

## Experimental Study of Demolding Properties on Stereolithography Tooling

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*Direct tooling using stereolithography (SL) photopolymer has been developed as rapid tooling for short-run injection molds. However, the tool strength, thermal conductivity, and erosion resistance of SL mold are lower than that of the conventional metal mold. Previous study has showed that the tool life was limited under 200 shots and tool damage often occurs during part ejection. In this paper, experimental data from a demolding properties test are presented and discussed. The experiments were performed using various cooling time, hold pressure, and mold temperature. The experimental data were analyzed by measuring demolding force and surface roughness to evaluate tool life and failure mechanism in order to obtain a working range for the process parameters. The test result shows that the demolding force has close relation with cooling time and mold temperature.*  
[DOI: 10.1115/1.2716752]

*Keywords: demolding properties, rapid tooling, failure mechanism*

### 1 Introduction

The rapid-prototyping (RP) process has been used increasingly for developing new products. All of the RP processes involve adding layers of material to construct three-dimensional parts and patterns directly based on computer-aided design (CAD) models. RP patterns can be employed in visual inspection, form-fit analysis, and prototype tooling.

Rapid tooling (RT) is a RP extension for small production runs. Presently, stereolithography (SL) is the most popular, prominent and effective means of producing three-dimensional (3D) parts

from photosensitive resins. Direct tooling using stereolithography photopolymer has been proposed as rapid tooling for short-run injection molds [1,2].

So-called Direct AIM™ (ACES injection molding) utilizes SL patterns generated on a stereolithography apparatus (SLA) from 3D systems as mold inserts in injection molding. Previous works have shown that the tool life was limited under 200 shots, and tool damage occurred commonly during part ejection [3–5]. The experimental results obtained by Hopkinson and Dickens [3] indicate that the trend of the ejection forces is related to cooling time. Furthermore, they pointed out that lowest ejection forces were measured at the lowest cooling time and the highest forces were observed for the longest cooling time. Also, the effects of cooling time on tool temperature appear to be significant, suggesting that an early ejection is preferable.

Injection molding is a high-pressure and high-temperature casting process. The primary shortcomings of the SL mold in the injection molding process are that the tool strength, the thermal conductivity, and the erosion resistance are lower than those of the conventional metal mold. Tool life and production quantity are main concerns in injection molding; thus, the demolding properties, which are strongly related to the tool life, of the SL mold are vital. In this study, a demolding property test of SL mold is performed to evaluate the tool life and the failure mechanism of the mold. Experiments were performed with various cooling times, hold pressures, and mold temperatures to measure the demolding forces and surface roughness.

### 2 Experiments

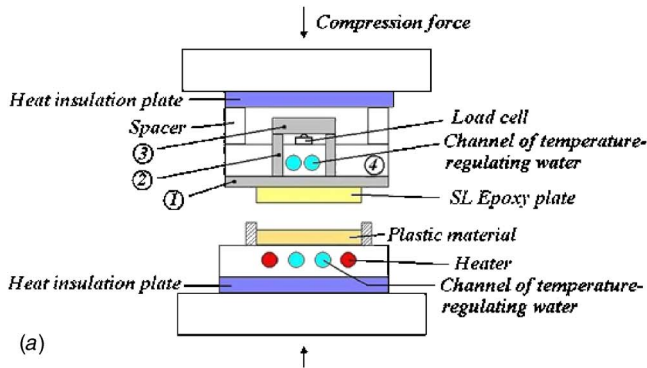
The failure mechanism of the SL mold used in injection molding can be analyzed by measuring the demolding forces and variations in the surface roughness of the SL mold. Figure 1 presents the analytical experimental apparatus designed and constructed for this purpose. A compression test fixture was set on a 50 KN hot press machine to simulate the packing, cooling, and demolding involved in the injection molding process. During the process, the SL epoxy plate was simulated as an injection mold insert. When the hot press machine acts on both the SL epoxy plate and the plastic material at a particular pressure, it is represented as the packing phase of an injection molding cycle. The mold temperature, hold pressure, hold time, and cooling time are the four test parameters. The best combinations of injection molding conditions [6] are used as the fixed parameters:

- Hold pressure/time=10 MPa/5 s
- Mold temperature=50°C
- Cooling time=240 s

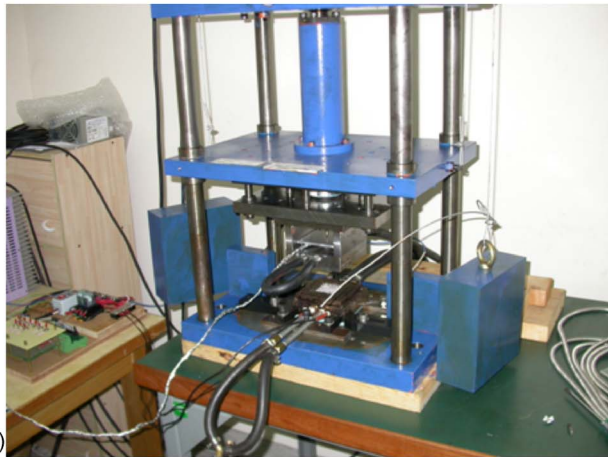
Table 1 lists the range of the test parameters.

In Fig. 1, the components ①, ②, and ③ are joined together, and component ④ is used to guide component ②. Polypropylene (PP) was used as a molded plastic material, and was heated and maintained at 210°C before it was cooled. The SL epoxy plate with a thickness of 3 mm was made from SL 5510 resin using ACES (accurate clear epoxy solid) build style. This epoxy plate was

Contributed by the Manufacturing Engineering Division of ASME for publication in the JOURNAL OF MANUFACTURING SCIENCE AND ENGINEERING. Manuscript received March 18, 2006; final manuscript received November 2, 2006. Review conducted by Dong-Woo Cho. Paper presented at the McMat 2005 Mechanics and Materials Conference (McMat 2005-1.T2.A-55).



(a)



(b)

**Fig. 1 Experimental setup: (a) Compression test fixture and (b) hot press machine with the compression fixture**

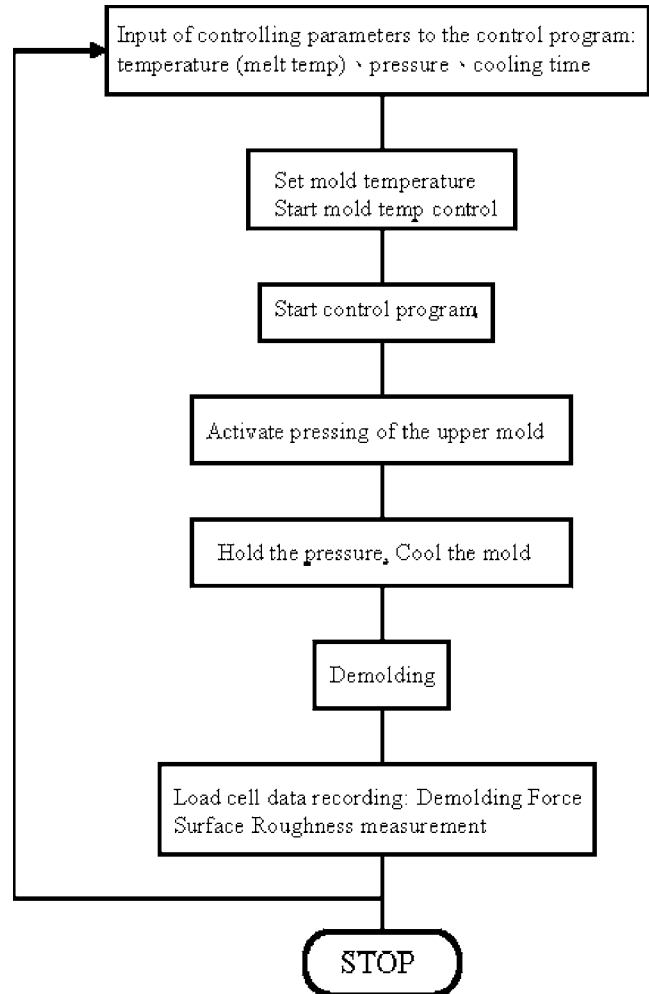
fixed in the upper mold plate (component ①) via bolt joints. Thermocouples were placed in the upper and lower mold plates of the test fixture to measure the temperatures of the tool and plastic material. Two cartridge heaters, connected to a temperature controller, were used to melt the plastic material. The cyclic-water-type mold temperature regulator was connected to the upper and lower mold plates as a cooling cycle channel. The demolding forces were measured using a load cell (KYOWA LM-20KA), which was mounted on the upper position of the fixture. A data acquisition unit, National Instruments NI 6024E, with a visual program LABVIEW, was used on a PC to calculate and plot the signals from the load cell. The surface roughness of the SL epoxy plate was measured before and after the test was performed, using a Mitutoyo SURFTEST MST-211 machine. Figure 2 shows the flow chart that describes the molding procedure along with the related parameters.

### 3 Results and Discussion

The focus of this experiment was to investigate the effects of various process parameters on the demolding properties. Several experiments were performed to determine trends and the effective range of the process parameters in the experiments.

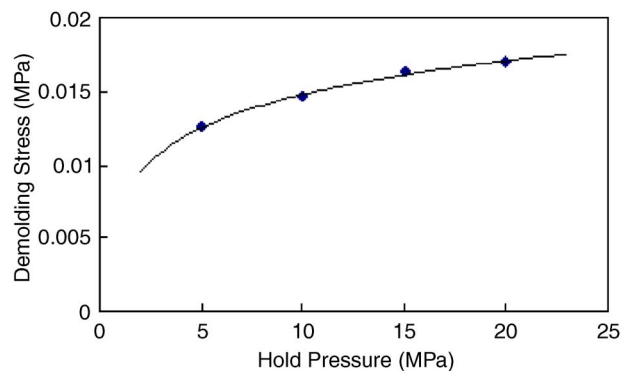
**Table 1 Test parameters**

Test parameter	Variation range
Mold temperature (°C)	30, 40, 50, 60
Hold pressure (MPa)	5, 10, 15, 20
Hold time (s)	1, 5, 10, 20
Cooling time (s)	120, 180, 240, 300



**Fig. 2 Flowchart of the molding procedure**

**3.1 Effect of Process Parameters.** Previous results have shown that tools are commonly damaged during part ejection [3], indicating that the tool failure mechanism is related to the demolding force. Figure 3 plots the results of the relationship between the demolding stress (which is the demolding force divided by the contact area of the SL epoxy plate) and the hold pressure. The demolding stress increases with the hold pressure. However, the rate of increase of the demolding stress declines as the hold pressure increases. This trend differs from that in the case of a metal



**Fig. 3 Effect of hold pressure on the demolding stress, under the conditions, hold time = 5 s, cooling time=180 s, mold temperature=50°C**

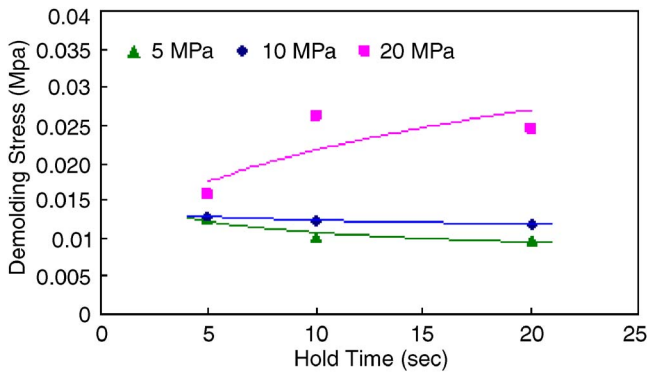


Fig. 4 Effect of hold time on the demolding stress at hold pressures of 5 MPa, 10 MPa, and 20 MPa, under the conditions, cooling time=180 s, mold temperature=50°C

mold [7]. In this case, a much higher hold pressure compacts the surface of the molding material more tightly onto the SL epoxy plate (SL mold), whose surface is microscopically rough and uneven. This mechanism is considered to be that by which the demolding stress increases.

Additionally, the effect of the hold time on the demolding stress should be considered, since the time required for which the pressure was held varied with the shape, size, and purpose of the product to be injection molded. Figure 4 shows the effect of hold time on the demolding stress. At a high hold pressure of 20 MPa, longer hold time corresponds to a higher demolding stress. However, at a low hold pressure of 5 MPa or 10 MPa, the demolding stress decreases as the hold time increases. These results can be explained as being caused by competition between shear stress and friction. Shear stress developed because of the contraction of the molding material during cooling. This phenomenon occurred on the contacting surface of the SL mold and the molding material. At high hold pressures, the maximum static friction between the surfaces of the molding material and the SL mold can exceed the shear stress mentioned above, preventing the shear stress from destroying the micromechanical attachment and surface adhesion between the contacting surfaces of the molding material and the SL mold. Therefore, a good mechanical attachment and surface adhesion condition can be maintained more completely as the time for which the pressure is held increases, increasing the demolding stress. However, the maximum static friction between the surfaces of the molding material and the SL mold decreases as the hold pressure is reduced. When the hold pressure is sufficiently low to cause the maximum static friction to be less than the shear stress generated by the shrinking of the mold material, the shear action can begin to destroy the attachment and adhesion

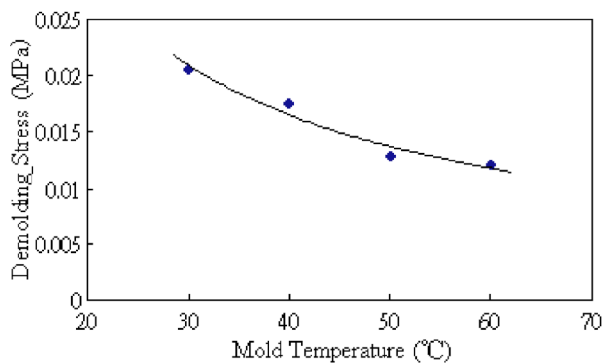


Fig. 5 Demolding stress against mold temperature under the conditions, hold pressure=10 MPa, hold time=5 s, cooling time=180 s

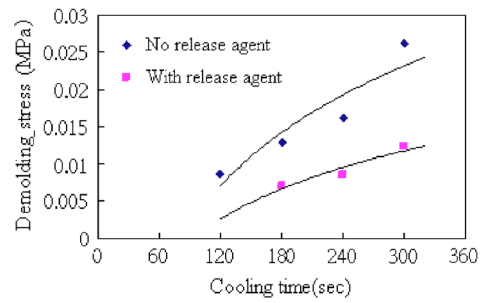


Fig. 6 Effect of cooling time on the demolding stress under the conditions, hold pressure=10 MPa, hold time=5 s, mold temperature =50°C

conditions between the surfaces of the molding material and the SL mold. Therefore, the resultant demolding stress at low hold pressure is smaller than that at high hold pressure. Furthermore, the destruction of the attachment and adhesion between the contacting surfaces of the molding material and the SL mold becomes more serious as the time increases or the holding pressure declines. Accordingly, the demolding stress decreases.

In the injection molding process that uses the SL mold, the mold temperature may not exceed the glass transition temperature,  $T_g$  (68°C), of the SL material. Figure 5 indicates effect of mold temperature on the demolding stress. The demolding stress decreases as the mold temperature rises. Figure 6 shows the effect of the cooling time on the demolding stress at a specified mold temperature. Under mold conditions with or without the release agent, the demolding stress increases with the cooling time. Moreover, the magnitude of the demolding stress when no release agent is used always exceeds that in the case in which the agent is used. Suppose that the release agent used is sufficient to prevent the surface adhesion of the mold and the molding material; the difference between the magnitude of the demolding stress without a release agent and that with a release agent can be considered to represent approximately the strength of the surface adhesion between the surfaces of the SL mold and the molding material. This difference increases with the cooling time. Moreover, the demolding stress in the case with the release agent can be considered to have resulted primarily from the breaking of the mechanical attachment between the surfaces of the SL mold and the molding material. A longer cooling time corresponds to a lower temperature and a greater deformation resistance of the molding material; thus, breaking the mechanical attachment becomes much harder

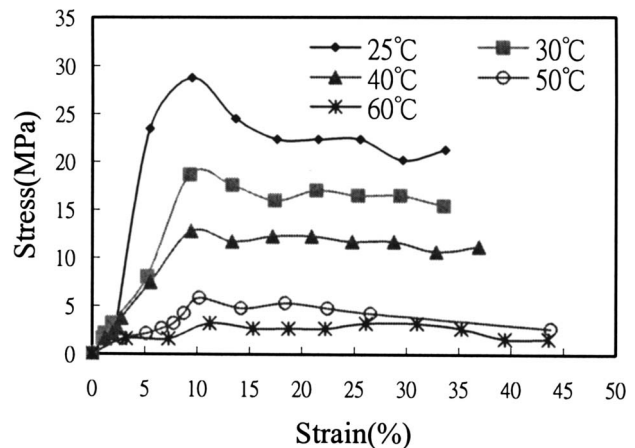
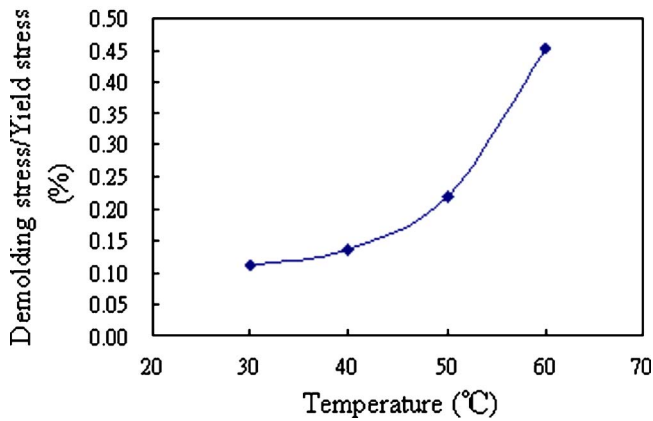


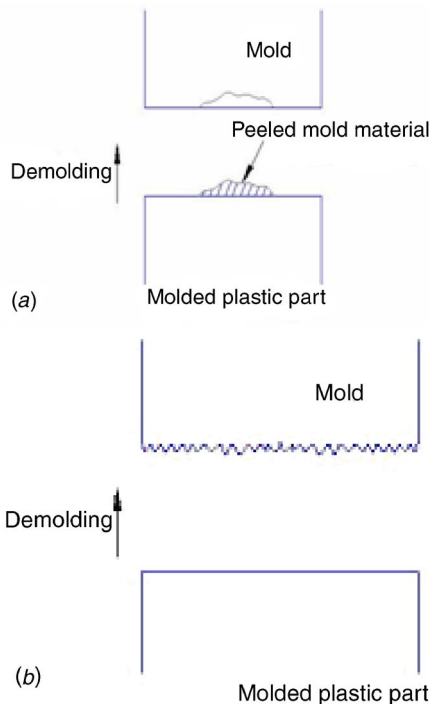
Fig. 7 Compressive stress-strain curves of SL epoxy at various temperatures



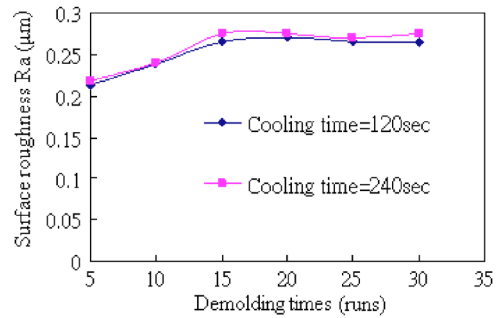
**Fig. 8 Comparisons of demolding stress and yield stress of SL mold material with temperature: variation of the ratio of demolding stress to yield stress**

as the cooling time increases, so the demolding stress increases. The experimental results in Fig. 5 can also be explained with reference to the mechanism mentioned herein.

**3.2 Thermal Investigation.** The effect of the demolding stress on the mold depends on the characteristics of the mold material [8–10]. Figure 7 presents the compressive tests results for the SL mold material (epoxy) used in this study. This figure indicated that the SL mold material exhibits the typical stress-strain behavior of plastics: plastic flow occurs when the magnitude of the stress reaches the yield value. Moreover, the yield stress substantially declines as the temperature of the SL mold material rises, indicating that, as the mold temperature rises, the ability of SL mold resistance damages declines greatly. Figure 8 plots the yield stress of the SL mold material and the demolding stress against temperature. Obviously, under the operating range of mold temperatures, the effects of the demolding stress on the SL mold



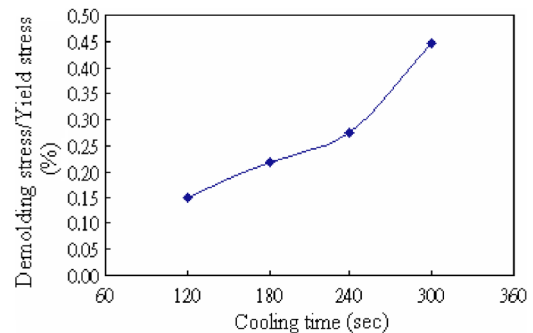
**Fig. 9 (a) Peeling of the mold wall surface and (b) roughening of the mold wall surface**



**Fig. 10 Demolding times versus surface roughness of SL mold (hold pressure=10 MPa, hold time=5 s, mold temperature =50°C)**

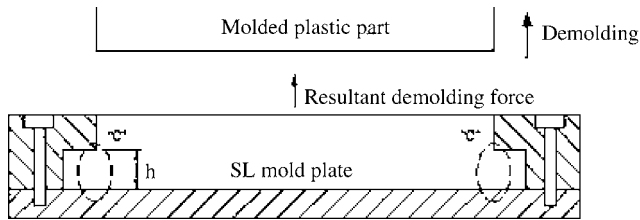
may become increasingly worse as the mold temperature increases. However, the demolding stress remains far lower than the yield stress of the mold material. Therefore, the peeling of the surface layer from the cavity wall in the SL mold, due to demolding (Fig. 9(a)) cannot easily occur. The roughening of the surface of the cavity wall (Fig. 9(b)) should also be slight. Figure 10 presents the variation of the surface roughness of the cavity wall with the demolding times. There was a slight increase of the surface roughness of the core/cavity after the demolding experiment, i.e., an increase from 0.20–0.22 μm to 0.23–0.25 μm. This is attributable to the plastic deformation of the core/cavity induced by demolding force. As expected, the mold cavity surface becomes slightly rough during the initial period of demolding, but after 15 runs of demolding, its surface roughness is maintained at an acceptable value: it no longer varied (detectably) with the increase in the number of run of demolding. Figure 11 shows the effect of the cooling time associated with demolding on damage to the SL mold. A longer cooling time is associated with a more detrimental effect of the demolding function on the SL mold because increasing the cooling time increased the demolding stress (Fig. 6), although the SL mold was maintained at a constant mold temperature and its strength did not change.

**3.3 Design of SL Mold.** Although the ratio of demolding stress to the yield stress of the SL mold material usually did not exceed 0.5% under normal operating conditions, it is not directly responsible for damage to the surface of the mold wall. Notably, however, the area of contact between the molded part and the mold insert governs the resultant force in demolding. The SL mold plate with a cavity in the shape of the SL mold is usually fixed onto the mold base using a screw or a clamping plate (as shown in Fig. 12). Therefore, the strength of the fixed position on the SL mold plate and the magnitude of the resultant demolding force must satisfy the following relationships:



**Fig. 11 Effect of cooling time on the ratio of demolding stress to yield of an SL mold (hold pressure=10 MPa, hold time=5 s, mold temperature =50°C)**





**Fig. 12 Method for fixing SL mold plate onto the mold base (C: area of resistance to demolding force)**

$$S > F \quad (1)$$

where  $S$  is the strength of the fixed position on the SL mold plate and  $F$  is the resultant demolding force.

However, for

$$S = \tau_y \times A_C = 0.5\sigma_y \times h \times l \quad \text{and}$$

$$F = \sigma_d \times A \quad (2)$$

where  $\tau_y$  and  $\sigma_y$  represent the shear and compressive yield strengths, respectively, of the SL mold material,  $A_C$  is the cross-sectional area of the  $C$  section at the fixed position on the SL mold plate;  $h$  is the height of the  $C$  section;  $l$  is the total length of the position fixed by the clamping plate on SL mold plate (or the total length of the  $C$  section);  $\sigma_d$  is the demolding stress, and  $A$  is the area of contact between the molded part and the SL mold plate. Substituting Eq. (2) into Eq. (1) yields the following equation:

$$0.5\sigma_y \times h \times l > \sigma_d \times A \quad (3)$$

Based on Figs. 8 and 11, assume  $\sigma_d \leq 0.005\sigma_y$ ; then, the SL mold design must satisfy

$$h \times l > 0.01A \quad (4)$$

to prevent the destruction of the SL mold plate by the demolding forces of the SL mold.

In practical applications, creep and fatigue characteristics of the SL mold material should be taken into consideration, so that Eq. (4) must be modified as follows:

$$n \times h \times l > 0.01A \quad n > 1 \quad (5)$$

where  $n$  is the design factor. Therefore, when designing an SL mold, the minimum allowable cross-sectional area considered for the area that breakage is most likely to occur is dependent on the contact area between the SL mold plate and the molded part. As such, maximum tool life is then realizable.

#### 4 Conclusions

This study included the design and construction of a set of test apparatus to simulate packing, cooling, and demolding in the in-

jection molding process in which SL mold is used; the demolding forces were measured. Based on the experimental results, the demolding stress of the SL mold in the injection molding of a plate of PP plastics was analyzed. Moreover, the effect of the demolding stress on the damage to the SL mold was investigated. The following conclusions are drawn.

1. When applications of the SL mold is employed, the demolding stress may increase with the increasing hold pressure, the reducing the mold temperature, and the increasing cooling time.
2. When the hold pressure exceeds 10 MPa, the demolding stress increases with the hold time.
3. The surface roughness of the SL mold plate does not change dramatically with the increase of the demolding times.
4. The demolding force damages the SL mold mostly at the locality where the SL mold plate is fixed to the supporting structure or where the section of SL mold plate has the smallest cross-sectional area. Therefore, when designing an SL mold, the minimum allowable cross-sectional area considered is dependent on the magnitude of the contact area between the SL mold plate and the molded part stated above. As such, maximum tool life is then realizable.

#### Acknowledgment

The authors would like to thank the National Science Council of the Republic of China for financially supporting this research under Contract No. NSC 92-2212-E-009-005.

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