Fundamental Study on Influence of Ground Surface Characteristics on Mold Releasability in Compression Molding of Thermosetting Phenol Resin

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In the compression molding of thermosetting resins, surface characteristics of the metal molds, such as wear resistance, corrosion resistance, and mold releasability, are important for the stable mass production of high-quality products. The surface coatings are generally applied to improve the surface characteristics of the metal molds. However, the thickness of the surface coatings is limited to only a few micrometers since the surface coatings should guarantee the shape accuracy of the metal molds. Because of the thin coatings, the finished surfaces of the metal molds often affect the mold releasability. This study experimentally investigated the mold releasability from the ground surfaces. A thermosetting phenol resin was compression-molded onto the ground surface with different surface roughnesses. Then, the influences of surface characteristics on the mold releasability from ground surfaces were discussed by measuring tensile load when the molded resin was vertically separated from the ground surface as the mold release force. As a result, it was found that there was a maximum height roughness Rz of the ground surface where the mold release force became lower. Therefore, the relationship between the surface roughness profile of the ground surface and the mold releasability was investigated.

NOMENCLATURE

R_z = maximum height roughness
R_{pk} = reduced peak height
R_{vk} = reduced valley depth

1. Introduction

In the production of plastic products, the characteristics of the metal molds are important for the stable mass production of high-quality products. For example, characteristics such as wear resistance, corrosion resistance, and mold releasability are important. Accordingly, surface coatings with high hardness and corrosion resistance are generally applied to the metal molds. However, the surface coatings of the precision metal molds pose a problem of life in continuous production because only thin coatings with a thickness in the order of micrometers can be deposited to maintain the shape accuracy of the metal molds. In addition, the surface profiles of the precision metal molds with the thin coatings often affect mold releasability since the machined surfaces of the precision metal molds are directly transferred to the molded products. For example, there are research reports in which the mold release forces in transfer molding and injection molding were measured[1), 2)]. However, the mold release forces from the machined surfaces of the precision molds have not been clarified. Therefore, measuring of the mold release forces from the machined surfaces of the metal molds and improving the mold releasability are an important approach in the mass production of plastic products.

In this study, the mold release releasability from ground surfaces, which are widely used as finished surfaces for precision metal molds, was experimentally investigated. Thermosetting phenol resin was compression-molded onto workpieces of the ground surfaces with different surface roughnesses, and the load when the molded resin was released from the ground surface in the vertical direction was measured as the mold release force[3)]. Then, the influence of the surface roughness profile of the ground surface on the mold releasability and the mold release factors were investigated.

2. Mold Releasability Test for Ground Surface

2.1 Workpiece of Ground Surface

As the ground surfaces used in the mold releasability test, workpieces with different surface roughness were prepared by varying the grinding wheels and grinding process conditions. The SEM images of the ground surfaces and the processing conditions are shown in Fig. 1. The surface of cold die steel SKD11 (width of 28 mm, length of 31 mm, thickness of 5 mm) was ground with a vitrified bonded wheel with alumina abrasive grains (Noritake Co., Limited) using an NC surface grinding machine (Okamoto Machine Tool Works, Ltd. , KSK-Z1). Five types of workpieces with different R_z were prepared by varying the abrasive grain size of the grinding wheel and the step amount of the grinding wheel. The SEM images show that the pitch of grinding marks increases as the R_z increases, which means that the surface profile changes. In this experiment, ten or more workpieces were prepared under the same processing conditions, and the mold releasability tests were carried out on each of the processed surfaces immediately after grinding.

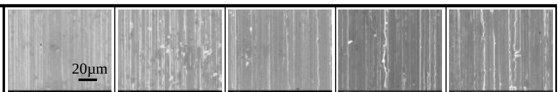
SEM image						
Workpiece		G320s1	G320	G120	G60s2	G60
R_z		0.85 μm	1.44 μm	2.00 μm	2.78 μm	3.30 μm
Feed speed		1300 mm/min				
Grinding allowance		Rough: 0.017 mm [Grinding depth: 0.002 mm] Fine: 0.003 mm [Grinding depth: 0.001 mm]				
Step amount		Rough: 2.00 mm Fine: 1.00mm	Rough: 5.00 mm Fine: 4.00 mm	Rough: 5.00 mm Fine: 4.00 mm	Rough: 4.00 mm Fine: 2.00 mm	Rough: 5.00 mm Fine: 4.00 mm
Grinding wheel	Abrasive grain	WA				
	Grain size	320	320	120	60	60
	Grade	H				
	Structure	8				
	Bond	V32R		V35R		

Fig.1 Ground surfaces and ground conditions

2.2 Thermosetting Phenol Resin Tablet

Phenol resin is a typical thermosetting resin used in the plastic molding market. Therefore, a novolac-type phenol resin was used as the molding material in the mold releasability test. Table 1 shows the compounding ratio of the thermosetting phenol resin. A powdered phenol resin containing a curing agent was used as the base resin. Glass beads with a particle size of 20 to 30 µm were mixed as an aggregate to increase the mechanical strength of the molded resin. In addition, an infinitesimal amount of powdered zinc stearate was added as a wax constituent to achieve boundary separation between the ground surface of the workpiece and the molded resin.

About 60 µL of ethyl alcohol was added as a binder to each material mixed based on the compounding ratio in Table 1, and the mixture was stirred. Next, the mixture was compressed into a cylindrical shape using a mold to prepare a tablet as a molding material. Here, the compounding amount of each material shown in Table 1 means the amount of one tablet.

Table 1 Composition of thermosetting phenol resin

Component	Volume [%]	Volume [mm^3]	Weight [g]
Phenol resin powder (Lignyte Co., LTD., LR-412)	30	457.8	0.69
Glass filler (Unitika LTD., UB-02EG)	70	1068.2	2.78
Zinc stearate	–	–	0.0080

2.3 Mold Releasability Test with Compression Molding

A schematic diagram of the mold releasability test equipment for compression molding of thermosetting resin is shown in Fig. 2. First, a workpiece with the ground surface facing up heated to the molding temperature is set into a holder, and a metal mold also heated to the molding temperature is temporarily clamped to the workpiece surface. Next, a thermosetting phenol resin tablet and a plunger are put into the metal mold, and compression molded. After holding the resin tablet, the plunger and the workpiece for the curing time, the metal mold with a molded resin is raised at a constant mold release speed. Then, the maximum tensile load at the moment when the ground surface and the molded resin are vertically separated is measured as the mold release force. Table 2 shows the mold releasability test conditions. The ground surface of the workpiece was compression-molded with the thermosetting phenol resin into a circular shape with a diameter of 14 mm for 10 minutes at a molding pressure of 0.82 MPa. After that, the mold release force was measured when the molded resin and the ground surface were separated vertically at a constant speed of 10 mm/min. Fig.3 shows the results of the mold release force measurement on the ground surface (R_z 2.87 µm). It can be seen that the maximum tensile load was measured as the mold release force.

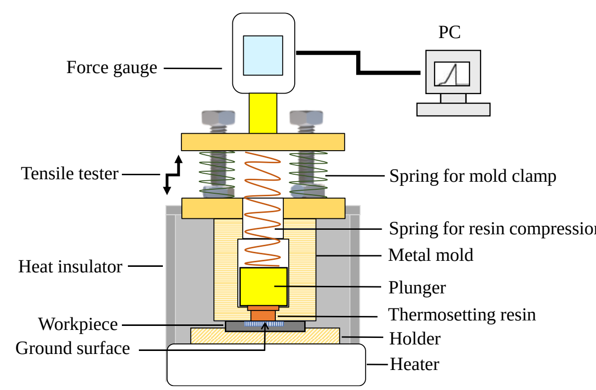


Fig.2 Schematic diagram of mold releasability test equipment

Table 2 Releasability test conditions

Mold clamping force	250 N [25 kg]
Molding pressure	0.82 MPa [8.36 kg/cm^2]
Molding speed	100 mm/min
Molding temperature	423 ± 5 K [150 ± 5 °C]
Cure time	10 min
Separation speed	10 mm/min
Contacting area	154 mm^2 [Φ14 mm]

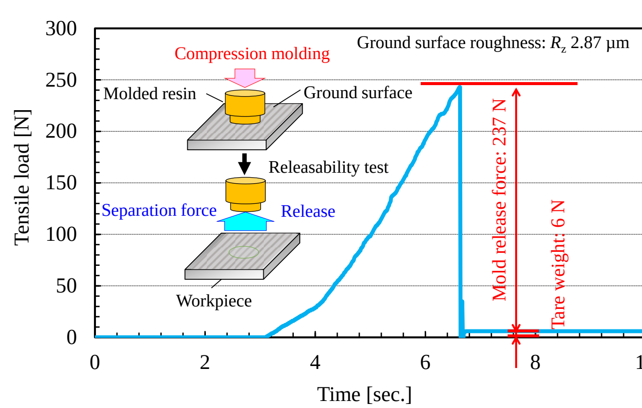


Fig.3 Variation of tensile load and mold release force from the ground surface

3. Results of Mold Releasability Test on Ground Surface

3.1 Relationship Between Surface Roughness and Mold Release Force

Fig. 4 shows optical micrographs of the ground surface and the molded resin surface after the mold releasability test. As the R_z of the ground surface decreases, the molded resin partially adheres onto the workpiece surface. Therefore, it is clear that the formability deteriorated due to the cohesive failure of the molded resin when the R_z of the ground surface is too small.

Fig. 5 shows the relationship between the mold release force measured by the mold releasability test and the R_z of the ground surface. It can be seen that the mold release force of the ground surface has an inflection point where the mold release force becomes the lowest in the range of R_z 2 to 3μm.

Next, the cohesive failure rate of the molded resin was calculated using equation (1) as an index of the formability of the thermosetting phenol resin on the ground surface. Fig. 6 shows the relationship between the cohesive failure rate of the molded resin after the mold release test and the R_z of the ground surface. The cohesive failure rate decreased as the R_z of the ground surface increased. Similar to the results of the mold release test in Fig. 3, the formability deteriorated as the R_z decreased.

$$\text{Cohesive failure rate} = 1 - \frac{\text{Maximum height roughness } R_z \text{ of ground surface}}{\text{Maximum height roughness } R_z \text{ of molded resin surface}} \quad (1)$$

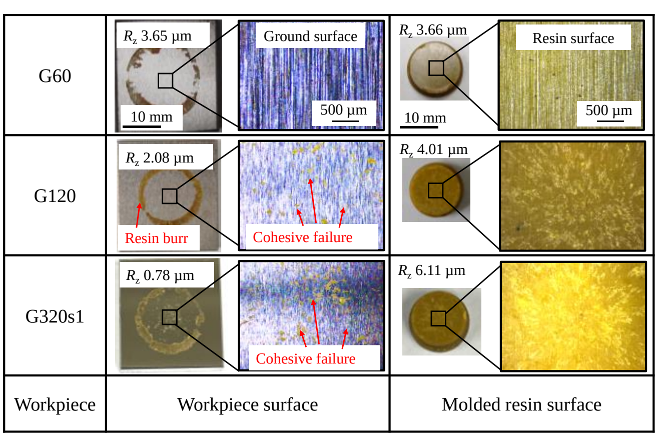


Fig.4 Ground surfaces and molded resin surfaces after mold releasability tests

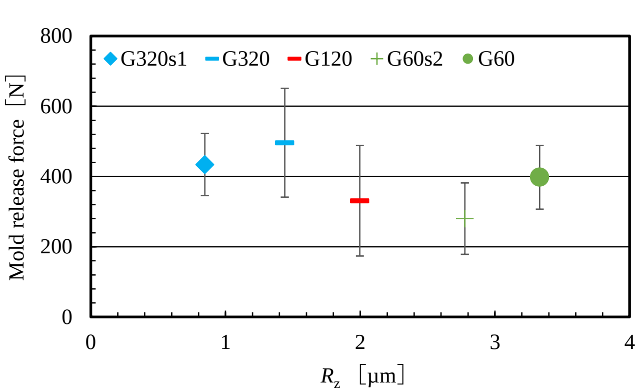


Fig.5 Relationship between mold release force and R_z of Ground surface

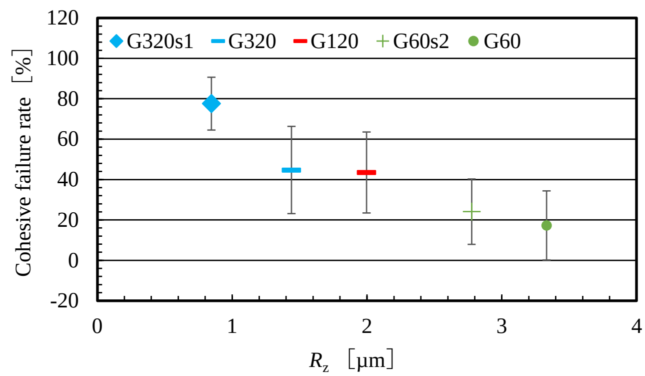


Fig.6 Relationship between cohesive failure rate and R_z of ground surface

3.2 Relationship between Surface Roughness Profile and Mold Release Force

Fig. 7 shows the surface roughness profiles and bearing area curves of the ground surface [4]. The bearing area curves show that the R_{pk} and the R_{vk} change as the surface roughness of the ground surface decreases. Then, the relationship between the bearing area curve and the mold release force was investigated. Fig. 8 shows the relationships between the mold release force and the R_{pk}, and the R_{vk} and the mold release force, respectively. Similar to the relationship between the mold release force and R_z in Fig. 9, there are a R_{pk} and a R_{vk} with the lowest mold release forces. Next, in order to consider the effect of the peaks and valleys of the surface roughness profile on the mold release force, the ratio of the peaks to valleys was determined and the relationship with the release force was investigated. Fig. 10 shows the relationship between the mold release force and R_{pk} / R_{vk}. Because of the proportional relationship, it is considered that the mold release force becomes smaller as the R_{pk} is lower and the R_{vk} is deeper.

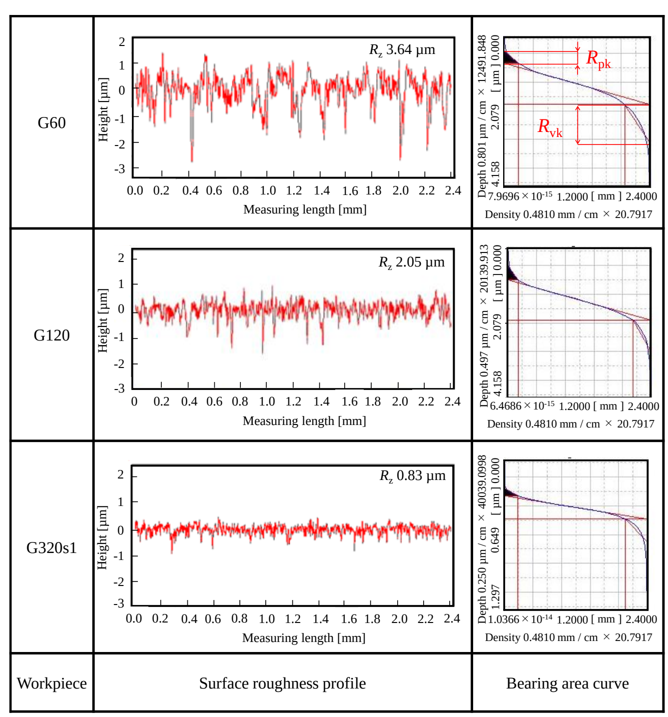


Fig.7 Surface roughness profiles and bearing area curves

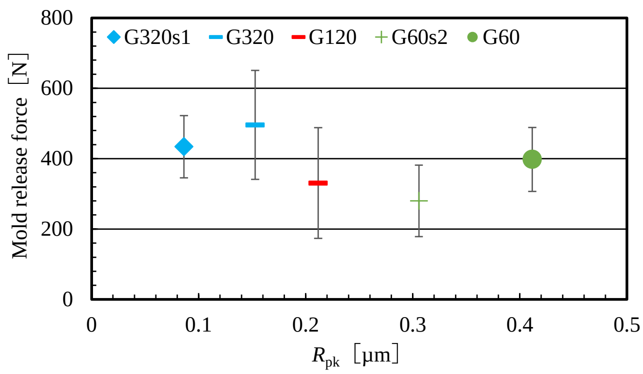


Fig.8 Relationship between mold release force and R_{pk} of ground surface

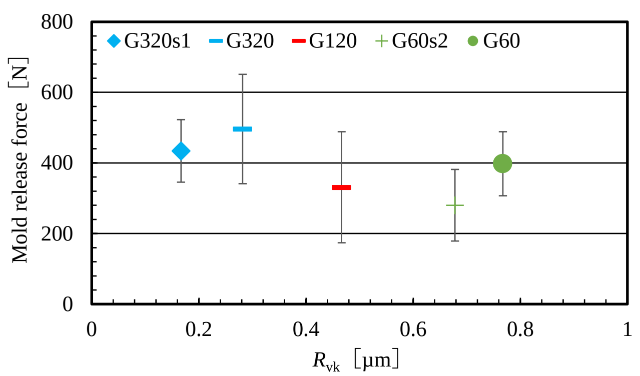


Fig.9 Relationship between mold release force and R_{vk} of ground surface

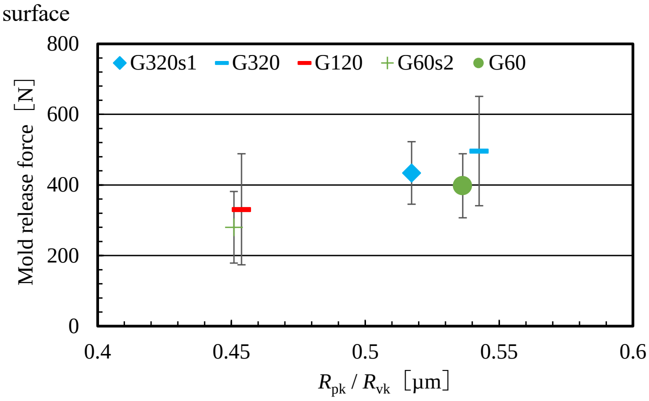
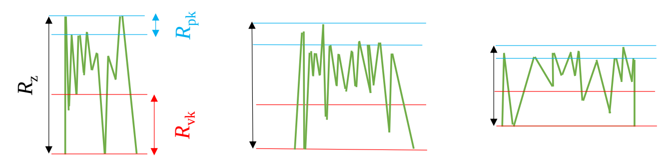


Fig.10 Relationship between mold release force and R_{pk} / R_{vk} of ground surface

3.3 Mold Release Factors in Surface Roughness Profile

Fig. 11 shows schematic diagrams of the surface roughness profiles of the ground surfaces with different surface roughness. In the case of the (a) R_z 3.5 μm, a rough surface roughness profile is formed with a higher protrusion peak R_{pk} and a deeper protrusion valley R_{vk}. Therefore, the adhesion area with the molded resin becomes large. As a result, there is no cohesive failure and the formability is excellent, but it is considered that the mold release force is increased due to the anchor effect. On the other hand, in the case of the (b) R_z 2 to 3μm, a surface roughness profile is formed with a low protrusion peak Rpk and a deep protrusion valley R_{vk}. Therefore, cohesive failure rarely occurs, the formability is excellent, and the mold release force is also low since the anchor effect is reduced. However, in the case of the (c) R_z 0.75 to 1.5 μm, a very fine surface roughness profile is formed with a lower protrusion peak R_{pk} and a shallower protrusion valley R_{vk}. Therefore, the molded resin that has penetrated the fine surface roughness cannot be released from the ground surface, and the cohesive failure rate increases. In addition, it is considered that the mold release force would increase because the fracture strength of the molded resin is included.

From the above discussion, it is considered that the R_{pk} and the R_{vk} in the bearing area curve are considered to be the mold release factors for the ground surface. Therefore, there would be an appropriate surface roughness profile that provides excellent mold releasability.



(a) R_z 3.5 μm (b) R_z 2 – 3 μm (c) R_z 0.75 – 1.5 μm

Fig.11 Schematic diagrams of surface roughness profiles of ground surfaces

4. Conclusions

(1) The mold release force is the smallest when the maximum height roughness R_z of the ground surface is 2 to 3 μm.

(2) As the maximum height roughness R_z of the ground surface decreases, the cohesive failure rate of the molded resin increases and the formability deteriorates.

(3) The anchor effect is considered to be a factor that deteriorates mold releasability in the high R_z range. On the other hand, the cohesive failure of the molded resin is considered to be a factor that deteriorates mold releasability in the region where the R_z is small.

(4) There exists an appropriate surface roughness profile that provides excellent mold releasability from the ground surface.

Acknowledgments

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