Using Polymer Compounds in Place of Metal Material to Make Cost-Effective Parts

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ABSTRACT: The use of plastic materials in place of metals is attractive because of their versatility and ease of batch fabrication, which reduces costs. This article investigates the possibility of using nylon compounds in place of metal materials to make cost-effective parts through microinjection molding. Experimental results showed that the plastic parts were well formed with high accuracy and reproducibility through microinjection molding. The average tolerance in the dimensions of the plastic parts was less than 20 μm. The resulting composites with 15 wt % carbon particles exhibited the optimum improvement in accuracy, reproducibility, and wear resistance. In addition, the wear loss of the metal parts without lubrication was 4–10 times higher than that of the polymer compounds. The results revealed that the ball-screw plates made with nylon compounds exhibited high accuracy, reproducibility, and wear resistance, could be produced at low cost, and they could successfully replace S316 metal parts in microinjection molding. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 102: 1645–1652, 2006

Key words: nylon; polymer composite; accuracy; shrinkage; wear; microinjection molding

INTRODUCTION

Ball-sliding plates, ball-locking plates, adaptors, screws, etc. are widely used in advanced machines, such as IC packaging machines, IC inspection machines, microinjection machines, robots, automatic actuators, etc. The main function of these parts in machines is to transform line motion into back turn motion. This requires high accuracy, low noise, and low wear abrasion. Thus, cost-effective parts with high accuracy and wear resistance are in great demand.

The current manufacturing process uses metal powder injection molding to fabricate these parts.[1,2] Figure 1 shows the assembly of the linear guide-way and its components, including ball-sliding plates. However, high distortion often occurs in parts because they need to be sintered at high temperatures.[3–5] Thus, extra labor is needed to mill and polish parts to match the contours of related components. The cost of a metal part, such as a ball-sliding plate, can reach US $1.2 per piece. Competition will be dramatically increased in the market if the cost of such parts can be reduced to under US 30 cents per piece. This would save US $45,000 in a month if 50,000 pieces were fabricated. Thus, cost and accuracy are the main topics of this article. The batch fabrication of plastic materials with high accuracy through microinjection molding is found to be the best choice.

Plastic compounds, such as polyoxymethylene (POM) or acetal, Nylon, liquid crystal polymer, etc., are widely used in gears and fans, where high wear resistance and accuracy are required.[6,7] However, most parts such as gears and fans need to possess high strength, wear resistance, and accuracy, but plastic materials cannot satisfy these requirements. The inclusion of inorganic fillers in polymers for commercial applications is primarily aimed at improving stiffness.[8,9] Huang et al.[10] successfully made micro gears and pumps with POM compound through microinjection molding. It was found that POM with 20 wt % added glass fillers had the lowest wear abrasion and high accuracy. Thus, in addition to accuracy and wear, the cost of manufacturing can be dramatically reduced if ball-locking or ball-sliding plates can be made with plastic materials with added fillers through microinjection molding.

The microinjection molding process, which permits cost-effective mass production of micro structures from a wide variety of high-performance plastics, is a key enabling, specialized technique with a unique set of challenges.[11–15] Kukla et al.[16] defined microinjection molded parts as (1) parts with micro weight, (2) parts with micro structured regions, and (3) parts with mi-

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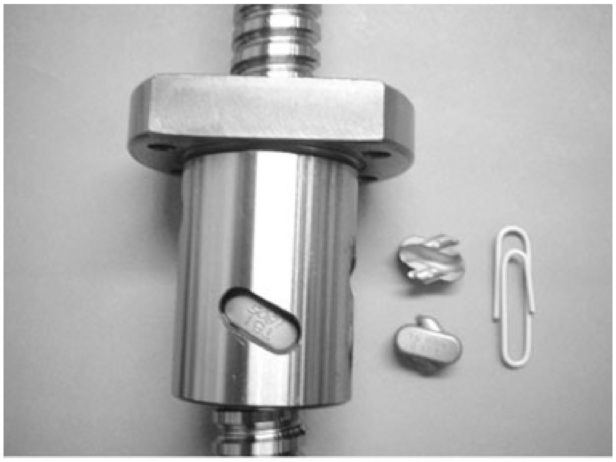

Figure 1 The assembly of the linear guide-way and its components, including ball-sliding plates.

cro precision dimensions. Parts with micro weight are parts with masses of a few milligrams, but their dimensions are not necessarily on the micrometer scale. Parts with micro structured regions are characterized by local micro features on the micrometer order, such as micro holes and slots. Parts with micro precision are parts of any dimension that have tolerances in the micrometer range. This article focuses on the third type, that is, molded parts with tolerance less than 20 μm.

In this study, instead of forming metal parts through metal powder injection molding, we formed plastic parts with high accuracy using microinjection molding. Ball-sliding plates, which are currently on the market, were studied and fabricated. To achieve the goal of high accuracy, the mold cavity was carved by means of micro electric discharge machining (μEDM) and micro wire EDM. Quality plastic parts were also molded using a precision injection machine, in which melt could be injected with precision on the order of micrograms. An arburg injection machine with 25 tons of clamping force was used to batch produce plastic parts. We aimed to cut the cost per piece from US $1.2 to 30 cents or less. The molding technique used here can also be extended to the production of other metal parts. Here, the critical properties, including shrinkage, accuracy, cost, wear abrasion, and strength, of nylon polymer with added micro particles were systematically established and compared with those of a metal material.[17,18]

EXPERIMENTS

Materials and specimens

High performance polymer nylon 66 is an engineering thermoplastic with excellent physical wear resistance, self-lubrication, and processing properties. Products produced with nylon 66 compound include rollers, bearings, gearwheels, etc. Thus, nylon 66 polymer was selected here as an experimental material to replace a metal material (S316 steel) that is widely used and commonly formed through metal powder injection molding. Plastic compounds with high accuracy were produced in batches through microinjection molding. The materials used in this study included pure nylon 66, nylon 66 with 15 wt % added glass fillers, and nylon 66 with 15 wt % added carbon fillers. The pure nylon 66 and nylon 66 with 15 wt % added glass fillers were made by Toray Industries, Japan. The nylon 66 with 15 wt % added carbon fillers was made by DSM Engineering Plastics, The Netherlands.

The ball-sliding plate had a width of 6 mm, a length of 13 mm, and a 3.5-mm pitch diameter, as shown in Figure 2. A round specimen with a diameter of 8 mm and a thickness of 10 mm was selected to perform wear tests (ASTM G 99−04). In addition, a dog-bone with a thickness of 4 mm, a width of 10 mm, and a length of 60 mm was selected to perform tensile tests (ASTM D 638).

Processing windows

The processing window is an effective tool for finding the range of processing parameters for manufacturing high quality parts. In this experiment, the injection pressure and the melt temperature were significant processing parameters. The injection pressure and melt temperature were also varied point by point to find the processing window. Short-shot or flash in parts was located outside the boundary of the processing window. The permissible injection pressure, called the mechanical ability, could not exceed 2300 bars in

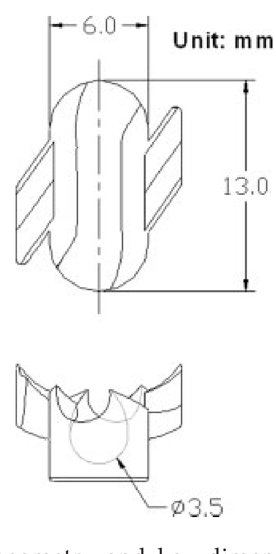

Figure 2 The geometry and key dimensions of the ball-sliding plate had a width of 6 mm, a length of 13 mm, and a 3.5-mm pitch diameter.

this window. All the tests were conducted using an Arburg injection machine (25 tons, 220S).

Quality evaluation

To examine the shrinkage and accuracy of the polymer compounds, parts made with nylon 66 with glass and carbon fillers were compared with metal parts in this study. They were measured with a coordinate measurement machine (CMM, Poly, Italy). The precision level of the measurements was 1 μm. The dimensions of the mold cavities for nylon 66 polymer and S316 metal were enlarged in advance by 1.3 and 19.5%, respectively, to compensate the shrinkage of parts. After molding, the S316 metal parts needed to be sintered at a temperature of 1300°C for 2 h. The pitch dominates the quality of ball-screw plates. Thus, here, the shrinkage in pitch of the ball-screw plate was analyzed. The shrinkage (η) could be calculated as follows:

$$\eta = \frac{p - p'}{p} \times 100\% \quad (1)$$

where represents the pitch dimension in the mold cavities, which were enlarged in advance by 1.3 and 19.5%, respectively, for the nylon 66 compounds and S316 metal. p' represents the pitch dimension in the parts that were measured after injection molding in the case of the nylon 66 compounds and sintered at a temperature of 1300°C in the case of the S316 metal. The average shrinkage of the parts was determined based on 10 specimens. The reproducibility of the parts was evaluated as a standard of accuracy. Ten measured plastic parts were selected from the 11th – 20th mold. That is, the first 10 pieces were discarded because their quality was unstable. The allowable deviation in the precision of parts currently available on the market is normally 20 μm. Thus, the level of accuracy achieved here was considered acceptable when the deviation in the precision of the parts was $<$20 μm.

Wear tests were carried out by using a pin-on-disk tester (Micro phonics, USA). The surface roughness of the disk, which was 120 mm in diameter, was 0.2 μm (Ra). Round specimens were placed in contact with the disk at a position located 37 mm from the center and rotated from 5000 (1.16 km) to 40,000 revolutions (9.30 km) with a step increase of 5000 revolutions at a constant speed of 70 rpm. The vertical load on the pin was 0.75 kg. The specimens were cleaned and dried after they were rotated. Then, the weight of each specimen was measured using an electronic weighing machine (Honeywell, UK). The weight loss (Wl) was then calculated as follows:

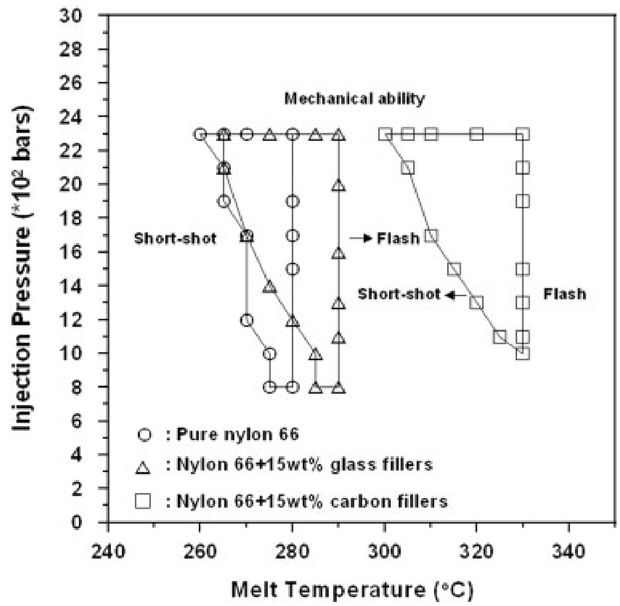

Figure 3 The processing window of the polymer with added fillers.

$$W\ell = \frac{W - W'}{W} \times 100\% \quad (2)$$

where W is the weight before wearing and W' is the weight after wearing. To achieve high quality, low weight loss is required. The tensile tests were conducted using a universal testing machine. The average strength was obtained from 10 specimens for every tested part.

RESULTS AND DISCUSSION

Filling behavior of the parts

The processing window of the polymer compounds is shown in Figure 3. The formability of a polymer compound is better when the processing window is larger. The quality of the parts is degraded when the processing parameters are outside the range of the window. Short-shot is produced in parts when processing exceeds the left-hand boundary of the window. Flash occurs in parts when processing exceeds the right-hand boundary of the window. In addition, the mechanical ability of the injection machine is exceeded when processing exceeds the top boundary of the window. The processing window of pure nylon 66 is smaller than those of the other two compounds. That is, short-shot or flash easily occurs in parts.

Here, the processing zone shifted to the right when fillers were added. In other words, the injection pressure and melt temperature had to be increased as the fillers were added. Short-shot parts were formed when the forming pressure and melt temperature

Figure 4 Photograph of ball-sliding parts made with S316 metal and nylon 66 compound.

were low. Higher melt temperatures between 300 and 330°C for polymer with 15 wt % added carbon fillers were applied for duplicating parts.

A photograph of plastic parts with the above processing window is shown in Figure 4. It can be observed from the photograph that the ball-sliding parts made with nylon 66 compound were well formed through microinjection molding. The parts in the upper left portion of the photograph were composed of S316 metal material and made through metal powder injection molding. The parts in the upper right portion were made with pure nylon 66, the parts in the lower left portion were made with 15 wt % added glass fillers, while the parts in the lower right portion of the photograph were made with 15 wt % added carbon fillers.

Reproducibility and cost of the parts made with polymer compounds and metal material

The reproducibility of ball-sliding plates is normally evaluated as a standard of accuracy. As shown in Table I, the average deviation between the designed and actual dimensions of the parts made with pure nylon 66 polymer, nylon 66 with 15 wt % added glass fillers, and nylon 66 with 15 wt % added carbon fillers was 18, 9, and 6 μm respectively. These results show that the reproducibility of the parts was outstanding, since the achieved tolerance level was <20 μm. That is, ball-sliding plates with high accuracy could be successfully made through microinjection molding. However, the tolerance of the metal parts varied randomly from 10 to 93 μm. The average tolerance of the metal parts was 47 μm, which was higher than the designed deviation. The tolerance of the metal was higher and varied randomly because they had to be sintered at a high temperature of 1300°C after metal injection molding. Thus, extra labor was needed to mill and polish the metal parts to match the contour of the assembly, leading to high cost per part. The metal parts exhibited the largest deviation in precision, while the parts made with nylon 66 compound with added carbon fillers exhibited the least deviation. That is, the reproducibility of the parts made with nylon 66 polymer with added carbon fillers was the best, while the reproducibility of the metal plates was the worst in this study.

TABLE I
Reproducibility and Cost of Ball-Sliding Parts Made from Plastic Compounds and a Metal Material (μm)

Material	Nylon 66			Nylon 66 + 15 wt % GB			Nylon 66 + 15 wt % CB			S316 metal		
Mold No.	Δw	ΔL	Δp	Δw	ΔL	Δp	Δw	ΔL	Δp	Δw	ΔL	Δp
1	−25	−25	−17	−25	−21	−14	+11	+9	+11	−20	−40	−25
2	−24	−24	−15	−24	−20	−14	+8	+7	+10	−80	−90	−60
3	−23	−24	−14	−13	−16	−10	+8	+7	+10	−15	−41	−10
4	−23	−24	−14	−13	−12	−6	+9	+6	+10	−35	−40	−32
5	−20	−20	−13	−11	−11	−6	+6	+7	+5	−68	−79	−33
6	−12	−13	−7	−6	−7	−3	+4	+2	+3	−32	−63	−20
7	−11	−13	−7	−6	−6	−2	+4	+3	+4	−63	−81	−30
8	−11	−14	−8	−4	−3	−1	+1	+1	+2	−93	−88	−48
9	−10	−13	−7	−3	−2	−2	+3	+2	+3	−51	−41	−30
10	−11	−13	−6	−2	−3	−1	+1	+2	+3	−41	−41	−25
Avg. dev.	−17	−18	−11	−11	−10	−6	+6	+5	+6	−50	−60	−31
Total avg. dev.		−18			−9			+6			−47	
Cost per piece (cost per 50,000 pieces)[a]	US 20 cents (US $10,000)			US 20 cents (US $10,000)			US 30 cents (US $15,000)			US $1.2 (US $60,000)		

Designed dimensions: width (w) = 6 mm, length (L) = 13 mm, pitch diameter (p) = 3.5 mm. Δ, Deviation between the actual and designed dimensions of the ball-sliding plates, e.g., $\Delta w = 5.975 - 6 = -0.025$mm $= -25$ μm for the 1st mold for nylon 66. + (−), Actual dimension higher (lower) than the designed dimension.

[a] 50,000 pieces needed in a month.

As shown in Table I, the average tolerances of the parts made with pure nylon 66 polymer in terms of width for the first five molds were 25, 24, 23, 23, and 20 μm, respectively, all of which were higher than the total average tolerance of 18 μm. However, the average tolerances stayed between 10 and 12 μm after the fifth mold was produced. The same situation occurred with the length and pitch. In fact, the measured samples were chosen from among the 11th – 20th pieces because the previous pieces were low in quality. The same situation also occurred with parts made with polymer with added glass or carbon fillers. Faulty parts were often produced at the beginning because of unstable mold and melt temperatures. That is, high quality parts could only be fabricated when the mold and melt temperatures were stable.

The cost of the ball-sliding plates made with pure nylon 66 polymer or nylon 66 with 15 wt % added glass fillers was US 20 cents per piece, while it was US 30 cents for those made with nylon 66 polymer with 15 wt % added carbon fillers. However, the cost of the metal parts reached US $1.2 each, about 5 times higher than that of the parts made with the polymer compounds. The total cost included the cost of the mold, material, molding, and assembly. The ball-sliding plates made with any kind of nylon 66 polymer compound through microinjection molding exhibited high accuracy and required less labor. Meanwhile, the ball-sliding plates made with the S316 metal material exhibited low precision and required more labor. The cost savings would be US $45,000–50,000 if the metal was replaced with polymer compounds with microinjection molding and if 50,000 pieces were fabricated per month. The results show that the accuracy and cost of the ball-sliding plates made with nylon 66 compound were far better than those of the metal parts.

Shrinkage analysis of polymer compounds and metal

The pitch shrinkage results for the nylon 66 compound with different added fillers and S316 metal are shown in Figure 5. The average shrinkage in the pitch of the parts made with pure nylon 66 polymer, nylon 66 with 15 wt % added glass fillers, and nylon 66 with 15 wt % added carbon fillers was 1.6, 1.46, and 1.13%, respectively. Nylon 66 with 15 wt % added carbon fillers exhibited the least shrinkage. The shrinkage of polymer with 15 wt % added glass fillers was next greatest. The shrinkage of polymer with 15 wt % added carbon fillers was 0.34% lower than that of pure nylon 66. This clearly shows that adding fillers to the polymer effectively reduced shrinkage. When the polymer was in the melting stage, the fillers with lower expansion coefficient reduced the activity of the molecules, resulting in significantly lower volume expansion of the molecules. Then, crystallization of the molecules was retarded by the fillers during the frozen stage. Thus, shrinkage was reduced when fillers were added to the polymer.

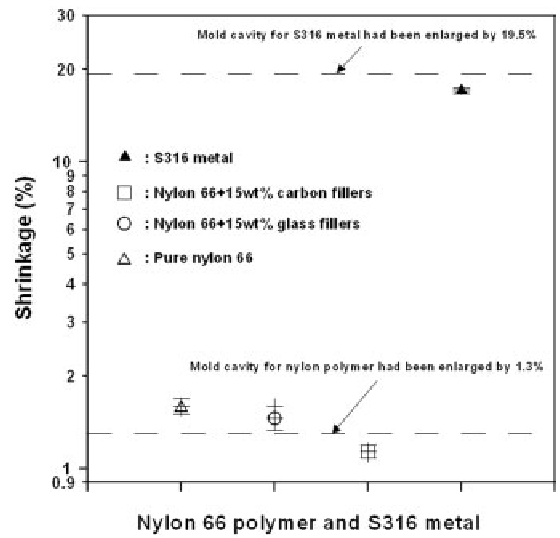

Figure 5 The pitch shrinkage results for the parts made with nylon 66 compound with different added fillers and S316 metal.

However, the shrinkage in the pitch of the parts made with S316 metal was 17.07%, which represented a 2.43% deviation from the designed shrinkage. The shrinkage of the S316 metal parts was difficult to control because they had to be sintered at a high temperature of 1300°C after metal injection molding. The tolerance in the metal parts, thus, was higher and random. The results revealed that the nylon composites made through microinjection molding exhibited significantly lower tolerance and shrinkage than the S316 metal parts made using metal injection molding did.

As Figure 5 shows, larger error deviations occurred with the polymer compound with added glass fillers. We speculated that a possible reason could be that the glass particles were not uniformly distributed in the polymer compound. To determine the actual reason for this result, an scanning electron microscopy (SEM;, Jeol, JSM-6700F) image of the polymer compound with 15 wt % added glass fillers was taken and is shown in Figure 6. The nylon 66 compound with 15 wt % added glass fillers showed agglomeration. Large error deviations among the 10 specimens thus occurred, because the glass particles were not uniformly distributed in the polymer compound.

Meanwhile, smaller error deviations occurred in the case of the polymer compound with added carbon fillers. The particles were uniformly distributed in the polymer compound with 15 wt % added carbon fillers, as shown in Figure 7. The error deviations among the 10 specimens were small, because the carbon particles

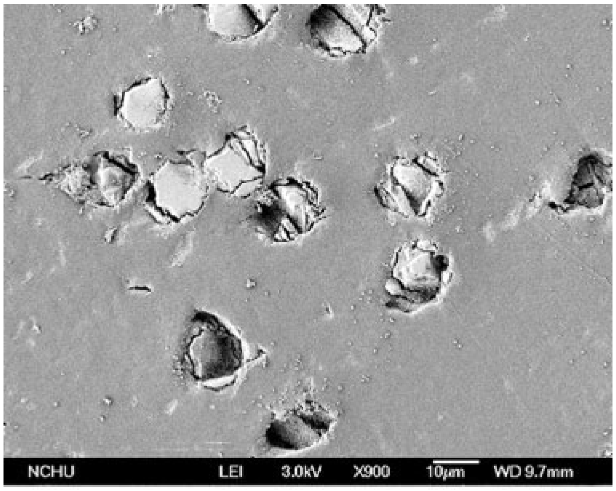

Figure 6 SEM image of polymer nylon 66 with 15 wt % added glass fillers.

were uniformly distributed in the polymer compound. The same conditions were found in the tensile tests, which will be discussed in the last section. The varying uniformity of the different fillers induced error deviations in shrinkage and strength. The kneading of the polymer and fillers was the key factor affecting the uniformity of the composites.[9,10] The nylon compounds with added glass and carbon fillers, respectively, were provided by different vendors. Thus, uniform distribution of fillers in polymers is required for the production of reinforced composites.

A photograph of three different ball-sliding plates, which were used to verify the measured shrinkage of the polymer compounds, is shown in Figure 8. The ball-sliding plates at the top had a width of 3 mm and a length of 13 mm, and were made with pure nylon 66. The mold cavity had previously been enlarged by 1.6%. The ball-sliding plates at the bottom left had a width of 5 mm and a length of 11 mm and were made with nylon 66 with 15 wt % added glass fillers. This mold cavity had previously been enlarged by 1.5%. The ball-sliding plates at the bottom right were made with nylon 66 with 15 wt % added carbon fillers. In this case, the mold cavity had previously been enlarged by 1.2%. It can be observed from the photograph that the plastic parts were well formed through microinjection molding. The average tolerances of the plastic parts, made in mold cavities that had been enlarged, were between 3 and 6 μm, which was far less than 20 μm. The results clearly show that plastic parts could be made with high precision and reproducibility when precise shrinkage was achieved in the mold cavity.

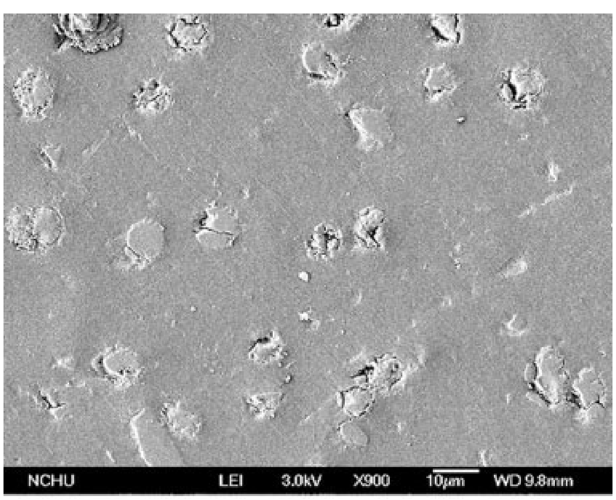

Figure 7 SEM image of polymer nylon 66 with 15 wt % added carbon fillers.

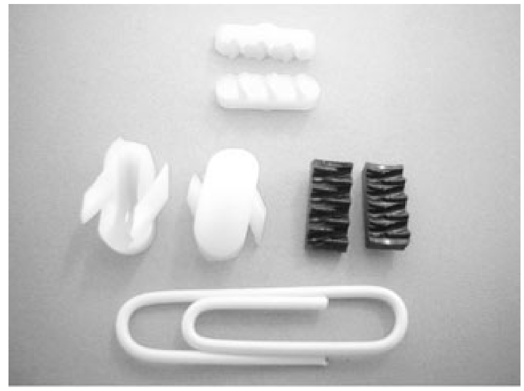

Figure 8 Photograph of ball-sliding plates with measured shrinkage.

Wear behavior of metal and polymer compounds with added fillers

The weight loss of the nylon 66 compounds with different added fillers and the S316 metal is shown in Figure 9. The surface roughness of the wear disk was 0.2 μm (Ra). The wear loss increased steadily as the rotation distance increased for every tested specimen. The weight loss reached 3.44, 0.81, 0.38, and 0.16%, respectively, for the metal, pure nylon 66, nylon 66 with 15 wt % added glass fillers, and nylon 66 with 15 wt % added carbon fillers after the specimens were rotated ~9 km. The weight loss of the S316 metal increased significantly, while the weight loss of the nylon 66 compound with added carbon fillers increased very little. The pure nylon 66 and nylon with 15% added carbon fillers resisted wear abrasion applied 4 and 10 times, respectively, more than the metal material did. This contradicts the intuition that metal exhibits better wear resistance.

To understand the wear behavior of the nylon 66 polymer and S316 metal, an SEM image of the pure nylon 66 polymer following wearing was taken and is

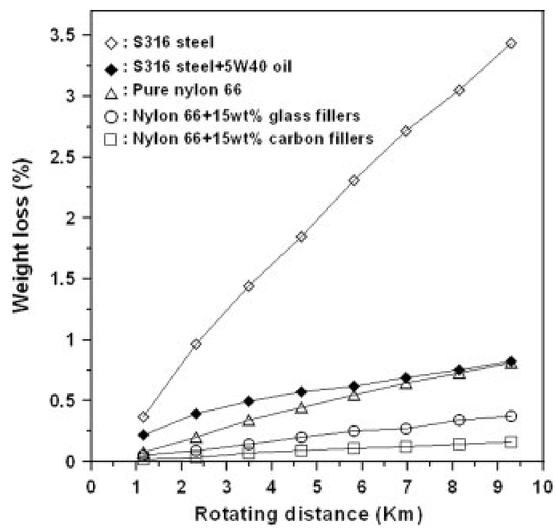

Figure 9 Weight loss for S316 metal and nylon 66 compound with different added fillers as determined through wear tests.

shown in Figure 10. The worn surface of the pure nylon 66 was slightly damaged, because nylon 66 polymer is self-lubricating and can resist wear abrasion. On the other hand, the worn surface of the S316 metal showed serious damage, as shown in Figure 11, resulting in significant weight loss. In addition, 5W40 oil (Aral, Germany) was used to lubricate the disk surface as a metal specimen was wearing. The weight loss of the metal specimen was effectively decreased when lubrication oil was added to its 0.2 μm rough surface. The weight loss of the metal material with 5W40 lubrication was very close to that of the pure nylon 66 polymer. However, the lubrication oil easily induced pollution and increased the required labor.

In contrast, the weight loss decreased significantly when fillers were added to the polymer compound.

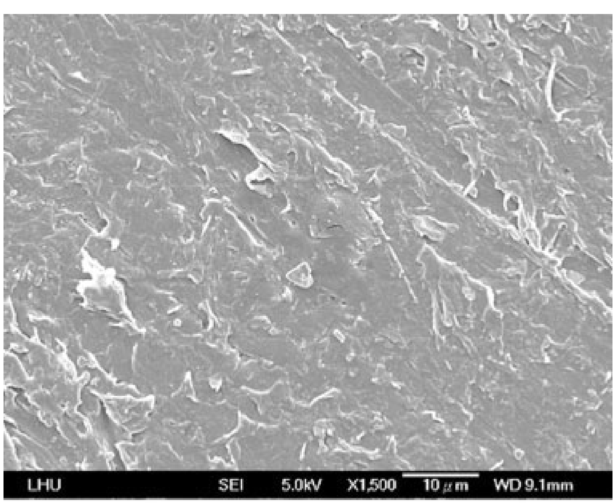

Figure 10 SEM image of pure nylon 66 polymer after wearing.

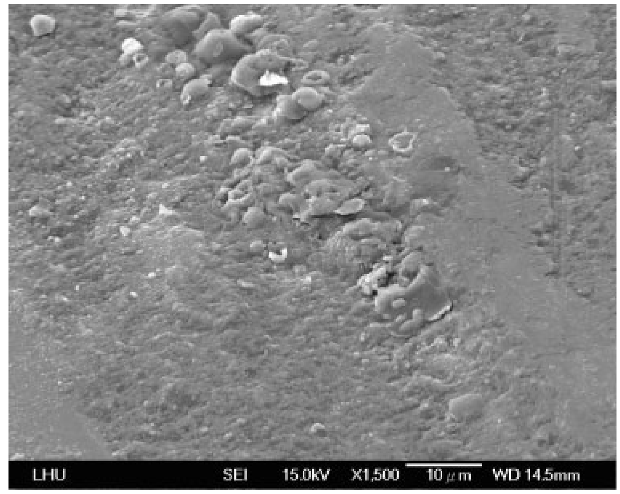

Figure 11 SEM image of S316 metal after wearing.

The weight loss decreased by 0.43 and 0.65%, respectively, for polymer compound with added glass and carbon particles when compared with pure nylon 66. The wear abrasion was the least in the case of nylon 66 polymer with added carbon fillers. During wearing, the polymer in the compound was stripped, leaving only the carbon fillers, which were much harder than the polymer or glass fillers and resisted wear abrasion. After the fillers were worn down, the next layer of polymer compound continued to wear. This clearly shows that adding fillers to the polymer effectively increased the wear resistance, especially in the case of polymer with carbon filler. The results revealed that nylon 66 polymer compound is a good wear-resisting material that can replace metal material. Nylon 66 polymer with added carbon fillers exhibited the best wear resistance in this article. Nylon 66 polymer with added glass fillers exhibited the next best wear resistance.

Mechanical properties of metal and polymer compound with added fillers

The tensile strengths of the nylon 66 polymer with added different fillers and S316 metal is shown in Figure 12. The tensile strength increased significantly when fillers were added in the polymer. This result agrees with the rule of mixtures,[19] which says that the mechanical properties of a polymer compound are proportional to the weight fractions of the polymer and filler. The tensile strengths of the polymer compound with 15 wt % added glass fillers and carbon fillers were 16.73 and 32.05%, respectively, which were higher than that of pure nylon 66. These results show that the mechanical properties of the nylon 66 polymer could be effectively improved by adding fillers.

The average tensile strength of the S316 metal exceeded that of the pure nylon 66 and the nylon 66 with

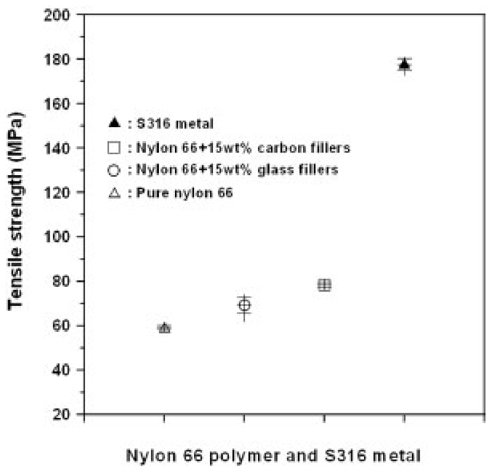

Figure 12 Tensile strengths of nylon 66 polymer compound and S316 metal.

15 wt % added carbon fillers by 2 and 1.3 times, respectively. These results agree with those obtained in another study,[20] in which the strength of a metal was several times that of plastics. The ball-screw plates made here nylon compounds were not stronger than the metal ones, but that they exhibited high precision in dimension, high reproducibility, low wear abrasion, and low cost, and could replace metal in the near future.

Larger deviations in strength occurred in the polymer with 15 wt % added glass fillers. The glass particles agglomerated in the polymer with 15 wt % added fillers, as discussed in *Shrinkage analysis of polymer compounds and metal* section, resulting in large error deviations. Distributing such fillers uniformly in polymer is the best way to decrease such large deviations in strength.

CONCLUSIONS

Ball-sliding plates made with nylon 66 polymer compounds in this study exhibited excellent accuracy, reproducibility, and wear resistance, and low cost, and could successfully replace S316 metal parts made through microinjection molding. The total average tolerances between the designed and actual dimensions of the polymer compound were between 6 and 18 μm, which was less than the designed tolerance of 20 μm. The results showed that the reproducibility of the ball-sliding plates with added glass or carbon fillers was outstanding. The cost of the plastic parts was reduced from US $1.2 to 30 cents per piece.

Shrinkage was significantly reduced when fillers were added. Nylon 66 polymer with added carbon fillers exhibited the least shrinkage, while pure nylon 66 polymer showed the greatest shrinkage. Three different ball-sliding plates made with pure nylon 66, nylon 66 with added glass fillers, and nylon 66 with added carbon fillers, respectively, were well formed, based on the measured shrinkages. In other words, highly dependable plastic parts could be precisely fabricated through microinjection molding.

The weight loss of the nylon 66 compound was far less than that of the metal material because nylon 66 polymer is self-lubricating and can resist wear abrasion. In addition, the weight loss decreased significantly when fillers were added to the polymer compound. The nylon 66 polymer with added carbon fillers exhibited the best wear resistance. The tensile strength increased significantly when fillers were added in the polymer. Larger amounts of added glass fillers agglomerated easily and were not uniformly dispersed in the polymer, resulting in large shrinkage and strength deviations. Thus, distributing glass particles uniformly in polymer is important for producing high quality parts.

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