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ORIGINAL PAPER

Investigation on surface roughness of injection molded polypropylene parts with 3D optical metrology

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Abstract
Surface roughness is an important design specification for injection-molded plastic parts that are widely used in the consumer electronics, packaging, and automotive industry. Surface roughness serves both the appearance and functional requirements of injection moldings. It is not only influenced directly by the mold cavity surface, but also by injection molding parameters. However, there are few systematic studies on the effects of molding parameters on the surface roughness of molded parts. This study is to investigate the effects of molding parameters on the surface roughness of injection molded polypropylene parts. The molding parameters studied include cooling time, injection speed, holding pressure, and holding time. It turns out that the mold surface roughness plays the dominant role, while the molding parameters also exhibit a large influence on the surface roughness of molded parts. Among the parameters studied, the injection speed has the largest effect while the cooling time having the least effect on the surface roughness. This study implies that the surface roughness of molded parts can be cost effectively manipulated to a certain degree through controlling molding parameters, instead of modifying the surface furnish of mold cavity at a high cost.

Keywords Surface roughness · Injection molding · Molding parameters · Optical metrology

1 Introduction

Injection molding is a widely applied technique for mass production of plastic parts with complex geometry. Compared with thermosets and elastomers, thermoplastics are dominated in injection molding due to their easy processing and recyclability. However, they have relatively weak mechanical properties, and thus are often blended with reinforcing fibers [1–4], to enhance their mechanical properties for different applications. Due to their lightweight, easy manufacture for complex shapes, and low cost, thermoplastic injection moldings are widely used in and automotive and consumer electronics industry, such as thin-walled frames and housings for laptop computers and mobile phones. Injection molding is a complicated process which involves many molding parameters such as molding temperature, cooling time and rate, injection pressure, etc. Dimensional accuracy is an important quality characteristic for injection molded parts, and many efforts are made to understand and control the shrinkages and warpages [3–5]. Surface roughness is another important quality characteristic that affects the appearance and functional requirements. Surface roughness not only influences the appearance of molded parts such as color, gloss and texture, but also affects their functional requirements such as the adhesive property, surface paint-ability, friction coefficient, and wear-ability, etc. Therefore, it is critical to the overall quality and important to consumers. It is known that the surface roughness of mold cavity directly influences the surface roughness of injection molded parts. However, few studies have been done to investigate systematically the effects of molding conditions on the surface roughness of injection molded parts.

In the literature, a few studies were reported on the surface roughness of injection moldings. Zhang et al. [6] studied the effects of mold surface roughness on cavity filling of polymer melt in micro injection molding. Surace et al. [7] studied the effect of cavity surface roughness and wettability on the filling flow in micro injection molding, and concluded that the state of the polymer-mold interface played an important role in the filling of thin-wall micro injection molding. Liu et al. [8] studied the effects of surface roughness and processing

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parameters on heat transfer coefficient between polymer and cavity wall during injection molding, and the surface roughness of injection moldings obtained under different molding conditions was measured and compared. They concluded that the surface roughness was in good agreement with the heat transfer coefficient value. Kuroda et al. [9] studied the effect of talc size on surface roughness and glossiness of injection molded PP parts for automotive application, and their results indicated that both the PP shrinkage and density of talc affected the surface roughness. Kaneda et al. [10] investigated the optical properties of high density polyethylene in injection molding, and their results indicate that the surface roughness of molded parts increased as the mold surface roughness increased. Theilade et al. [11] studied the surface microstructure replication in injection molding, where the mold surface topography was transcribed onto the plastic part with complicated mechanisms. They concluded that the replication quality depended on several molding parameters significantly, especially for the mold temperature. Lucchetta et al. [12] studied the effects of rapid mold temperature variation on the surface topography replication and appearance of injection molded parts. Wang et al. [13] indicated that the surface temperature of mold cavity had a very significant influence on part surface appearance. As the mold surface temperature increased, the surface roughness of parts reduced and the surface gloss increased. Murakami et al. [14] examined the effects of melt viscosity and molding conditions on the replication of microscopic v-groove features in injection molded parts, and the melt temperature, mold temperature, injection velocity and holding pressure were investigated in their study. They concluded that the molding conditions for a lowered melt viscosity led to the improved replication. Vera et al. [15] examined the effects of PP with different melt flow rates on the replication of nanostructures in injection molding. Oliveira et al. [16] studied the surface roughness of injection molded acrylonitrile butadiene styrene (ABS) parts, and assessed the morphology, roughness, and gloss of the surface in relation to the molding parameters. They concluded that the mold temperature, the injection temperature, and the holding pressure were the most influent parameters that affected the surface properties. Chivatanasoontorn et al. [17] studied the influence of surface texture pattern on the scratch behavior of injection molded PP and polycarbonate using a progressive load scratch test. Lee et al. [18] reduced the surface roughness of injection molded microcellular parts by inserting a polytetrafluoroethylene (PTFE) insulator layer between the mold and the polymer melt, to keep the interfacial temperature above the polymer crystallization temperature during the filling stage. Chen et al. [19] used the induction heating technology to vary the mold temperature, to improve the surface quality of microcellular injection molded parts. Their results showed the surface roughness could be reduced by 80% with the induction heating system. Chen et al. [20] also studied the effects of gas counter pressure and mold temperature variation on the surface quality and morphology of the microcellular polystyrene foams.

From the literature review above, there are many factors that would affect the surface roughness of injection molded parts. These factors include the plastic resins used, the surface roughness of tooling system (i.e., mold cavity surface), and the molding parameters. PP has been widely used in automotive, consumer electronics, and packaging industry [21–24], and is selected in this study. In the scenario of that the plastic material and the mold are selected, there are few studies on how the molding parameters affect the surface roughness of parts. Therefore, this study is to investigate the effects of molding parameters on the surface roughness of injection molded PP parts. The processing parameters studied include cooling time, injection speed, holding pressure, and holding time. Understanding the effects would be helpful for us to manipulate the surface roughness, without modifying the mold surface at a high cost.

2 Experimental

2.1 Experimental material

The plastic material used in this study is PP supplied by ExxonMobil, and the grade is PP1074KNE1. The melt flow index (MFI) is 20 g/10 min, and the density is 0.9 g/cm^3. It is a nucleated homopolymer resin with mold release and anti-static properties. It has a melting point of about 162 °C. It is a low cost, widely used semi-crystalline polymer. The plastic resin was used as received.

2.2 Injection molding machine

Figure 1 shows the injection molding machine used for producing specimens, and it was Engel E-victory 30 with a 30-ton clamping force. The screw diameter is 22 mm with a length/diameter (L/D) ratio of 30.

2.3 Injection mold

A two-part family mold was designed to produce two parts with one shot, as shown in Fig. 2. The fan gate was selected to allow the rapid filling of the two mold cavities, achieve a uniform material flow, and minimize backfilling and part warpage. The steel insert mold base from DME (Model 08/09 U Style Frame) was cut with a Haas CNC machining center.

Fig. 1 Engel injection molding machine

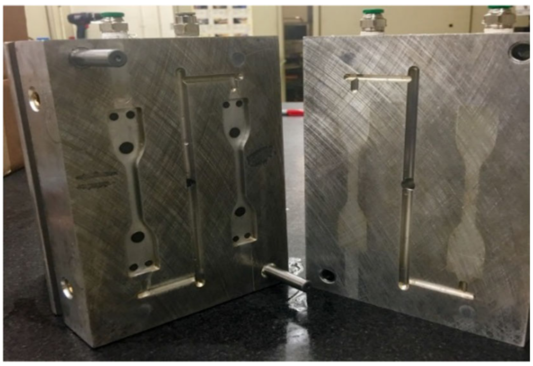

Fig. 2 Fabricated mold

Table 1 Baseline molding parameters used

Barrel temperature (°C)	240
Injection speed (cm/s)	12
Injection pressure (MPa)	25.0
Holding pressure (MPa)	12.5
Holding time (s)	12
Cooling time (s)	20
Short volume (cm^3)	25

2.4 Molding parameters

The injection molding baseline was chosen based on the material properties (e.g., melting point and melt flow index) and the injection molding machine capability, as shown in Table 1.

The molding parameters such as the injection speed "I", holding pressure "H", holding time "T", and cooling time "O", were selected as the factors that influence the surface roughness of injection molded parts. Each factor has 4 levels, as shown in Table 2.

Fig. 3 Zegage 3D optical profiler used in the study

To identify quickly the effects of these selected molding parameters on the surface roughness, a completely randomized single factor experiment was designed based on the baseline molding condition. Each of the four molding parameters (e.g., injection speed) was varied from level 1 to 4 while keeping the other molding parameters the same in the baseline parameter table. For each molding condition, five samples were collected for the surface roughness measurement.

2.5 Surface roughness characterization

The surface roughness of moldings was characterized with the ZeGage™ 3D optical profiler (Zygo Corporation), as shown in Fig. 3. It is a non-contact tool for quantitative measurements of 3D form and roughness on a wide variety of materials. It has a sub-nanometer precision, and measures and visualizes surface roughness with one-million-pixel image sensor. It complies with IS 25178 surface roughness parameters.

Figure 4 shows the areas measured on the mold cavity surface in this study. There were four areas (A, B, C, D) measured along the melt flow direction, and the size of each area was about 2 by 2 mm. The fan gate was located at the end that was close to the area A. For injection molded parts, the surface roughness of the corresponding areas was measured. The surface roughness of each area was the average roughness within the measured area.

Table 2 Molding parameters studied

Level	Injection speed I (cm/s)	Holding pressure H (MPa)	Holding time T (s)	Cooling time O (s)
1	8	10.0	8	10
2	12	12.5	12	20
3	16	15.0	16	30
4	20	17.5	20	40

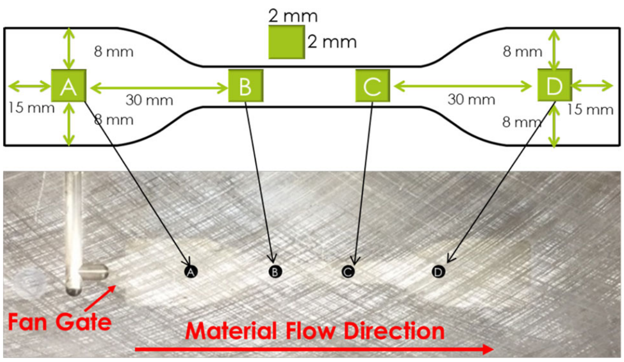

Fig. 4 The schematic of surface roughness measured areas on the mold cavity and parts

3 Results and discussion

3.1 Surface roughness of mold cavity

There are several different roughness parameters in use, but Ra (arithmetic average roughness for 2D) and Sa (arithmetic mean height for 3D) are most common. Sa is a 3D parameter expanded from the roughness (2D) parameter Ra, and they are defined by ISO 25178-2 and ISO 4287, respectively. Sa represents an overall measure of the texture comprising the entire measured surface. Table 3 shows the surface roughness Sa data measured for the areas on the mold cavity surface. 3D surface roughness (Sa) ranges from 2.795 to 4.718 μm for the selected areas on the mold cavity surface. Figure 5 shows the typical 2D and 3D graphs obtained from the ZeGage™ 3D optical profiler.

Table 3 Surface roughness of the areas measured on the mold surface

Locations on mold	Average surface roughness S_a (μm)
Area A	2.795
Area B	4.178
Area C	3.332
Area D	3.895

3.2 Surface roughness of parts

Injection molded parts were fabricated based on the baseline molding condition shown in Table 1. Single factor experiment design was applied. Each single factor, such as injection speed “I”, holding pressure “H”, holding time “T”, and cooling time “O”, was varied from level 1 to 4, to obtain different molding conditions. For each molding condition, five samples were collected for surface roughness measurement. Figure 6 shows the typical 3D surface roughness for the areas A and B of injection molded parts obtained at the injection speed of 8 cm/s. It seemed that the texture of the mold was replicated to the surface of the injection molded parts. Figure 7 shows the effects of different molding conditions on the surface roughness of parts in the areas A, B, C and D. The surface roughness for the areas A, B, C, D on the mold is also displayed on the graphs. All the selected molding parameters affected the surface roughness of the molded parts, but it seemed that the injection speed had a largest effect, as it was indicated by the large deviation from the mold surface roughness. The higher injection speed would increase the melt temperature and decrease the viscosity, which could change the interfacial conditions between the mold and the polymer. It seemed that the cooling time had the least effect on the surface roughness. During the mold filling, the polymer flow pattern is typically called a fountain flow or bubble flow, as shown in Fig. 8. The outside layer freezes rapidly when in contact with the cold mold surface, while the central hot plastic remains molten. As more polymer melt is pushed into the cavity, it flows through the central channel, displacing the material already there, which forms a new flow front

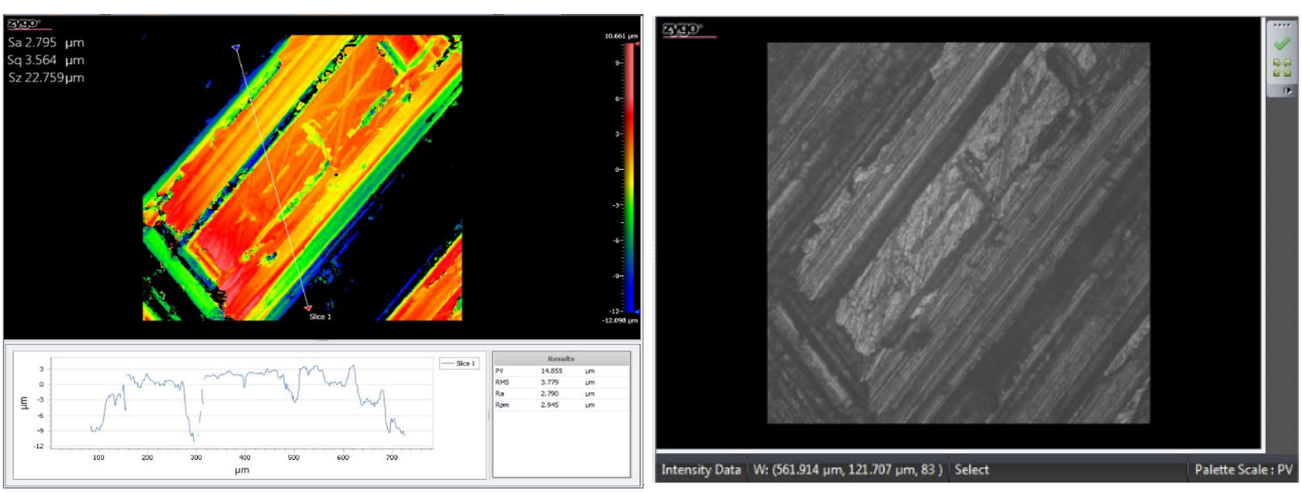

Fig. 5 Typical 2D and 3D surface roughness of measured area A on the mold

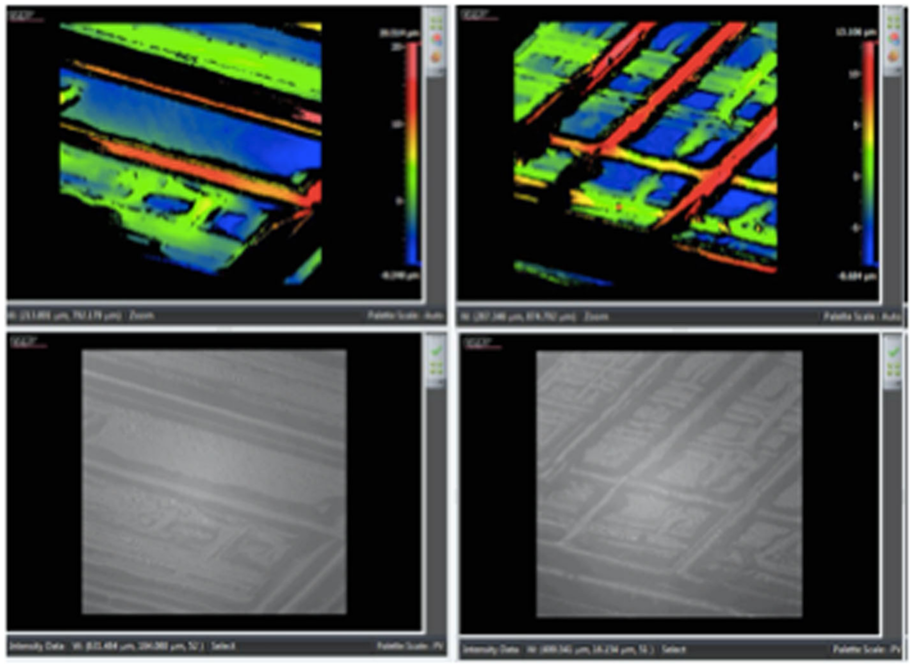

Fig. 6 Typical 3D surface roughness of measured areas A and B on the part

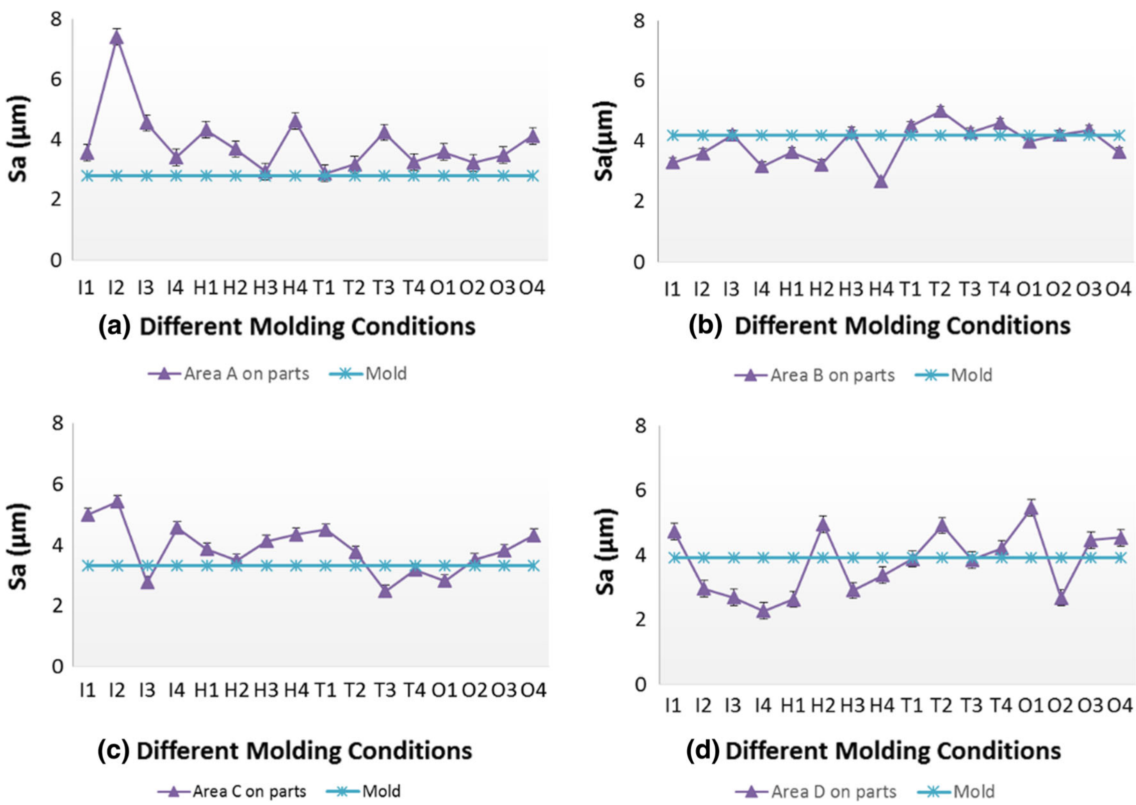

Fig. 7 Effects of different molding conditions on the surface roughness: **a** area A, **b** area B, **c** area C, **d** area D

[25]. As the flow front behaves like a bubble being inflated, a combination of forward flow and outward flow, thus this flow pattern is often called fountain flow. The frozen layer was formed rapidly at the beginning, which largely determined the surface roughness.

Figure 9 shows the surface roughness difference, Delta Sa, between the parts and the mold in the same areas under different molding conditions. It further indicates that the injection speed, among the four processing parameters studied, has the largest effects on the surface roughness. From Figs. 7 and 9,

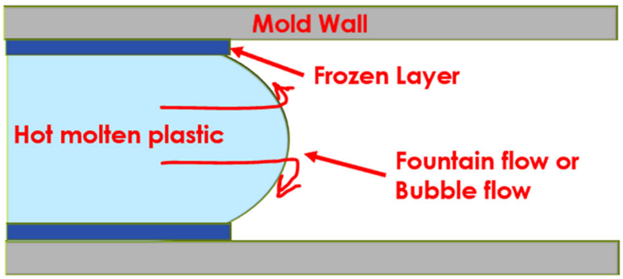

Fig. 8 Fountain flow or bubble flow during mold filling

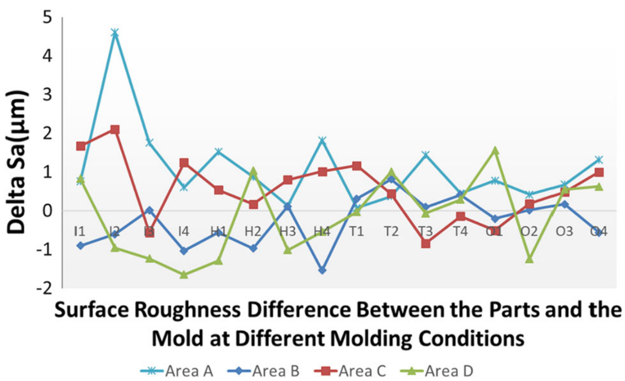

Fig. 9 Roughness difference delta Sa between the parts and the mold at different molding conditions

it can be seen that the surface roughness changes within the range of about 6 µm around the surface roughness of the mold at the different molding conditions.

4 Conclusions

This paper investigated the surface roughness of injection molded PP parts with a non-contact 3D optical profiler under different molding conditions. Although the surface roughness of mold largely determined the surface roughness of molded parts, the molding conditions also had a large influence. Among the four parameters studied (i.e., cooling time, injection speed, holding pressure, and holding time), it seemed that the injection speed had the largest effects on the surface roughness, while the cooling time had the smallest effects on the surface roughness of parts. The surface roughness for several areas along the flow path was measured, but they showed the similar behaviors. This study demonstrated that molding conditions did affect the surface roughness of molded parts significantly, as the part surface roughness could deviate 6 µm from the mold surface roughness. This study implies that the surface roughness of injection moldings can be manipulated to a certain degree through controlling molding conditions, instead of modifying the surface furnish of mold at a high cost. As the single factor experiment design was used, the interaction effects between the factors were not investigated in this study. A more systematic modeling, including the interactions between the factors, need to be conducted in the future.

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