Study of Ejection Forces In The AIM™ Process

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1 Abstract

The AIM™ process has been used to successfully produce short runs of injection moulded parts. One of the main drawbacks of the process is the tendency of the tools to be damaged during part ejection[1].
At De Montfort University a successful AIM™ moulding cycle has been developed in which simple shapes from polypropylene are produced and the ejection forces required are measured. Two different ejection methods are used; one uses conventional ejector pins and the other uses a conformal ejector pad. The tool surface roughness is measured before and after moulding to observe any changes caused by ejection. Results show that ejector pins require a lower ejection force than a conformal ejector pad and this may contribute to longer tool life for the AIM™ process. Possible reasons for the results are discussed along with recommendations for further work.

2 Background

2.1 The Direct AIM™ Process

The SL process is a proven technique for the rapid manufacture of parts from CAD designs and it has been used successfully in the production of short run injection moulding inserts [1,2,3,4]. SL tooling inserts are used during the prototyping stage of new product development when parts made from the final materials and using the final production technique are required. The AIM™ process may also be used to manufacture end use parts, however relatively low yields and long moulding cycles limit its use.
With non-aggressive moulding materials and favourable geometries, SL tools are capable of producing hundreds of parts when used correctly [3,4]. The aim of the research currently being carried out at De Montfort University is to investigate the limits on tool life caused by more difficult moulding geometries, as it is with these geometries that the SL process has its most distinct advantage over traditional tool manufacturing methods.

2.2 Mould Failure During Part Ejection in the Direct AIM™ Process

The most common source of failure in SL moulds has been described as the result of the moulding cooling onto features in the core causing it to break during ejection[1] (see Figure 1).

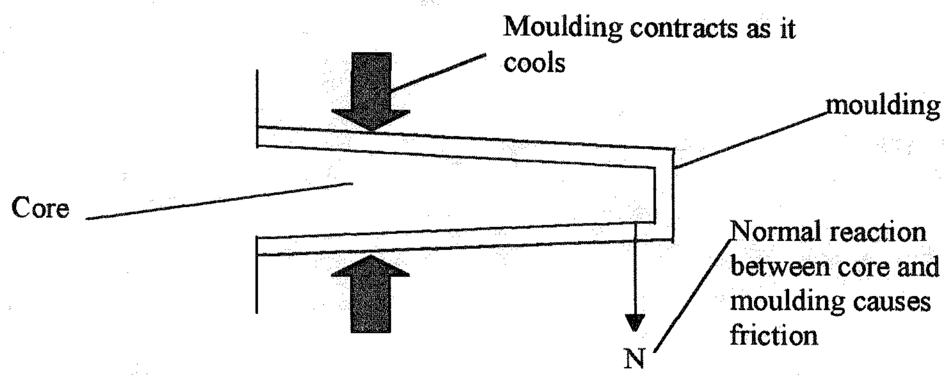

Figure 1. As the Moulding Cools it Contracts onto the Core

It can be seen from Figure 1 that as the part cools it contracts onto the core. It is this contraction along with the surface roughness of the core which leads to high ejection forces and therefore tool failure during ejection. Previous work in this area using steel tools has investigated the sources of high ejection forces and their effect on the quality of the moulded part[5]. In the case of direct AIM™ tooling, the ejection forces are even more important as it is the tool itself which may be damaged.

2.3 The Study of Ejection Forces in Injection Moulding

As mentioned above, previous work in this area has been carried out with a view to minimising damage to the moulded part. In the case of direct AIM™ tooling the emphasis for the research is different but many of the principles of ejection in conventional injection moulding still apply.
An equation predicting the ejection force based on various material properties of the mould and moulding has been developed by Glanvill and Denton[5]. The equation is based on ejecting a tube from a core. The use of a tube rather than a closed cylinder like the one used in this research is significant as the ejection force will not need to overcome a partial vacuum between the mould and moulding.

The equation is given as:

$$Fe = \frac{\alpha.(Tm - Te).D.E.A.\mu}{D[(D/2t - (D.\gamma /4t)]}$$

Where:
Fe = Ejection Force
α = coefficient of thermal expansion of moulding material
Tm = melting temperature of moulding material

Te = ejection temperature of moulding material
D= diameter of core
E = Youngs Modulus of moulding material at Te
A = Area of contact between core and moulding in direction of ejection
μ = coefficient of friction between moulding material and core
t = thickness of moulding
γ = Poisson's ratio for moulding material

2.4 Different Methods of Part Ejection

A number of alternative methods are used for part ejection in the injection moulding process. The simplest and most common method uses ejection pins, however in some cases ejection may be performed using ejector pads, air ejection, sprue pulling or combinations of these [6]. In this research the use of ejector pins and pads are investigated. The reason for assessing pad ejection is because the production of an ejection pad should be relatively simple using stereolithography.

2.4.1 Pin Ejection

During the design of an injection moulding tool, ejector pins are positioned in a way to allow a clean ejection from the mould without damaging the moulding. The addition of ejector pins to a mould adds complexity, lead time and cost and is generally kept to a minimum.
After a part has been moulded and allowed to cool, the mould opens and the ejector pins are pushed forward to free the part from the mould. Ejector pins are generally evenly spaced within a mould to provide an even ejection, however extra pins may be required where ejection is more difficult such as with deep features in the mould.

2.4.2 Pad Ejection

Pad ejection is very similar to pin ejection except that whole areas of the part are pushed by the pad as opposed to scattered points with pins. This provides a more even ejection and is preferred for larger parts which may be damaged by pins.
A major drawback of using ejector pads is the increased complexity in their manufacture. However with the flexibility of stereolithography, a conformal ejector pad could easily be produced and fixed to ejector pins to provide a more even ejection.

3 Research Methodology

The purpose of this research is to investigate the process of part ejection in the direct AIM™ process by observing any changes in surface roughness of tools. Also, any effects of ejection method were studied by measuring the ejection forces required.

3.1 Tool Design

The basic tool design was based on investigating the principle of failure during ejection as shown in Figure 1. Two factors which required attention were the possibility of using both pin and pad ejection for the same tool and also to ensure that the core would be able to with stand the ejection forces without breaking.

3.1.1 Allowing Both Pin and Pad Ejection

To allow both pin and pad ejection the closed cylinder shape (shown in Figure 1) had a collar added to its base as shown in Figure 2. This design also allows the use of thinner cores with the same ejection set up.

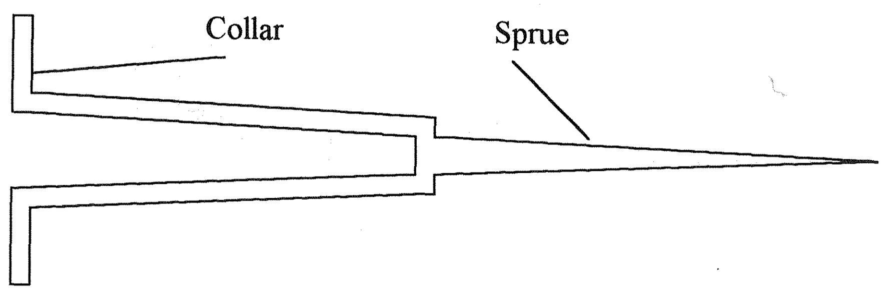

Figure 2. Cross Section of Test Mouldings Produced

3.1.2 Ensuring that the Core Would Not Break During Ejection

In order to produce a number of mouldings and perform a number of tests it was important to ensure that the core would not break off during ejection. Using the equation described earlier to predict the ejection forces along with estimates of material properties and temperatures an acceptable core design was found. Appendix 1 shows the estimates of material properties and tool temperatures based on previous work. These data are fed into Glanvill and Denton's equation and tool dimensions which may result in failure are calculated. Based on these calculations it was decided to use a core with an overall length of 40mm and diameter of 20mm with a 2mm wall thickness.

3.2 Equipment

The equipment required for this research is described briefly below.

3.2.1 Injection Moulding machine

A Battenfeld 600 CDC 60 ton injection moulding machine was used. This was controlled by a UNILOG4000 text based programming language which allows easy changing of the many parameters involved in the injection moulding process.

3.2.2 Injection Moulding tools

The tools used were made from solid SL5170 resin using the ACES™ build style on an SLA250 machine (see Figure 3). The mould design included a single round core feature to ensure an even shrinkage of the moulding onto the core. The core was 38mm long with a base diameter of 16mm and a 1.5° taper. A 40mm diameter flange

at the base provided an area for ejection and all wall thicknesses were 2mm. The design of the tool with no large flat areas ensured that part distortion after an early ejection would not occur.
The parts were built so that the direction of ejection would be parallel to the z build axis, this maximised the effects of stair stepping on part ejection but is commonplace in the production of SL injection moulding tools. To maintain repeatability between different moulds each insert was thoroughly cleaned between part building and post curing. No other form of finishing was used. Equally spaced steel ejector pins were used to eject the mouldings.

Figure 3: ACES™ Injection Moulding Inserts Used

3.2.3 Measurement of Surface Roughness of Cores
The surface roughness of the cores were measured using a Taylor Hobson Talysurf machine. The Talysurf drags a stylus over a surface, plots its profile and calculates the roughness average (Ra).

3.2.4 Measurement of Ejection Forces
The ejection forces were measured using 3 load cells each of which consisted of a 4 arm wheatstone bridge. The load cells were mounted behind the ejector pins to measure forces in the direction of ejection (see Figure 4).

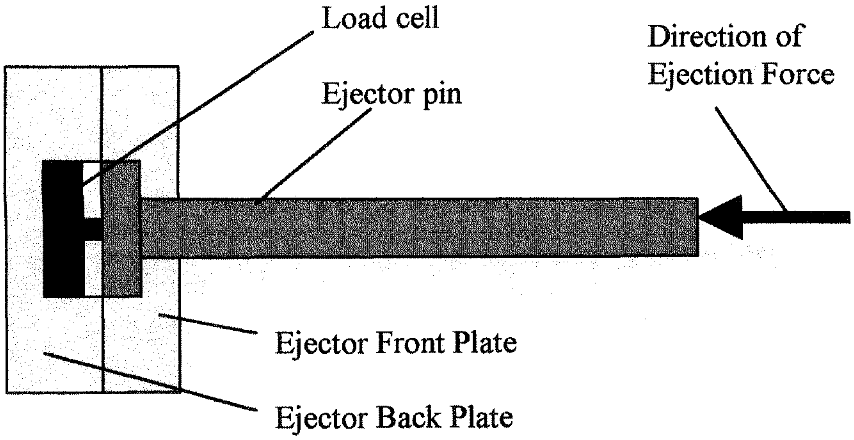

Figure 4. The Load Cells Housed Behind the Ejector Pins

3.2.5 Measurement of Tool Temperatures

The tool temperature was measured from the centre of the core using a K Type thermocouple. The SL core had a 2mm hole from the base to the centre of the core. After part building, the thermocouple was inserted into the hole and then SL5170 resin was injected into the hole ensuring that no air was trapped. The core was then post cured in the normal way for 1 ½ hours.

3.2.6 Data Acquisition with Visual Programming

The signals from the load cells and the thermocouple were fed into an analogue signal conditioning unit. This unit, which was controlled by HPVee visual programming software, was used to amplify the analogue signals before sending them to the host computer; it also provided excitation for load cells.

The HPVee programming language allowed a great deal of flexibility in terms of acquisition and manipulation of the data. For example, the effects of friction recorded when actuating the ejector pins could be simply measured and automatically subtracted from the ejection reading each time a moulding was ejected.

3.3 Experimental Conditions

3.3.1. Measurement of Surface Roughness

Measurements of surface roughness were made at 12 fixed positions to ensure repeatability between results. At a distance of 7mm from the base of the core, 6 equally spaced points were measured for surface roughness. Similar readings were taken at a distance of 7mm from the top of the core.

3.3.2 Injection Moulding Machine Parameters

Melt injection was performed at the lowest speed possible on the machine which was 5% of full speed. The peak injection pressure measured by the load cells through the ejector pins was 2000 psi (14MPa) and no packing pressure was applied as no surface ripples due to cooling in the mould could be seen.

3.3.3 Cycle Times and Tool Cooling

Cooling times were varied as these would greatly affect the melt temperature at ejection (Te) which, according to Glanvill and Denton's equation will affect the ejection force (Fe). The longest cooling time used was 480 seconds and the shortest time was 20 seconds.

For each moulding, the core temperature was allowed to cool to 55 degrees C before the next shot was performed. This ensured that the tool was below its glass transition (Tg) at the start of each cycle.

3.3.4 Data Acquisition Parameters

Measurement of the ejection forces required a quick sampling rate of 1000Hz to catch the peak values. The raw signal included some noise and was smoothed to compensate. The rate of change of tool temperature was much slower and a sampling rate of only 1Hz was required for this.

4 Results

4.1 Surface Roughness

Surface roughness measurements were taken to assist with estimating the ejection forces and to observe any changes caused by running the tools.

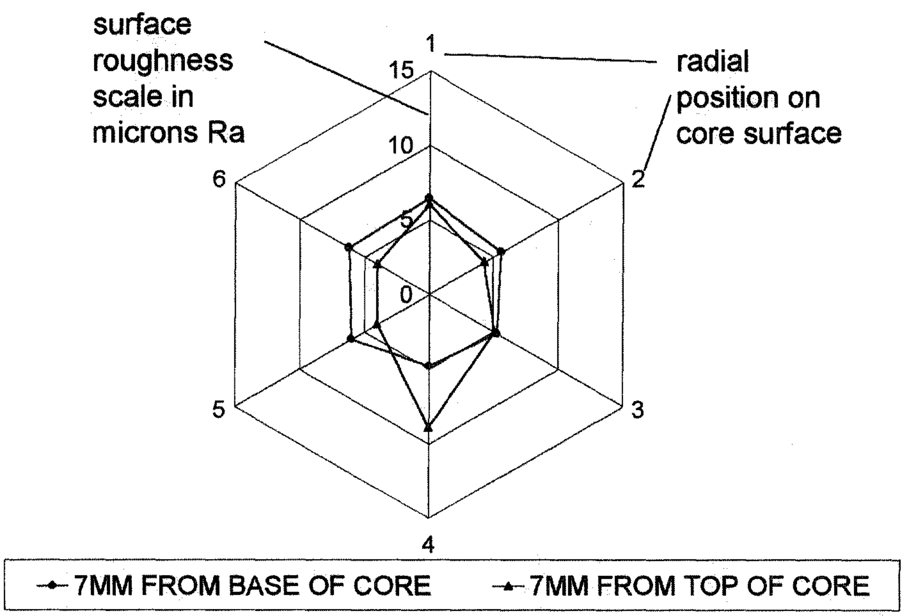

Figure 5. Polar Plot of Surface Roughness of Core Used with Ejector Pins Before use.

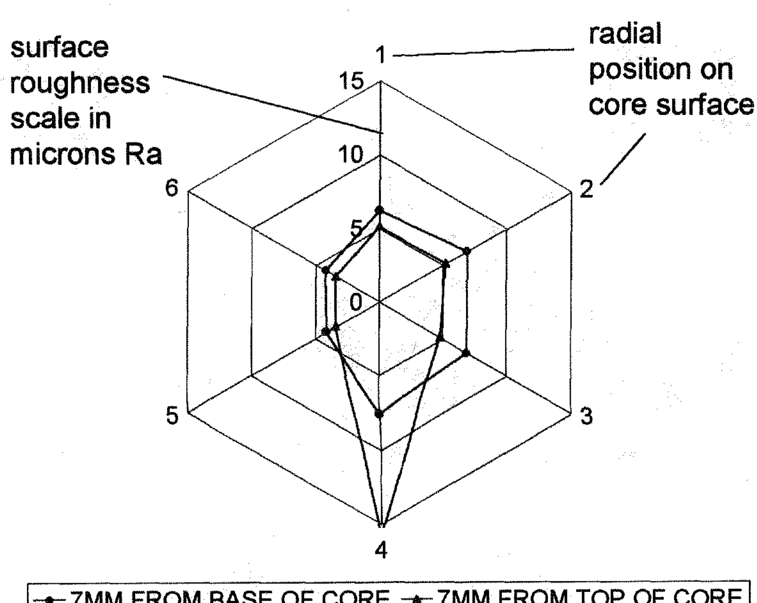

Figure 6. Polar Plot of Surface Roughness of Core Used with Ejector Pad Before use.

4.1.1 Roughness Average Values

Figure 5 shows a polar plot of the surface roughness of the tool which was used with ejector pins before any mouldings were taken. Figure 6 shows a similar plot for the tool which was due to be used with an aluminium ejector ring. Both plots show that the surface roughness measured was between 3 and 7 microns Ra except for position number 4, 7mm from the top of each core. Bubbles could be seen on these parts at this position which explains the higher Ra values.

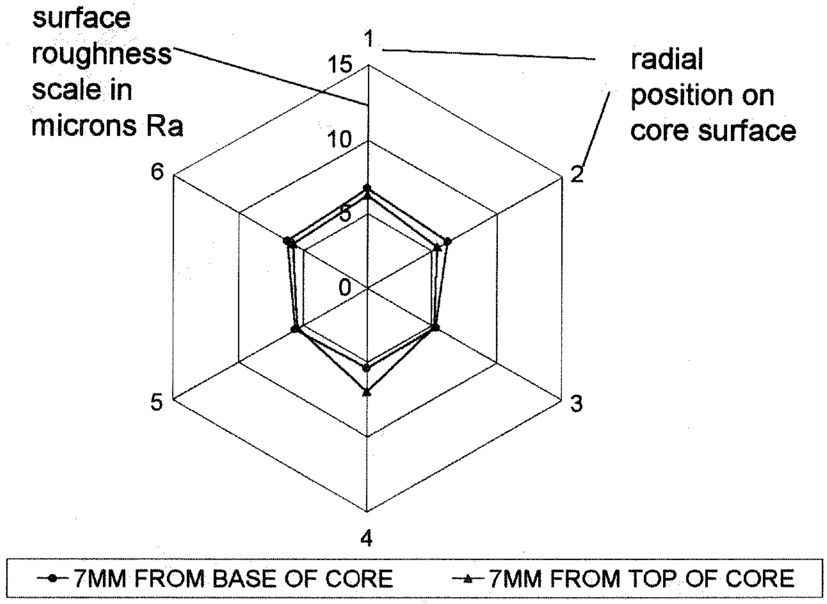

Figure 7. Polar Plot of Surface Roughness of Core Used with Ejector Pins After 50 Shots

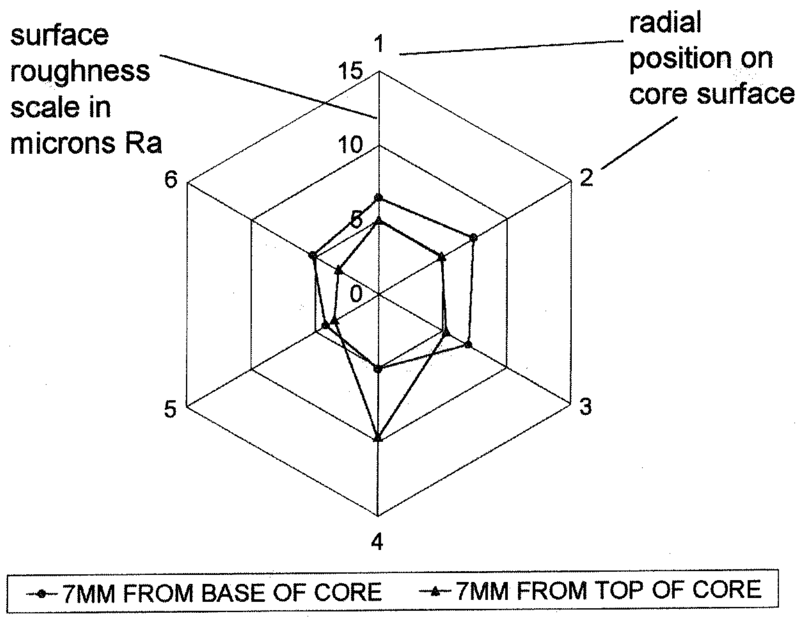

Figure 8. Polar Plot of Surface Roughness of Core Used with Ejector Pad After 50 Shots

Figures 7 and 8 show the polar plots for the cores shown in Figures 5 and 6 after 50 shots had been taken. There appears to be no real change in surface roughness after 50 mouldings for 11 of the 12 points measured. The roughest point on the original plots appears to have been smoothed after 50 mouldings.

4.1.2 Surface Profile Traces

Figure 9 shows a typical surface profile from the core used with pin ejection before any mouldings had been made. As expected, a regular "shark tooth" profile can be seen. Figure 10 shows the surface profile from the same point on the same core after 50 shots. There appears to be no change in the profile of the surface roughness and this is consistent with the results which showed no change in Ra values.

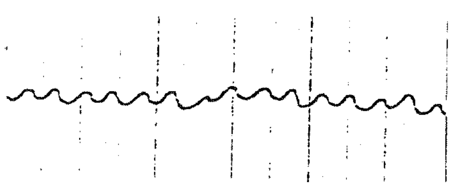

Figure 9. Surface Roughness Profile of Core Before Being Used with Pin Ejection

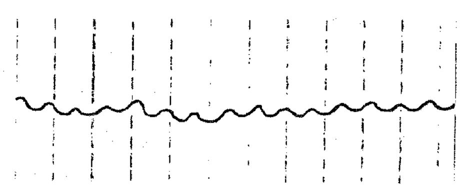

Figure 10. Surface Roughness Profile of Core After 50 Shots had been produced with Pin Ejection

4.2 Pin Ejection

Figure 11 shows the ejection forces recorded against cooling time for mouldings ejected with ejector pins. The graph shows that as cooling time is increased (and therefore melt temperature at ejection is decreased) ejection force is increased. This is consistent with Glanvill and Denton's equation as are the magnitudes of forces which are up to 300 Newtons.

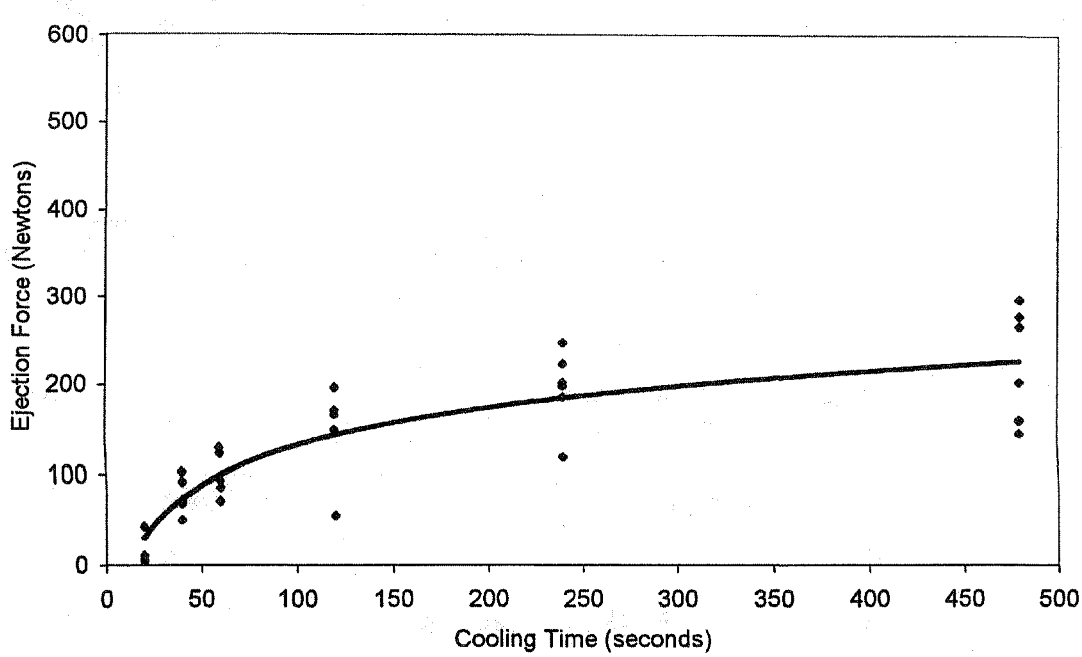

Figure 11. Graph of Ejection Force against Cooling Time Using Ejector Pins

For each specified cooling period there appears to be a significant range of ejection forces measured. The reason for this may be that the temperature of the moulding varies when the ejection time is kept the same. The temperature measured inside the core appears to be consistent with the ejection times, however the core material is an insulator so the temperature at the centre of the core may only give a rough indication of the moulding temperature. It is important to remember that it is the temperature of the moulding rather than the temperature of the centre of the core which will dictate the ejection force.

4.3 Aluminium Ring Ejection

Figure 12 shows the ejection forces plotted against cooling time for parts ejected using an aluminium ejector pad. Unlike the graph for ejector pins there is no discernible difference when ejecting after longer cooling times. Also, the forces measured are higher (up to 500 Newtons) than those found with ejector pins.
The reason for higher ejection forces was thought to be due to greater cooling at the base of the core due to the aluminium ejector pad acting as a heat sink. In order to test this theory, an ejector pad made from Nylon with a much lower thermal conductivity was used and tested.

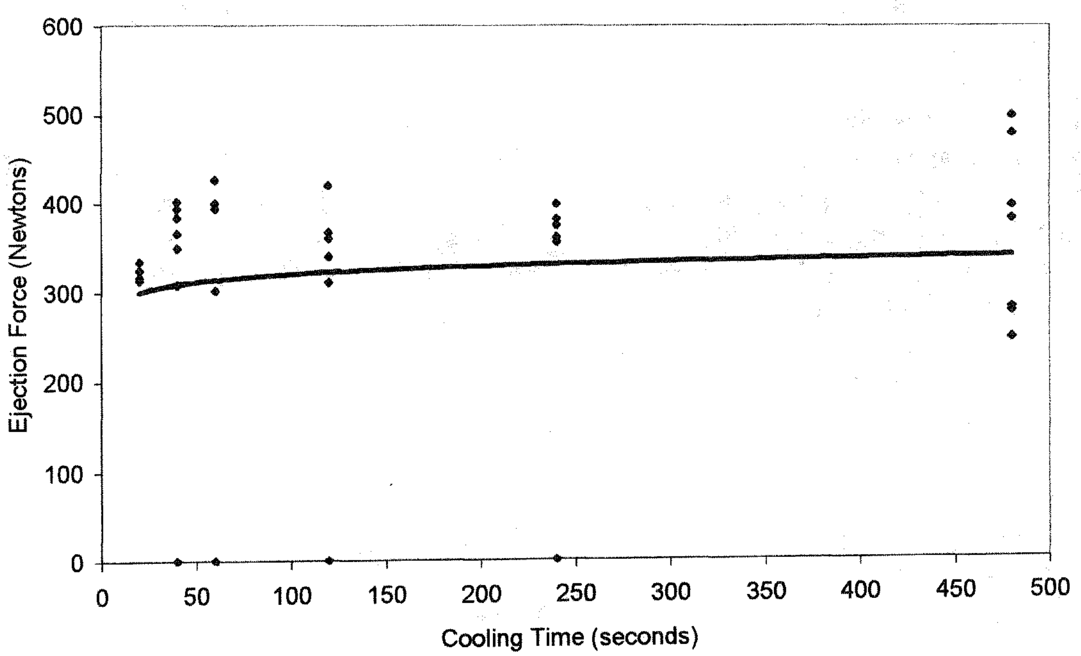

Figure 12. Graph of Ejection Force against Cooling Time Using Aluminium Ejector Pad

4.4 Nylon Ring Ejection

Figure 13 shows the ejection forces plotted against cooling time for parts ejected using a Nylon ejector pad. The graph is almost identical to that for the aluminium ejector pad. This suggests that the higher ejection forces are caused by the method of ejection rather than any local cooling caused by heat sinks in the tool.

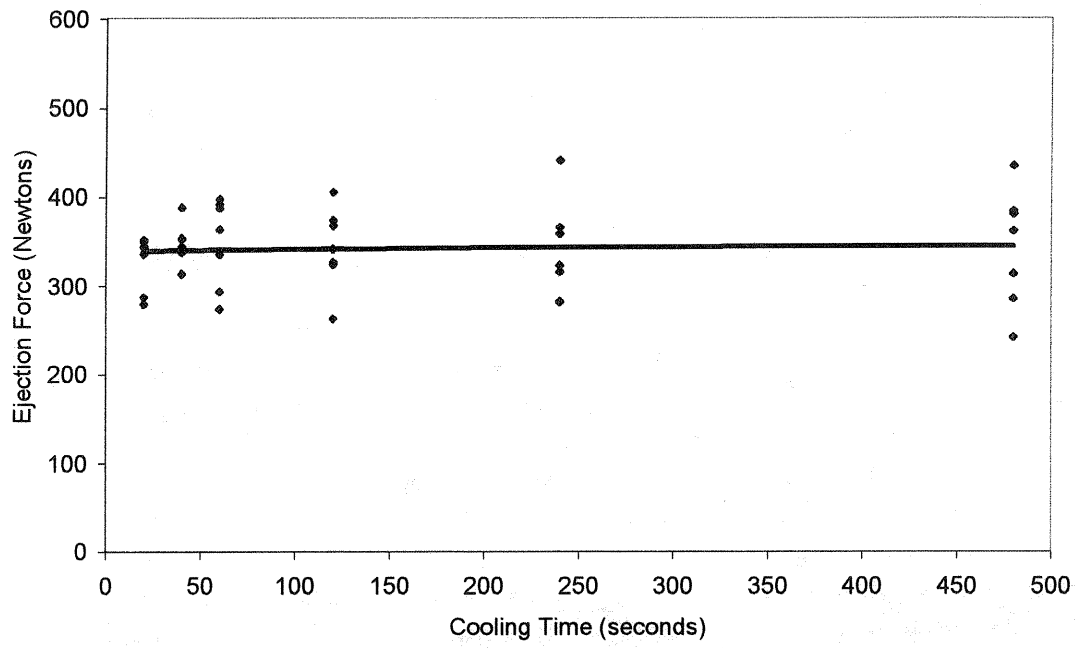

Figure 13. Graph of Ejection Force against Cooling Time Using Nylon Ejector Pad

5 Conclusions and Discussion

5.1 Surface Roughness of Cores

The measurements taken after 50 shots showed that for most parts of the tool surface there was no change in surface roughness. This suggests that there is no plastic deformation of the tool surface and measurements of roughness taken from the mouldings are similar to those of the tool. This indicates that during ejection, either the tool or the moulding or both are able to deform elastically before returning to their original state.

5.2 Ejection Forces

All of the ejection forces measured were within the range which might be expected from the equation provided by Glanvill and Denton. The forces recorded using ejector pins increased as expected with longer cooling times however this was not the case with pad ejectors. One possible reason for the higher ejection forces using pads is that air is not able to fill the void between the mould and moulding at the early stages of ejection. If this is the reason for higher ejection forces, then it suggests that the use of pins allows air to fill the gap between mould and moulding thus reducing the ejection force. It is possible that using pins causes the moulding to bend while still on the core thus allowing air between the mould and moulding. Indeed, given that the ejection force versus cooling time graph profile using pins is similar to that predicted by

Glanvill and Denton's equation using an open cylinder, this theory would seem reasonable.
Another possible reason for higher ejection forces using pads is that the ejection profile using pads is steeper than that using pins. This suggests that the moulding is pushed off more quickly using pads and therefore the acceleration applied is greater which requires a higher force.

5.3 Further Work

The results presented above showed two areas which are difficult to explain and therefore require closer attention. Firstly the higher ejection forces using ejector pads may be investigated by performing tests with different ejector methods. For example ejection with 2 ejector pins could be compared to that with 6 ejector pins. If a more even ejection results in a higher force then it could significantly ease mould design with fewer pins.
Secondly, the variation in ejection forces after the same cooling time may be explained by some variation in the actual temperature at ejection. Further tests should be performed with the temperature of the moulding being recorded rather than the temperature of the centre of the core.

6 References

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Appendix 1

Glanvill and Denton's equation for ejection force is:

$$Fe = \frac{\alpha.(Tm - Te).D.E.A.\mu}{D[(D/2t - (D.\gamma /4t)]}$$

The equation can be re-written as:

$$Fe = \frac{D^2\, \alpha(Tm\text{-}Te).E.\pi.L.\mu}{D^2.(1/2t - \gamma/4t)}$$

Where L is the core length.

The D^2 cancels out on top and bottom so the theoretical ejection force Fe is independent of core diameter.

Using the following figures, ejection forces for different core diameters can be evaluated.
$\alpha = 6.8 \times 10\text{-}5$ K-1 (linear)
Tm = 160oC
E = 245 MPa
$A = \pi.D.L$
$\mu = 0.5$
t = 2mm
$\gamma = 0.35$
Length of Tool (L) = 40mm

Using an ejection temperature (Te) of 100oC gives an ejection force of 289N
Using an ejection temperature (Te) of 60oC gives an ejection force of 482N

These predicted forces (remembering that a trapped vacuum has not been accounted for) can be compared with the predicted tool strength which is governed by cross sectional area and tool temperature.

Max Temp of Tool = 80oC
Tensile Strength of Tool at 80oC = 12MPa

Therefor for failure at 80oC:

$$Fe > 12.\pi(D/2)^2$$

For a 10mm diameter tool $12.\pi(D/2)^2 = 942$N
For a 20mm diameter tool $12.\pi(D/2)^2 = 3768$N

These calculations show that both a 10mm and 20mm diameter core should be strong enough to resist tensile failure assuming no vacuum exists between the mould and moulding.