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Design Regression for Identification of Optimal Components for Metal Powder Injection Molding

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Abstract

Production components fabricated by metal powder injection molding are analyzed for features to identify the design window for this powder technology. This reverse approach lets the designer see where PIM has a high probability to succeed. The findings show that the most suitable components tend to be less than 25 mm in size and less than 10 g in mass, are slender, and have high complexity.

Keywords: metal powder injection molding, design, regression analysis, complexity.

1. Approach

A collection of 220 PIM production parts were obtained from vendors around the world. Out of these, 154 non-duplicate metallic designs were used for the analysis; the excluded designs were either duplicates, pilot components, or did not have information on the material. The final inventory included titanium, iron, steel, stainless steel, tungsten alloy, and cemented carbide components. The breakdown was 49% stainless, 15% specialty alloy (electronic and magnetic), 22% iron or steel, 8% cemented carbide, 4% titanium, and 2% tungsten alloy. This distribution is similar to prior material partitions that showed 55% of the components in production (not designs) were stainless steels. Even more impressive were the range of applications, literally from automotive components to watch cases, including parts used in firearms, hand tools, locks, computers, business machines, orthodontics, surgical instruments, kitchen devices, electrical connectors, microelectronic packages, and cellular telephones. Price and production quantity information were not consistently supplied, so we must recognize these are significant factors that impact success, beyond the design features treated here.

Each design was photographed on square grid paper and measured for mass, outer dimensional envelope (maximum x-y-z box), nominal size (three thicknesses, three widths, and three lengths), projected area (when lying as flat as reasonable with the maximum projected planar area), and perpendicular thickness to the projected area. Measurements were taken using a combination of laboratory scales, micrometers, calipers, and a manual coordinate measuring machine, depending on the feature and its size. Generally dimensions were measured to four significant digits and mass to three significant digits. Many of the design parameters were previously identified in studies on the cost of injection molding tooling and powder injection molding tooling. These components are best illustrated by the new cellular telephone designs. Tabulations included the geometric attributes, materials, manufacturer, device name, identifying photograph, and categorization of attributes (number of holes, ribs, protrusions, slots, undercuts, surface texture, lettering, teeth, threads, and so on). These latter attributes were used to determine the design complexity. During component measurement and data entry, the exact manufacturer and its geographic location were unknown, so raw data were determined in a blind manner with respect to the component source.

As a note on the premise of this study, the metrics are based on the number of designs, not the number of parts. For example, orthodontic brackets were included in the study, a smaller one having a mass of 0.055 g and a larger one having a mass of 0.08 g. These are fabricated in quantities reaching up to 20,000 per day. A few cellular telephone devices were included that were 0.3 g and 2.2 g, and reached peak production rates of 100,000 per day. On the other hand a golf club head and magnetic solenoid were included that had masses of 341 g and 180 g, but the reported production quantities were just 100 per day. Each design was given equal weighting in this analysis; if the statistics were based on the number of parts produced, then the low mass designs would dominate. Our intent is to establish information on design viability.

2. Findings

Several properties were measured to assess for a pattern in PIM. From the statistical profile, a typical design can be characterized by the following independent attributes:
- 11 g mass (central 50% are from 3.5 g to 21.5 g)

- 29 mm maximum dimension (central 50% are from 18 mm to 42 mm)
- 2.2 mm wall thickness (central 50% are from 1.5 mm to 3.2 mm)
- wall thickness ratio in a design 2.3 (central 50% are from 1.6 to 4.6)
- 3.8 cm^2 projected area (central 50% are from 1.8 cm^2 to 7.3 cm^2)
- 7.4 cm^3 outer embracing volume (central 50% are from 2.1 cm^3 to 20.1 cm^3)
- effective density from 25% to 30% of theoretical (75% are below 45%)
- slenderness of 0.14 (central 50% are from 0.07 to 0.30)
- complexity of 69 specifications (central 50% are from 38 to 127).

This inventory provides a view that PIM is most successful for smaller components with thin walls and moderately high complexity. These also tend to be produced in larger quantities, an aspect not included in this analysis. Correlation analysis looked to see if there were any systematic trends. Statistically significant correlations were found between maximum size and mass, projected area and mass, and slenderness and wall thickness. However, there was no statistically significant correlation between thickness and mass, thickness and projected area, slenderness and mass, nor slenderness and projected area. On the other hand, four important patterns were detected as in scatter plots that showed clustering or nonlinear patters. For example the thickness was related to the logarithm of the projected area, and except for five designs, it demonstrates the peak thickness tends to be clustered in the 1 to 10 cm^2 projected area range. Likewise, slenderness tends to peak for a mass near 10 g, meaning designs with the median mass are the most variable in slenderness. Complexity also tended to peak at the intermediate mass levels. The number of features (complexity) versus mass gave a peak at near 20 g. An audit of the designs with a mass below 1 g found they had an average complexity of 50. On the other hand, the ten most complex designs had an average mass of 51 g. Finally, complexity and slenderness tended to have a clustering. Although the two parameters were not correlated, plots showed that 90% of the designs cluster into a triangle defined by a slenderness near 1 and low complexity to a very low slenderness and high complexity.

Using the characteristics listed above, the inventory of designs was examined to find any "typical" examples. Indeed, several were close matches to the overall profile, and the specifics of seven are listed in the full paper as referenced below, along with photographs and full statistical data.

3. Key Elements of Success

From a first consideration, the material is a significant factor. Stainless steels are the dominant material and the vast majority of components are fabricated from ferrous alloys (steel, stainless steel, iron-nickel alloys, magnetic and electronic alloys, and some tool steels), followed by tungsten-based and titanium alloys. All other materials are relatively specialized by comparison. Ceramics have a different competitive environment, since alternative casting, machining, and deformation processes are not credible options. Second, most PIM designs are low in mass. The median mass for designs that reach production (in two different reports) is near 10 g. Compared to competitive technologies, PIM is most successful for designs that involve complicated, small, thin-walled (slender), and intricate shapes.

An important finding is that the successful PIM designs tend to show clusters in the successful combinations of mass-slenderness-complexity. The most common are the medium mass designs, near 10 g, that have up to 200 features and can range up to a slenderness of 1.0. For smaller masses, less than 1 g, the number of features is restricted, generally below 50, and the component has a lower slenderness near 0.5. High mass designs, over say 60 g, have a decreasing number of features as mass increases and are generally very slender.

In short, PIM appears to excel at the production of large quantities of smaller, slender, and complex stainless steel components with a mass near 10 g. Larger and smaller components are possible, with a diminished design window. In contrast, PIM is not favored by thick, large, and simple shapes, especially if produced in lower quantities from easy to machine lower melting temperature, nonferrous metals such as brass or bronze.

4. Conclusions

Metal powder injection molding has been in continuous use since the 1970s, emerging as a manufacturing technology that excels in the production of small, complex ferrous components for a wide variety of applications. Inherently, PIM is not a low cost process when compared with screw machining, stamping, and other traditional technologies; however, it has succeeded in niche areas where the combination of design features, complexity, size, slenderness, low mass, and production cost make for a winning combination.

5. Reference

B. Smarslok and R. M. German, "Identification of Design Parameters in Metal Powder Injection Molding," *Journal of Advanced Materials*, 2005, vol. 37, no. 4, pp. 3-11.