THE SELECTION OF MOULD DESIGN VARIABLES IN DIRECT STEREOLITHOGRAPHY INJECTION MOULD TOOLING

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1. Abstract

The introduction of rapid prototyping has allowed engineers and designers to generate physical models of required parts very early on in the design and development phase. Further to this the use of stereolithography (SL) cavities as a rapid tooling method has allowed plastic prototype parts to be produced in their most common production manner; by injection moulding. The process is best suited to small production runs where the high costs of conventionally machined tooling is prohibitive.

One of the major drawbacks of the SL injection moulding process is the susceptibility of the tools to premature failure. SL tools may break under the force exerted by part ejection when the friction between a moulding and a core is greater than the tensile strength of the core resulting in tensile failure.

Very few justified recommendations exist concerning the choice of mould design variables that can lower the part ejection force experienced and reduce the risk of SL tool failure. This research investigates the ejection forces resulting from injection moulding polypropylene (PP) and acrylonitrile-butadiene-styrene (ABS) parts from SL tools which are identical in all respects except for their build layer thickness and incorporated draft angles. This work attempts to identify appropriate evidence for recommendations with respect to these design variables and SL injection moulding.

The results show that adjustment of draft angle results in a change of part ejection force as a reasonably linear relationship. An adjustment of the build layer thickness results in a change in part ejection force as a more non-linear relationship. The adjustment of build layer thickness had a greater effect on ejection force than the adjustment of draft angle. In both cases greater ejection forces were experienced by ABS parts as compared to PP parts. The results also show that the surface roughness of all tools remains unchanged after moulding a number of parts in both polymers.

2. Background

2.1 Stereolithography Tooling for Injection Moulding.

The introduction of rapid prototyping has allowed engineers and designers to generate physical models of required parts very early in the design and development phase. However the requirements of such prototypes has now progressed beyond the validation of geometry's and onto the physical testing and proving of the parts. For such tests to be conducted the part must be produced in the material and by process intended for the production intent part. For injection moulded parts this situation highlights the requirement of a rapid mould making system that can deliver these parts within the time and cost boundaries. During the early years of stereolithography (SL) it was never envisaged that this process could be used to directly produce tooling. The glass transition temperature of SL parts available was only ~65°C while the typical temperature of an injected polymer is >200°C and early SL parts also suffered distortion.

Despite these supposed limits successful results were achieved by SL users world-wide, including the Danish Technological Institute, Ciba Specialty Chemicals (now Vantico), the Fraunhofer Institute, the Queensland Manufacturing Institute and Xerox Corporation (Jacobs, 97).

There exists other methods that could be used to create the required tooling to produce such mouldings, including resin cast moulds. These processes have been compared with SL injection moulding (Luck, 95) in the production of a typical quantity of parts, where the SL moulding process was found to be a superior alternative for producing design-intent prototypes.

SL injection moulding has also been compared with other direct RP mould generating techniques for producing a typical development quantity of mouldings. These RP methods included Cubital Solider (acrylic), EOS and Sintered glass filled nylon (Roberts, 98). Of these moulds only the SL moulds successfully produced the required number of parts and further more were still capable of producing further mouldings at the end of the trials.

It has also been noted that some of the other alternative techniques involve additional steps in the process, therefore becoming an indirect process and not really rapid tooling (Jayanthi, 97). Other advantages of the process have been highlighted beyond the prototype validation phase; since the tool design has been verified the lead-time and cost involved in the manufacture of production tooling is reduced (Heath, 96).

2.2 Tool Failure During Part Ejection

The most common source of failure in SL moulds has been described as the result of the required moulding contracting onto features in the core causing these features to break during ejection (Jacobs, 1996), see Figure 1. Low tool strength especially at elevated temperatures has been cited as a contributory factor to failure.

Current recommendations for use of SL tools published by 3D Systems suggest that an extensive cooling period is needed prior to part ejection (Decelles, 1996). However research carried out at De Montfort University has suggested that as short a cooling time as possible should be adopted in order to gain a successful moulding (Hopkinson, 1998b). After part ejection, the tool should be allowed to cool sufficiently before the next part is moulded.

2.3 Factors Contributing to the Ejection Force

The ejection force required in injection moulding is governed by the static friction which exists between the mould and the moulded part and any effects caused by partial vacuums as the part is pushed from the mould (Menges, 1986). The static friction force is a function of the normal reaction between the mould and moulding, the coefficient of static friction between the mould and moulding and the area of contact between the mould and moulding parallel to the direction of ejection (Menges, 1986).

Previous research has shown that the cooling time prior to ejection affects the normal reaction between the mould and moulding and therefore affects the ejection force required. By using different tools with identical dimensions the effects of partial vacuums may be nullified and by using a constant cooling time (and hence a constant normal reaction between the mould and moulding), the effects of the coefficient of static friction may be assessed (Hopkinson, 1998a). For most material combinations the coefficient of friction between two bodies is governed by the surface roughness of their contacting surfaces. SL parts may be built with different layer thickness' which in turn result in different values of surface roughness. Tooling draft is used to reduce the force required for part removal. The extent of this draft angle results in the amount of change required to the geometry of a part/cavity. This research is aimed at assessing the effects of the layer thickness and tooling draft angle on the ejection force required.

3. Research Methodology

3.1 Tool Design

Figure 2 shows the core and cavity inserts used along with a sample moulding produced in this research. The moulding consists of a sprue, a closed cylinder which freezes onto the core and a lower flange which the ejection pins act upon. The cylinder is 40mm long with a 20mm outside diameter and 2mm wall thickness. Three ejector pin holes are built into the core insert to facilitate part ejection.

In order to assess the effects of layer thickness on ejection forces, three sets of inserts were produced. These inserts had layer thicknesses of 0.05mm, 0.1mm and 0.15mm. In order to assess the effects of tooling draft angle on ejection forces, another three sets of inserts were produced. These inserts had draft angles of 0.5º, 1º and 1.5º. All inserts were produced on an SLA350 SL machine using SL5190 resin. The inserts were oriented in the SLA vat in such a way as to ensure that the direction of ejection would be perpendicular to the layers (i.e. in the direction of the Z axis).

3.2 Measurement of Surface Roughness

Measurements of surface roughness were made before and after moulding to assess any smoothing which may occur during the moulding process. 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 around the circumference of the core were measured for surface roughness. Another 6 equally spaced points around the core were measured at a distance of 7mm from the top of the core.

3.3 Injection Moulding Parameters

The ejection forces were measured for 15 parts from each tool. Silicone based release agent spray was applied to both the core and cavity inserts prior to the 1st and 11th moulding. Melt injection was performed at 5 cm^3/second. No packing pressure was applied as no surface ripples due to cooling in the mould could be seen. A cooling period prior to ejection of 40 seconds was used as this had proved to be the optimum time in previous experiments (Hopkinson, 98a) with similar tools which allows minimum heat to be transferred into the tool while the part is still rigid enough to withstand ejection. For each moulding, the core temperature was allowed to cool to 55ºC before the next shot was performed, this ensured that the tool was below its glass transition (Tg) at the start of each cycle. The only difference between the moulding parameters used for the two materials was the melt temperature; 185ºC for PP and 240ºC for ABS.

3.4 Measurement of Ejection Forces

The ejection forces required were measured using strain gauge based load cells which were located behind the three ejector pins. The readings from the load cells were digitised using an analogue to digital converter. The digital signals were sampled at 1000Hz and processed using HPVee visual programming software.

4 Results

4.1 Surface Roughness Measurements

The pre-moulding Ra measurements made from the draft angle inserts showed virtually no difference between the surface roughness of the cores for each of the angles utilised; 10µm each. The pre-moulding Ra measurements showed a strong relationship between build layer thickness and surface roughness i.e. layer thicknesses of 0.15, 0.1 & 0.05mm resulted in Ra values of 15, 10 & 3 µm respectively.

The mean Ra values of the post-moulding surface roughness for both layer thickness and draft angle tests are very similar to those found in the pre-moulding tests. There is no evidence to show that the tools are smoother after moulding with either polymer.

4.2 Ejection Forces

Figure 3 indicates that cavities built with the thicker layers result in higher ejection forces in the SL moulding process for both polymers. The increase in ejection force with larger layer thicknesses (and therefore higher surface roughness) is as expected because the higher the surface roughness, the more deformation work is required to separate the surfaces in contact.

Figure 4 indicates that greater tooling draft angles result in lower ejection forces in the SL moulding process for both polymers.

Both sets of results also shows that for the all the experiments the application of release agent prior to moulding (applied prior to shots 1 and 11) does reduce the ejection force. A gradual increase in force is then noted in subsequent shots as the release agent is removed from the tool surface.

5 Conclusions

5.1 Surface Roughness

The results from the measurement of the surface roughness of the layer thickness tools indicate that a larger layer thickness results in a rougher surface. The post-moulding tests for surface roughness show that there is no noticeable change in surface roughness after the cores had been used for injection moulding for either the layer thickness or draft angle tooling inserts. The fact that there appears to be no change in surface roughness after moulding seems a little surprising at first. However investigations into heat transfer in the core during moulding show that the heat from the polypropylene penetrates the SL core at a very slow rate (Hopkinson, 1999). By ejecting the part after a 40 second cooling period the surface of the core is above its Tg at the time of ejection and acts in a rubbery way. This means that the two materials will give way as the moulding is pushed across the core's surface and return to their natural positions after the moulding has been fully removed.

5.2 Ejection Forces

The lowering of ejection forces with the application of a silicone release agent is of very little surprise as this lowers the friction experienced between the mould and part surfaces. The results do show that this agent is not removed entirely by one shot, rather allowing a gradual increase in the ejection forces experienced over a number of shots as it is steadily removed.

The increase in ejection force with larger layers is consistent with the higher surface roughness measured in these tools. A larger layer thickness results in deeper surface peaks and troughs which results in a greater quantity of material needing to deform to facilitate ejection. This in turn leads to a higher ejection force.

The results show that the ejection forces are lower for greater draft angles. This is of no surprise as the use of draft is usually used to reduce the force required for removal of the part from the mould (Rees, 1995).

These experiments have shown that by comparison of the two sets of results the effect of build layer thickness is greater than the tooling draft angle on the part release forces in SL injection moulding. This difference is likely to be due to the effect of changing the respective variables on the surface roughness of the SL tool surface. This is demonstrated by comparison of figures 5 & 6.

The research presented in this paper indicates that smaller layer thicknesses and greater draft angles result in lower ejection forces and may reduce the possibility of tool failure during part ejection. Unfortunately building parts with smaller layers involves extra time and cost while the use the use of a high draft angle places compromises on a parts intended geometrical design. However the results also show in both experimental cases (although much less so for the draft angle experiments) that a linear change of an experimental variable (the amount of draft angle or the build layer thickness) equates to a non-linear degree of change in the part ejection force. This may indicate optimum values for the experimental variables which would incur the lowest part ejection force whilst allowing a minimum disruption to a parts intended geometry (draft angle) and build time (layer thickness).

In both experiments ABS parts resulted in higher ejection force than PP parts. The differences between the materials that may effect the ejection force are shrinkage and physical properties. PP is a semi-crystalline material which has higher total shrinkage than ABS but the vast majority would occur after the part has been ejected from the tool due to it's very slow rate of shrinkage. PP is more flexible than ABS and therefore more easily deformed upon ejection reducing the friction between the part and tool surfaces, resulting in a lower ejection force.

5.3 Suggestions for further work.

The surface roughness tests in this research showed results that did not indicate any wear incurred by the moulding process. However both polymers; especially PP, are particularly non-aggressive moulding materials and a more aggressive material (such as a glass filled polymer) would be more likely to cause wear to the low strength SL substrate.

Another polymer specific factor that may effect the ejection force experienced is the shrinkage. Although polypropylene is a semi-crystalline polymer with a large percentage of volumetric shrinkage it is very slow to occur. A large majority of this may occur after the part has been ejected from the mould. The use of a polymer with higher or lower in-moulding shrinkage may also effect the ejection force.

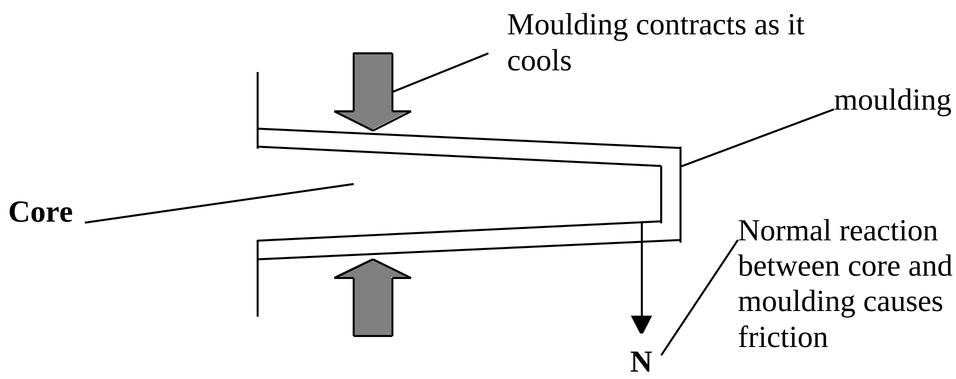

Figure 1: As the moulding cools it contracts onto the core

Figure 2. Core and cavity inserts along with moulding including sprue

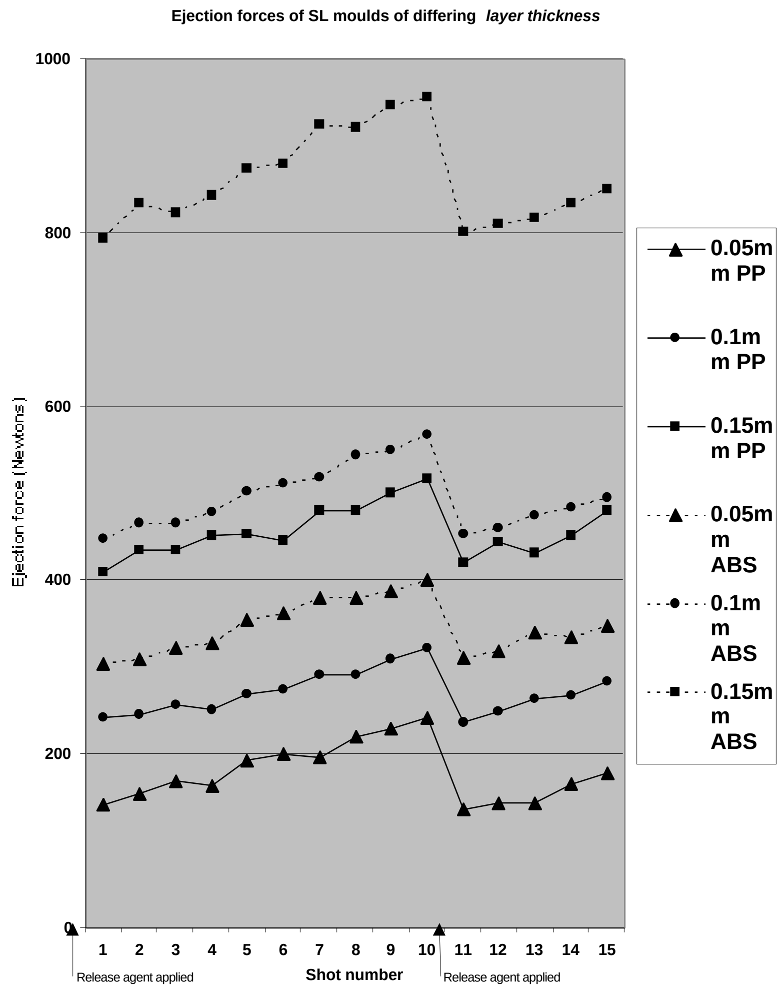

Figure 3. Graph showing ejection force against shot number for tools built with different layer thicknesses

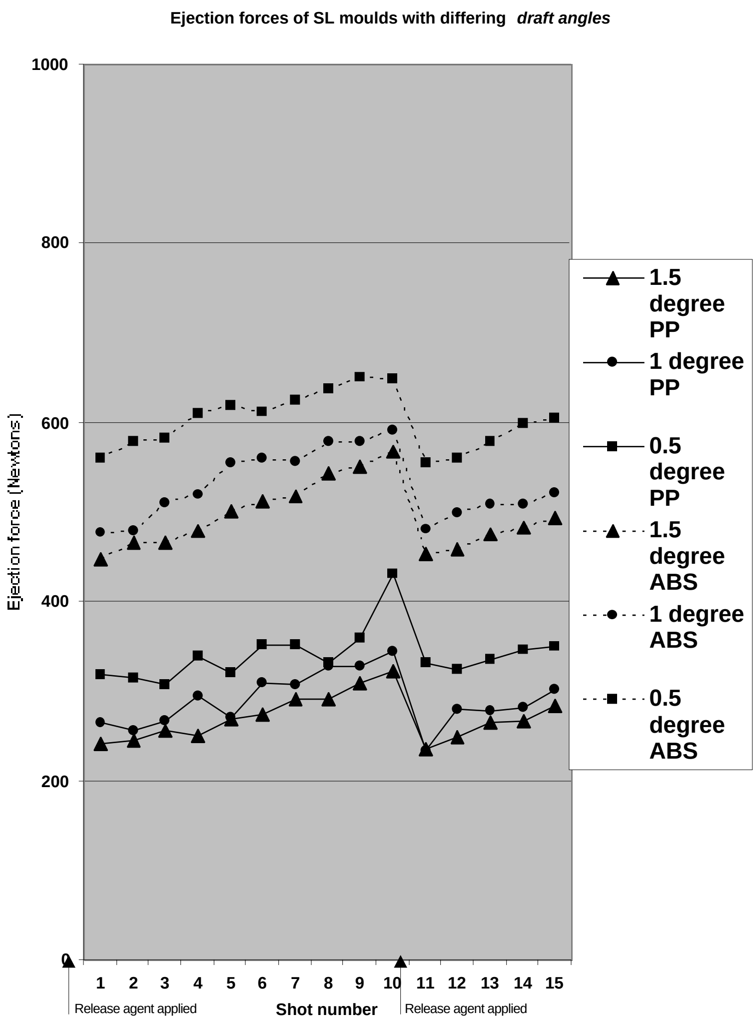

Figure 4. Graph showing ejection force against shot number for tools built with different draft angles.

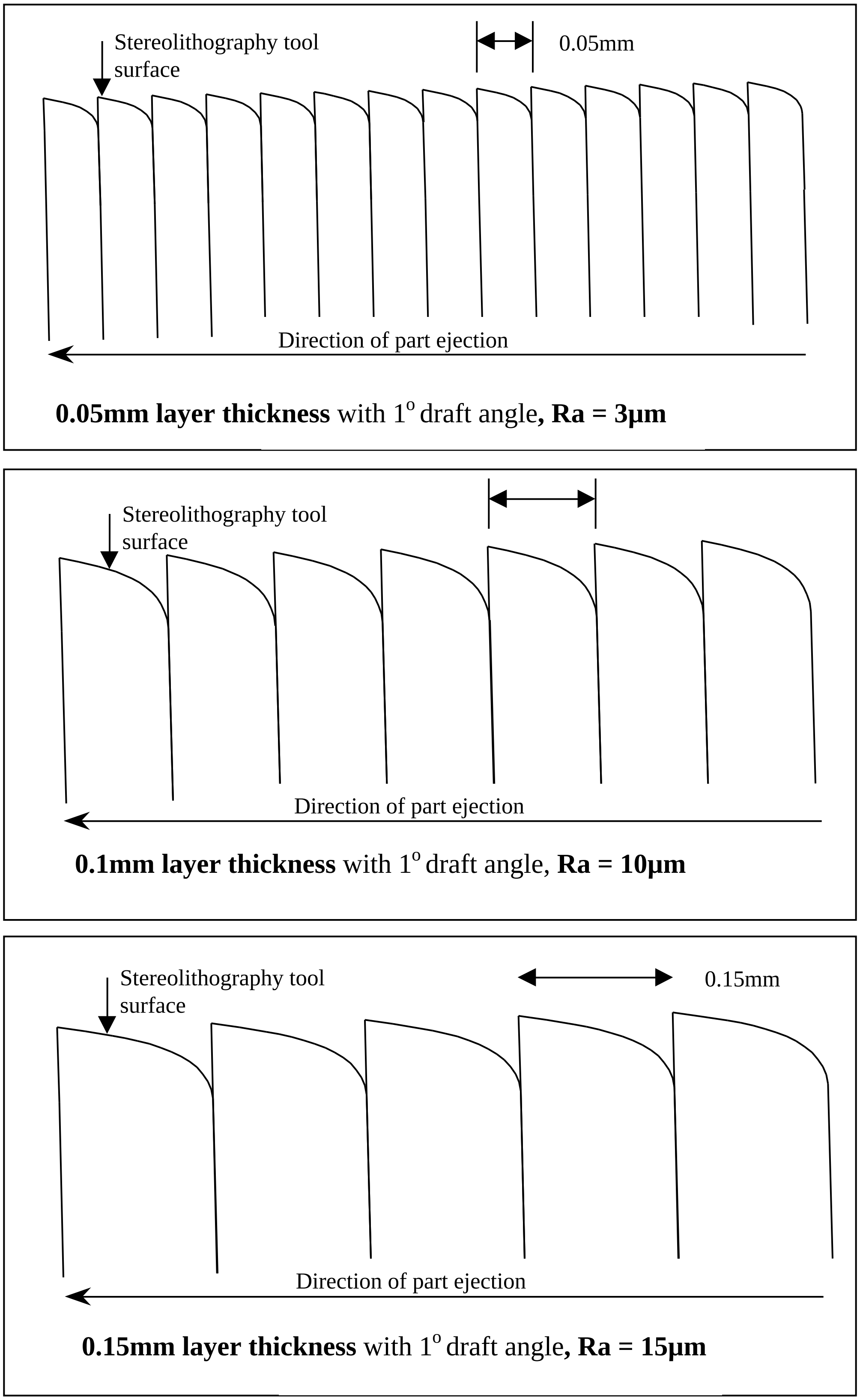

Figure 5. The effect of layer thickness alteration on tool surface Ra.

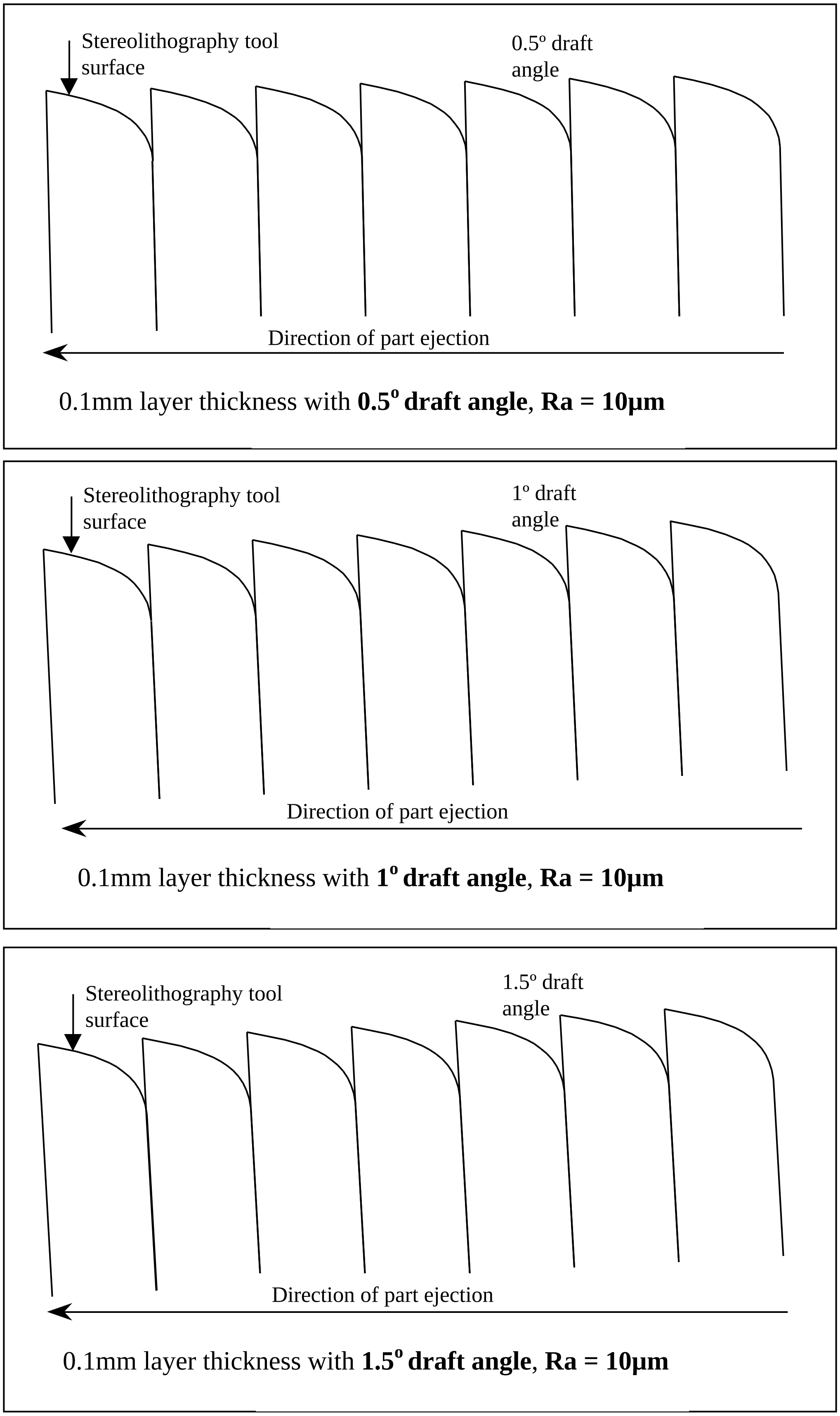

Figure 6. The effect of draft angle orientation on tool surface Ra.

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