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# Investigating Polymer-Tool Steel Interfaces to Predict the Work of Adhesion for Demoulding Force Optimisation

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## Keywords

*Polymer friction,  
Work of adhesion,  
Demoulding force prediction.*

## Ključne riječi

*Trenje polimera,  
Radnja adhezije,  
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## 1. Introduction

Demoulding, or ejection, of parts from the tool is a critical stage of replication processes such as injection moulding and hot embossing. As the size of the component being replicated is reduced both the parts themselves and associated tooling becomes more prone to damage due to their reduced strength. Forces preventing demoulding of parts are generally a combination of differential shrinkage of the part and tool, adhesion and/or the possible formation of a suction force.

Friction is generally considered as the result of adhesion and/or deformation. Experimental results have shown that at higher tool surface roughness deformation dominates. This deformation can be elastic, with no permanent damage to the part or it can be plastic where

*Original scientific article*

Demoulding parts from replication tools is a critical stage of replication processes such as injection moulding and hot embossing. This challenge increases as part size decreases since components and associated replication cores become more fragile and liable to damage. Understanding interfacial characteristics between a polymer and the tool surface is critical to optimise the demoulding of such parts from replication tools. The strength of the polymer-tool interaction is characterised by the adhesion energy and is specific for a particular polymer-tool pair. It's magnitude depends upon the tool material, the chemical structure of the polymer, the processing conditions and the surface roughness.

Interfacial characteristics of a variety of polymer-tool steel surfaces are being studied by measuring contact angles of polymer droplets on the surfaces to predict the work of adhesion. The experimental set-up, selection of test parameters and main challenges faced to date are described and preliminary experimental results presented. In addition a description of how these results may be used to predict the force needed to demould parts from replication tools is discussed.

## Istraživanje sučelja polimer - alatni čelika zbog predviđanja adhezijskog rada s svrhom optimiziranja sile otvaranja kalupa

*Izvorni znanstveni rad*

Odvajanje dijelova iz višekratnih kalupa je kritična radnja procesa kao što su injekcijsko brizganje u kalup i vruće utiskivanje. Ovaj se problem povećava kako se proizvod dimenzionalno smanjuje, te pripadajuće jezgre postaju više lomljive i podložnije nastajanju oštećenja. Razumijevanje interakcija površina polimera i alata je najbitnije za optimiranje vađenja proizvoda iz višekratnih kalupa. Čvrstoća veze između polimera i alata karakterizirana je energijom prijanjanja i specifična je za određeni par polimera-alat. Veličina energije prijanjanja ovisi o materijalu alata, kemijskoj strukturi polimera, proizvodnim uvjetima i površinskoj hrapavosti.

Mjerenjem kutova kontakta polimernih kapljica na površinama alatnog čelika proučavane su karakteristike interakcija površina različitih kombinacija polimer - alatni čelik sa svrhom predviđanja sile prijanjanja. Opisane su postavke eksperimenta kao i glavna problematika do danas, te su isto tako prikazani i rezultati pokusa. U nastavku provedena je diskusija o mogućnosti korištenja dobivenih rezultata za predviđanje sile odvajanja dijelova iz višekratnih kalupa..

there will be permanent damage to the replicated parts after demoulding, visible in the form of ploughing or scoring of the part surface. At lower tool surface roughness the adhesion component of friction dominates. The most important adhesion mechanisms have been categorized as consisting of thermodynamic/chemical adhesion, electrical / electrostatic adhesion and capillary attraction. However as reported by Ebnesajjad [1] it is difficult to assign adhesive bonding to a specific mechanism.

Understanding interfacial characteristics between the polymer and tool surface is critical to optimise part demoulding. This paper focuses on the adhesion component of friction and how parameters relevant to quantifying it can be determined experimentally using the method of contact angle measurements.

Symbols/Oznake	
$\theta$	- Contact angle, - Kut dodira
$\gamma_{LV}$	- Surface tension of the liquid in equilibrium with its saturated vapour - Površinska napetost tekućine u ravnoteži s zasićenom parom
$\gamma_{SV}$	- Surface tension of the solid in equilibrium with its saturated vapour - Površinska napetost krutnine u ravnoteži s zasićenom parom
$\gamma_{SL}$	- Interfacial tension between the solid and the liquid - Površinska napetost između krute i tekuće faze

## 2. Using contact angles to quantify adhesion

The objective of this experiment is to quantify the wettability between a solid substrate and a viscous liquid, in this case between simulated tool surfaces and a polymer using the method of contact angles. Quantitatively a contact angle,  $\theta$ , is the interior angle formed by the substrate being used and a tangent to the drop interface at the apparent intersection of the three interfaces. The tangent line and contact angle are shown schematically in Figure 1.

A static contact angle on a flat surface is commonly defined by Young's equation, which is essentially a force balance. This equation includes the interfacial surface tensions between solid and liquid, solid and vapour and liquid and vapour and is given by:

$$\gamma_{LV} \cos\theta = \gamma_{SV} - \gamma_{SL} \quad (1)$$

where the interfacial tension between the solid and the liquid is given by  $\gamma_{SL}$ , while the surface tension of the liquid and solid in equilibrium with their saturated vapour are given by  $\gamma_{LV}$  and  $\gamma_{SV}$  respectively.

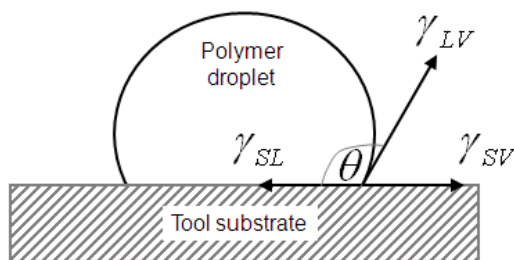


Figure 1. A polymer droplet on a tool substrate at equilibrium

Slika 1. Uravnotežena kapljica polimera na uzorku alata

The two principle methods to measure contact angles are the Wilhelmy plate method which is a specific form of tensiometry and goniometry which uses a profile image of a drop to find contact angles. Associated

software analyses the profile image and the contact angle is returned. Profile images can also be recorded for additional analysis.

Anastasiadis and Hatzikirialos [2] measured interfacial characteristics for a series of polymer/wall interfaces using the sessile drop method to calculate the work of adhesion. Part of a broader project relating polymer/wall interface adhesion to the onset of wall slip, the stainless steel substrates tested included both a clean one and others that had been modified through the application of two different fluoropolymers to alter their surface energy. The measured contact angles of polymer droplets and the polymer surface tensions were used to calculate the work of adhesion of the various interfaces. The critical shear stress at which slip was initiated was found to scale linearly with the work of adhesion.

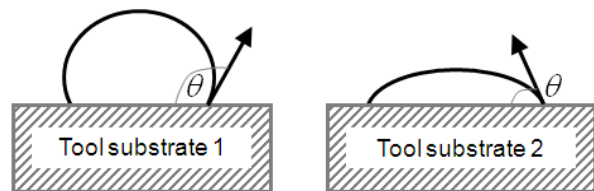
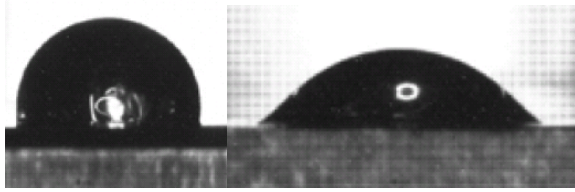


Figure 2. How polymer droplet contact angles vary with replication tool surface

Slika 3. Promjena kontaktnog kuta kapljice na površini alata

Navabpour et al [3] performed experimental work to quantify adhesion between low density polyethylene (LDPE) and various non-stick coatings. Granules of LDPE were placed on the substrate to be evaluated inside the heated oven and positioned in front of a microscope. As the LDPE granules melted drops formed. After reaching steady state the angle between the drop and the surface was recorded as the LDPE contact angle. The images presented in Figure 4 show a clear difference between coated and uncoated substrates.



**Figure 4.** Contact angle variation between coated and uncoated substrates (Navabpour et al)

**Slika 5.** Promjena kontaktnog kuta kod prekrivene i neprekrivene površine uzorka (Navabpour et al)

### 3. Experimental set-up

An apparatus manufactured by Dataphysics, [4] and typically used to measure contact angles of liquids on surfaces at room temperature, forms the basis of the experimental set-up. Key elements of the apparatus include a microscope, a backlight, a specimen table and a computer monitor as shown in Figure 6. For this particular application the apparatus was modified with a number of attachments. Specifically a thermal chamber with an integrated Peltier module surrounds the test-piece and the dosing needle is replaced by a heated needle. The heated needle is used to store the polymer prior to dosing onto the test pieces. The surfaces to be tested are inserted into the temperature chamber. Independent temperature control of the heated needle and temperature chambers is possible so that behaviour of the hot polymer as it meets a cooler tool surface can be evaluated.



**Figure 6.** Overview of the complete test apparatus for measuring contact angles

**Slika 7.** Uređaj za mjerenje kontaktnih kuteva

Figure 8 shows a close-up of the test apparatus. The thermal chamber is in the centre of the image with the microscope and lighting elements of the device on the left and right hand side respectively. The heated needle

and dosing system protrude into the thermal chamber from the top of the thermal chamber.



**Figure 8.** Close-up of the test apparatus

**Slika 9.** Povećana slika uređaja

### 4. Test parameters and procedure

#### 4.1. Test parameters

Adhesion between the polymer and substrate depends upon the tool material, the chemical structure of the polymer, the processing conditions and tool surface roughness. The initial experimental studies will focus on a specific polymer; Poly methyl meth acrylate (PMMA). Three different tool surfaces generated from a single supply of steel commonly used for injection moulds are used for initial trials. These surfaces were generated using a polishing process to create a mirror finish. Two of the three surfaces were then "roughened" to produce the target surface roughness levels.

Surface generation through polishing was specifically selected so the resultant surfaces would have an isotropic surface profile and not be influenced by test orientation. After surface generation characterisation of the surfaces was performed to create surface data which can be used in the development of the demoulding force model. Target surface roughness levels were selected based on experimental work reported by Sasaki et al [5] who showed that an optimal surface roughness exists where the demoulding force for an injection moulded part is at a minimum. Surface roughness levels on both sides of this optimum value were selected.

In addition to three different tool surface roughness values relevant processing parameters, specifically the melting temperature of the polymer and the tool surface temperature, are varied during testing to understand how they affect the contact angles. The specific processing

parameters follow the guidelines of the polymer supplier and are summarised in

Table 1.

Table 1: List of test parameters

Tablica 2: Popis parametara pokusa

Parameter	Units	Low	Mid	High
Tool surface roughness	µm	0.0261	0.0362	0.166
Polymer melt temperature	°C	210	250	290
Tool surface temperature	°C	50	70	90

#### 4.2. Test procedure

An overview of the test procedure is:

- 1) A quantity of polymer granules should be loaded into a container which is then placed in a temperature control chamber and heated to the required polymer melting temperature.
- 2) A quantity of the polymer should then be drawn into the heated needle which should be set at the polymer melting temperature.
- 3) The reservoir of polymer is then removed from the temperature control chamber and the test surfaces inserted instead.
- 4) The temperature of the thermal control chamber should then be reduced to a suitable temperature so that the tool surface can reach the required test temperature.
- 5) The polymer is then dosed onto the tool surface for measurement as a sessile drop.

The testing phase of this project is ongoing.

## 5. Discussion and Conclusions

The rationale for the use of contact angle measurements and selection of the test parameters has been presented together with a description of the test apparatus and procedure.

This investigation constitutes an important element of the development of a model for reliable prediction of demoulding forces. It is planned that the model will 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.

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