments. On top of the organization is the central **MANAGEMENT** with the vision, systems view, and structure required to balance and coordinate the diverse inputs from the underlying four segments -

* OPERATIONS AND PRODUCTION
* SALES, MARKETING, AND PROMOTION
* FINANCIAL MANAGEMENT
* RESEARCH, DEVELOPMENT, AND ENGINEERING.

For a fully operational PIM production house (24 hours a day, 7 days a week), the OPERATIONS AND PRODUCTION segment will constitute 60 to 70% of the activities, while in a university or research institution the RESEARCH, DEVELOPMENT, AND ENGINEERING segment will constitute 60 to 70% of the activities. The relative activity can be measured by parameters such as employment, expenses, or physical space. The balance among the four segments differs between operations, but all involve these four activities.

Overall, in production PIM operations the distribution of costs is approximately 5% MANAGEMENT, 60 to 70% OPERATIONS AND PRODUCTION, 15 to 20% SALES, MARKETING, AND PROMOTION, 5% FINANCIAL MANAGEMENT, and 5 to 10% RESEARCH, DEVELOPMENT, AND ENGINEERING. On the other hand, in the first two years a start-up operation will have a heavier emphasis on SALES, MARKETING, AND PROMOTION, and unfortunately less emphasis on OPERATIONS AND PRODUCTION. Depending on the technology level, there might also be a disproportionate early emphasis on RESEARCH, DEVELOPMENT, AND ENGINEERING. As success occurs, each PIM operation should mature to match the profile of a production house. These figures are variable between companies, product lines, materials, and industry sectors. Further, beyond this activity breakdown, there are enormous differences in financial performance. For example, profits in PIM are as high as 60% of sales, but two-thirds of the PIM operations are operating at a loss. Although the underlying cost structure seems similar, process yields differ by a factor of four between start-ups and fully operational sites.

This benchmarking activity has several goals:

1. provide an objective evaluation basis for any firm to establish their relative placement on the continuum of PIM activities.
2. help management identify areas where specific actions might provide immediate gains by addressing deficiencies.
3. help visualize the future and the robust management systems view needed to be a world-class PIM operation.
4. provide a road map for building a systems approach to expeditiously create a world-class operation.
The road map should not confuse symptoms with causes - putting in place a machine or policy does not immediately or directly make for a world-class PIM operation. The core is in the intangibles, the management and operations system, since once the equipment is installed the large difference is in the execution, implementation, and integration of the equipment within an overall operation.

The full quantitative survey has three levels. First it discusses the attributes of a world-class, best operation. This includes statistics taken from the top 5% of the PIM industry, providing benchmark goals for any aspirant. The second level arranges 100 yes-no questions that any participant can use to evaluate for weaknesses and strengths in their own or a vendor’s operation. This is an audit that provides a first step toward creating an action plan for the future. Finally, the third level states the attributes evident in the leading operations by actions and characteristics that tend to cluster into 14 topic areas.

**ATTRIBUTES OF WORLD-CLASS OPERATIONS**

A world-class operation should be one of the first we think about when asked for a leader. With globalization, the leading firms will compete against each other, even though located around the world. Hence, leaders will be easily recognized on a global basis and almost by definition world-class operations are leaders. In PIM, the leaders are recognized by attributes such as the following:

- they ship only consistently high quality products
- they have a wide diversity of customers and are responsive to customer requests and needs
- they have quantitative performance advantages, often evident in terms of financial performance such as profitability and return on investment
- they are excellent in managing their business knowledge and intellectual property (including technical, marketing, and operational details)
- they have accurate management information systems
- they have widespread recognition in the industry
- they attract visionary individuals that are recognized as leaders in the field (leading firms attract leading individuals or leading individuals help create leading firms)
- they value and work in partnership with their employees, customers, and vendors; and in they respect their competitors
- they attack important problems that develop new markets, customers, and processes
- they are innovators that set the agenda for the future of the industry.

The world-class leaders exhibit success metrics that challenge the whole industry. Since technology is not directly the key to being a world-class actor, then we must examine the business practices. By their stature, the leaders define the *de facto* resources needed to grow toward the best practices, especially in the critical areas of long-range planning, financial performance, marketing, and operation systems. These firms are well-planned enterprises. They have time plans for reaching various goals. They allocate resources to reach their strategic objectives. To discriminate the leaders from the followers, observe how the leaders plan, replan, and execute, with constant attention to resources and progress. This characteristic of multiple stage planning, replanning, and resource allocation, is an underlying attribute that is hard to observe, yet is probably the most important discriminator between PIM operations. As often stated, those that plan consistently do better than
those that do not plan, but those that consistently replan do even better.

Some of the common measures for success can be captured in financial behavior including sales, profits, return on investment, return on assets, sales per employee, productivity, and economic value-added. The attached table provides a summary of the quantitative attributes for the top 5% of the industry. Immediately it is evident these are very productive and larger operations. Sales per employee or per molder are well over two times the industry average. However, note top performance is distributed around the world, and is not concentrated in any one binder or debinding technology. In terms of attributes consider the top 5% of the PIM industry is categorized as follows:

- custom versus captive; 37% of the production is for captive use, 63% for outside customers
- geographic distribution; 20% are Asian, 27% are European, and 53% are North American
- primary material focus; 77% are metallic, 20% are ceramic, and 3% are cemented carbides
- debinding practice; 35% use thermal, 19% use solvent, 19% use catalytic, 3% use drying, and the balance use a mixture of technologies
- molding pressure: 87% use high pressure molding, 13% use low pressures
- feedstock; about 80% of the feedstock is mixed in-house
- mixers; they own 20% of the installed mixers
- molding capacity; they own 26% of the installed molding capacity
- furnaces; they own 19% of the installed furnaces
- sintering capacity; their furnaces tend to be larger, consequently they control 49% of the installed sintering capacity
- sales; they account for 63% of the annual PIM industry sales
- employment; they account for 42% of the industry employment
- profits; they account for 81% of the industry profit.

In PIM, other important performance metrics might include quality factors, such as defects per million parts (some are at 0 defects shipped per 35 to 50 million parts), process yield (probably from 94 to 98%), cycle time in molding (6 to 15 seconds is typical, often with 4 to 32 cavity molds), machine utilization (typical is 67% and many cases are close to 100%), achievable standard deviation on tolerances (some are at 0.1% variation and a few are at 0.02%). Other attributes for measuring success might include; sintered properties - mechanical, optical, magnetic, thermal, electrical or corrosion resistance; tooling construction time, cost, and life; carbon control; purchasing rigor and vendor qualification procedures; feedstock homogeneity; and patent base.

Based on a quantitative study of the PIM industry, several attributes are embedded in the attached 100 questions. Hence, when a specific metric is given, such as sales per employee, it is taken from fresh industry-wide data. These questions allow a relative evaluation based on simple YES or NO answers. In all cases there is at least one PIM firm that can answer YES, so all of these best practices are realistic. Although simplistic, it allows for self-evaluation while providing a balance over topics to sense the sophistication of a PIM operation and provide a guide to areas where specific upgrades are needed. Consistent YES answers indicate you are operating at the top plane or are lying to yourself. As a percentage of the 100 questions, more than 65% YES puts you at the highest level (probably only 5% to 10% of the PIM operations in the world are at this level). The results can remain private or be shared. Most important, strengths and weaknesses will come into focus to allow planning for growth into a world-class level.
Quantitative Characteristics of the Top 5% of PIM Operations

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METRICS OF SUCCESS QUESTIONNAIRE

To conduct the survey, 100 discerning questions were assembled into a YES or NO answer format. They were grouped according to five key categories (Management, Operations, Sales and Marketing, Financial, and R&D and Engineering) to subdivide the analysis to see where attention is needed. The 100 questions remain confidential and the responses of individual companies likewise remain private, but the summary findings based on 60 out of 550 surveyed firms gives a good sense of the PIM industry. Below is a sampling of a few findings that best seemed to peg the developmental level of the industry, summarized here

MANAGEMENT

Most all PIM firms (over 75%) can easily access the background (education and prior experience) of key employees, officers, and directors

Only 25% of the firms have contracts signed by key employees that prevent them from moving directly to competing PIM firms.

OPERATIONS AND PRODUCTION

4-6
More the 75% of the firms have accurate prior order histories that can be used for cost estimation in the quotation of new orders?

But only 25% of the firms produce components that join two materials or two green pieces into a single assembly prior to sintering?

**SALES, MARKETING, AND PROMOTION**

About half of the industry is set up to allow prospective customers to submit engineering data and images for quotation via the internet?

Only 15% of the firms have written marketing plans that are coupled to strategic moves into new products or industries.

**FINANCIAL MANAGEMENT**

About 80% of the firms own all of the major production equipment in their facilities (mixers, molders, debinding, and sintering furnaces).

But only 15% of the firms use any forms of supplier-owned inventory.

**RESEARCH, DEVELOPMENT, AND ENGINEERING**

Over two-thirds of the PIM operations have application engineers assigned to new products or new customers.

But only 20% of the PIM operations have any formal training for the technical staff in intellectual property and its protection.

Thus, there is a distribution in qualitites very evident in the PIM industry. The overall scoring leads to the distribution in best practice attribute as shown in the survey.

- ✔ over 64 YES answers (out of 100) indicates a leading PIM operation, one of the top 10% (top 55 in the world)

- ✔ 55 to 64 YES answers indicates a strong contender, in the top 25% (top 135 in the world) and with effort it could become a leader

- ✔ 40 to 54 YES answers puts you in the group of probable survivors, but there are some basic problems; still in the top 50% of PIM operations (top 275 in the world)

- ✔ below 40 YES answers indicates significant weakness, questionable chance of survival, in need of structural improvements, current practices will inhibit growth and long-term stability, in the bottom half of all PIM operations.

Note that bankrupt and discontinued PIM operations were included in the survey to capture the
distribution in behaviors associated with the best practices and with probable success. Several of the operations scoring below 40 YES answers have a questionable future, and in some cases have sales per employee at 30% of the industry average and no profits. This underperforming group is composed of approximately 50% start-up operations (those with less than two years of operating history). The balance of the underperforming PIM operations are either now defunct or privately held and never achieved the technical, business, and financial performance levels associated with sustained success. A few of these remain in niches, but in general the bottom half of the PIM operations are characterized by poor technical and financial performance, and are not attractive acquisition opportunities. Most likely they will remain small and disappear with the owner’s death.

Further insight is possible from the score distributions. Statistical analysis shows some consistent characteristics, including important points that are associated with the leaders:

- The top PIM operations (top 25%) are dominated by companies that have outstanding MANAGEMENT structures.
- 67% of the overall leaders also are very strong in OPERATIONS AND PRODUCTION; likewise, the lowest overall firms consistently have not paid attention to these details.
- SALES, MARKETING, AND PROMOTION helps ensure a good operation, but many of the leading PIM firms are focused on internal production, so there is only a poor correlation to overall rating.
- The top operations are all above average in FINANCIAL MANAGEMENT.
- 93% of the leaders also have the highest scores in RESEARCH, DEVELOPMENT, AND ENGINEERING.

There is a high correlation between the relative ranking in RESEARCH, DEVELOPMENT, AND ENGINEERING and the overall ranking of the PIM operations. As noted, the leading firms generally are built on very sound technical foundations.

LEADERS

So which operations populate this upper tier, denoted as the leading firms - those with the best
practices? Well that depends on what area is select for emphasis, but here is an alphabetical listing of the names of the few firms that show up as leaders on the basis of overall performance or special skills that should be benchmarks for various activities important to PIM. Many others are close to this group, but did not distinguish themselves in any special category. Out of the 550 known operations, it would be difficult to provide details, and the performance of individual participants must remain confidential. Other companies probably belong on this list, but survey data were not available. As results are submitted by a broader range of companies, then the list will become more accurate. Please note this is not a complete listing, since not all of the industry was included in the survey. (The survey did include several defunct operations, most of the top 15% of the current 550 operations, and about 40 other selected smaller operations). The final ranking was based on characteristics that gave discrimination as follows:

**Overall Best Practice Operations**

**Strong Contenders**

**Operations with Strengths in Selected Areas**

The leaders are located around the world (Canada, Germany, Israel, Japan, Singapore, Taiwan, Switzerland, Spain, and USA), consist of large firms and smaller, privately held companies, and are involved in both metal and ceramic PIM. Many are custom, and some do both captive and custom molding. Likewise, as noted earlier, there is no single technology route that appears crucial to becoming a leading operation - some buy feedstock, but most mix their own; most use high molding pressures, but some are successful with lower pressures; most focus on metallic materials, but oxide ceramics and carbides are also fabricated by the leading firms; debinding is performed by a diverse set of techniques, so clearly the debinding route is not critical; and about one-third fabricate for themselves and their own designs, so captive versus custom is not a dominant factor. What is dominant is that the best practices reflect an integrated systems view of PIM.

**CHARACTERISTICS OF LEADING PIM OPERATIONS**

This final section synthesizes summary statements on the characteristics that are evident in those operations identified as leaders in PIM. It includes aspects embedded in the questions listed above. There might be some disagreement on the details, but the principles captured in the following statements seem to be most characteristic of performing as a leader in PIM.

The leading firms share these attributes categorized in the following areas and explicit examples are provided in the detailed survey -

- leveraged -
- individuals -
- intellectual property -
- image -
- defined business -
- modern -
- customer relations -
- supplier relations -
- employee relations -
- planning -
- technology -
SUMMARY

This paper is built on a labor of love. I have invested the bulk of the past 20 years in developing technology, engineers, and scientific principles for PIM as the industry expanded from negligible sales in garages with substantial financial losses to participation by large multi-national firms with industry annual sales now exceeding $800 million and outstanding profits. This shift in the PIM industry has occurred over just the past few years. Dramatic gains have taken place in applications, materials, customers, and performance. During 1997 it became evident that major expansion was taking place, far in excess of that anticipated. As the founding members of the PIM club thrived, a large wave of second entries arose. These newer operations benefitted from the learning (that means mistakes) made by the original 30 companies that stated in the early 1980's. Most of those first operations did not survive, or if they exist it is in name only, since most have undergone several ownership changes. So what was needed to make it a successful industry? That is the key focus of this paper and the underlying best practices survey.

The questions and analysis were built from careful study on the PIM industry and its behavior patterns over the past few years. There is now a means to predict and manage success. One of the key derivatives from this document is insight into the metrics of the leading PIM operations and the characteristics needed to join that club. Its will accelerate industry growth by quantification of the systems view needed for success.
An Analysis of the Powder Injection Molding Industry Global Market

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ABSTRACT

An analysis of the powder injection molding (PIM) worldwide industry is underway. Data are being collected and analyzed and will cover technologies, markets, trends, applications, sales, properties, and profits. Data collection methods include industry surveys, conversations, database searches, and verification surveys and reports. Profiles on powder and feedstock suppliers, equipment manufacturers, parts makers and major users have been included. Relevant patents have been collected and abstracts will be given as well as literature that has been published in the field. The field is defined as both ceramic and metal systems and even includes some new combinatorial material systems only possible by a powder approach (including cemented carbides). The analysis has been broken down geographically to North America, Europe and Eastern Asia with data presented worldwide. PIM can be defined as an advanced manufacturing technology and is aligned with the evolution of advanced materials, formed to net-shapes and used in a wide variety of industrial and consumer product applications. The industry as a whole is strong and continues to grow at a surprisingly strong 40% annual rate. Continually, companies are investigating the technology and implementing either their own manufacturing capability or making the decision to buy from or acquire existing manufacturers.

TECHNOLOGY

PIM is the process of manufacturing metal and ceramic parts from small powders (normally around 20 micrometers or less) using injection molding technologies, typically used by the plastic industry to manufacture high volume components. Metal and ceramic components can be made by preparing a feedstock of powders and polymers that can be processed on a standard low or high-pressure molding machine. The components are removed from the die and the binder system is extracted chemically, thermally or by a combination method. The components are then consolidated by heating to a temperature just below the melting temperature until near full density is reached. This sintering process is well known to the ceramics and powder metal industries. Final components have the mechanical properties of other full density metal and ceramic...
components formed by conventional manufacturing techniques like machining, stamping and forging.

MARKETS

Worldwide there are more than 525 companies with direct employment in PIM parts production. Additionally many powder suppliers, equipment vendors, research institutes, consultants and professional organizations are involved in promoting the technology totaling more than 6000 people. These activities amount to another 1000 firms. The commercial value of PIM production for the year 2000 is estimated to exceed $800 million in sales and is growing rapidly. The identified market for components exceeds $2 billion by 2009 in present day dollars.

Figure 1. PIM Sales History and Forecast

Roughly half of all production is by companies that use the components for internal products (captive). Custom manufacturers make up the other half of the industry and are made up of a large number of smaller companies that manufacture custom components on a bidding basis. Several of these firms have been highly successful and have expanded in the last couple of years to meet customer demands. Additionally, plastics parts manufacturers are beginning to see the value of expanding their product offerings and have begun or are investigating PIM. Table 1 lists several parts applications and whether they are most likely produced by companies making for internal consumption or by a custom parts fabricator.

MATERIALS

A wide variety of commercial ceramic, metal and carbide materials are available via PIM with stainless steel, alumina, silica, iron, and various lower carbon steel grades dominating the market. The value of metallic and ceramic parts production by PIM is relatively equal, although there are differences in how the markets operate. In ceramic production, many of the components are larger, and sell at a lower price. Also, for commercial production, ceramic companies tend to make parts by a variety of manufacturing technologies e.g., they use uniaxial compaction, CIP, PIM, and tape casting. One of the largest segments of the ceramics PIM market is manufacture of casting cores for high performance turbine applications. They manufacture a silica or alumina airfoil shape that is destroyed in the manufacturing process. Essentially a complex shape is
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<tr>
<td>cutlery</td>
<td>X</td>
<td>X</td>
<td>casting refractories</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 1 PIM Part Applications

injection molded out of the ceramic and then a high performance metal is cast around the ceramic insert. The insert is then chemically leached out of the preform, creating a complex shaped hollow turbine blade. This technology utilizes low-pressure molding and a great deal of handwork to finish the part. Other ceramic producers that are highly profitable include the shaping of nonoxide ceramics – silicon nitride, silicon carbide, and aluminum nitride type materials.

Based on sales, alumina and silica make up roughly a quarter of the industry, stainless steel and iron-based materials make up about half of the industry with the other ceramics and metals making up the remaining industry. On a sales basis, stainless steel dominates the PIM industry including powder purchases and value of finished components. In most cases carbon is fully extracted, so carbon control is relatively easy, making stainless steels the largest growing material system and may have the largest potential for moving PIM into new applications.

Cemented carbides, a small but growing segment of the industry find applications in wear components and tooling. Because of difficulties in coupling to designs for these high wear applications the technology is moving slowly in this field, but recent advances coupling to designs for these feedstocks and processing are leading to increased growth.

Increasingly companies are turning to feedstock suppliers as opposed to compounding the material themselves. There are currently 20 companies that indicate that they have commercially available metal and or ceramic feedstocks. We see fewer powder suppliers and some of these may look to manufacture feedstocks as value-added products. As more and more companies turn to preformulated feedstocks, the technology will continue to grow because of greater part-to-part uniformity. We expect that there will be consolidations in the PIM industry in the next several years. Already, offers have been made for several of the smaller firms. A primary example is the recent acquisition of Thermat Inc. by a large medical parts manufacturer, Medsource Technologies, Inc. and the acquisition of ANVAL by Carpenter Technologies.
METRICS TO SUCCESS

Many companies continue to investigate the technology, including a large number of custom and captive plastic manufacturers, companies for in-house production of components, casting companies because of environmental concerns, and companies that manufacture machined components because of the economics. Because they are making an investment today, these companies can often enter the market fairly quickly. The know-how and metrics for success exist and can be garnered by talking with people in the industry or even buying the talent that is necessary i.e. with long-term manufacturing experience. Companies, consultants, and research organizations will provide the technical knowledge and the parameters necessary to reach profitable production in a short time. With all of the knowledge available, new operations do not need to continue to rediscover the technology. However, because this information is out there, does not mean it will be used. Many of the concerns in the industry have solutions, but they are not being addressed by all manufacturers, in some cases leading to a tarnished image for the technology. Concerns include variability between vendors because of differences in feedstock or machine capabilities, quality issues, lack of use and understanding of process fundamentals, limited intellectual knowledge base and the inability for small companies to market effectively.

DESIGN CONSIDERATIONS

Final properties of PIM materials are similar, and now even superior, to other forming processes. It is even possible to produce properties of steels rivaling those of forgings by using advanced processing schemes and improved sintering cycles. Strengths up to 3 GPa (435ksi) and 3% elongation are possible. Other property requirements (thermal, magnetic, electrical, optical) generally are competitive with standard forming technologies. Complex shapes with high performance requirements and high production volumes are necessary to compensate for the high start-up tooling investment. History shows cost reductions of 30% or substantial performance enhancements are necessary to sell customers on PIM.

Generally, PIM is best suited for smaller, complex shaped components. Although larger components have been produced, they are unusual. More design data are available for metal components than for ceramic or carbides. In general, if a component requires 5 plus machine tool set-ups, MIM is a candidate for consideration. Table 2 gives typical design considerations.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Typical</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum length, mm</td>
<td>2 – 200</td>
<td>1000</td>
</tr>
<tr>
<td>Wall thickness, mm</td>
<td>0.01 – 10</td>
<td>25</td>
</tr>
<tr>
<td>Mass, g</td>
<td>0.02 – 150</td>
<td>20,000g</td>
</tr>
<tr>
<td>Part Cost, $</td>
<td>0.30 – 2.50</td>
<td>500.00</td>
</tr>
<tr>
<td>Production Quantity</td>
<td>200 – 150,000</td>
<td>20,000,000</td>
</tr>
<tr>
<td>Tolerances, mm</td>
<td>0.03 – 0.30</td>
<td>2.0</td>
</tr>
<tr>
<td>Surface Finish for metal parts, RMS</td>
<td>32</td>
<td>16 (with secondary operation)</td>
</tr>
</tbody>
</table>

Table 2. Design Criteria for PIM

Often, both metal and ceramic components requiring several machined parts can be manufactured in one step by PIM, saving material and ultimately cost. Tolerances are generally dependent on three factors: molding sophistication, binder composition and mixture homogeneity, and debinding approach. Size variations in a component are generally limited but success has been reported with combinations of thick and thin sections with up to 100 fold variation. The
opportunities in micro miniature molding of components are enormous. While these components do not consume large quantities of powder, they promise high volumes in fields like biomedical, electronics, communications, and sensors. Currently design information is limited. Computer automated design (CAD) systems do not have modules with built in PIM design advisors. Increased designer training is required to continue to move the technology forward.

SCIENTIFIC IMPACT OF MIM BUSINESS

PIM technology and practice have moved into profitability because the necessary critical mass in scientific and practical knowledge has been achieved. Market growth directly correlates with the number of publications on MIM. Market pull has driven the production of powders and science has responded; new alloy powders in tailored particle size ranges are becoming available for PIM and the cost of common metal injection molding (MIM) alloys has decreased as volume has increased.

Mixing has moved toward more tightly controlled continuous techniques and feedstocks have become standardized. Several large chemical and technology companies, as well as several smaller specialty companies have developed preformulated systems available to any customers. Tooling and molding are now standard practice with much less "black art" know-how.

Debinding and sintering are moving to high volume continuous processes. The cycles and protocols are well established. Recent efforts in mold-flow modeling and some modeling of debinding and sintering will add to these protocols. As a point of reference, the ten most significant developments in PIM are as follows:

<table>
<thead>
<tr>
<th>Significant Developments in MIM</th>
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<tbody>
<tr>
<td>1. Increased awareness – training books, conferences, papers, workshops, and seminars.</td>
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<tr>
<td>2. Standardized feedstocks</td>
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<tr>
<td>3. Continuous sintering furnaces</td>
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<td>4. Standard molding machines with closed loop feedback controls</td>
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<td>5. Debinding rules for shape retention</td>
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<tr>
<td>6. Identification of optimal powder characteristics, implementation via water atomized powders</td>
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<tr>
<td>7. Combined debinding and sintering equipment</td>
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<tr>
<td>8. Customized continuous mixers</td>
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<tr>
<td>9. Composition control via atmosphere C-O-N-H interactions</td>
</tr>
<tr>
<td>10. Environmentally benign polymers and debinding cycles</td>
</tr>
</tbody>
</table>

Other factors include: a larger more knowledgeable workforce; largely ignored intellectual property; lower powder prices; and the driving forces to high volume, cost effective manufacturing technology.

PIM MATERIAL STANDARDS

Once again the metals and ceramics industries differ on how they operate. Ceramics applications tend not to follow material standards for PIM. Instead companies specify properties. The supplier and customer agree on properties before the component is put into production. Ceramics are often used for their insulation or high temperature properties and are less dependent on their structural properties or how the component is produced. Metal components, on the other hand, are very dependent on the density, processing, and grain size of the material and properties can vary greatly. As such, there are efforts underway in both North America through MPIF standards activities and even more actively in Europe through the Thematic Network, a part of the European Powder Metal Association with funding assistance from the European Community. Metals by PIM follow very closely their machined counterparts and can even have superior properties because of unique alloy systems and/or carefully controlled microstructures. In fact, the European Community has established research and development efforts in PIM in the
following areas: process development, binder development, debinding, graded structures, standardization, rapid tooling. Sixteen projects are currently funded (Haupt).

PIM MARKETING

Powder injection molding is served by a host of organizations, none of which are focused on the specific needs of the industry. The European community is fairly well organized through the Thematic Network of EPMA and has 34 members. In Japan and the Far East, there is no organization that directly serves this community although each country has either a materials or processing cluster (for example the Japan Powder Metallurgy Association). In North America, Metal Powder Industries Federation (MPIF) has the Metal Injection Molding Association with approximately 25 company members. This represents less than 10% of the parts manufacturers in North America and until recently none of the suppliers to this industry. The ceramics industry has even less focused representation on PIM with a few small organizations like the Ceramics Manufacturers Association that does nothing special for the companies that use PIM technologies. Reportedly, PIM operations are not compelled to join with competitors to unify the image as yet.

Powder injection molding has a lot to offer to a whole host of industries including more efficient manufacturing, improved properties, reduced costs, new materials; to put it simply a better way of doing business. To do this, the PIM industry needs to come together in a more cohesive, dedicated body. Existing organizations may not be able to do this if they are not able to differentiate the benefits over the established processes. We believe that the industry needs a new organization that is devoted to the market development and technology and is not restricted by other activities and special interest groups. Recently a group met to discuss moving forward with a marketing activity on behalf of the industry and will meet again during the summer of 2000. (James)

CONCLUSIONS

The PIM industry is a healthy, vibrant, industry on a fast-paced growth track. This manufacturing technology has much to offer a host of industries from jewelry makers to small engines and consumer products. The prospects are great and the industry should look forward to years of growth and prosperity as well as technical improvements that will open new markets.

REFERENCES


