A PERFORMANCE STUDY OF PRODUCTION TOOLING OBTAINED BY A P/M ROUTE

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ABSTRACT

The present study examines the durability of a mold insert produced by a recently developed rapid tooling method based on powder metallurgy principles. The mold insert was made for a standard multi-unit die frame fitted into an injection molding machine. An unfilled reground mixture of polyethylene and polypropylene was injection molded using the mold insert. The wear of the mold insert and the molded parts were monitored by tracking changes in weight, surface roughness, and dimensions during a long production run. It was determined that there was no appreciable wear on the mold insert after the injection molding of 20,000 plastic parts.

INTRODUCTION

Rapid fabrication methods for tooling are driven by reducing the time for delivering a product to the market. There are currently various rapid tooling methods for injection molding. These approaches are governed by the length of the manufacturing cycle targeted for the tooling. Prototype tooling is usually less durable with thermal conductivities that do not support short cycle times [1]. Desirable attributes for a production tool are: (1) smooth surface; (2) good mechanical properties; (3) superior wear resistance; (4) good thermal conductivity; (5) simple fabrication process; (6) little or no post processing [2].

Recently a material and process have been developed for making mold inserts for injection molding [2]. In this process a master of the desired part is used to fabricate a silicone rubber mold. The silicone mold is then used to cast a feedstock. The green part is removed and sintered. A mold insert manufactured by this rapid tooling process was used in the present study.

The rapid tooling process has the characteristics listed in the following table.
Table I. Characteristics of the Present Process

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Numerical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse Rupture Strength, MPa</td>
<td>800 ± 50</td>
</tr>
<tr>
<td>Impact Strength, J</td>
<td>8 ± 1</td>
</tr>
<tr>
<td>Wear Volume, mm³</td>
<td>30 ± 10</td>
</tr>
<tr>
<td>Hardness, HRC</td>
<td>35 ± 5</td>
</tr>
<tr>
<td>Surface Roughness, R₉ μm</td>
<td>1.2 ± 0.1</td>
</tr>
<tr>
<td>Tolerance, %</td>
<td>0.2</td>
</tr>
<tr>
<td>Time to Fabricate, days</td>
<td>5</td>
</tr>
</tbody>
</table>

In this paper a mold insert was fabricated using this process and tested in a 30-ton Engel injection molding machine. 20,000 plastic parts were molded in this insert without any wear. Further testing with the injection molding of filled nylon is in progress. An overview of other tooling applications such as mixing paddles for extruders are also presented.

EXPERIMENTAL

Injection Molding
The mold insert was fitted into the multi unit die (MUD) frame on the Engel 30-ton injection molding machine. A reground mixture of polypropylene and polyethylene was injection molded using an Engel 30-ton injection molding machine. The parameters in the table below were used.

Table II. Injection Molding Parameters for Mixed Polypropylene and Polyethylene

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Speed Profile, mm/s</td>
<td>100</td>
</tr>
<tr>
<td>Mold Temperature, °C</td>
<td>10</td>
</tr>
<tr>
<td>Barrel Temperature, °C</td>
<td>190 / 200 / 200 / 160</td>
</tr>
<tr>
<td>Switchover Pressure, bar</td>
<td>45</td>
</tr>
<tr>
<td>Packing Pressure Profile, bar</td>
<td>40/30/20/15</td>
</tr>
<tr>
<td>Packing Time, s</td>
<td>10</td>
</tr>
<tr>
<td>Cooling Time, s</td>
<td>13</td>
</tr>
</tbody>
</table>

During the injection molding study, the following tool and part sampling procedures were employed. The mold insert was removed for quantitative and qualitative analysis after 450, 1,450, 2,500, 5,000, 10,000, 15,000 and 20,000 parts were molded. The mold insert was weighed to determine any weight loss due to wear. Measurements of critical dimensions were also noted to quantify wear. Surface roughness measurements were taken on the mold face at each interval. Plastic parts were also removed for dimensional characterization. Every 10th part molded, up to the 100th part was set aside for analysis. After the 100th part every 100th part was removed and characterized up to the 1,500th part. Between 1,500 and 5,000 parts, 10 parts were sampled in the neighborhood of every 500th part. Subsequently, sampling occurred at every 1,000th part to 20,000 parts. Features that could be easily dimensioned in a repeatable manner were identified and measured. Part-to-part variations in dimensions were noted.

Measurements
The Optical Gaging Products Smartscope was used to make measurements on the mold insert. The Smartscope is a system that allows the user to define the features to be measured visually. A computer mouse is used to outline the desired features of the sample on the video image. The software then makes
the measurements from the outline. Vernier callipers and a micrometer screw gage were used to measure the thickness of the plastic parts.

**Surface Roughness**

Surface roughness measurements were obtained using a Brown and Sharpe Pocket Surf. These measurements were taken on the master and the resulting mold insert during various stages of service. The values for the roughness average ($R_a$, $\mu m$) were recorded. The Pocket Surf was calibrated before any measurements using a reference specimen and a riser plate.

**RESULTS**

Figure 1 shows the mold insert and the injection molded mixed polyethylene and polypropylene part. Using the mold insert shown, 20,000 plastic parts were injection molded. Figure 2a is a schematic of the mold insert detailing the location where dimensions were taken. Figure 2b shows the locations of thickness dimensions on the plastic part.

Figure 3 is a graphical representation of the weight of the mold insert versus the number of plastic parts molded. It can be observed that there was no measurable weight change. Figure 4 shows the surface roughness of the mold cavity as a function of the number of plastic parts molded. It can be seen that the surface roughness remains unchanged.

Figure 5 shows dimensions taken from the mold insert at various intervals during the molding cycle. Measurements were taken from the locations described in Figure 2a. It can be observed that there is no change in the dimensions of the mold insert. This implies that no wear has taken place. Figure 6 shows measurements taken from the molded plastic part from the locations described in Figure 2b. These dimensions also show no change as a function of the number of parts molded.

**DISCUSSION**

The results show that the present rapid tooling process can be used to make production quantity injection molded parts. A decrease in the mold insert weight would have indicated mold insert wear; however, no weight loss was observed for the 20,000 parts that were molded. The surface roughness also remained the same as a function of the number of parts molded. The various dimensions on the mold insert and on the part also remained unchanged. The above observations conclusively demonstrate that there was no measurable wear.

Inserts made using processes such as the Direct Aim®, vacuum-cast epoxy, machinable composite board, aluminum, and P-20 steel are capable of making $25^\circ$, $100^\circ$, $1000^\circ$, and $10,000^\circ$ ABS parts respectively [1]. When compared to other tooling methods such as epoxies, CNC machined aluminum and the laser sintered rapid tool, the present process provides a significant time saving since it only takes 5 days to make a tool while the other methods have a delivery in the neighborhood of 2 weeks [3]. The current process also offers a significant time saving when compared to the 4 weeks that it takes for traditional machined steel tooling to be fabricated [1]. Using ABS the cycle times for Direct AIM, vacuum-cast epoxy, aluminum 7075 and P-20 steel tools were 4.5, 4, 0.5, and 0.5 minutes respectively [1]. The present material showed a cycle time of 0.5 minutes for the regrind mixture of polyethylene and polypropylene. The present process has the potential for embedding conformal cooling channels. Depending on the cooling channel geometry the cycle time could be reduced further [4]. The surface finish of the present process is currently $R_a < 1.2 \mu m$ compared to the $R_a < 0.03 \mu m$ of a machined tool steel. Final grinding as well as process modifications can be used to further improve the surface finish.
Figure 7 shows the wear of various tooling materials in terms of volume loss of material (ASTM G65-94A). The material made by the present process shows a volume loss of $30 \pm 10 \text{ mm}^3$. This is comparable to wear values of M2 and D2 tool steels. This plot indicates the strong potential for fabricating production quality tooling using the present material.

The present process has also been used for developing mixing paddles for a twin screw extruder. The mixing paddles were approximately 0.5" X 1" X 2" and have either a flat or helical profile (Figure 8). For this application, the dimensions were required to be within 0.002". The paddles showed no dimensional change after compounding 400 kg of alumina. In another test, a 300 kg mixture of epoxy resin and silica were compounded. The weight loss and dimensional change from the paddles made by the present process was similar to those of paddles fabricated using A-11 tool steel. The present process will also be used in the fabrication of prototype die compaction punch sets in the future.

SUMMARY

This paper details the capabilities of a recently developed rapid tooling process. It is concluded that tooling within $\pm 0.2 \%$ dimensional precision of the master can be fabricated in $\sim 5$ days. The tooling had a surface roughness of $1.2 \pm 0.1 \mu m$, transverse rupture strength of $800 \pm 50 \text{ MPa}$, impact energy of $8 \pm 1 \text{ J}$, hardness of $35 \pm 5 \text{ HRC}$, and a wear of $30 \pm 10 \text{ mm}^3$.

Applications were developed in the areas of injection molding tool sets and mixing paddles for twin-screw extruders. In the application of the injection mold insert, 20,000 mixed polypropylene and polyethylene parts were molded without measurable wear. In the paddle application, the precision required for a moving part could be achieved. 400 kg of an alumina-polymer feedstock were compounded in the extruder without measurable wear on the paddles. The compounding of 300 kg mixture of an epoxy resin and silica indicated that the current material had similar wear properties as A-11 tool steel. Numerous other opportunities await exploration for this promising technology.

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REFERENCES

Figure 1. Mold insert and fabricated plastic part

Figure 2. Dimensional measurement locations on mold insert and fabricated plastic part.
Figure 3. Change in weight of the mold insert through the production cycle

Figure 4. Change in surface roughness of the mold insert cavity through the production cycle
Figure 5. Change in dimensions of the mold insert through the production cycle.
Figure 6. Change in dimensions of molded parts through the production cycle.
Figure 7. Wear properties of tooling materials (ASTM G65 – 94 Method A).

Figure 8. Mixing paddles fabricated using the present process.