The Effect of Powder Type and Powder Size on Dimensional Variability in PIM

Rudolf Zauner
Austrian Research Centers in North America
Materials & Production Technology Center
200 Innovation Boulevard
State College, PA 16803

Donald F. Heaney, Jobe C. Piemme, Chantal Binet and Randall M. German,
The Center for Innovative Sintered Products
The Pennsylvania State University
118 Research Building West
University Park, PA 16802

Abstract

Dimensional variability for metal powder injection molding (MIM) using 316 L grade stainless steel was investigated. This portion in the series of experiments on dimensional variation is concerned with the influence of the powder type and powder size on dimensional variability. Since particle size distribution, powder surface area, and surface chemistry vary depending on the powder used, the study parameters are known to have substantial influence on the physical properties and rheological behavior of the feedstock. Such variability originating from early process decisions carries over into final product dimensional precision and is exaggerated in the later steps of molding, debinding, and sintering. A design of experiments (DOE) approach is used to statistically investigate the effect of powder type and powder size on the variability of multiple dimensions of a typical powder injection molded component in the different stages of the PIM/MIM process.

Introduction

Metal injection molding (MIM) has emerged as a viable method of producing complex shaped parts at a competitive cost [1]. The MIM process uses a combination of powder metallurgy and injection molding technologies to produce net-shape parts and is comprised of five main subprocesses: raw materials selection (powder/binder), feedstock preparation, injection molding, debinding, and sintering.

One of the advantages of powder injection molding is its ability to produce parts with complex geometry without machining. However, to stay within the ever tighter tolerances demanded by component manufacturers' customers, MIM parts have to be produced with a high degree of dimensional control in order to minimize the dimensional variability of critical dimensions (German [2], Kulkarni [3]).

According to German [2], powder injection molding is an attractive process when the following component features apply: thickness ranging from 0.2 to 20 mm, mass ranging from 0.02 to 1000 g, moderate levels of shape complexity, and smooth surfaces. The typical range of tolerances is between 0.1 and 1 mm.

Dimensional Variability

The dimensional capability of powder injection molding is often cited as ±0.3% (Kulkarni [3], for example), ranging from ±0.15% to ±0.5% (Vonderohe *et al.* [4]), compared to conventional P/M processes which are usually accurate to ±0.1%. The dimension of a part with the nominal dimension of 10 mm and a tolerance of 0.3% would therefore range from 9.97 to 10.03 mm. Dimensional tolerances of ±0.3% are the industry standard, although Hens and Grohowski [5] report tolerances better than ±0.1%. However, few technical details have been provided with these statements.

Dimensional variation can be caused by factors stemming from any step of the MIM process. Kipphut and German [6] studied the effects of powder characteristics on the shape retention of MIM parts. Li *et al.* [7] looked at the rheological properties of binder systems in feedstocks and how each property affected shrinkage homogeneity, which has a direct effect on dimensional variation. Weaver and German [8] found that reducing the dimensional variation in green parts caused by injection molding improved dimensional control in the final sintered part. Hu and Hwang [9] studied swelling and deformation of MIM parts during solvent debinding and found that the total expansion of the component increases with debinding temperature and binder content. German and Bose [1] state that the sintering step contributes the largest dimensional variability to a MIM part; this is primarily because the part undergoes most shrinkage during this process step.

In this study, the effects of powder type and powder size on dimensional variability were investigated. Powder characteristics play an important role in the MIM process. Studies have been conducted to show the effect of powder size, powder shape, powder size distribution, and surface area. Arakida and Miura [10] studied fine (-20 μm) and coarse (-150 μm) gas- and water-atomized powders and their effect on packing density and fluidity. Their work showed that fine gas-atomized powder exhibits a higher density, which in turn produces improved mechanical properties. Dihoru *et al.* [11] found that the instability index for feedstocks increases with particle size. Almost all of the studies that dealt with powder characteristics focused on rheometry rather than dimensional variation. The focus of this study is on dimensional variation and its dependence on powder type, particle shape, and particle size.

Experimental Design

This DOE (design of experiments) is a study from a family of multiple DOEs that investigate factors affecting dimensional variability and focuses on the influence of powder type and powder size on dimensional variation. In the DOE study, a wide variety of parameters including powder loading, compounding techniques, molding parameters, and sintering parameters are studied. In this part of the DOE, two different powder types (different particle shapes) and two different powder sizes were examined in the green and debound states and their dimensional variablility was evaluated.

Before the actual DOE experiments were started, a baseline process for the experiments was set up. This baseline process has the following characteristics:

- Wax/polymer-based binder system
- Dry powder mixing with binder components
- Compounding in twin-cam compounder with 65 vol.% powder loading
- Molding on hydraulic 55 ton injection molding machine

- Solvent debinding in heptane

Figure 1 shows a drawing of the PIM component used in this study. With each DOE condition, the dimensions of 120 parts were measured using a SmartScope and their variability was calculated. A gauge R&R was carried out prior to the experiments in order to check the repeatability and reproducibility of the dimensional measurements. The error was found to be within the acceptable limit and independent of the operator.

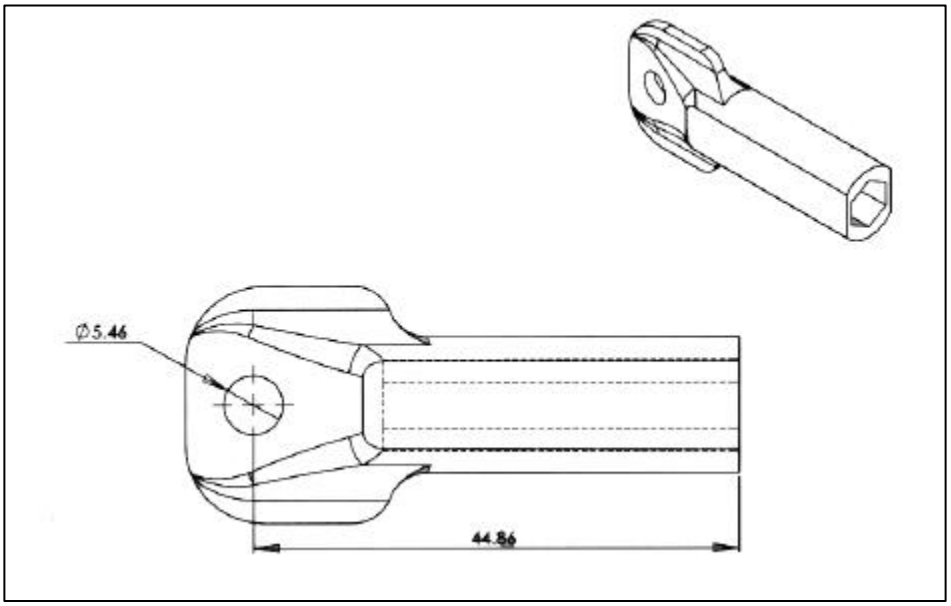

Figure 1: Drawing of the PIM component

Powder Properties (Powder Types and Powder Sizes)

Due to their different production routes, the commercial powders used showed very different properties. Figure 2 shows three SEM images of the powders used. While Type 1 powder particles are spherical and rounded, Type 2 powder particles are irregular in shape. The particle size distribution of the powders was obtained using laser-scattering and shows a narrower distribution for the powders of Type 1 (see Figure 3). For Type 1, powders with two different mean particle sizes (-16 µm and –22 µm) were studied, while for Type 2 only one powder was used in this study. The differences in particle size and shape resulted in different feedstock viscosities at the molding temperature.

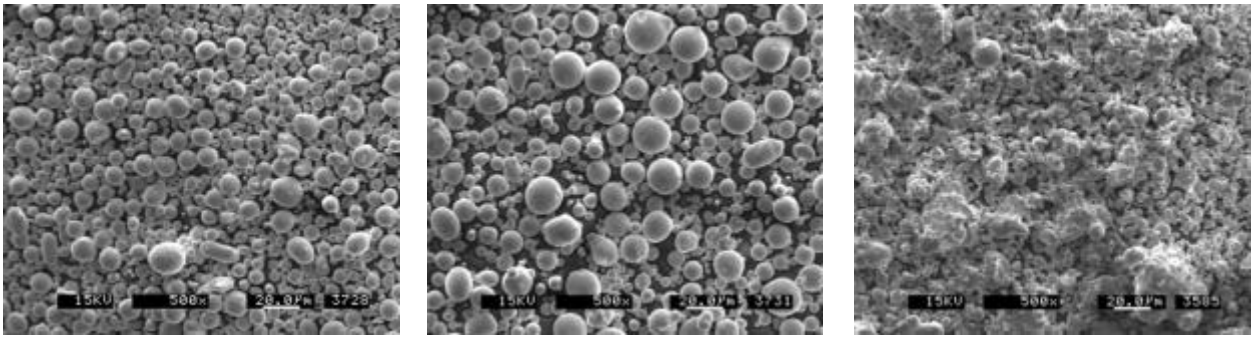

Figure 2: SEM Type 1, -16 µm SEM Type 1, -22 µm SEM Type 2, -22 µm

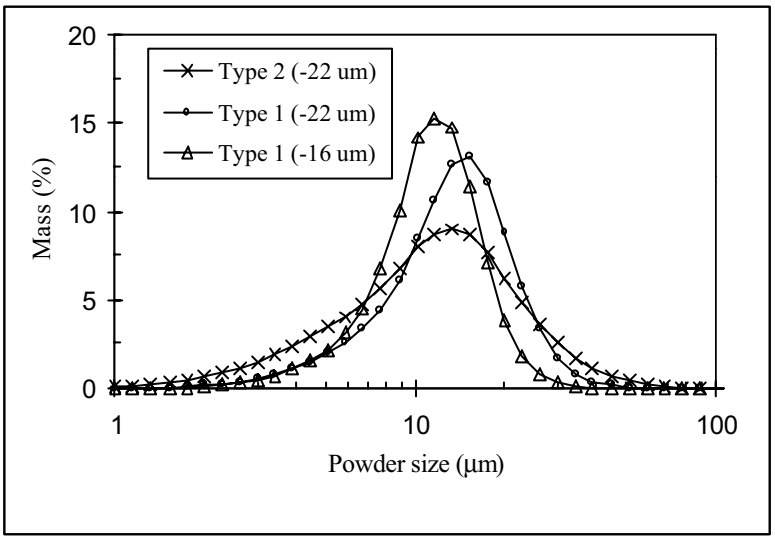

Figure 3: Particle size distributions of Type 1 and Type 2 powders

As-Molded Components (Green Parts)

The dimensions studied were a component length dimension (tool dimension 44.86 mm, see Figure 1) and a core hole diameter (tool dimension 5.46 mm). Figures 4 and 5 show the dimensional variation in the core holes and the lengths of the green components, respectively.

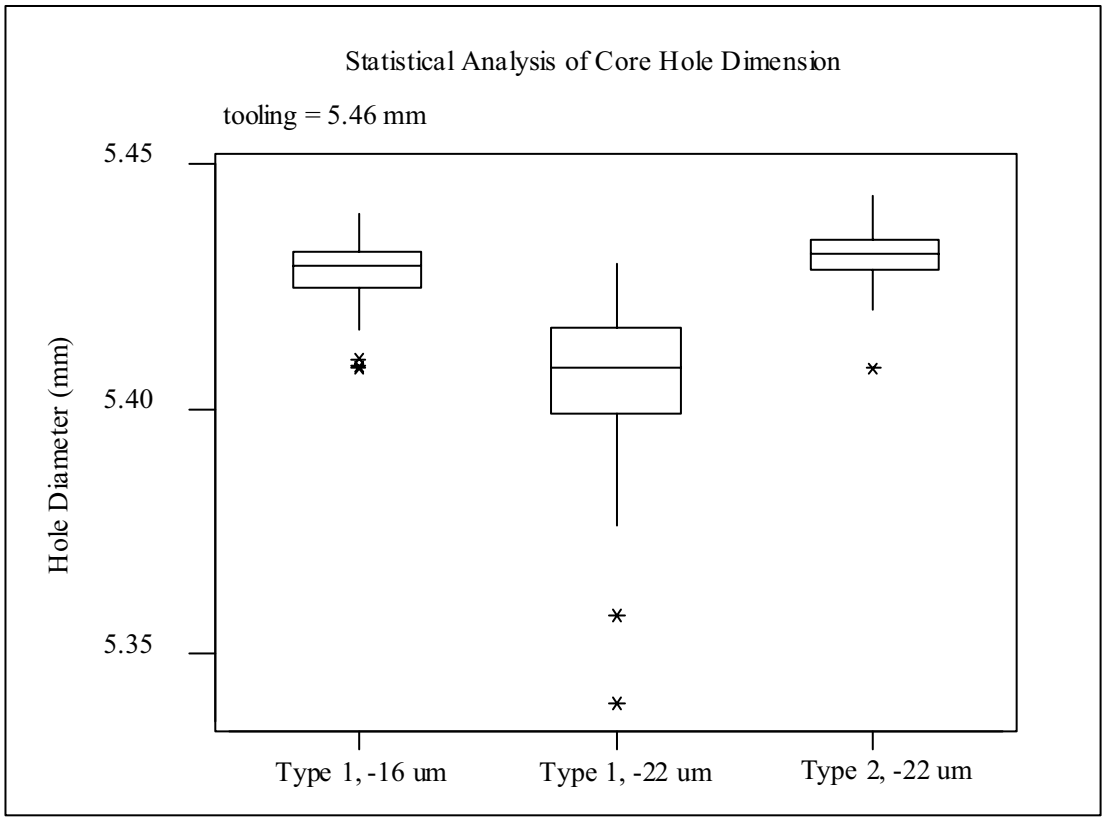

Figure 4: Variability of core hole dimension (green components)

The graphs show a line drawn across the box at the median. The bottom of the box is at the first quartile (Q1) value, and the top is at the third quartile (Q3) value. The whiskers are the lines that extend from the top and bottom of the box to the adjacent values. The adjacent values are the lowest and highest observations that are still inside the region defined by the following limits:

lower limit: (Q1 - 1.5 (Q3 - Q1))
upper limit: (Q3 + 1.5 (Q3 - Q1)).

Outliers are points outside of the lower and upper limits and are plotted with asterisks (*).

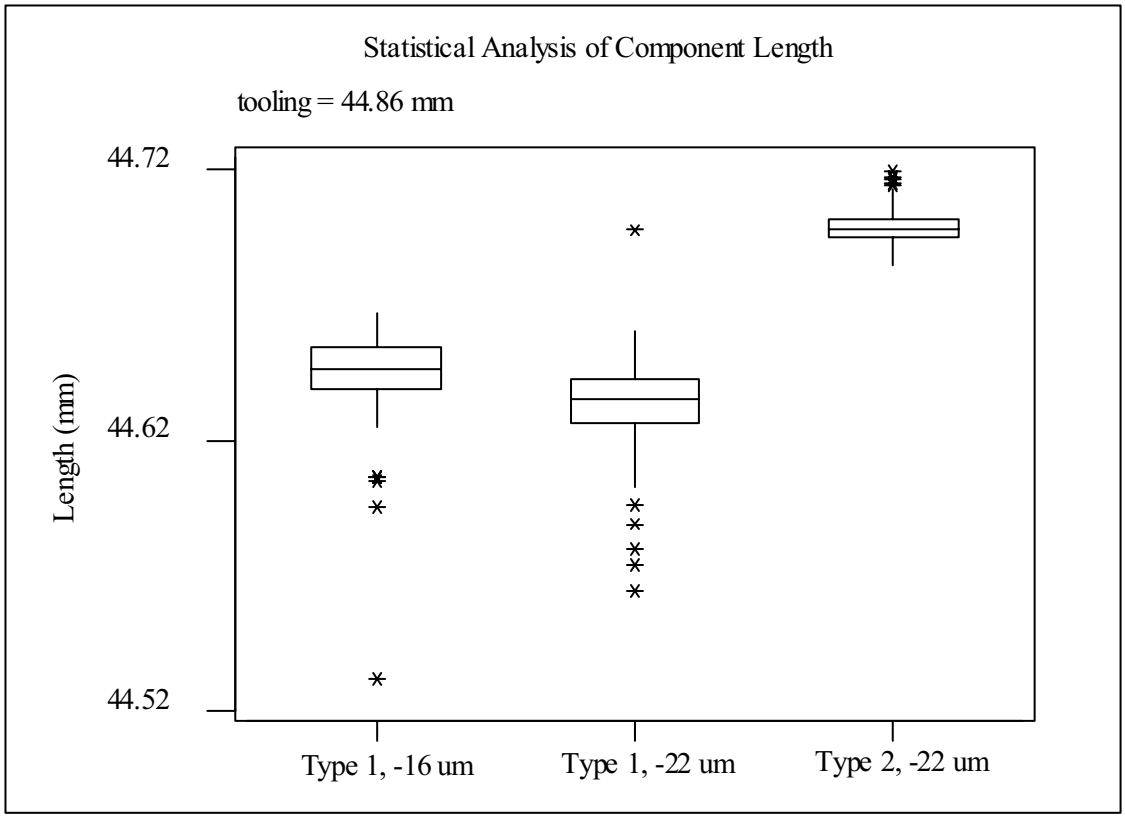

Figure 5: Variability of length dimension (green components)

The experiments showed a difference between the average shrinkage of the core dimension and the shrinkage of the length dimension of the component. Table 1 shows the average shrinkage of the different powders. Independent of the powder size and powder type, the average shrinkage of the core hole ranged from 0.64% (Type 2, -22 μm) to 0.99% (Type 1, -22 μm), while the average shrinkage of the component length ranged from 0.50% (Type 2, -22 μm) to 0.35% (Type 1, -22 μm). This observation suggests anisotropic shrinkage during molding.

The dimensional variation in the green state showed a clear dependence on both powder size and type. The variation was smallest for Type 2 powder and smaller for Type 1, -16 μm powder than for Type 1, -22 μm powder. Table 2 shows the dimensional variation of the different powders. These results are consistent for both the core hole dimension and the length dimension.

Table 1: Shrinkage after molding and debinding

Feedstock	Core hole (green) [%]	Length (green) [%]	Length (debound) [%]
Type 1, -16 µm	0.60	0.47	0.46
Type 1, -22 µm	0.99	0.50	0.44
Type 2, -22 µm	0.54	0.35	0.30

Table 2: Dimensional variability after molding and debinding

Feedstock	Core hole (green) [%]	Length (green) [%]	Length (debound) [%]
Type 1, -16 µm	0.12	0.04	0.06
Type 1, -22 µm	0.28	0.04	0.05
Type 2, -22 µm	0.10	0.01	0.02

Solvent-Debound Components

A very similar dependence was observed for the solvent-debound parts (Figures 6 and 7) as has already been observed in the green state. Solvent debinding took place in heptane at 60°C.

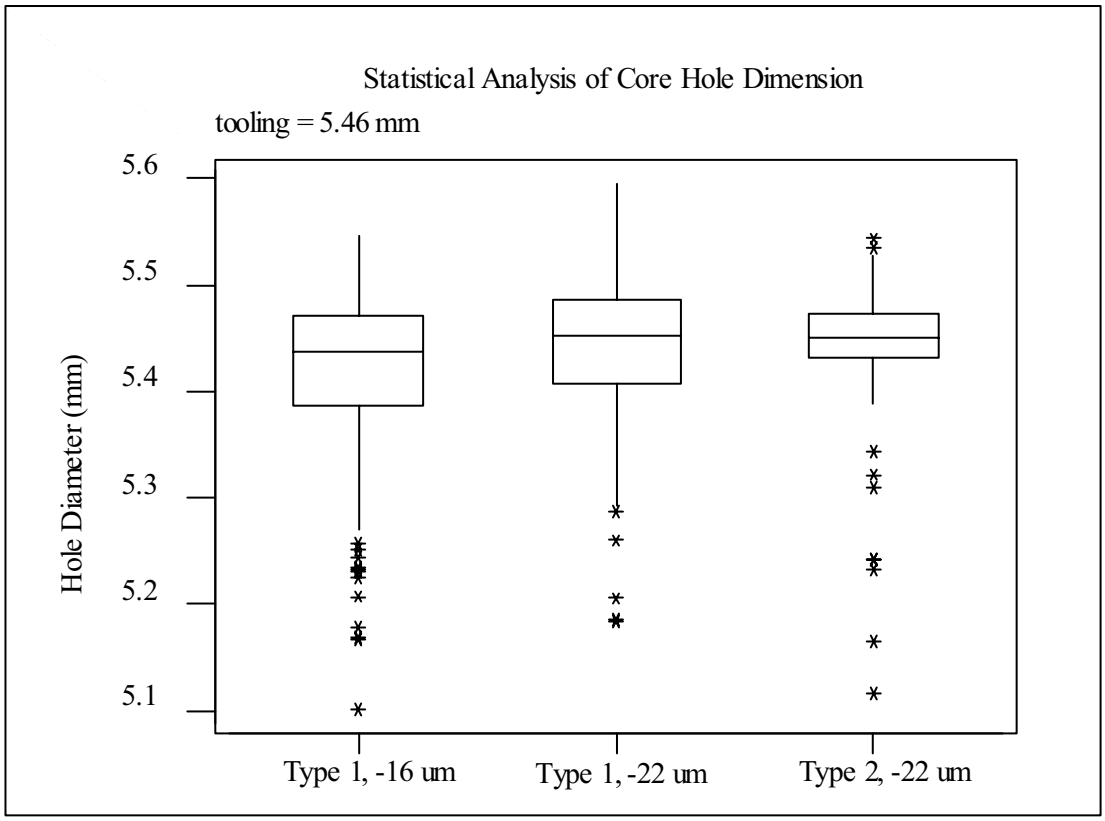

Figure 6: Variability of core hole dimension (solvent-debound components)

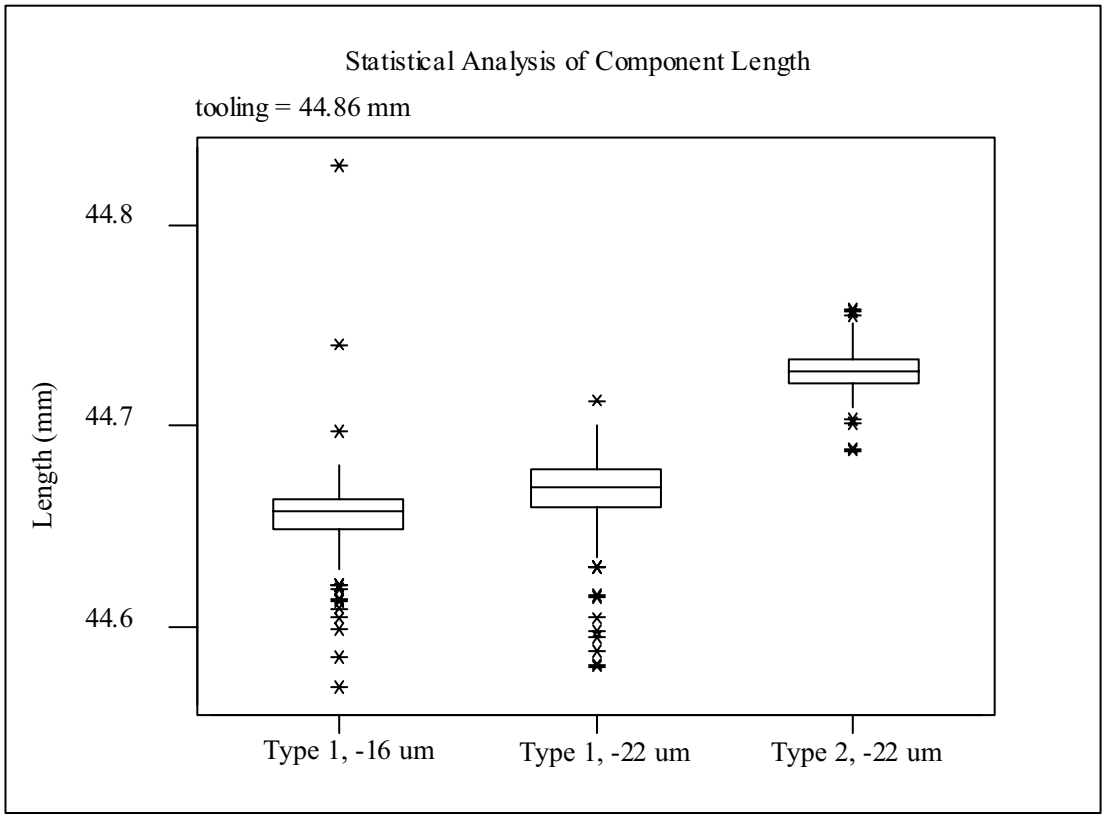

Figure 7: Variability of component length (solvent-debound components)

The variability after solvent debinding was observed to be higher than after molding. This behavior is independent of the powder type and particle size studied (see Table 2). A slight swelling occurred during solvent debinding which led to a decrease in the shrinkage of the components (see Table 1). The swelling seems to be binder-related and is probably caused by solvation of the wax component and a softening of the backbone binder component.

Conclusions

Dimensional variability was studied in dependence on the powder type and particle size. It was found that in the green and solvent-debound states, both dimensional variability and shrinkage increased with increasing particle size. Furthermore, components showed greater dimensional variability and less shrinkage after solvent debinding, suggesting that the components swell during solvent debinding, which could cause variability. The shrinkage of a core hole dimension (and also its variability) was consistently larger than that of the length of the part, leading to the conclusion that the components are subject to anisotropic shrinkage. As far as particle shape is concerned, it was observed that irregular powders with agglomerates and a wide particle size distribution result in better dimensional precision than rounded particles of the same mean size. Likely reasons for this are the fact that irregular particles “interlock” with one another and therefore provide better shape retention in the green and debound states and that wider particle size distributions produce better packing and more particle-particle contacts.

References

1. R. M. German and A. Bose, *Injection Molding of Metals and Ceramics*. Metal Powder Industries Federation, Princeton, NJ, 1997, pp. 231-239.
2. R. M. German, "A Rationalization of the Powder Injection Molding Process for Stainless Steels Based on Component Features," *Advances in Powder Metallurgy and Particulate Materials*, Metal Powder Industries Federation, Princeton, NJ, no. 5, 1998, pp. 71-83.
3. K. M. Kulkarni, "Dimensional Precision of MIM Parts under Production Conditions," *The International Journal of Powder Metallurgy*, vol. 33, no. 4, 1997, pp. 29-41.
4. T. Vonderohe, P. Hauck, T. McCabe, and J. Hastrich, "Dimensional Tolerance Control of PIM Parts in Production," *Advances in Powder Metallurgy and Particulate Materials*, Metal Powder Industries Federation, Princeton, NJ, no. 5, 1998, pp. 49-57.
5. K. F. Hens and J. A. Grohowski, "Advanced Quality Control for Precision PIM Components," *Advances in Powder Metallurgy and Particulate Materials*, Metal Powder Industries Federation, Princeton, NJ, 1995, no. 6, pp. 295-302.
6. C. M. Kipphut and R. M. German, "Powder Selection for Shape Retention in Powder Injection Molding," *International Journal of Powder Metallurgy*, 1991, vol. 27, pp.117-124.
7. Y. Li, B. Huang, and X. Qu, "Viscosity and melt rheology of metal injection moulding feedstocks," *Powder Metallurgy*, 1999, vol. 42, pp.86-90.
8. T. J. Weaver and R. M. German, "Achieving Real Dimensional Control of +/-0.1%," *Advances in Powder Metallurgy and Particulate Materials*, Metal Powder Industries Federation, Princeton, NJ, 1996, no. 19, pp. 233-241.
9. S. C. Hu and K. S. Hwang, "Length Change and Deformation of Powder Injection-Molded Compacts during Solvent Debinding," *Metallurgical and Materials Transactions A*, vol. 31A, 2000, pp. 1473-1478.
10. Y. Arakida and R. Miura, "Powder injection molding as a metal forming process – effects of powder morphology, size and size distribution," *Key Engineering Materials*, vol. 53-55, 1991, pp. 377-382.
11. L. V. Dihora, L. N. Smith, R. Orban and R. M. German, "Experimental Study and Neural Network Modeling of the Stability of Powder Injection Molding Feedstocks," *Materials and Manufacturing Processes*, 2000, vol. 15, no. 3, pp. 419-438.