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A Study of Friction Testing Methods Applicable to Demoulding Force Prediction for Micro Replicated Parts

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A STUDY OF FRICTION TESTING METHODS APPLICABLE TO DEMOULDING FORCE PREDICTION FOR MICRO REPLICATED PARTS

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ABSTRACT

For replication processes to be deemed successful it must be possible to remove the replicated parts from the tool after processing. With decreasing part and feature size the challenge of demoulding replicated parts increases since the resulting parts and replication tooling used are more delicate and can be easily damaged. Predictive demoulding force models can be used to optimise the part, tool and process parameters to maximise the likelihood of success. Developing accurate models for this process requires knowledge of the dominant interfacial contributions to friction and knowledge of the size scale at which the dominant contributions operate together with an understanding of how these might change as process parameters vary. This paper explains the dominant contributors to friction at the micro scale and reviews test methods which are available to isolate and quantify each of these contributors.

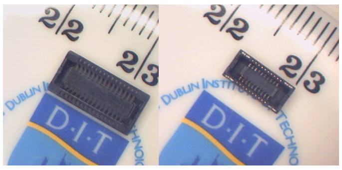
KEYWORDS

Micro replication, friction, demoulding force modelling.

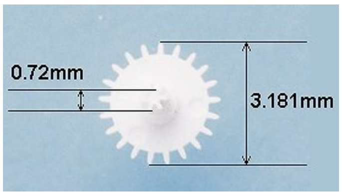
1. Introduction

Replication technologies have a key role to play in producing components consistently in large volumes at a relatively low cost. Such technologies use a die or a mould to generate the desired structures. A broad range of micro replication technologies have been developed in recent years, allowing the realization of parts with features from hundreds of µm to tens of nm (10^{-4} m to 10^{-8} m) in different materials such as polymers and ceramics. When a replicated part reaches a condition that it will remain stable outside of the tool it is forcibly demoulded or ejected from the replication tool. This force, typically applied via a series of ejector pins, is needed to overcome retarding forces which develop at the component and tool interface.

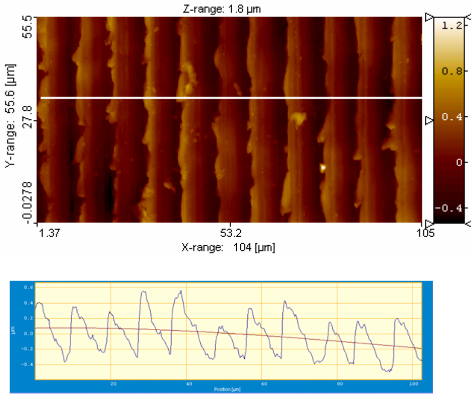
With conventional-sized moulded parts quite large ejection areas can be used and the parts themselves are suitably rigid so that they are unlikely to be damaged by activation of the ejector pins. However as part size reduces, the potential sites where ejection pins can act are reduced and the parts themselves become weaker and more prone to damage when mechanically stripped from tool cores. Examples of parts with such micro features, together with an image of a replication tool surface and sectional profile created using SPIP software [1] are shown in Figure 1.



Micro miniature connector housing and assembly (0.4mm pitch)



Micro gear and pinion [2]



Micro replication tool and surface profile

Figure 1: Typical micro products and the surface of a micro replication tool.

For both micro and conventionally-sized parts demoulding failure results from shear stress due to friction and thermally-induced stress due to cooling. Examples of part deformation caused during demoulding by the shrinkage differences between tool and polymer are shown in Figure 2 [3].

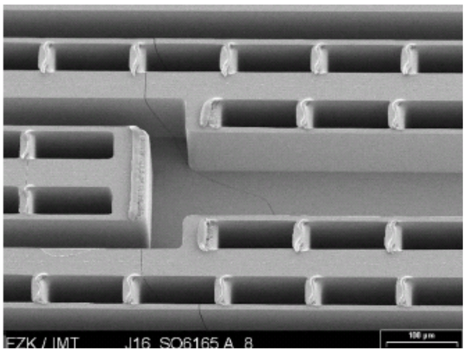


Figure 2: Example of micro structure deformation caused by demoulding process [3].

This paper defines “demoulding force” as that necessary to initiate the ejection movement of the part only, thereby not including frictional effects from the actual ejection mechanism. An ability to quantify such demoulding forces prior to tool fabrication helps designers, particularly designers of smaller components, to optimize replication tools to minimize the demoulding force and resultant stress on replicated parts.

A number of models have been proposed to predict the demoulding force of replicated parts from replication tools, all assuming the existence of an accurate coefficient of friction. This paper describes the importance of such coefficients for existing demoulding force models and summarises the dominant contributors to friction at the micro scale. This is followed by a review of the suitability of standardised test methods to measure friction at the micro scale together with a review of the testing methods developed specifically to measure friction coefficients in the context of replication processes.

2. Demoulding force and friction in the context of demoulding force models

During the cooling phase of a replication process, parts shrink onto and are constrained by the replication tool. This shrinkage causes stress to build up in the cross section of the part [4] and results in the generation of forces normal to the surfaces restrained from shrinking. The stresses which develop are strongly related to normal pressure and therefore to shrinkage, part stiffness and mould packing. These forces are those resulting from contact pressure between the tool and core. If atmospheric pressure doesn’t exist between the part and core during demoulding a suction force may be generated. This is the product of atmospheric pressure and surface area on the top of the core. These primary demoulding force components are illustrated in Figure 3.

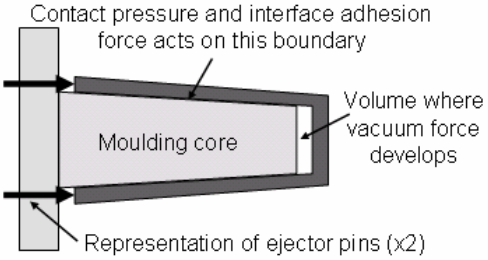


Figure 3: Primary contributors to demoulding force.

A tangential force is required to overcome the effect of these frictional forces and create relative motion between the part and tool during part demoulding. Most mathematical models to quantify the force needed to demould parts from replication tools derive from the empirical law of Coulomb friction [4]. For parts which shrink onto cores, such as sleeves or box-shaped parts, the release force F_R is given as:

$$F_R = \mu \times P_A \times A_C \qquad (1)$$

Where μ is the coefficient of friction P_A is the contact pressure and A_C the area of contact. An outline of demoulding force models based on Coulomb’s law is shown in Figure 4.

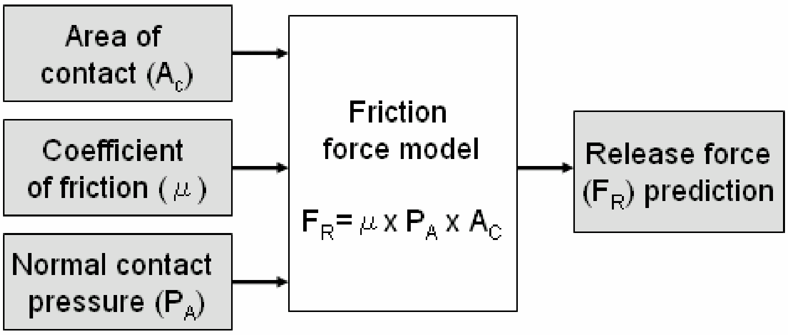


Figure 4: Outline of demoulding force models.

While the nominal contact area can be measured relatively easily the friction coefficient and contact pressure can have various interpretations. For simple geometries, such as cylindrical parts which shrink onto a core, thick-walled cylinder theory can be used to predict the contact pressure between the replicating tool and the replicated part assuming the material properties and part geometry details are known. For more complex geometries Finite Element Analysis has been applied to predict the contact pressure [5]. However the magnitude of μ depends upon several factors such as the materials concerned, mould surface roughness, moulding pressures, demoulding velocity, and mould temperatures. The approach typically followed, effectively treating the effects of friction as a "black-box" produces a single number which can mask the contribution made by different friction mechanisms. To more clearly understand the situation at the micro scale the specific contributors to friction at this scale are briefly discussed.

3. Dominant contributors to friction at the micro scale

Interpreting the friction of organic polymers to describe part demoulding is complex since there are many influencing factors. Building upon Bowden and Tabor's [6] friction law Briscoe [7] presented an interpretation of organic polymer friction based on a two-term non-interacting model where the frictional work is dissipated in two distinct regions; an interface zone and a subsurface zone as shown in Figure 5. The overall friction force F is assumed to consist of two components; one relating to adhesion, $F_{adhesion}$, and the other to deformation or hysteresis, $F_{deformation}$:

$$F = F_{adhesion} + F_{deformation} \qquad (2)$$

The adhesion term is a surface effect, regarded as occurring to a depth in either surface which does not exceed molecular dimensions (Angstroms), whereas the deformation term is a bulk phenomenon. This deformation component of friction, which results from delayed recovery of the elastomer after indentation by a particular asperity, is a bulk effect governed by the relative velocity of the surfaces as well as the overall pressure distribution. Each term of this non-interacting model includes contributions from different interface phenomena.

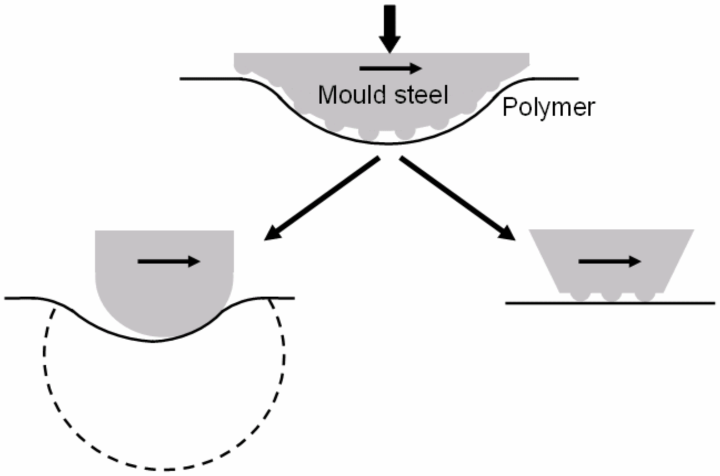


Figure 5: Separation of friction into deformation and adhesion components.

3.1 Adhesion component of friction

Adhesion is a surface effect for which various definitions have been proposed. Wu [8], states that: *Adhesion refers to the state in which two dissimilar bodies are held together by intimate interfacial contact such that mechanical forces can be transferred across the interface. Mechanical strength of the system is determined not only by the interfacial forces, but also by the mechanical properties of the interfacial zone and the two bulk phases.*

For the purposes of this review adhesion mechanisms have been categorized as consisting of thermodynamic/chemical adhesion, electrical / electrostatic adhesion and capillary attraction as shown in Figure 6 (adapted from Garbassi et al [9]).

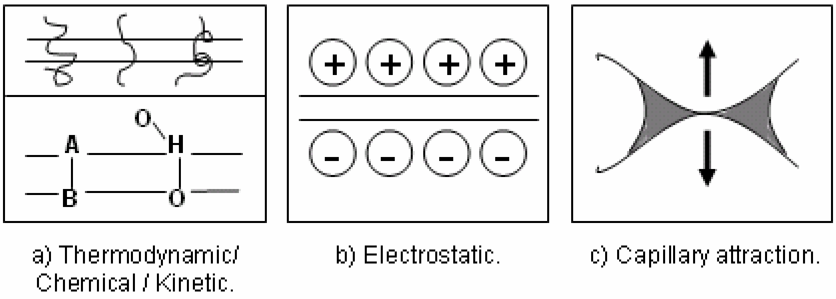


Figure 6: Fundamental adhesion mechanisms.

In the case of thermodynamics / chemical / kinetic adhesion some materials may merge at the joint by diffusion or inter-diffusion of chains if the molecules of both materials are mobile and soluble in each other. This is particularly effective with polymer chains where one end of the molecule diffuses into the other material. During sintering, when metal or ceramic powders are compacted and heated, this mechanism causes atoms to diffuse from one particle to the next joining the particles together. Wake [10] has reported that attempts to extend this diffusion theory to polymer/metal systems were not successful.

Electrostatic adhesion arises from charge generation (triboelectrification) or charge transfer during contact. Some conducting materials may pass electrons to form a difference in electrical charge at the joint resulting in a structure similar to a capacitor and creating an attractive electrostatic force between the materials which accounts for the resistance to separation. Ebnesajjad [11] described the electrostatic mechanism as a plausible explanation for polymer-metal adhesion bonds. In this case the metal will be the electron donor and when the contact is broken the polymer surface will get a negative charge.

When surfaces have a micro-roughness the gaps between contacting asperities can become filled with water resulting in the development of a meniscus force (capillary attraction). This is particularly likely to happen in high humidity environments where a liquid film develops between the replicating tool and the replicating part. Adsorption of moisture at the narrow gap can lead to the formation of a liquid bridge resulting in surface tension.

3.2 Deformation component of friction

The deformation component of friction can be further divided into ploughing and hysteresis contributions. Ploughing friction models assume that the dominant contribution to friction is the energy required to displace material ahead of a rigid protuberance (or protuberances) moving along a surface. Ploughing deformation in replication processes results from the sliding of replicated parts across features such as asperities and burrs which may remain from the tool fabrication process. Hysteresis is dependent on the viscoelastic properties of the elastomer and occurs due to delayed recovery after indentation by a particular asperity. It is governed by the relative velocity of the surfaces, the demoulding rate, as well as the overall pressure distribution.

4. Determining a suitable coefficient of friction

The coefficient of friction is defined as the ratio of the tangential force required to slide a body along a surface and weight of the actual body itself. The static coefficient of friction is typically higher than the dynamic coefficient of friction. To ascertain realistic friction coefficients Bataineh and Klamecki performed actual demoulding experiments of ring shaped geometries and these values were then used to predict the demoulding force [12]. This approach assumes that the coefficient will be the same for the geometry tested and the geometry being modelled. For convenience and speed it is desirable to evaluate friction coefficients using dedicated, standardised tests.

4.1 Standardised friction test equipment and methods

Equipment for such testing must support the two bodies being studied, move the bodies relative to each other in a controlled fashion, apply a normal force and measure the magnitude of the tangential friction force opposing relative motion. Several different designs of friction testing rigs, or tribometers, have been developed for commercial applications. Two of the simplest tribometers are the sled and inclined plane types as shown in Figure 7.

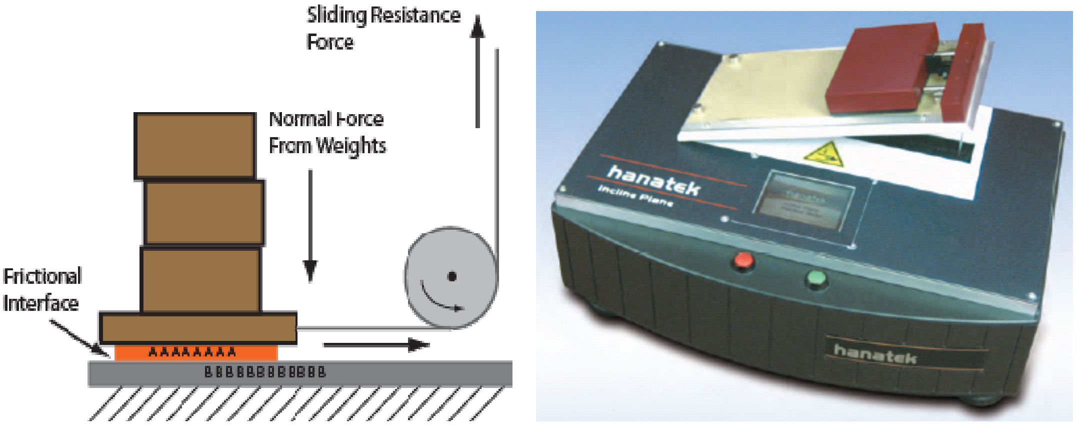


Figure 7: Tribometers for commercial application [13, 14].

A key issue in friction testing is the repeatability of the results (within the same laboratory) and the reproducibility of the results (between one laboratory and another). According to Blau, with the proper care friction test results can be extremely repeatable and, to a lesser degree, reproducible [15]. To address this problem standards have been developed by several organisations. Specific test standards, describing sled-type tests, include JIS K 7125, ISO 8295 and ASTM D1894.

Maldonado [16] measured the coefficient of friction for polymers sliding across steel and aluminium surfaces using a modified form of ASTM D 1894. Results reported show that the coefficient of friction varies significantly with increased load. However the experiments were not performed at temperatures or pressures representative of conditions within a replication tool. This is important for replication processes, particularly at the micro scale, where quite high replication pressures can be found.

If larger normal forces are needed to generate the increased normal pressure then the sled-type friction tribometer is not suitable and a friction tester of different construction is typically used. An example of such a device is the pin-on-disk test rig as shown in Figure 8. The axial hydraulic actuator allows the application of a higher normal pressure.

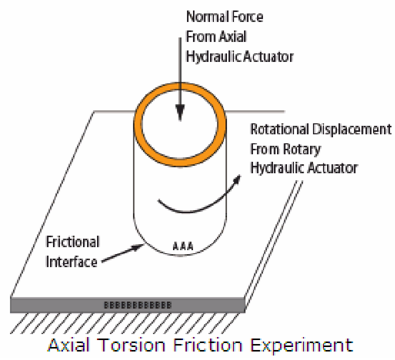


Figure 8: Tribometer concept for higher normal force values [13].

The equipment described is not suitable for measuring a representative coefficient of friction which can be used in demoulding force models. Burke and Malloy [17] described the difficulties in defining such coefficients since it depends on processing, material, product and mould design variables. Experimental work to determine suitable values using simulated replication trials has led researchers to develop friction testing devices which specifically simulate replication processes.

4.2 Replication-style friction testing

The requirements for such equipment include being able to test specimen with varying surface roughness under a defined, adjustable, normal force (effectively replication pressure). The influence of replication process parameters such as replication pressure, replication temperature, demoulding temperature, and demoulding rate, on the demoulding force has been studied using such equipment and the results are discussed below.

Ferreira et al [18] developed an apparatus to study the effect of different parameters on the coefficient of friction relevant for the ejection of plastic parts from moulds. The effects of tool polish direction, surface roughness and test temperature on the coefficient of friction were studied. Results showed that testing temperature and surface roughness had a significant effect on the coefficient of friction for PC. No parameters studied had a significant effect on the coefficient of friction for PP, although the polish direction and roughness did have some effect. In general the coefficients of static friction observed for PC and PP were larger than previously published data.

Pouzada et al [19] studied the static coefficient of friction under moulding conditions. The equipment developed enabled the determination of an optimal surface roughness that corresponds to the minimum coefficient of static friction. The test data obtained was sensitive to temperature, the surface roughness and the pressure between the contacting surfaces.

Worgull et al [20, 21] observed that demoulding forces may vary by several factors depending on the process parameters selected and the quality of the tool. A test apparatus designed for mounting in a tensile testing machine was described and results presented based on varying parameters. These friction test results show the static coefficient of friction increases as the velocity decreases. Worgull et al [20] have published results of simulated replication trials where various demoulding rates were studied. Static coefficients of friction at 1mm/min were substantially higher than those at 5mm/min.

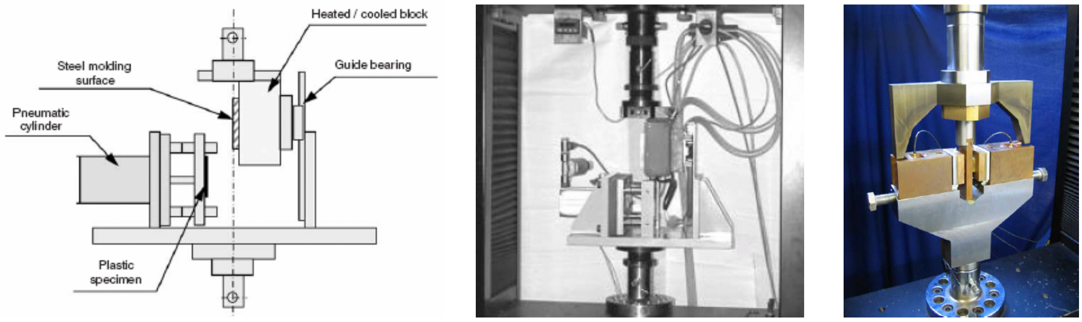
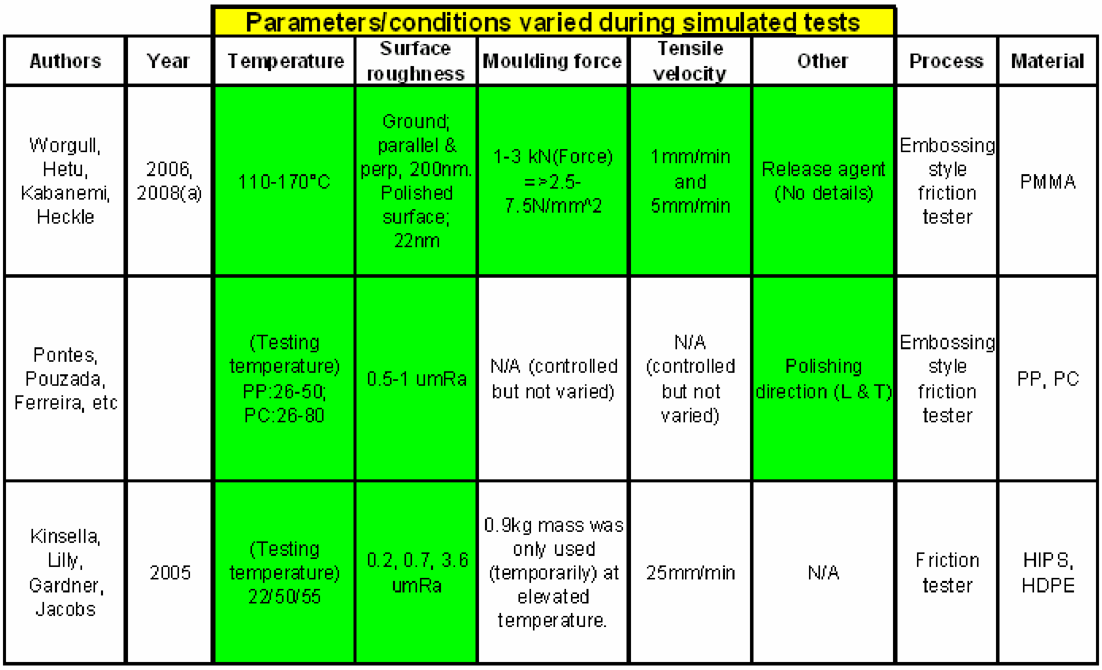


Figure 9: Friction test devices created to simulate replication conditions [20, 21].

The process parameters varied during these trials together with additional results of friction testing trials presented by Kinsella et al [22] are summarised in Table 1. Ejection force is a function of: normal force (pressure/shrinkage), surface roughness, surface finishing direction, material (of both tool and component), temperature (mould temp at ejection and processing temperature) and the demoulding rate.



		Parameters/conditions varied during simulated tests						
Authors	**Year**	**Temperature**	**Surface roughness**	**Moulding force**	**Tensile velocity**	**Other**	**Process**	**Material**
Worgull, Hetu, Kabanemi, Heckle	2006, 2008(a)	110-170°C	Ground; parallel & perp, 200nm. Polished surface; 22nm	1-3 kN(Force) =>2.5-7.5N/mm^2	1mm/min and 5mm/min	Release agent (No details)	Embossing style friction tester	PMMA
Pontes, Pouzada, Ferreira, etc		(Testing temperature) PP:26-50; PC:26-80	0.5-1 umRa	N/A (controlled but not varied)	N/A (controlled but not varied)	Polishing direction (L & T)	Embossing style friction tester	PP, PC
Kinsella, Lilly, Gardner, Jacobs	2005	(Testing temperature) 22/50/55	0.2, 0.7, 3.6 umRa	0.9kg mass was only used (temporarily) at elevated temperature.	25mm/min	N/A	Friction tester	HIPS, HDPE

Table 1: Friction process parameters varied during simulated replication trials.

The test equipment described used material and surface roughness values typical of microstructured tools.

5. Discussion

By measuring the actual demoulding force for a series of injection moulded parts Sasaki et al [23] confirmed an optimum roughness for the core which minimizes the ejection force. This is consistent with experimental results by Grosch [24] who concluded that friction on smooth and rough surfaces is from different mechanisms. That on smooth surfaces is attributed to "adhesion" and that on rough surfaces to "deformation".

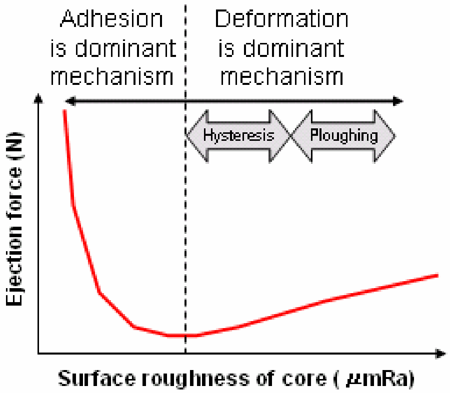


Figure 10: Dominant mechanisms contributing to ejection force.

In terms of the deformation component of friction, asperities or other surface roughness features physically slide across each other during the demoulding process.

Any damage to the surface of the replicated part can be viscoelastic, or hysterectic, without any physical scratching, or it can be plastic, with resulting physical scratching or ploughing. Such damage to the replicated surface after demoulding has been reported by Sasaki et al [23].

With the possible exception of thermodynamic/chemical or kinetic adhesion, which is unlikely to occur due to the timescale of a typical replication process such as injection moulding or hot embossing, it is difficult to isolate specific friction mechanisms during physical testing. However attempts have been made to reduce the impact of specific mechanisms during such experimentation. Examples include optimizing the choice of materials (both replication tool and replication material) and the selection of optimum process conditions (such as ensuring that the polymer is dried correctly and that the actual test is conducted in a controlled humidity environment). Specific coatings and lubricants have also been applied in order to isolate the effects of specific friction mechanisms.

Another issue is that the tool surface condition may change during processing as noted by Packham who highlighted a number of problems associated with mould sticking and fouling [25]. Mould fouling relates to the build-up of deposits on the mould surface after a number of moulding cycles. The use of release agents can be suitable for larger components but may not be suitable for micro replication processes since replication dimensions may be affected. Yamamoto et al [26] proposed a chemically adsorbed fluorocarbon nano-release film on the mould surface to facilitate demoulding without any loss in mould precision. Moulding trials showed that initial resistance to ejection was high and then it dropped suddenly. The coating was shown to be effective up to 20k shots. A washing process was performed at 10k cycles when a contact angle measurement showed that the coating had lost its effectiveness. After the washing process the demoulding force was again found to increase before settling down to a lower level. These results suggest that mould fouling will actually tend to reduce the demoulding force.

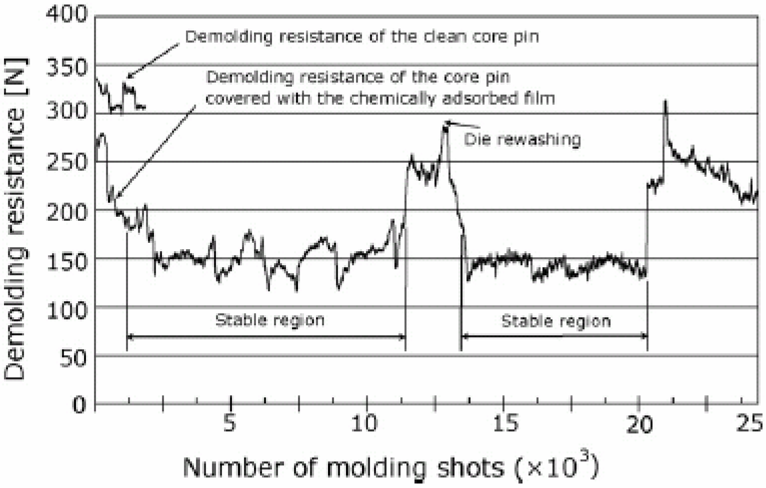


Figure 11: Demoulding force as a function of the number of moulding shots [26].

6. Conclusion

An accurate coefficient of friction is critical to predict demoulding forces using existing models. Challenges associated with finding accurate values for these coefficients have been described. Blau has highlighted that the conditions used to obtain friction coefficients must be clearly stated and understood to ensure that they represent the planned application [15]. Due to the conditions to be found in a replication process this precludes the use of existing friction coefficient data, commonly presented by material suppliers and used by design engineers, in demoulding force models.

To help in efforts to reduce the overall demoulding force it is desirable to be able to isolate the contribution of each friction mechanism to the overall demoulding force. To date successful attempts in this respect have not been reported in the context of quantifying demoulding force. Efforts towards the development of an improved demoulding force model which examines the fundamental contributions to demoulding friction are ongoing at the authors' institutions.

Acknowledgements

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