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

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ABSTRACT

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.

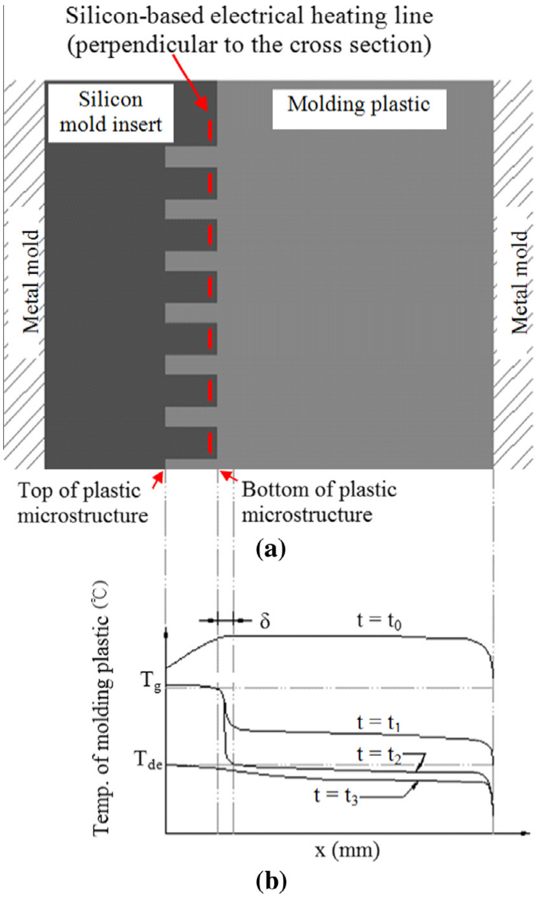


Fig. 1. (a) Cross-section of heat-generable mold insert in use, (b) expected temperature distribution of the plastic during cooling in the molding process. T_g: glass transition temperature of molding plastic; T_{de}: de-molding temperature; t_0: start time of the cooling stage; t_1: several seconds 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, ℓ 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); α_p and α_{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

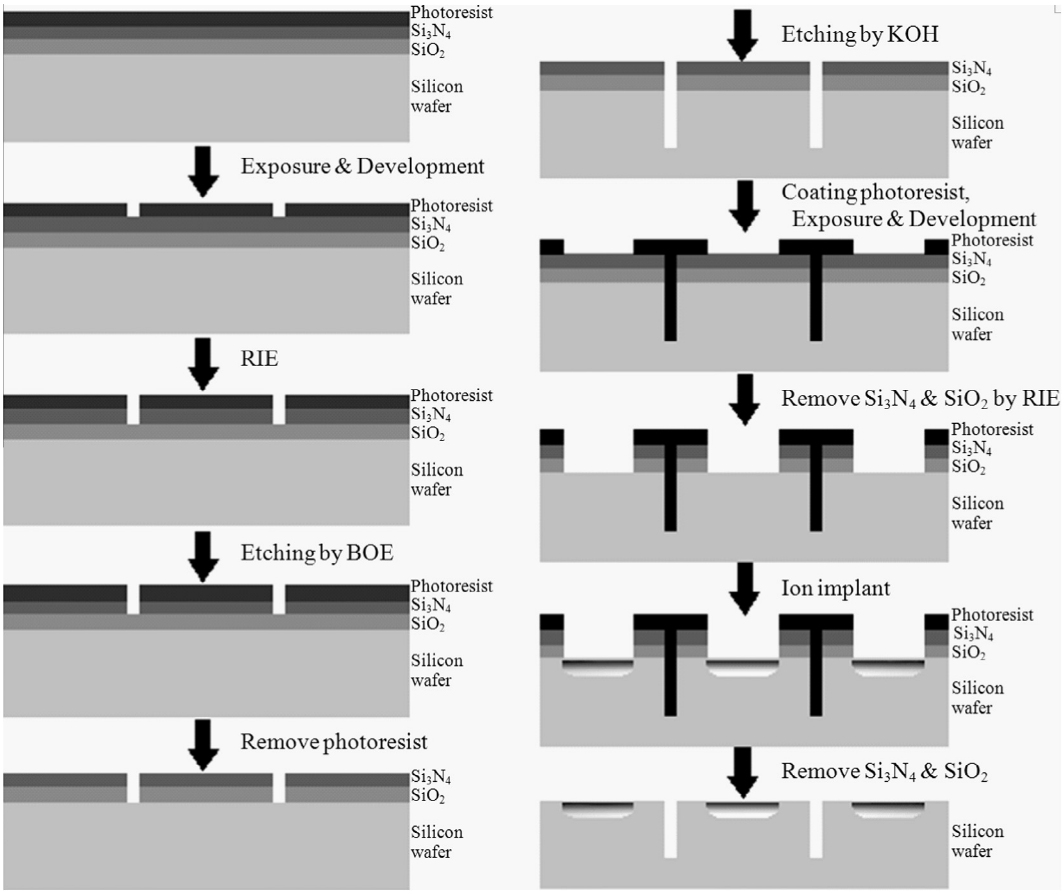


Fig. 2. Fabrication process of heat-generable mold insert.

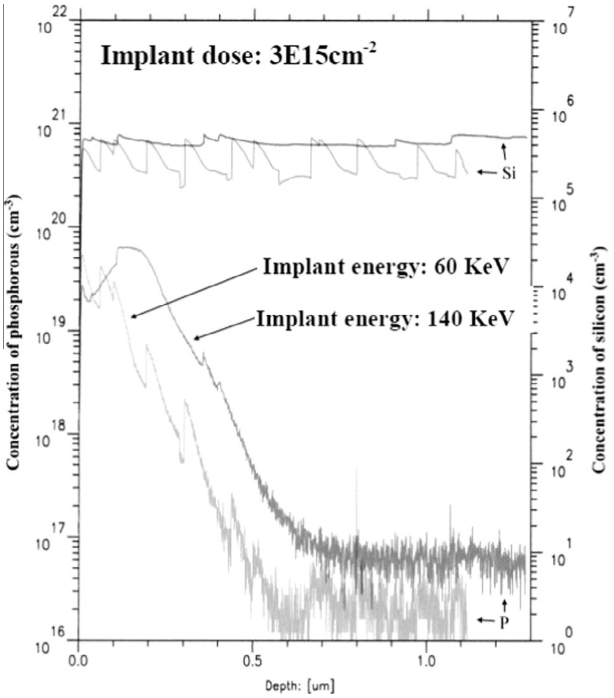


Fig. 3. Distribution of concentration of phosphorus ions under the surface of the doped silicon wafer in the depth direction, obtained by SIMS analysis.

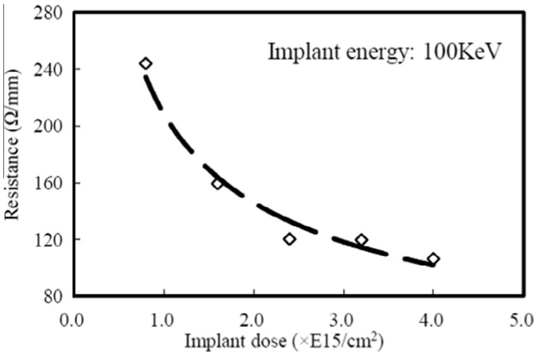


Fig. 4. Effects of implanted dose on the resistance of the silicon-based conducting line.

of a general injection molding process is about 30% of the initial value. In comparison, the effect of the pressure variation on the resistance is weak, as shown in Fig. 6(b). Fig. 7 plots the resistance of the silicon-based conducting line under cyclic variations of temperature and pressure. Evidently, the resistance characteristic of the conducting line does not change with the cyclic variation of temperature or pressure, which fact demonstrates that the novel mold insert proposed herein suffices for use in continuous injection molding.

In real injection molding, the conducting lines embedded in the silicon mold insert are charged with an initial voltage that slightly exceeds 50 V, which is the breakdown voltage of the silicon-based conducting line developed here [18–20]. Then, the power supply is immediately shifted to the constant-current-control model (with a current of 1.6 A) to reach stable power when "breakdown" occurs.

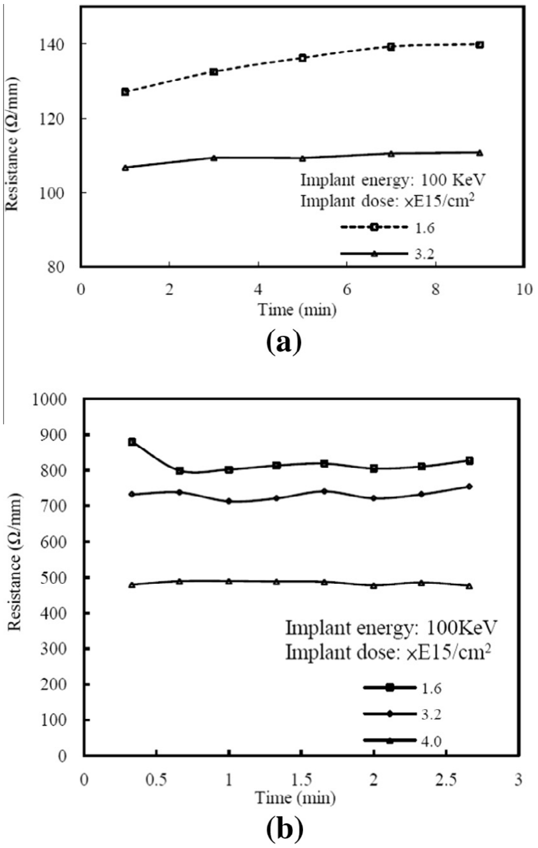


Fig. 5. Variations of the resistance of the silicon-based conducting line with time at (a) 170 °C, 0 MPa, and (b) 20 °C, 12.5 MPa.

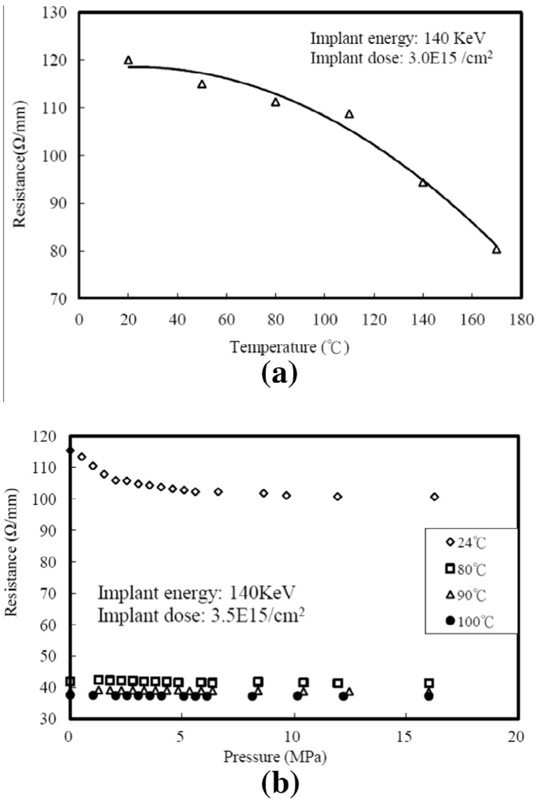


Fig. 6. Effects of (a) temperature, and (b) pressure on the resistance of the silicon-based conducting line.

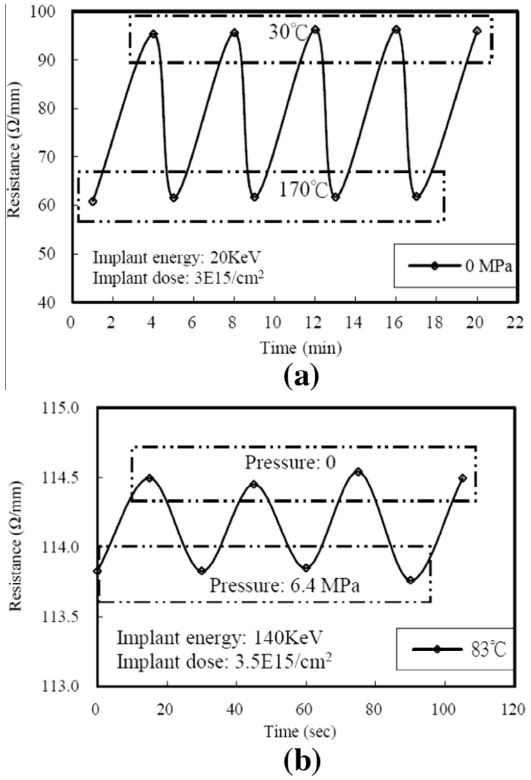


Fig. 7. Variations of the resistance of the silicon-based conducting line with time under (a) cyclic variation of temperature, and (b) cyclic variation of pressure.

Fig. 8 plots the effect of the original resistance of a doped conducting line on the magnitude of the stable power at breakdown. The achievable power falls as the original resistance increases. In the design of the heat-generable mold insert presented herein, the data plotted in Figs. 8 and 4 are important for determining the number and the layout of the silicon-based conducting lines in the mold insert, as well as the conditions for ion implantation.

4. Application of heat-generable mold insert to the injection molding of micro-structures

In this work, as described above, the developed heat-generable mold insert is adopted to control the thermal/mechanical states of the molding plastic during cooling to solve the de-molding

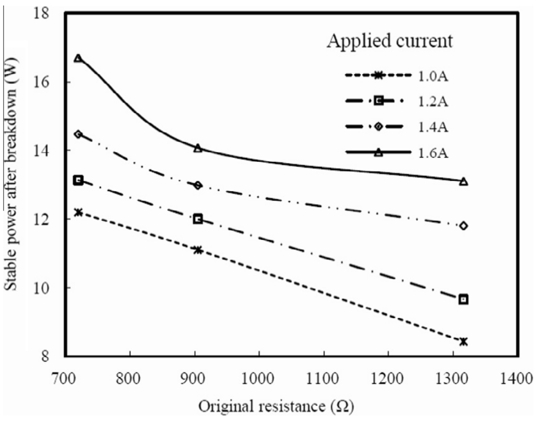
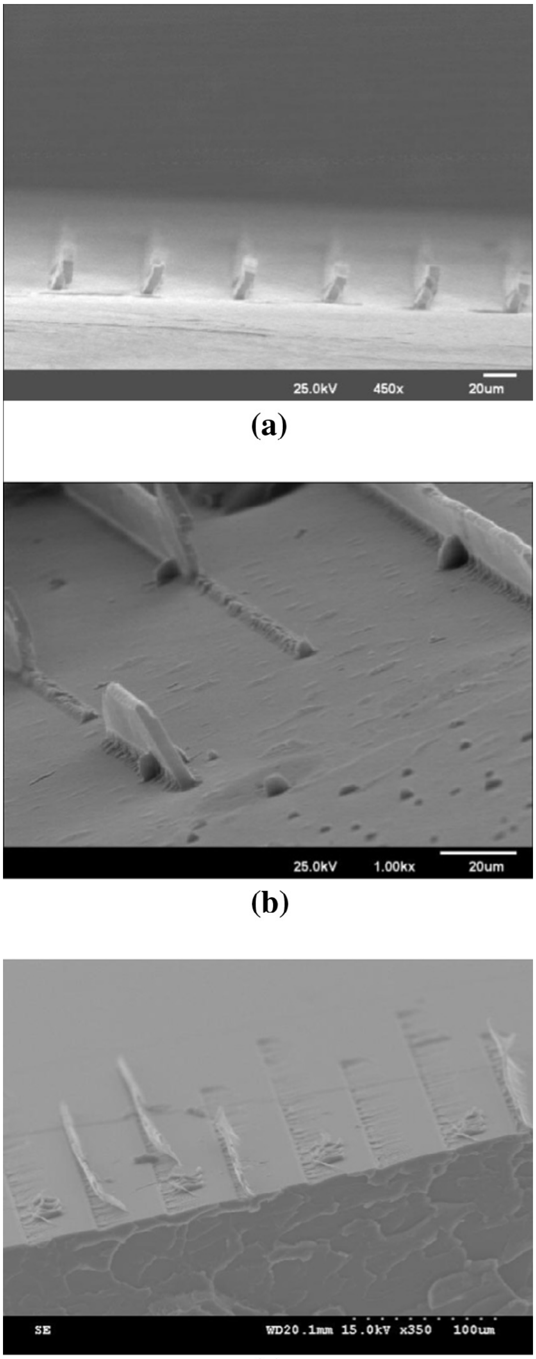


Fig. 8. Effects of original resistance of doped conducting line on stable power value that could be reached by breakdown.

problems that arise in the injection molding of micro-structures [21]. Some molding defects in the micro-structures with high aspect ratios that are caused by the shrinkage of the plastic, as shown in Fig. 9, can easily be detected, when a common injection molding process is used in which the novel mold insert developed in this work is not used. Fig. 9(a) displays the tilt of the molded micro-structure. Such a defect is thought to occur during de-molding as the shrinkage of the plastic causes a small shear stress. Greater shrinkage of the plastic produces more shear stress and mold-gripping force, leading to the fracture of the micro-structure, as presented in Fig. 9 (b). The most serious situation is that the molded micro-structures are sheared off from their base and remain in the micro-cavities of the mold insert, as presented in Fig. 9(c).

Fig. 10 illustrates an example of the timing of the power on/off of the developed "micro-heaters" embedded in the mold insert during injection molding. When the temperature of the mold (metal mold plate) descends just to the glass transition temperature of the molding plastic during cooling, the silicon-based conducting lines are charged immediately to heat the surface of the mold insert and thus actively control the distribution of the temperature in the molding plastic. Fig. 11 plots the variations of the temperature in the mold insert at various heating powers in the mold-cooling stage. The range of temperatures increases with the heating power. Additionally, the temperature of the mold insert declines rapidly to the temperature of the mold when the power is off. Fig. 12 shows some of the results of applying the developed heat-generable mold insert. As shown in Fig. 12, in all of the sub-areas of a rectangular molded area of dimensions of 8 mm by 8 mm, micro-structures can be de-molded perfectly, except at the edge of the sub-area marked "9E" which is farthest from the center of the molded area. A larger power-density of the mold insert or a longer heating duration is necessary to release more thermal stress in the molded plastic and thereby further improve the efficacy or expand the effective moldable area of the



(a)

(b)

(c)

Fig. 9. Various molding defects, caused by the shrinkage of the plastic, and of the micro-structures. (a) tilt, (b) fracture and (c) shear off of the micro-structure.

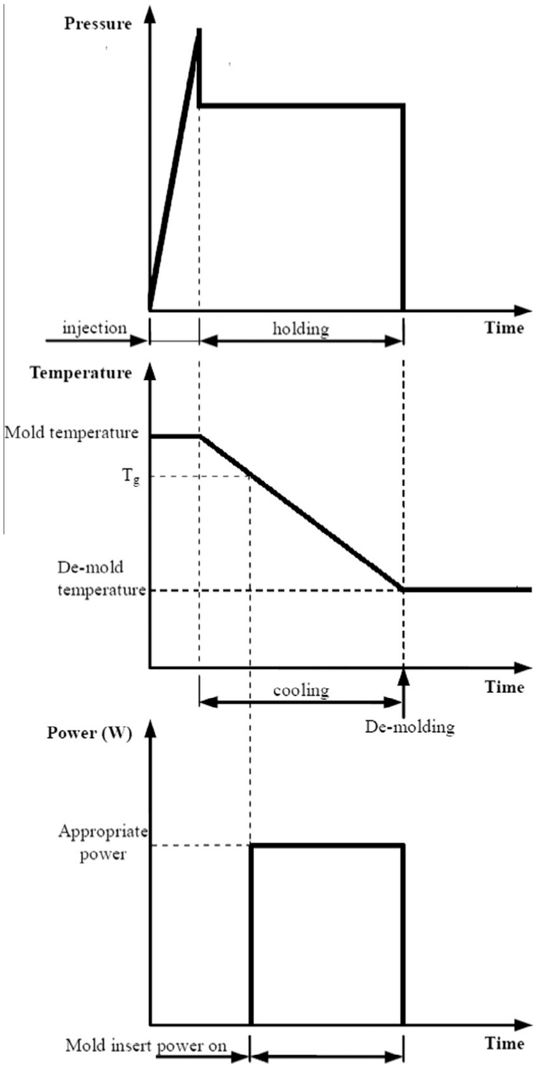


Fig. 10. Timing of the power on/off of the micro-heaters in the mold insert in an injection molding process.

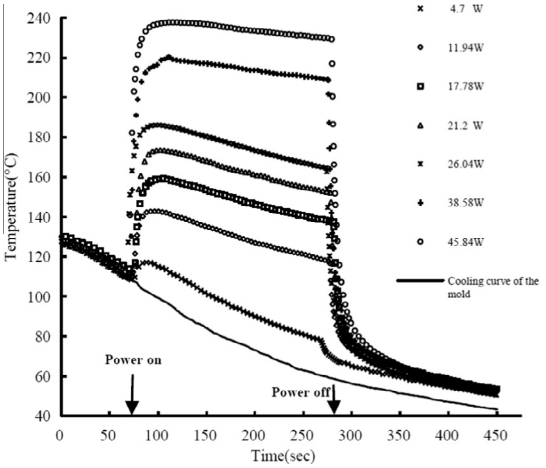


Fig. 11. Variations of the temperature of the mold insert heated by various powers during mold-cooling.

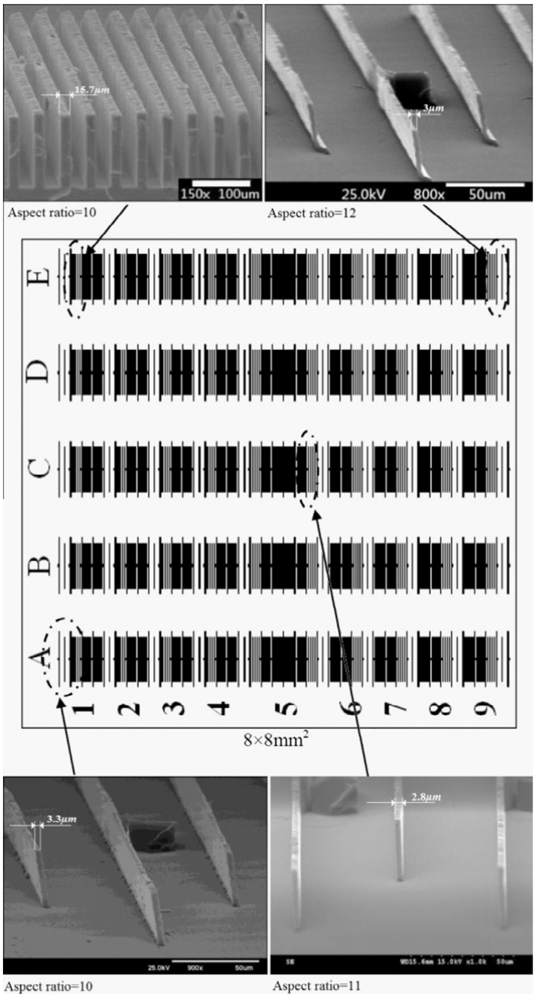


Fig. 12. Results of application of heat-generable mold insert presented herein. Molding conditions: PMMA microstructures, barrel temperature 250 °C, mold temperature 120 °C, injection pressure 60 MPa, mold insert started to power on when the mold temperature decreased to 106 °C.

novel mold insert. However, excessive heating of the mold insert itself will also cause defects. Fig. 13(a) presents the collapse of the molded micro-structures, which is caused by the poor strength of the de-molded plastic when the temperature is too high.

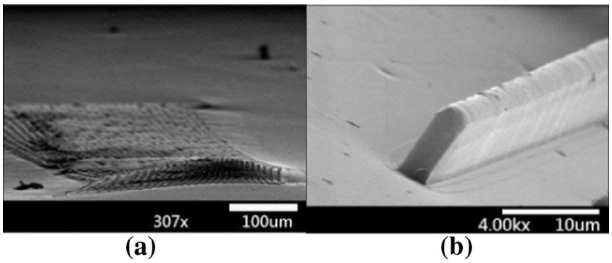


Fig. 13. Defects caused by the excessive heating of the mold insert. (a) collapse of micro-structures, (b) weld-line.

Fig. 13(b) displays the weld-line on the surface of the base plate near the base of a micro-structure. The weld-line defect is considered to be caused by the re-melting of a micro-structure after solidification.

This study investigates the operation window of the injection molding of micro-structures using the developed novel mold insert with the layout of micro-cavities presented in Fig. 12. Fig. 14(a) and (b) show the operation windows in cases in which the micro-structures have a uniform aspect ratio of three and four, respectively. These data reveal that a higher aspect ratio of the micro-structures corresponds to a stricter requirement of the heating conditions of the mold insert. Moreover, mold inserts with higher power-densities must be developed.

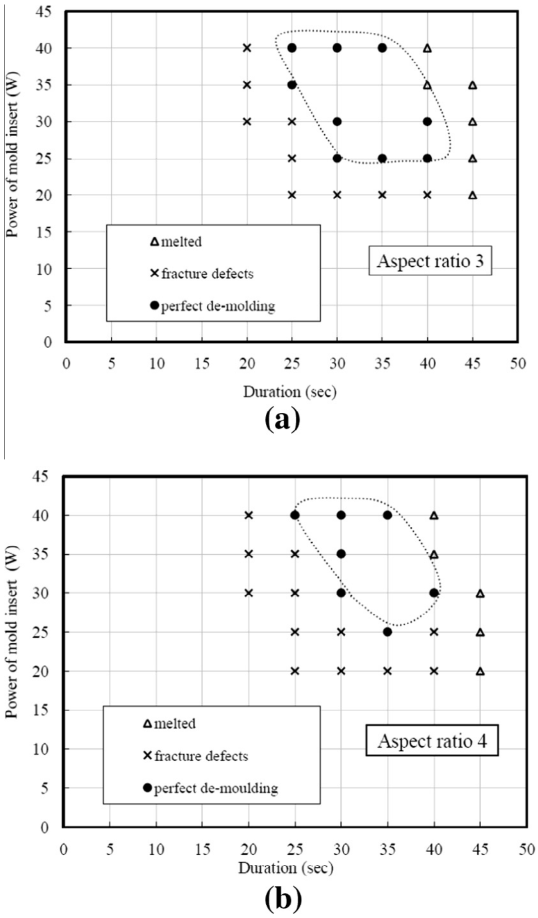


Fig. 14. Operation window of the injection molding of PMMA micro-structures with aspect ratios of (a) three, and (b) four using the heat-generable mold insert. Barrel temperature 250 °C, mold temperature 120 °C, injection pressure 60 MPa, mold insert started to power on when the mold temperature decreased to 106 °C.

5. Conclusion

A micro-heater-embedding mold insert for the injection molding of plastic micro-structures with high aspect ratios was presented. The micro heater, created by implanting phosphorus ions into the surface of a silicon mold insert, was demonstrated to exhibit stable physical properties and excellent heating performance, making it very appropriate for continuous injection molding. Using these micro heaters to heat the wall of the mold insert with micro-cavities and the nearby plastic for a sufficient duration at a sufficient power in the cooling stage, reduces both the shrinking stress that is produced in the plastic and the de-molding force. Therefore, the de-molding destruction of the injection molded micro-structures can be eliminated. Furthermore, the effective moldable area of the injection molding of micro-structures can be expanded.

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