SIMTech Technical Report (PT/02/033/FT)

Development of Mould Design Technologies and Process Parameter Studies in Micro Moulding Process

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(Forming Technology Group, 2002)

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1 BACKGROUND

With the global trend in plastics injection moulding industry slants towards precision moulding and miniaturisation, there are growing demands in the manufacturing of mirco-precision components in plastics. Micro moulding technologies can therefore open completely new possibilities for many applications in different disciplines.

The ability to produce acceptable metering accuracy and homogeneity of very small quantities of plastic melt is a key challenge in the micro moulding process. In the conventional reciprocating screw injection moulding process, polymer materials are melted and injected into mould cavities through a screw-barrel system. It is scarcely possible to produce parts weighing less than 0.1 g in a cost efficient manner on conventional injection moulding machines [1]. This is because there are limitations to reduce the screw dimensions due to screw strength and plastic pellets feeding considerations, and also because of the possible melt back flow encountered in the screw channels when very high injection pressure is used. Moreover, in micro component moulding using conventional injection moulding machines, cycle times are usually longer than necessary because the sprue and runner sizes are not always proportionally reduced due to the consideration to minimise material residence times and melt degradation. A new generation of injection moulding machines is therefore necessary for the micro moulding technology.

In order to control metering accuracy and homogeneity of the very small quantities of melt in the micro moulding process, a new generation of machines that use a separate screw plasticising unit and a plunger injection system have been developed [2, 3], as shown in Figure 1. During the moulding process, plastic pellets are fed into the extrusion screw, where they are plasticised by the heating and shearing effects, and then enter into the dosing barrel. When the melt in the dosing barrel reaches the set-point, it will be transferred into the injection barrel, the injection plunger will then inject the melt into the mould cavities. To capitalise on anticipated demands for micro injection moulding machines, these machine builders have developed novel systems designed to consistently, accurately, and rapidly manufacture moulded parts that weigh less than 0.1 g [4]. With the expectation of rapidly growing applications for micro-moulded parts, machine manufacturers have predicted that the market for micro-moulding machines will have doubled in the next few years due to the growth in demand for micro-sensors in automotive applications alone [3].

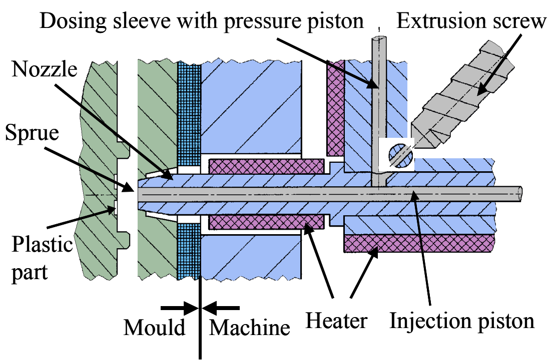


Figure 1 Micro injection moulding system

Microsystem technology is an interdisciplinary engineering science. The micro moulding activity encompasses the full spectrum of polymer moulding from product design to tool design and fabrication, and the application of innovative injection techniques. The moulding machine, tooling, material and process, as well as component handling and inspection, need to be specially addressed. For the new generation of micro injection moulding machines, new mould design concepts and methods have to be adopted to meet the requirements of the new machines.

2 OBJECTIVE

The objective of this project was to develop mould design techniques for the new generation of micro injection moulding machines and to study the moulding behaviour of polymer materials in the micro moulding system.

Keywords: Micro; Moulding; Polymer; Mould; Design

3 METHODOLOGY

3.1 Micro Part Design

Mould design was studied for two micro components. One component studied was a lens array with nineteen “micro” lens surfaces designed on the top and bottom sides of the lens array, as shown in Figure 2. The overall dimension of the part was 12x3x2 mm. This type of lens array is widely used in the optical industry. The polymer material selected for this component was polycarbonate (PC) to utilise the advantages of its optical properties, mechanical and process properties.

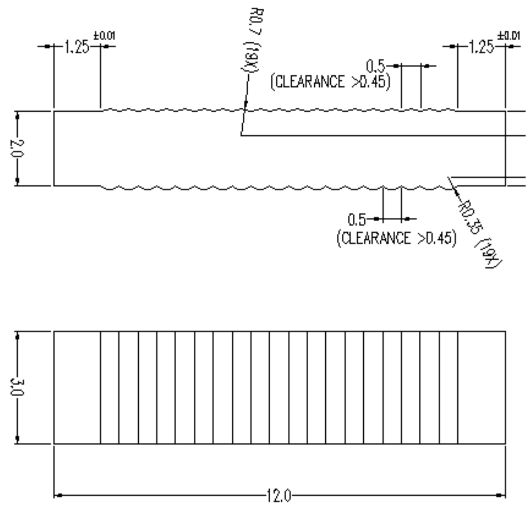


Figure 2 Micro lens array design

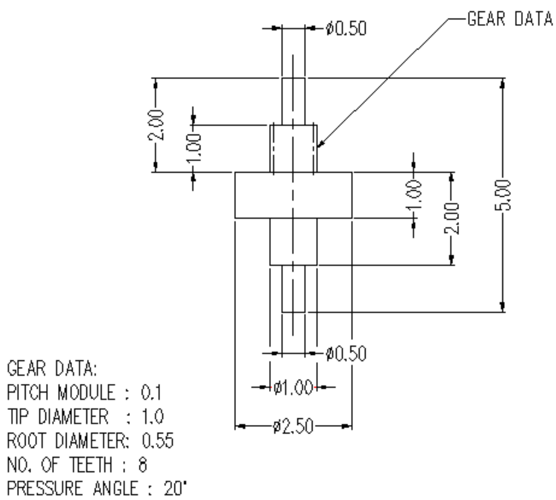


Figure 3 Micro gear design

The other component studied was a micro gear with a shaft as shown in Figure 3. The gear was an 8-thooth gear with a tip diameter of 1 mm. The root diameter of the gear was 0.55 mm and the gear pressure angle was 20^0. The polymer material used for the gear was polyoxymethylene (POM).

3.2 Micro Mould Design

Micro mould design and fabrication is a very important area in the micro moulding process engineering. A mould is a highly sophisticated device that comprises many parts requiring high quality steel. Whether a micro component can be successfully moulded is dependent, to a large extent, on the design and fabrication of the injection moulds.

3.2.1 Mould Structure

The injection nozzles for micro injection moulding machines are usually designed in such a way that they are able to protrude out to reach the parting plane of the mould. This provides the polymer melt with a minimum path distance to the cavities and reduces the runner waste. Mould designers must bear this in mind when design micro moulds for such injection moulding machines, though different types of mould configurations may be used [5], e.g. two-plate or three-plate moulds, with different types of gates and runner designs.

A three-plate mould design, as shown in Figure 4, was used for the micro components studied in this work. Two three-plate micro moulds were designed and fabricated for the lens array and the gear components respectively. The micro lens array mould was a single cavity tool and the mould for the micro gear was a two-cavity mould.

Because of the structure features of the lens array the gating point was designed on the side of the lens array. While for the gear mould, the gating point was designed at one end of the shaft.

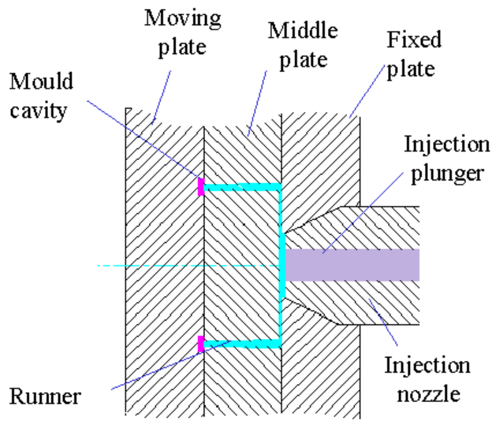


Figure 4 A three-plate mould with injection nozzle extended to the middle plate

3.2.2 Nozzle Contact and Runner Ejection

In a conventional injection moulding machine, the injection nozzle can move forward and come in contact with the mould sprue bushing under a hydraulic pressure during the melt injection process, directing the polymer melt into the mould. The nozzle operates as a leak-proof device, which provides a melt passageway with a minimum pressure and thermal loss [6]. For a micro moulding machine with a nozzle design as shown in Figure 1, the nozzle position is fixed once a mould is mounted on to the machine, and the nozzle is forced in contact with the injection mould under a mechanical locking force.

For the two moulds used in the present study, a tapered surface was designed on the fixed plate to contact with the tapered injection nozzle surface, as schematically shown in Figure 5. It can be observed from this figure that in this design the front tip of the injection nozzle is sub flush to the fixed plate. A space between the nozzle tip and the moving plate will be formed when the mould closes, and a thin disk-shape runner will be formed in the front of the nozzle during the melt injection process.

Since the tapered surface on the fixed plate of the mould is extended to the edge of the plate, a reverse tapered angle will be formed at the tip of the disk-shape runner during the forming process. Because of the reverse angle on the disk-shaped runner, the runner will be kept on the fixed plate side when the mould opens, thus breaking the gate from the part at the parting line.

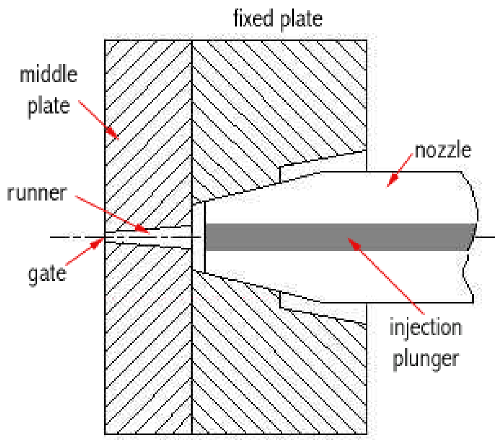


Figure 5 Contact between nozzle and mould plate

3.3 Rheological Properties Study and Mould Runner System Design

In the micro moulding process small or micro size runners and gates are needed since the process targets at mini to micro components. Polymer melts are subject to very high shear rates during flow through such runner and gate systems. Although the effects of such severe processing conditions on the functionality and longevity of the final components are yet to be addressed [7], the viscosity and flowability of the polymer melts will certainly be affected by the runner and gate designs.

As a simple estimation, the wall shear rate in a circular cross-section channel can be calculated as [6, 8]:

$$\gamma_w = 32Q/\pi d^3 \qquad (1)$$

where γ_w is the wall shear rate (s^{-1}), Q is the volume flow rate (mm^3/s), d (mm) is the radius of the flow channel. Since volume flow rate is a function of the injection speed and the injection plunger diameter in a plunger injection process, Equation 1 can be re-written as:

$$\gamma_w = 8V\, D^2/d^3 \qquad (2)$$

where D (mm) is the injection plunger diameter, V (mm/s) is the plunger injection speed. The shear rate in a runner is therefor a function of the injection speed, plunger diameter and the size of the runner system.

Presented in Figure 6 are estimated shear rates in runner systems calculated using Equation 2 for different plunger injection speed and runner dimensions in a plunger injection system with a plunger diameter of 5 mm. It can be observed from the figure that shear rate is very sensitive to the runner dimension. For the gate sizes used for the moulds in this work, 0.3 mm and 0.6 mm for the gear and lens array moulds respectively, the shear rate generated is in the range of 10^5 to 10^6 (1/s). This is much high compared with the conventional injection moulding process.

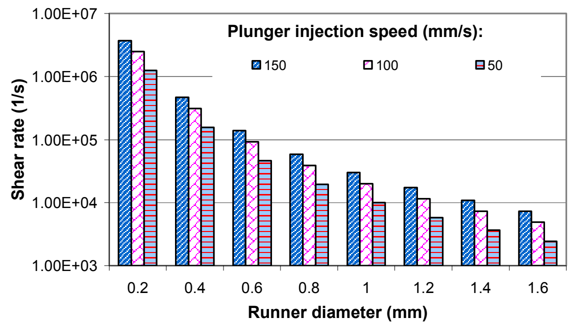
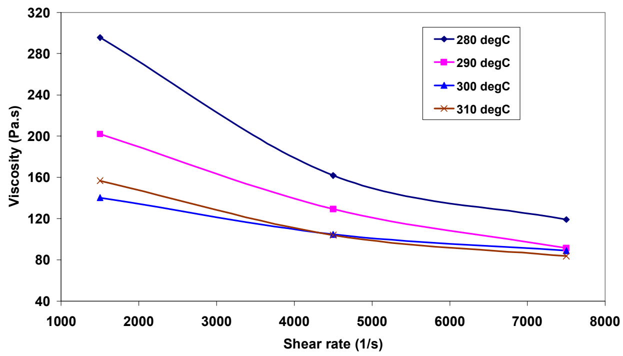


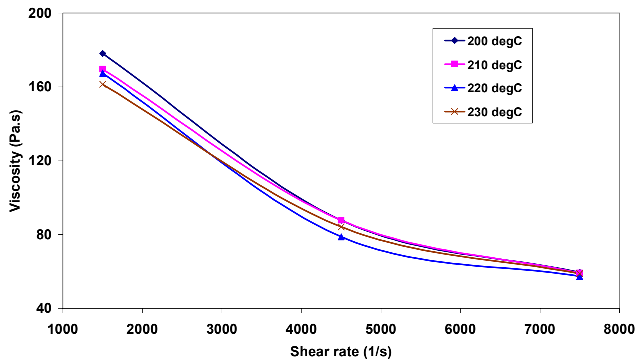
Figure 6 Shear rate in runner system with different dimensions

The rheological properties of the polymer resins used in this work were studied using a capillary rheometer. The viscosity curves of the polycarbonate (PC) and polyoxymethelene (POM) resins are presented in Figure 7a and 7b respectively as a function of shear rate.

It can be observed from Figure 7 that the viscosity of the PC is strongly affected by the process temperature, especially at low shear rates. As the shear rate increases, the effect of temperature decreases. The viscosity of the material generally decreases with the increase of shear rate. This shear rate effect is much stronger at low process temperature and low shear rate region. In plastics lens moulding low injection speed is usually employed for low residual stress moulding. Proper selection and control of process temperature becomes very important for the polycarbonate resin since at low shear rate region the viscosity is strongly affected by the process temperature.



(a). Polycarbonate resin



(b). Polyoxymethylene resin

Figure 7 Viscosity as a function of shear rate at different temperatures

Shown in Figure 8a is the runner system employed for the lens array mould. Considering the temperature sensitivity of the viscosity of the PC resin, a short runner system of 10 mm was used to reduce melt temperature drop during melt injection.

It is observed from Figure 7b that the temperature effect on the melt viscosity of the POM resin is not so significant compared with the polycarbonate resin. However, the melt viscosity is strongly affected by shear rate, especially in the low shear rate region. To obtain low melt viscosity during injection, a high injection speed may be used so that low viscosity can be achieved for easy micro cavity filling. A "micro" trapezoidal runner system with a height of 0.5 mm, and top and bottom widths of 0.5 and 0.8 mm respectively has been selected for the parts, as shown in Figure 8b.

(a). Runner system for the micro lens array

(b). Runner and gate for the micro gear

Figure 8 Runner and gate system for micro moulds

3.4 Moulding Experiment Studies Using Design of Experiment Method

Micro injection moulding experimental studies were carried out using the two micro tools. The micro injection moulding machine used was a Battenfeld Microsystem 50 moulding machine [9]. By using a screw pre-plasticiser, the machine uses a plunger of 5 mm diameter for melt injection to achieve precise measurable strokes to control melt accuracy [2, 3, 10].

The PC and POM resins, whose viscosity curves are presented in Figure 7, were used in the experiment studies for the micro lens array and micro gear components respectively. The moulding behaviour of the polymer materials in the micro tools was studied. Part and runner weight variations were analysed as functions of process conditions.

The design of experiment method (DOE) was employed to study how the moulding process was affected by the process parameters. To study how process conditions affected the part weight and the runner weight in the lens array moulding, a two-level half fraction factorial experiment design was generated and conducted for the micro lens array. The parameters studied included the metering size, mould temperature, melt temperature, cooling time, injection speed, and holding pressure time. Table 1 shows the parameter values used in the experimental study.

Table 1 Process parameters and its values

Factor	High Level	Low Level
Mould temperature (^{o}C)	120	80
Melt temperature (^{o}C)	310	290
Injection speed (mm/s)	50	20
Metering size (mm^3)	230	210
Hold pressure time (s)	2	0
Cooling time (s)	6	2

4 RESULTS AND DISCUSSION

4.1 Moulding Process and Moulded Components

Shown in Figure 9 and Figure 10 are photographs of the moulded micro gear and micro lens array parts respectively.

The injection moulds worked well on the Microsystem moulding machine. Part de-gating, ejection and runner falling went on well for both the lens and the gear moulds. The photographs of the runners in Figure 8 show that polymer melt flowed well in the designed flow channels.

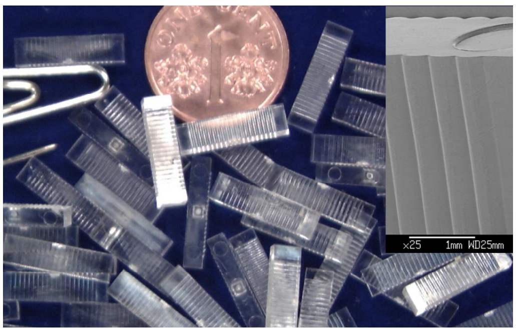


Figure 9 Moulded plastics micro lens arrays

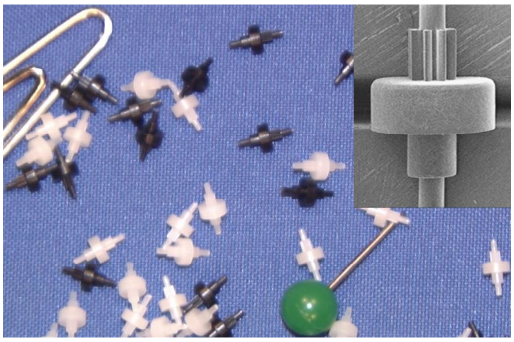


Figure 10 Moulded plastics micro gears

Listed in Table II are some physical features of the moulded micro lens array and gear parts. The part weight of the lens array moulded using PC was about 90 milligram. Since the part in this case was relatively "large", the runner system had a comparable volume to the lens array with a runner weight/part weight ratio of about 1.3. The part weight of the moulded gears however was only 8 milligram, much smaller compared to the lens array part weight. With the runner for the gears weighing 200 milligram, the runner weight/part weight ratio for the micro gears was 12.5.

Table 2 Physical features of the moulded micro lens array

Property	Lens Array	Micro Gear
Material	PC	POM
No. of mould cavities	1	2
Part weight (mg)	90	8
Runner weight (mg)	120	200
Runner weight /part weight	1.33	12.5

For micro part moulding, a big runner system is the general feature, especially when a big injection system is used. For the Microsystem moulding machine used in the present work, the maximum injection volume of polymer melt is 1,000 mm^3, which is one of the smallest on the market. In the micro gear moulding, although a runner/part ratio of 12.5 was used, the total melt volume injected in each moulding cycle was only 150 mm^3. This is only 15% of the machine injection capacity. Although it is possible to use a smaller runner and lower percentage of the machine capacity, there are other considerations that need to be borne in mind, e.g. the melt residence time and material degradation. In the present runner design defect-free components are formed.

4.2 Part Weight and Runner Weight

In the micro injection moulding process employing a plunger injection system, the melt metering setting is a critical factor affecting part quality [11]. This is because polymer melt back flow is not possible in the process, and all the metered melt, no matter whether it is under or over the desired amount, will be injected into the runner system and the mould cavities.

Presented in Figure 11 are the experiment results for the weight of the moulded parts and the runners obtained at the DOE process conditions.

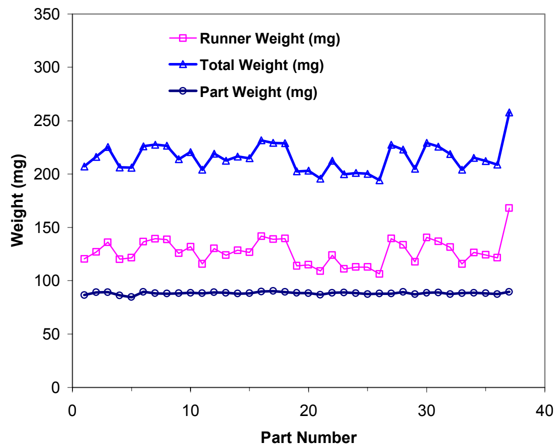


Figure 11 Micro lens weight and runner weight variation with process conditions

It is observed from this figure that the curves for the runner weight and the total weight of the runner and the part follow a similar pattern in responding to the change in process conditions. While for the part weight, which is in the same magnitude range as the runner weight, the variation is much smaller compared with the runner weight. This may be attributed to the fact that when more than the required amount of polymer melt is supplied to the injection barrel, it is easy to pack it into the runner system than press it into the mould cavity through the gate.

4.3 Process Parameter Effects on Part Quality

In order to study the effect of injection speed, an experiment was carried out over a series of injection speeds while the other conditions were maintained constant for the lens array moulding. The weight of the runner and part obtained are presented in Figure 12.

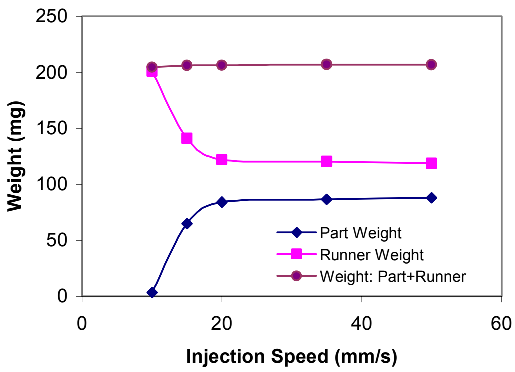


Figure 12 Effect of injection speed on part and runner weight

It is observed from the figure that while the total weight of the runner and part maintained at a constant value, the runner and part weight varied considerably at different injection speeds.

At low injection speeds very low part weight was obtained, indicating that the mould cavity was not fully filled. On the other hand, the runner weight was very high at these conditions. This is because the melt in the runner system cools down very quickly due to the small size of the runner and gate system. At low injection speeds, the melt moves slower in the runner and gate system and becomes more viscous or even solidified before the mould cavity is fully filled.

For the micro gear moulding, an experiment was carried out on different metering size settings to study the effects of metering size on part weight and runner weight. Shown in Figure 13 are the results of part and runner measurement as a function of the metering size. It can be observed that with low melt metering, both the part weight and the runner weight increased linearly with the metering size. However, after the metering size reached about 210 mm^3, little increases were observed in the gear part weight. On the other hand, runner weight was found to increase further even after a steady state of part weight was achieved. This is because any back flow of polymer melt is impossible in the plunger injection process. Once the cavity is filled, any further metering increase will result in bigger runners. The ideal metering size, therefore, should be the one that provides just enough polymer melt to fill the cavity.

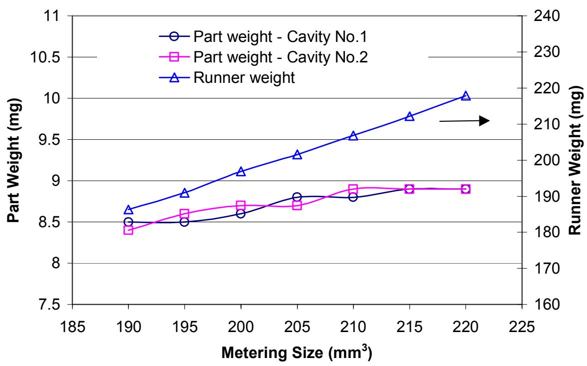


Figure 13 Micro gear part weight and runner weight as a function of metering size

5 CONCLUSIONS

- In the micro moulding process, for different product designs and polymer materials, different mould runner systems may be used for better melt flow and cavity filling. For materials with a shear sensitive viscosity, a small runner system may be employed to generate a high shear to reduce melt viscosity for easy micro cavity filling. For temperature sensitive materials, a short runner system should be used to minimise thermal losses.

- For micro injection systems with a screw-barrel plasticisation and plunger injection system, mould parting lines can be designed at the nozzle tip for better melt injection and pressure control. Unlike the conventional injection moulding processes using screw injection, it is a good practice in a plunger injection system to retain the moulded plastic runner on the fixed half of the mould. This can be achieved by designing a disk-shaped space at the front of the nozzle with a reversed taper angle. The forward movement capability of the injection plunger can then be utilized to eject the moulded runner.

- The process parameter that has the most significant effect on both the runner weight and part weight is the metering size. The effect on the runner weight is much more significant than on the part weight, especially when over metering settings are used. Control of part weight is more complicated and involves other processing parameters such as the injection speed and mould temperature.

6 INDUSTRIAL SIGNIFICANCE

The trend towards miniaturisation has brought about demands for increasingly small precision-moulded plastic components, especially in the areas of medical and information technologies. In order to meet the challenges towards miniaturisation, a new generation of moulding machines that use a separate screw plastication unit and a plunger injection system has been developed in the moulding industry for fabrications of micro components down to milligram levels.

Micro mould design and fabrication is one of the challenges in producing micro components with stringent dimensional and functional requirements. New mould design concepts and methods have to be adopted to meet the demand of the new machines. The technologies developed for micro mould design and micro moulding process will enable the moulding industry to quickly pick up the micro moulding technology – a key enabling technology for wide applications of MEMS devices.

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