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A STUDY OF DEMOULDING FORCE PREDICTION APPLIED TO PERIODIC MOULD SURFACE PROFILES

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Abstract

Demoulding components without damage to either the components or tool is critical to successful replication processes. Accurate demoulding force prediction prior to tool fabrication helps designers optimize replication tools to minimize the demoulding force and resultant stress on replicated parts. Various models have been proposed to predict demoulding forces. One such model, the stair-step model, was developed by Colton et al for stereolithographic moulding tools. This paper investigates applying the model to other periodic surfaces with validation using published experimental data. In addition validity of the model for application to micro mould surfaces produced by micro milling is discussed.

Introduction

Demoulding is the ejection of parts from a replication tool when the part has reached a condition that it will remain stable outside of the tool. To demould a part the forces retaining the part in the tool must be overcome. Moulding processes typically use a series of pins, called ejector pins, which are activated to push, and thus eject the part, when the mould opens. It is important that the replicated parts can be demoulded without damage to either the components or the replication tooling.

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. 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.

This paper aims to extend the application of one of these, the Colton et al model, to predict demoulding forces for regular periodic surfaces based on an understanding of the process parameters used to machine the replication tool surface together with an understanding of the replication process parameters to be used. An overview of demoulding force modeling is provided and this leads to a description of the Colton et al model. The adaption of this model for turned surfaces is followed by its implementation and validation and a study of the model robustness. The paper concludes with a discussion of the limitations of the existing model and proposals for future improvements.

Demoulding Force Modeling

Mathematical models for the demoulding of parts from replication tools, based on mechanical or thermo-mechanical models, have been developed by several researchers. Most have derived from the empirical law of Coulomb friction. For parts which shrink upon 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. The magnitude of μ depends upon the plastic-steel interface and also upon some processing parameters. While the area of contact can be measured relatively easily the friction coefficient and contact pressure can have various interpretations.

Menges and Mohren wrote that part shrinkage is constrained by the core, which causes stresses to build up in the cross section of the part [1]. Shrinkage results in the generation of forces normal to the surfaces restrained from shrinking. After demoulding the relative change in circumference, measured immediately, is used as a measure of tensile strain in the part cross section when still on the core. This strain, multiplied by the elastic modulus, the surface in contact and an assumed friction coefficient then gives an estimate of the force required to remove the part from the core resulting in the equation:

$$F_R = \mu \times E(T) \times \Delta d_r \times t \times 2\pi L \qquad (2)$$

where $E(T)$ the elastic modulus of the thermoplastic part material at ejection temperature, L the length of the part in contact with the mould core, Δd_r is the relative decrease in the diameter of the part and t the thickness. This is the force necessary to initiate ejection movement of the part only and relates to static friction. It neglects frictional effects from the ejection mechanism.

Glanvill and Denton described how to calculate the demoulding force for rectangular moldings [2]. The demoulding force was expressed as:

$$F_R = \frac{\alpha(T_m - T_E)\times E(T)\times \pi L\times \mu}{\frac{1}{2t}-\frac{\gamma}{4t}} \qquad (3)$$

Where T_m is the softening point of the thermoplastic polymer, T_E the temperature of the part at ejection, α the coefficient of thermal expansion and γ the Poisson's ratio of the polymer.

In 1991 Burke and Malloy highlighted the difficulties in defining the coefficient of friction and contact pressure since both depend on a number of processing, material, product and mould design variables [3]. They showed that the temperature of the plastic at the time of ejection, the quality of the steel surface, the direction in which the core was polished, and the draft angle of the core all affect the release force to varying degrees. An additional force, a "suction" force, may be generated during demoulding if atmospheric pressure doesn't exist between the part and the core upon separation of the plastic and steel. This is the product of atmospheric pressure and surface area on the top of the core. These primary contributors to the demoulding force are illustrated in Figure 1.

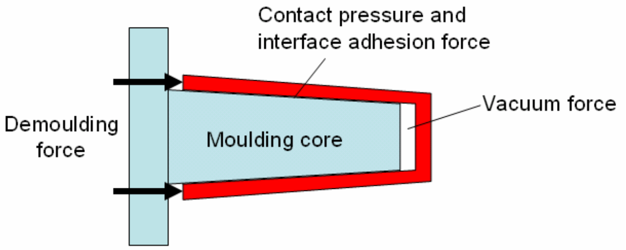


Figure 1: The primary contributors to demoulding force.

These demoulding force models assume a perfectly rigid, smooth male core with a plastic part shrinking onto it. The coefficient of friction must be modified to account for any additional mechanical interlocking due to, for example, increased surface roughness. Increased surface roughness will be experienced by stereo lithographic tools.

The Colton et al model

Replication tools produced using stereo lithographic processes have been used successfully and can provide several benefits for product development companies, particularly in terms of speed and cost for replicating small quantities of parts. Such tools have a large inherent surface roughness due to the layered tool fabrication process. During part demoulding deformation is the dominant mechanism due to the level of interlocking of the replicant and replicating tool. In 2001 Colton et al presented a model to quantify the ejection force for parts replicated with stereo lithographic tools [4].

This model identified the major factors causing demoulding force as thermal shrinkage and the inherent stair-step profile. This stair-step profile, due to the layered nature of the SL process, creates an undercut or overlap which complicates part demoulding. In 2002 Pham and Colton implemented this model [5]. It enables prediction of demoulding force based on mould dimensions, material properties and mould-building parameters. Injection moulding experiments were used to verify the model.

The overall demoulding force, F_{ej}, was modeled as consisting of two components:

$$F_{ej} = F_{fric,therm} + F_{def,stair} \qquad (4)$$

Where $F_{fric,therm}$ and $F_{def,stair}$ denote ejection force components due to thermal shrinkage and the inherent stair-step profile of the layered tools, respectively. The force component due to the stair profile was theorized to be the force necessary to deform the part and mould elastically to overcome the overlap. To facilitate this deformation the mould and part were modeled as a spring system consisting of "spring" constants for the part and mould.

The coefficient of friction applied is increased to an "equivalent" coefficient of friction, μ_{eq} , which incorporates the effect of the increased deformation needed for the mould and polymer parts to deform sufficiently to slide over each other. Combining the two components the overall demoulding force is described mathematically as:

$$F_{ej} = SA\times(\mu_{eq}\cos\theta - \sin\theta)\times P_{therm} \qquad (5)$$

Where,

$$P_{therm} = \frac{(\alpha_p \Delta T_p r_m - \alpha_m \Delta T_m r_m}{r_m \left[\frac{1}{E_p} \left(\frac{r_p^2 + r_m^2}{r_p^2 - r_m^2} + \upsilon_p \right) + \frac{1 - \upsilon_m}{E_m} \right]} \quad (6)$$

$$\mu_{eq} = \mu + \frac{\delta^2}{(\alpha_p \Delta T_p r_m - \alpha_m \Delta T_m r_m) \times l \times \cos\theta} \quad (7)$$

SA is the surface contact area projected in a direction parallel to the demoulding direction, ΔT is the change in temperature from injection to ejection points, r is the hydraulic radius, E is the Young's modulus, υ is Poisson's ratio, α is the coefficient of linear expansion, $_m$ and $_p$ are subscripts denoting mould and part, respectively. l is the build layer thickness and δ the overlap due to the inherent stair-step profile of the SLA tools both of which were derived from SLA machine parameters by Pham and Colton. These parameters are indicated in Figure 2.

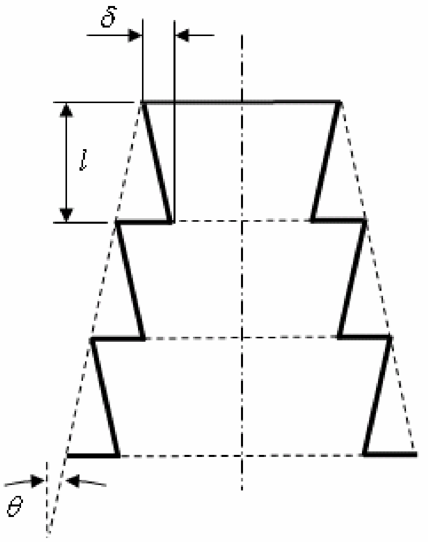


Figure 2: The build layer thickness, overlap and draft angle (adapted from [5]).

Adaptation of the Colton et al model for turned surfaces

This research set out to apply the Colton et al model to replication tools with different periodic roughness profiles. More specifically it attempts to investigate use of the model to predict demoulding forces based on an understanding of the process parameters used to machine the replication tool surface together with an understanding of the replication process parameters to be used.

The specific case described here relates to the injection moulding process where the mould core was manufactured using a turning process. The core geometry is a truncated cone as illustrated schematically in Figure 1. To adapt the model an expression is needed to relate the build layer thickness and the overlap from the original model to turning process parameters.

From an observation of Figure 2 it can be seen that the parameter l represents the period of the surface profile, while δ is the height of the asperities. A turned surface is also characterized by a periodic profile: Therefore, for such a surface, the feed (in mm/rev) which is the profile period corresponds to the parameter l, while the height of the feed marks corresponds to the parameter δ in the Pham and Colton model. The topography of a machined surface is the result of a kinematic contribution which is related to the geometry and the relative motion of tool and work piece, and a material interaction component due to ploughing at low uncut chip thickness values as compared to the cutting edge radius. For turned surfaces at medium high roughness values (say above Ra 1 µm), the kinematic component of roughness is the dominant one. The kinematic component of roughness for a turned surface can be calculated from the knowledge of the feed f and the tool nose radius R . Thus the arithmetic mean roughness of the core surface can be expressed as:

$$Ra = \frac{f^2}{32 \times R} \quad (8)$$

The height of the cutting marks corresponds to the Rt roughness amplitude parameter defined in relevant standards [6] and can be calculated as:

$$\delta = \frac{f^2}{8 \times R} \quad (9)$$

Both of these parameters are represented in Figure 3 together with the tool radius and feed direction and rate.

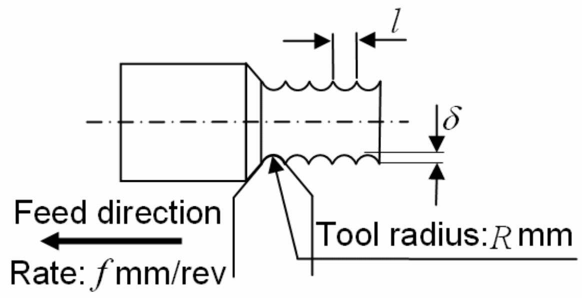
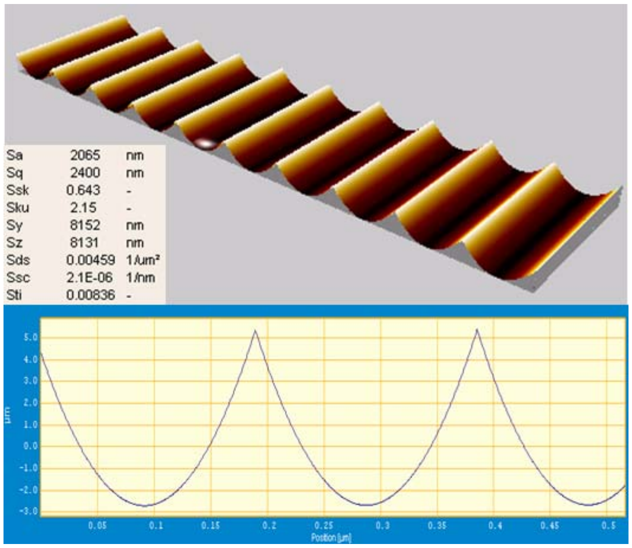


Figure 3: The model parameters as they relate to turning a moulding core.

The formulae for δ and f were validated using a surface generation model by Bissacco for modeling micro milled surfaces [7]. This model uses process parameters to create a digital representation of the machined surface that can be imported in commercial quantitative image processors such as SPIP [8] for further quantitative processing including the calculation of surface roughness. Representative images of the simulated surfaces created and analyzed are shown in Figure 4.



Sa	2065	nm
Sq	2400	nm
Ssk	0.643	-
Sku	2.15	-
Sy	8152	nm
Sz	8131	nm
Sds	0.00459	1/um²
Ssc	2.1E-06	1/nm
Sti	0.00836	-

Figure 4: Representative screen shots of simulated surfaces created and analyzed.

The roughness values predicted using the two approaches showed a very close match, therefore in this study, the simpler analytical formulation represented by the formulae (8) and (9) was used.

Model Implementation and Validation

The model was implemented in a spreadsheet. A simple geometry was selected for model validation in order to simplify the analysis. Introducing the complication of a complex geometry (such as a true moulded component) would complicate analytical implementation and introduce uncontrolled effects making model validation impossible. As part of the validation process published experimental data which related knowledge of the surface condition to actual demoulding forces was used. Hopkinson and Dickens performed an experimental comparison of the demoulding forces of cylindrical objects from aluminum cores of varying surface roughness (2 µm and 11µm) [9]. The rough aluminum tool was machined to replicate the surface roughness of a stereo lithography tool. A sectional view of the component by Hopkinson and Dickens together with a representation of the molding core used to validate the model is shown in Figure 5.

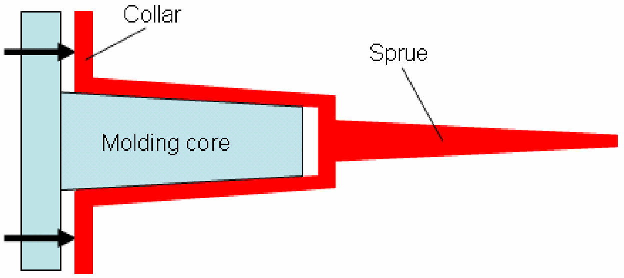


Figure 5: Sectional view of Hopkinson and Dickens component used for validation (adapted from [10]).

Dimensional details were:
Diameter of the collar at base = 40mm,
Diameter at opening of collar = 16mm,
Length of the moulding = 40mm,
All walls 2mm thick,
Draft on male feature = 1.5 degrees.

Users input the cutting tool radius and tool core surface roughness (Ra). The program then predicts values for the lathe tool feed and cutting marks height according to equations (8) and (9). Combining these values with details of the replicating tool, replicating material and replication machine process parameters the predicted demoulding force is presented. Material constants used in the model are listed in Table 1.

Constant		Units	Value
Expansion coefficient for polymer	α_p	mm/°C	6.80E-05
Expansion coefficient for mould	α_m	mm/°C	2.30E-05
Young's Modulus for polymer	E_p	N/mm^2	2.45E+02
Young's Modulus for mould	E_m	N/mm^2	6.90E+04
Poisson's ratio for polymer	υ_p	n/a	0.35
Poisson's ratio for mould	υ_m	n/a	0.33

Table 1: Material properties used in the model.

The test component molded by Hopkinson and Dickens was split into two parts; the main body and the collar. The demoulding forces were predicted for each section separately and resultant force values summed to predict the overall ejection force. Force values predicted by the model together with those reported by Hopkinson and Dickens (H&D) are shown in Figure 6. From the figure it is apparent that the model over predicts the demoulding force at lower surface roughness and under predicts the demoulding force at higher surface roughness.

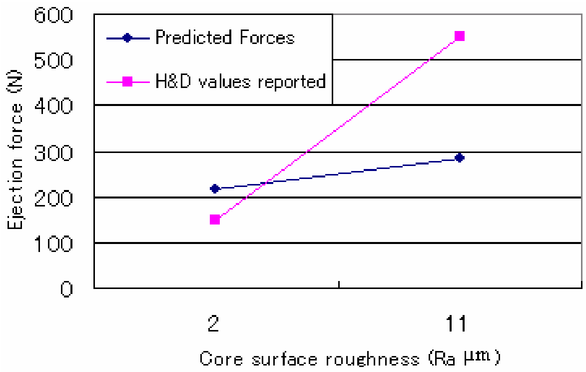


Figure 6: Forces predicted by the model and the forces reported by Hopkinson and Dickens.

Robustness of the Colton et al Model

Some replication process parameters required for the model were not reported by Hopkinson and Dickens. Consequently certain parameters were assumed. These include the temperatures of the mould at injection and ejection, the component ejection temperature and the polymer melting temperature in addition to the actual coefficient of friction.

To investigate errors associated with these assumptions a sensitivity analysis was performed to understand the level of variation that such errors might introduce. In addition to the assumed replication process parameters already listed the effect of varying the cutting tool radius was also studied. The parameter values used are shown in Table 2.

Parameter		Value	Force at low Ra (N)	Force at high Ra (N)	Force Delta (N)
Cutting tool radius (mm)	R	0.2	220.6	312.6	92
		1	216	257.4	41.4
Mould temperature at ejection (°C)	T_{me}	30	209	274.6	65.6
		60	227.5	292.9	65.4
Mould temperature at injection (°C)	T_{mi}	15	229.9	295.3	65.4
		49	210.2	274.7	64.5
Component ejection temperature (°C)	T_{pe}	40	235.6	301	65.4
		60	201	265.5	64.5
Polymer melting temperature (°C)	T_{pm}	160	205.7	271.2	65.5
		173	228.7	294	65.3
Coefficient of friction	μ	0.25	182.7	248.1	65.4
		0.4	317.1	381.5	64.4

Table 2: Parameter values used to study model robustness.

The cutting tool radius was found to have a significant effect on the ejection force, with ejection force increasing as the cutting tool radius decreases, particularly for the higher Ra situation. The coefficient of friction was also found to have a significant effect on the demoulding force.

Discussion and Conclusion

The demoulding forces predicted by the model show realistic values that lie inside the range of variability of the experimental results reported by Hopkinson and Dickens. However the model over predicts the demoulding force at lower surface roughness and under predicts the demoulding force at higher surface roughness. A computational analysis and comparison with this analytical analysis.may provide additional insight into why this is the situation. However, based on the results of the analysis already conducted, there are a number of reasons for this discrepancy which lead to considerations regarding the applicability of the Colton et al model to non stereo lithographic tools.

As can be seen from the robustness study of the model, the coefficient of friction will have a significant effect on the predicted demoulding force. However the friction coefficient value chosen, as indicated in Hopkinson and Dickens' experiments [11], is independent of the process parameters. Indeed such coefficient of friction is dependent on the normal pressure at the mould-part interface, particularly when friction stresses are close to the shear stress of the polymer. As a result the variation of shrinkage, and therefore normal pressure, does not produce a linear variation of the frictional force due to variation of the coefficient of friction at high loads.

Accurately predicting the shrinkage of such injection moulded parts can be difficult for non-simple geometries. Geometrical constraints, particularly in the case of complex geometries, are important factors in the calculation of ejection stresses and their distribution. A simple one dimensional unconstrained elastic calculation could result in a significant and unacceptable error.

While the model recognizes both components of friction (hysteresis and adhesion), explicitly through the staircase component of the model and implicitly through the coefficient of friction, it's implementation does not allow reliable quantitative predictions for the case studied. Therefore more suitable models that can more accurately incorporate such elements need to be developed.

The model only considers the kinematic component of roughness and therefore doesn't include effects of the cutting tool material-workpiece interaction. For example a low uncut chip thickness may result in increased smearing of the replication tool surface during tool fabrication. This will lead to increased undercuts which are likely to increase the overall ejection force due to mechanical interlocking of the polymer with, or below, such features [7]. Such smearing is a particular problem at lower surface roughness values and, since this is not accounted for in the model, suggests that the actual forces should be higher than those predicted. An example of such a surface generated by ball nose micro milling with a tool diameter of 200 µm is shown in Figure 7. The work piece material is a powder metallurgy tool steel with hardness of 58 HRC.

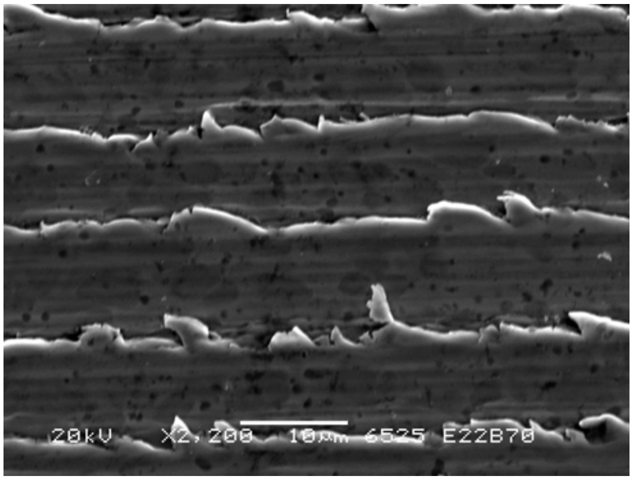


Figure 7: surface generated by micro milling [7].

Reducing part size increases the importance of being able to predict the ejection forces since micro components and replication tooling are more prone to damage. Hence the application of the Colton et al model to the micro scale, particularly for micro-milled replication tools, has been considered. Surfaces produced by ball-nose milling will necessarily use small ball-nose diameters. Particularly at low uncut chip thickness the kinematic component of Ra will not dominate. Therefore the specific ejection force will increase relatively to the macro scale resulting in relatively larger demoulding forces. Regarding the scalability effect there is a limit to scaling of surface roughness since the surface roughness will not decrease in proportion to the actual part size.

On the basis of the present investigation, the limitations of the Colton et al model with respect to demoulding force prediction, applied to non stereo lithographic moulds, have been highlighted. This investigation constitutes a starting point towards the development of a more suitable model for reliable prediction of demoulding forces. It is in fact believed that a more advanced model will be needed which does not assume elastic deformation but considers the viscoelastic behavior of the replicating material, together with any permanent deformation which might occur. Such a model must be suitable for implementation in Finite Element Modelling (FEM) packages to enable the analysis of complex geometrical configurations. An effort towards the development of such a model is ongoing at the authors' institutions.

References

[1] G. Menges and P. Mohren, How to Make Injection Moulds, Hanser, New York, (1986).

[2] A.B. Glanvill and E.N. Denton, Injection-mould Design Fundamentals, London, Machinery Publishing Co. (1963).

[3] C. Burke and R. Malloy, *SPE-ANTEC*, 1781-7, (1991).

[4] J.S. Colton, J. Crawford, G. Pham, V. Rodet, *Annals of CIRP*, **50**, 129-132, (2001).

[5] G.T. Pham and J.S. Colton, *Polymer Engineering and Science*, **42**, 681-93 (2002).

[6] ISO 4287, Surface texture: Profile method – Terms, definitions and surface texture parameters (1997).

[7] G. Bissacco, H.N. Hansen, L. De Chiffre, *CIRP Annals – Manufacturing Technology*, **55**, 593-596, (2006).

[8] SPIP™ The Scanning Probe Image Processor, Image Metrology A/S, www.imagemet.com.

[9] N. Hopkinson and P.M. Dickens, *Rapid Prototyping Journal*, **6**, 253-258, (2000).

[10] N. Hopkinson and P.M. Dickens, *Journal of Materials and Design*, 99-105, (1999).

[11] N. Hopkinson and P.M. Dickens, *Journal of Engineering Manufacture*, 214, (2000).

Key Words: Demoulding force models, machined surfaces