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DEVELOPMENT OF A FRICTION TESTING APPARATUS FOR DEMOULDING FORCE PREDICTION

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ABSTRACT

Friction between replication tools and replicated parts determines the force required to demould the part and also the stresses which develop in both the tool and the part during the demoulding process. Standardized equipment and procedures have been developed which strive to improve the repeatability and reproducibility of friction tests. Specific test standards, describing sled-type tests, include JIS K 7125, ISO 8295 and ASTM D1894. However these tests do not produce results which are representative of the conditions typically found within replication tools such as injection moulds or embossing tools. This paper reviews how this challenge has been addressed by other researchers and describes the development of an apparatus to measure friction under typical replication conditions. Experimental results for the thermal characterization of the device are reported.

KEYWORDS: Polymer friction, demoulding force prediction.

1. INTRODUCTION

In replication processes such as moulding, differential shrinkage rates for the polymer and tool material can result in the plastic material sticking onto protruding parts of the tool as the part begins to solidify in the mould cavity. The removal of such parts from the replication tool when the part has reached a condition that it will remain stable outside of the tool is known as demoulding or ejection. To demould a part those forces retaining the part in the tool must be overcome.

Moulding processes typically use ejector pins, which are activated to push, and thus eject the part. With conventional-sized moulded parts, large ejection areas can be used and the parts themselves are suitably rigid so that they are unlikely to be damaged due to 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.

Miniaturisation is a common trend in product development and is

likely to continue as designers strive to simultaneously increase functionality and decrease the volume of many consumer products. Benefits realisable through such miniaturisation include lower material consumption, lower weight, reduced inertia, faster system response, portability, lower energy consumption, as well as the possibility of realizing functionalities, such as minimal invasive surgery tools, which are only possible as a result of size reduction. To realise the full benefits it must be possible to produce micro products consistently in large volumes at a relatively low cost. Demoulding micro parts can be a significant problem for the manufacturing industry.

The work described in this paper is part of a larger project to establish a thorough understanding of the mechanism of demoulding from micro moulds and develop a predictive capability to optimise plastic part ejection at an early stage of tool design.

2. DEMOULDING FORCE MODELLING AND FRICTION COEFFICIENTS

The force needed to demould a component from a replication tool core, F_R, was quantified by Menges and Möhren [1] as:

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

where μ is the coefficient of friction of the moulded polymer (defined in ISO 8295), P_A is the moulding contact pressure (defined in ISO 294-4) and A_C is the part core surface area. The contact area is often assumed to equal the nominal part area which can be measured relatively easily, however the contact pressure and friction coefficient can have various interpretations.

Attempts to quantify P_A include the integration of sensors within the mould, part measurement followed by calculation and the use of simulation tools. Installing sensors within the replication tool can be difficult since part geometry can cause significant variation of the pressure distribution, particularly for square or rectangular cores where corner effects can be significant. Measuring parts immediately after demoulding and then performing calculations to infer the pressure based on part shrinkage relative to the tool core has been used for simple geometries. However the process is not instantaneous and involves certain assumptions which may be questionable, particularly for smaller components where the overall shrinkage might be difficult to measure. More recently the use of computer simulations to predict the overall interfacial pressure has become common.

The coefficient of friction is defined as the ratio of the tangential force required to slide a body along a surface and the normal component of force acting on it. The static coefficient of friction is typically higher than the dynamic coefficient of friction. In terms of modelling the demoulding force the maximum force, corresponding to the static coefficient of friction, must be quantified. Determining a suitable value of μ is complex since it

can be influenced by many parameters. Burke and Malloy [2] described the difficulties in defining such coefficients since it depends on processing, material, product and mould design variables. Two basic approaches can be identified; an experimental approach and a fundamental approach.

In terms of the experimental approach 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). To address this problem standards have been developed by several organisations. Specific standards, describing sled-type tests, include JIS K 7125, ISO 8295 and ASTM D1894. Such standardized tests do not represent conditions typically found in replication processes. This has led researchers to develop other techniques to measure friction coefficients. Some of these techniques use actual replication processes while others use test devices which specifically simulate replication processes.

Bataineh and Klamecki performed actual demoulding experiments of ring shaped geometries and these results were then used to predict realistic friction coefficients and ultimately the demoulding force [3]. This approach assumes that the coefficient will be the same for the geometry tested and the geometry being replicated.

Requirements for replication-style friction testing 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.

Ferreira et al [4] 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 [5] studied static friction coefficients under moulding conditions. Equipment developed enabled the determination of an optimal surface roughness corresponding 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 [6] and [7] 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 [6] 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.

Experimental results reported by the developers of these devices provide guidance on how the demoulding force varies. However the usefulness of these results is somewhat limited since only scant details, insufficient for the overall project being undertaken, of the actual surfaces used for the tests were provided. This work describes the development of a device to validate a model to predict demoulding force.

3. OVERVIEW OF THE FRICTION TESTER DEVELOPED

The most important property of the friction tester developed is that it accurately reflects the tribology of a real demoulding process. It must also be possible to vary relevant parameters so that an understanding of the interfacial tribology can be evaluated under different tool, polymer and process conditions. The friction tester was developed to cope with the conditions listed in Table 1.

Parameter	Value	Comment
Normal force range	2.2kN	Maximum load
Tangential force range	1kN	Other load cells available
Tangential sliding velocity	0.1~4 mm/s	Variable
Maximum temperature of the heated block	150°C	
Cooling rate of heated block	~1°C/s	
Contact area of tool inserts	25x25 mm	

Table 1: Specification details of friction test apparatus.

The friction tester consists of key functional areas as shown in Figure 1. Each of these areas will now be described in turn.
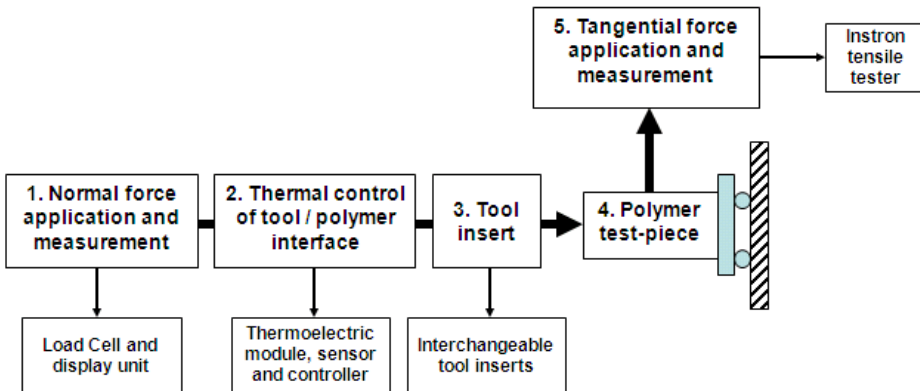

Figure 1: Key functional areas of friction test devices.

Normal force application and measurement: the normal force is applied using a manually operated power screw. An inline "donut" load cell washer (a Futek FSH00295-LTH300), is used to quantify the actual normal load applied and a bench-top digital display (FSH02512-IBT500) directly attached to the load cell.

A small amount of smearing of the polymer surface is expected at the interface with the tool surface since the interfacial temperature will be above the glass transition temperature of the polymer. The hand-wheel is used to provide continuous adjustment of the normal force.

Thermal control of tool/polymer interface: temperature control is important to ensure the tool surface is above the glass transition temperature of the polymer being tested prior to contact between the tool and polymer. Once the appropriate "embossing" time has elapsed the tool surface is cooled. To help ensure a constant temperature distribution across the tool surface during both heating and cooling phases a thermoelectric module was integrated into the design. This is used to both heat and cool the tool inserts. This helps to ensure a level of controllability of the actual cooling phase of the process, which was absent in the previous work already summarised.

During the cooling phase of the process heat energy is rejected from the thermoelectric module. Two heat sinks were integrated into the design to reject this heat to the surrounding environment. The thermoelectric module is controlled by a controller (An Oven Industries 5C7-195 benchtop controller) and a temperature sensor integrated as part of the heating block.

Interchangeable tool inserts: the friction tester is designed to accept interchangeable tool inserts. This allows tool inserts of different materials, surface roughness, coatings, etc to be fitted to the heated block. A cover plate is used to ensure that the tool insert is pressed against the heated block and thermal grease used to reduce the thermal resistance between the two. Ceramic plates are used as thermal insulators to prevent heat loss from the heated block into the frame of the device.

Polymer test pieces: the sample holder is supported on a carriage which slides along a rail on linear roller bearings. The carriage is attached to the crosshead of the tensile tester. Due to the formation of the "smearing" previously mentioned the size of the polymer test piece is smaller than the size of the tool insert surface. For initial trials parts with a test surface area of 10x10mm and an overall thickness of 6mm were moulded from PMMA (Lucite) material.

<u>Tangential force application:</u> the tangential force is applied to the sample holder carriage using the tensile tester into which the friction tester unit is installed, an Instron 5567. This tensile tester ensures the tangential force applied and associated displacement can be recorded.

An isometric view of the 3D CAD model of the friction tester is shown in Figure 2. Key functional areas are clearly indicated. The thermoelectric module is sandwiched between the heated block the heat-sink subassembly.
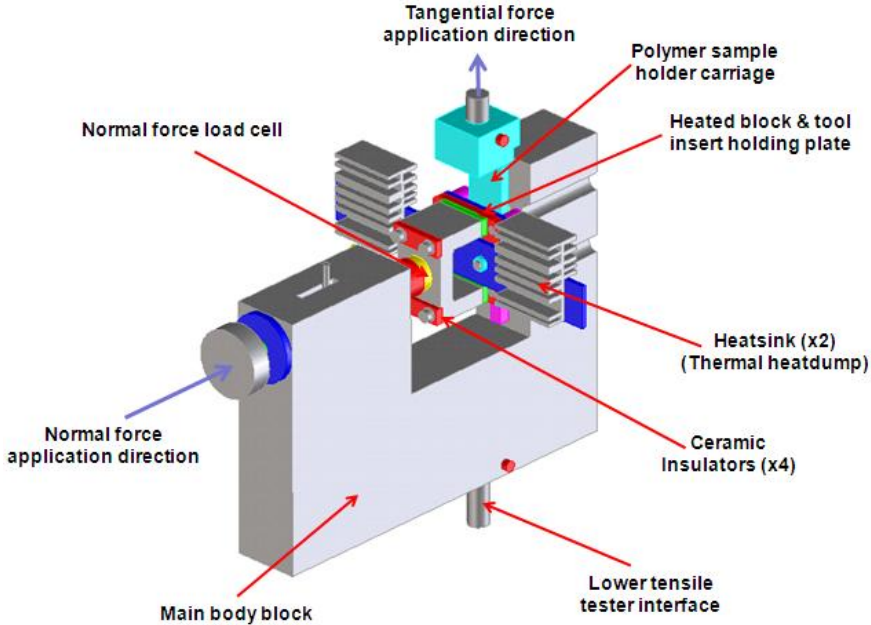

Figure 2: Key functional areas of friction test devices.

The primary elements of the friction tester were fabricated internally in the workshops of Dublin Institute of Technology, Bolton St. Standard components and the instrumentation needed was sourced from specialised suppliers. The assembled friction tester developed, installed in the tensile tester, is shown in Figure 3.

Figure 3: Friction test devices installed in the Instron tensile tester.

4. TEST PROCEDURE

The friction tester is designed to simulate a replication process before measuring tangential force. An overview of the test procedure is:

1) Tool insert and polymer test piece are placed into friction tester.
2) The tool insert is heated to a temperature above the glass transition of the polymer.
3) Tool insert (and heating unit sub-assembly) is moved using the threaded screw so that the tool insert is pressed against the polymer test piece with the appropriate force. This load is maintained for 1 minute and adjusted accordingly to account for any polymer relaxation.
4) Tool insert is cooled to the appropriate demoulding temperature (at a rate of ~1°C/s).
5) Once the temperature has reduced accordingly perform the friction test using the tensile tester. The friction tester will provide a force-deflection curve. The peak value recorded will be taken as the tangential force needed to initiate motion and used to calculate the coefficient of static friction.
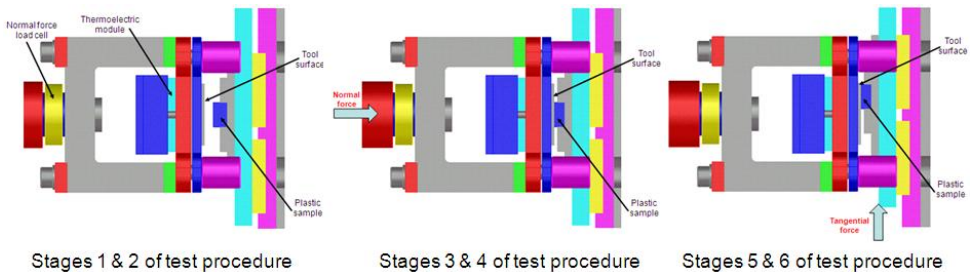6) The tool insert is then inspected under a microscope before being cleaned in preparation for the next test cycle.

Stages 1 & 2 of test procedure   Stages 3 & 4 of test procedure   Stages 5 & 6 of test procedure

Figure 4: 3D images of test procedure.

5. INITIAL DEVICE CHARACTERIZATION TRIALS

The initial characterization of the device was to demonstrate the effectiveness of the thermoelectric module to deliver the required temperature distribution across the tool insert during both heating and cooling. An IRISYS thermal imaging camera was used to perform this task. Due to the reflectivity of the tool insert surface a black coating was sprayed onto the tool surface. A photograph of the tool and a thermograph showing the tool insert at 115°C is shown in Figure 5.

The temperatures indicated by the thermographs were compared to those recorded by the temperature sensor on the heated block during both the heating and cooling phases. A good correlation between the thermograph, sensor and set-point temperatures was recorded during both heating and cooling with a maximum difference of ~3°C once the temperatures had stabilised.
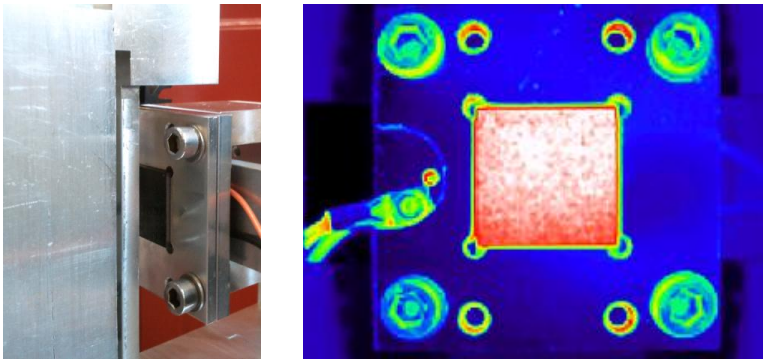
Figure 5: Close-up image of the plate used to secure the tool insert (black) to the heated block. The image on the right is a thermograph showing the tool insert at a temperature of 115°C.

6. CONCLUSIONS

A device which can be fitted to a tensile tester and used to measure friction force was designed and manufactured. Initial characterization of the thermal performance of the device has been completed and the results indicate that the temperature profile across the testing surface of the tool insert is constant. A capability trial is planned to prove the repeatability of the device. This device will be used as stage one of the validation of a model to predict demoulding force of polymer parts from replication tools.

7. ACKNOWLEDGEMENTS

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