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# Development of a heat-generable mold insert and its application to the injection molding of microstructures

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This work presents a heat-generable mold insert for micro injection molding that solves the problem of de-molding destruction. This mold insert is constructed from silicon wafer by silicon micro-fabrication. Micro electrical heating lines were formed in the wall of the micro mold cavity to control the temperature distribution and the sequence of local solidification of the filled plastic during injection molding. This design reduces the shrinking stress of the plastic filled in the mold. The micro electrical heating lines embedded in the cavity wall are silicon-based with specified resistance, and were fabricated by doping phosphorus ions precisely into the surface of the silicon cavity wall. Ion-implantation was adopted to dope phosphorus ions. The performance of the novel mold insert was studied. Then, the developed mold insert was applied for the injection molding of micro-structures with high aspect ratios. Experimental results reveal that electrical heating lines formed within the novel mold insert can supply stable heating power. These electrical heating lines are used to heat the cavity wall of the silicon mold insert and the nearby plastic with appropriate timing at sufficient power in the cooling stage, such that the de-molding force associated with contraction of the patterned plastic grips to the micro-structured mold insert, is reduced. Furthermore the de-molding destruction of the injection molded micro-structures can be eliminated. Optical micro-structures with aspect ratios of up to eight were successfully injection-molded.

## 1. Introduction

Micro-structured components have many potential applications. Plastics are very suitable for their fabrication. Therefore, technology for manufacturing plastic micro-structures is very important. Plastic micro-structures of high quality must be fabricated more economically as micro-structured components are becoming more extensively utilized. Injection molding is anticipated strongly to favor the mass production of plastic micro-structures of stable and good quality. However, the common characteristic of designed micro-structured components is that column- or wall-shaped micro-structures with high aspect ratios densely stand erect on a base plate, and these micro-structures cannot be given a draft or a taper angle because of limitations on the functional requirements of the product and the fabrication of mold insert. Accordingly, de-molding interference or the gripping of the mold insert by cooled molded plastic is liable to occur, causing de-molding fracture during the injection molding of plastic components with surface micro-structures [1–3]. This problem is considered to be caused by the stress field that is established by the difference between the shrinkage ratios of the plastic and the mold insert material. Although the shrinkage ratio of plastic can be regulated by controlling the specific volume of plastic inside the mold cavity with pressure applied during cooling, uniformly distributing the pressure to ensure uniform shrinkage of the molded plastic is difficult [4,5]. Additionally, the pressure on the plastic during cooling may cause not only residual stress in the molded product but also damage to the mold insert. Hence, the de-molding problem associated with the injection molding of micro-structures described above cannot be expected to be solved by applying a pressure to the plastic during cooling [6].

In recent years, variotherm mold technique [7–9] and surface modification such as PVD coating [10] have been applied to help the filling and de-molding in the injection molding of microstructures. Nevertheless, the issue due to thermal shrinkage described above does not completely be solved yet especially when the diameter (or the thickness) of the microstructure as small as 10 μm [10]. The dynamical mold temperaturing process leads to an increase in the cycle time as used in conventional process [11,12]. The high temperature range variation can also decrease the lifetime of the mold [13,14]. Moreover, high temperature inhomogeneities may occurs on the variothermally tempered mold wall [15].

This study proposes a novel mold insert and a new strategy for controlling temperature in a mold. The mold insert has an

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independent heating function that can be employed to increase rapidly the temperature of the walls of micro-cavities during cooling in an injection molding process, actively controlling the temperature distribution and the sequence of solidification of the plastic inside the mold cavity. This mold insert can greatly reduce the shrinking stress in the cooled plastic, solving the de-molding problem described above without having to use other auxiliary design such as the thermal stress barrier [16].

## 2. Design and fabrication of the heat-generable mold insert

Fig. 1 presents the concept of the heat-generable mold insert. This mold insert is made of a P-type single-crystal silicon wafer. Silicon processes are used to build micro-cavities of specified dimensions and shapes on the surface of one side of the mold insert. Ion implantation process is utilized to dope N-type phosphorus ions into specific areas under the surface on the same side of the silicon mold insert to make these areas electrically conducting [17]. Consequently, silicon-based electric-conductible micro lines with required resistance and pattern are formed at a fixed range of depth under the surface of the mold insert. These silicon-based conducting lines act as electrical heaters when connected to an external electrical power supply. Therefore, they can be applied to heat the wall of micro-cavities and the plastic near the wall at the right moment in the molding process to control the temperature distribution, the cooling rate and the solidification sequence of the plastic. Fig. 1(b) illustrates the expected temperature distribution of the plastic used in the developed novel mold insert during cooling in the molding process. δ is the thickness of the part that is between the high-temperature plastic in the micro-cavities and the low-temperature plastic in contact with the cooling metal mold plate at time $t = t_2$. The part of the plastic with thickness δ has a large temperature gradient, and is cooled from time $t = t_2$ to $t = t_3$, inducing thermal stress and the effect of gripping of the mold insert by the plastic. Accordingly, the thickness δ is important in determining the gripping force $F$ which the molded micro-structured component grips the mold insert in demolding. This gripping force $F$ can be expressed as follows.

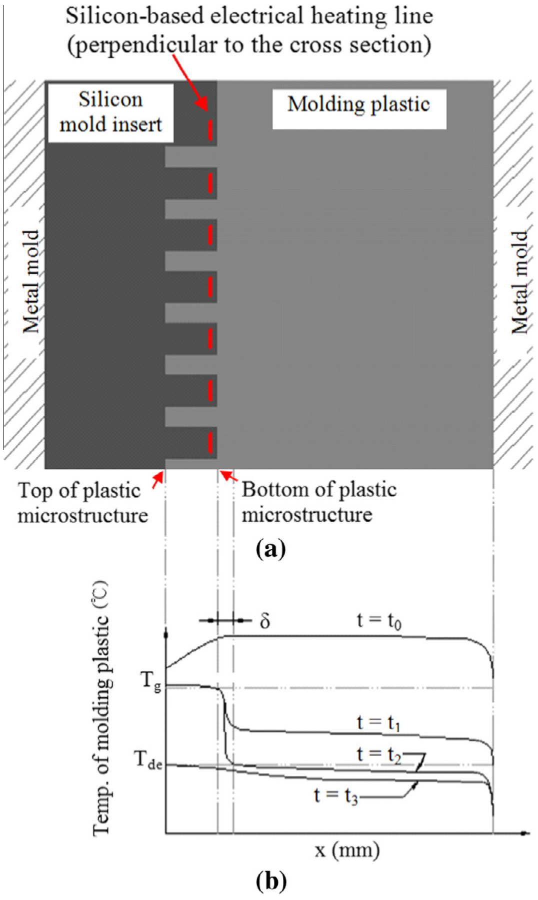

**Fig. 1.** (a) Cross-section of heat-generable mold insert in use, (b) expected temperature distribution of the plastic during cooling in the molding process. $T_g$: glass transition temperature of molding plastic; $T_{de}$: de-molding temperature; $t_0$: start time of the cooling stage; $t_1$: several seconds after the powering on of the electrical heating lines; $t_2$: time to power off of the electrical heating lines; $t_3$: time to beginning the de-molding.

$$F = \delta l\sigma = \delta lE[\alpha_p - (T_g - T_{de})/2 - \alpha_{si}(T_g - T_{de})] \tag{1}$$

Here, $\ell$ represents the length of the thickness δ in the direction parallel to the extension of the micro-structure; σ is the thermal stress; $E$ is Young's modulus of the molding plastic (supposed to be constant); $\alpha_p$ and $\alpha_{si}$ are the coefficients of thermal expansion (supposed to be constants) of the molding plastic and the silicon mold insert, respectively; $T_g$ denotes the glass transition temperature of the plastic used, and $T_{de}$ is the de-molding temperature.

Eq. (1) can be used to estimate the magnitude of the gripping force $F$ if the thickness δ was obtained from the temperature distribution plot of the filled plastic either by experiment measuring or by numerical simulation. In the practice, the thickness δ is expected to be thinned, by means of selecting an adequate set of input power and its timing of the electrical heating lines inside the mold insert, so as to reduce the gripping force $F$. Moreover, the gripping force $F$ decreases with the increase of the de-molding temperature.

Fig. 2 displays the process of fabrication of the novel mold insert. The sequence between structuring the micro-cavities and forming the electrically conducting micro lines (doping) can be exchanged to suit the design requirements of the mold insert.

## 3. Doping characteristics and performance of silicon-based electrically conducting lines

The implantation energy and dose are the main parameters in the ion implantation process. Distribution of the concentration of implanted phosphorus ions in the direction of wafer thickness are controlled by adjusting these two parameters, which determines the characteristics of the silicon-based conducting lines. Fig. 3 shows the results of the secondary ion mass spectroscopy (SIMS) analysis of two cases of doping with different implantation energies. The maximum of the concentration of phosphorus ions shifts to a deeper part of the silicon wafer as the implantation energy is increased. Fig. 4 presents the effect of the implantation dose on the resistance of the conducting line. A greater implantation dose yields a lower resistance.

Since the working temperature of a mold insert in the injection molding of micro-structures generally varies cyclically between room temperature and 170 °C, the property stabilities of the silicon-based conducting lines created by doping phosphorus ions demand attention. Fig. 5 plots the variations of resistance with time at constant temperature and pressure. The resistance of the silicon-based conducting line slightly increases with time at a given temperature, as plotted in Fig. 5(a), which effect can be neglected in the common injection molding of micro-structures with a cycle time that does not exceed one minute. Similarly, the resistance of the conducting line remains stable with time at a constant pressure (Fig. 5(b)). Fig. 6 reveals the effects of temperature and pressure on the resistance. The resistance of the silicon-based conducting line declines as the temperature rises (Fig. 6(a)), and the maximum variation of the resistance in the temperature range

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