REDUCING THE SURFACE DEVIATION OF STREOLITHOGRAPHY USING AN ALTERNATIVE BUILD STRATERGY

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1.0 ABSTRACT

Considerable research has been undertaken to assess the suitability of different post-process finishing techniques, when used to reduce the surface deviation of Stereolithography components. Such techniques are however limited, as irregular roughness on the SL master often results in a loss in geometric integrity before the desired finish is achieved. Hence, removing much of the design intent and traceabilty within the automated fabrication process. Although a number of research initiatives have been undertaken to design layer manufacturing systems which produce inherently smooth surface, the problem of finishing parts from existing systems remains. The solution currently under investigation by the author is to develop a smooth build cycle within the SL machine, eliminating the need for costly machine modifications.

The solution developed by the author uses a strategy, which relies on both part orientation and a fundamental change to the current SLA build cycle. By orientating parts into an optimum build direction, the paper shows how naturally occurring phenomena within the SL process can be used to produce low roughness over a 50-degree window of surfaces. The paper goes on to demonstrate how, by using a resin meniscus scanned between layers during the build process, this smooth envelope can be extended to encompass 90-degree of surfaces. By scanning fillets between each layer, a reduction in surface roughness of up to 400% can be achieved on some angled planes. The paper concludes that by using this new build algorithm, the roughness of SL tool cavities can be maintained below 9μm Ra on all surfaces. Hence, reducing or even eliminating the need for post-process finishing on all but the most accurate cavities.

2.0 INTRODUCTION

The application of layer manufactured components in the product development chain has in recent years extended from the production of simple models, prototypes and pre-production samples into the supply of accurate master patterns and cavities for a range of down-stream Rapid Tooling (RT) systems [1]. Of the available Layer Manufacturing Technologies (LMT), the Stereolithography (SL) process appears to dominates this sector, with the production of master patterns required for processes such as vacuum casting, cast resin tooling, sprayed metal tooling and the emerging Keltool process [2]. Down stream tooling processes now accounts for over 50% of the revenue generated within the RP industry [3]. More recently however, cavities manufactured directly on the SL machine have found applications in both high-pressure injection and reactive injection moulding [4].

Although it is now claimed that the SL process can maintain accuracy and repeatability of +/- 0.075-mm [5], the technique is not without it's limitations. In addition to the limited process knowledge and experience of running RT cavities using conventional moulding machines, a question remains over the quality of parts produced from cavities manufactured using layers. Layer manufacturing has always been synonymous with poor surface finish. This being mainly attributed to stair stepping which occurs when the layer edge is not parallel with the part surface. The result is that many SL components require a significant degree of post-process finishing before they can be used as tooling patterns [6].

With the manufacture of master patterns for in-direct rapid tooling, the problems associated with the high surface roughness on the layer manufactured component have been overcome using post-process finishing techniques such as abrasive finishing [7], surface coating [8], or in most cases, a combination of additive and abrasive finishing [9]. These techniques although suited to visual prototypes and masters for components with non-critical dimensions, cannot easily be applied with high accuracy to master pattern or direct RT tool cavities. Hand finishing is both detrimental to part geometry and inverse to the philosophy of Rapid Prototyping. By manually finishing an RP part, all traceabilty within the manufacturing chain is lost, as geometric problems identified during product appraisal may be a function of the finishing process rather than the initial design.

With direct layer manufactured tooling it is often impractical to undertake manual finishing, as the aspect ratio of many cavities makes hand finishing impossible without the use of specialist finishing equipment. Although research is currently underway to assess the automated finishing of SL tool cavities using process such as Ultrasonic Flow Polishing, such techniques will inevitable increase the lead-time and cost savings associated with rapid tooling systems.

It is the author's opinion that the solution to reducing the surface deviation of the SL process, lies in a fundamental change in the way layer manufactured parts are built, by eliminating stair stepping at source. A number of research teams have addressed this problem, by proposing theoretical solutions such as variable layer thickness parts [10] and the use of variable angled layer edges [11]. The main limitation with previously research is that new hardware must be developed before surface roughness can be reduced. Given that over 1000 SLA machines have now been sold by vendor 3D Systems [12], it is the authors opinion that a new build strategy should be developed which can be use on existing SL hardware, hence eliminating the need for expensive modifications or complete system replacement.

3.0 RESEARCH METHODOLOGY

A research project was started by the author in 1995 and was solely devoted to reducing surface deviation on SL components. The initial stage was to make a comparative analysis of different LMT process, to establish which attributes of the layer manufacturing process produce surface deviation [13]. By comparing eight of the leading RP systems, the research showed that in addition to layer thickness both the fundamental composition of each build layer and the profile of each layer edge have a unique effect on LMT surface topography. It was found that for SL process, particularly with the ACES build style, the composition of each layer has little overall effect on roughness when compared to either layer thickness or layer profile. However, with processes such as Laminated Object Manufacturing (LOM) and Selective Laser Sintering (SLS), the composition of each layer was found to have a more pronounced affect on surface roughness than layer thickness or layer profile.

By developing a mathematical model of the relationship between layer manufactured surface roughness and build angle, it was demonstrated that significant reductions in SL surface roughness can be achieved by changing either the layer edge profile or the layer thickness. However, by modelling it was also demonstrated that although thinner layers can produce smoother parts, reduced layer thickness will not eliminate stair stepping completely and can increase built time to an uneconomic level.

Research concluded that the most probable solution to the in-process part finishing of SL components is to identify methods of changing layer edge profile within the current SLA technology. If layer edge profile can be optimised, it may be possible to eliminate stair stepping and yield a significant reduction in surface deviation.

3.1 Roughness evaluation of SLA parts

Before any changes were made to the existing SL build strategy, a series of test samples were produced to establish a benchmark roughness for each of the commercial SLA systems [14]. Benchmarking was undertaken using an STL file of the geometry shown in Figure 1, which exhibits a range of angled surfaces in 2-degree increments from 0-degrees up facing, through to 180-degrees down facing. Using 3D Systems Maestro™ software, support structure was positioned at the edge of each down facing layer to ensure no witness mark were evident on the surfaces of interest. Part were then manufactured using SLA250, 350, and 500 machines in epoxy resin, in addition to samples manufactured in acrylic resin using the SLA250.

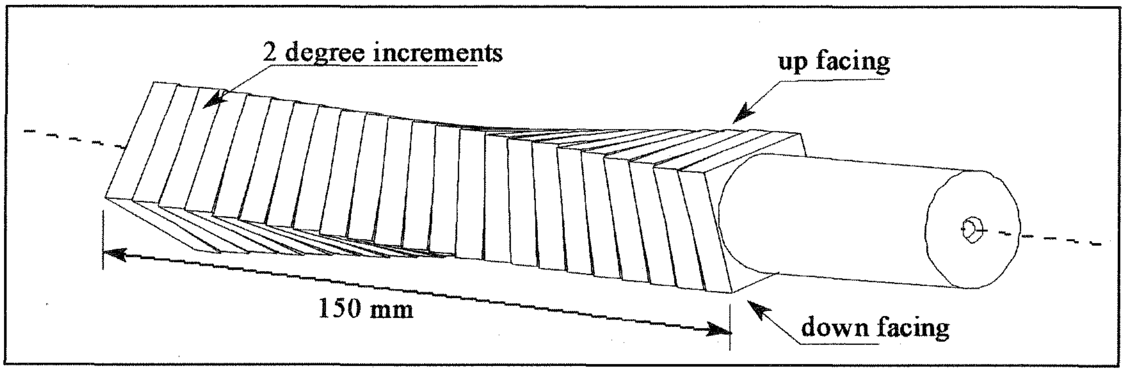


Figure 1 – Test sample geometry used to determine SLA roughness

By positioning the samples in a dividing head, accurate roughness average data was measured using a contact Taly-surf interfaced to a surface analysis package. Using the average of six-roughness measurement, a comparison between surface angle and roughness was made for each of the test samples. A graphical representation of this comparison is shown in Figure 2.

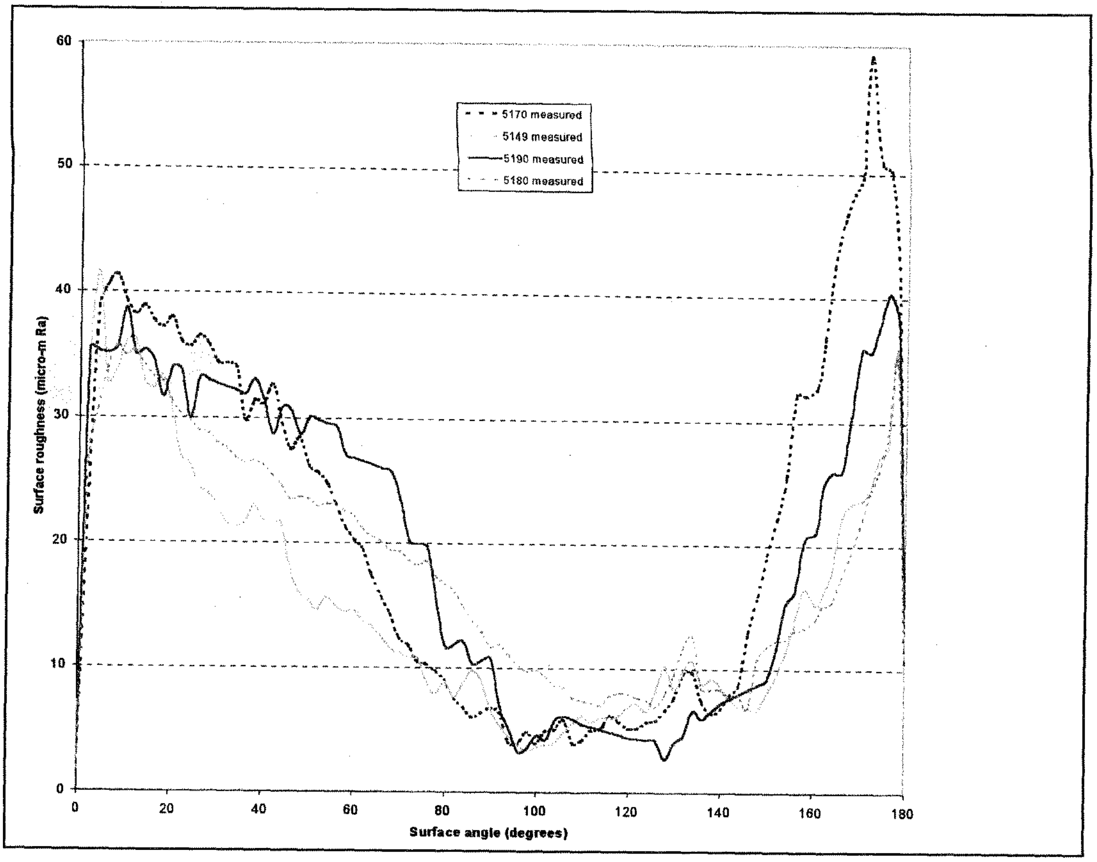


Figure 2 – Surface roughness comparison of different SLA systems

From Figure 2 a distinct trend can be seen between each of the roughness plots relative to surface angle. As surface angle increases, so surface roughness decreases, as the effects of stair stepping become less prevalent. At 90-degree surface roughness should reach a low point as no stair stepping occurs on vertical planes. After this point, roughness should again increase. It is generally accepted that the roughness of planes between 90 and 180-degrees should mirror those between 90 and 0-degrees. However, in Figure 2 this is not the case, as the roughness of planes between 100 and 150-degrees show a much lower surface roughness than initially expected. This would suggest that some attribute within the build process creates a natural smoothing effects on surfaces within this band of angles. Hence, by orientating the critical surfaces of parts within this smooth envelope a significant reduction in surface deviation can be achieved.

3.2 Utilising print-through on down facing surfaces

On investigation, it was found that the smooth surface envelope is the result of partially cured resin at the interface of down facing layers, which continues to cure during the subsequent scanning of the next layer. The result being a fillet of cured resin between the interface of layers producing lower surface deviation. The fillet is now known to be a function of the mechanism by which layers are bonded, known as print-through, and was considered by the author as a possible solution to overall surface improvement on down facing planes [15]. However, the smoothing fillet was only found to improve surface between 100 and 150-degrees. Unfortunately, print-through is a function of both laser power and scan speed and cannot easily be controlled in realtime by the process user. If print-through is to prove beneficial in reducing surface deviation on SL master patterns and cavities, it must therefore be combined with an additional smoothing strategy for angled surface either greater than 150-degrees or less than 100-degrees.

4.0 MENISCUS SMOOTHING

A method of reducing the surface roughness of SL components within the build envelope has been discussed by both Narahara at the Kyushu institute in Japan [16] and Smalley of SL manufacturer 3D Systems [17]. In Narahara's research, the process called 'lift-up irradiation' stretches a meniscus of liquid resin between each polymerised layer. The resin meniscus is then locked in place using scan data from a previous layer as shown in Figure 3.

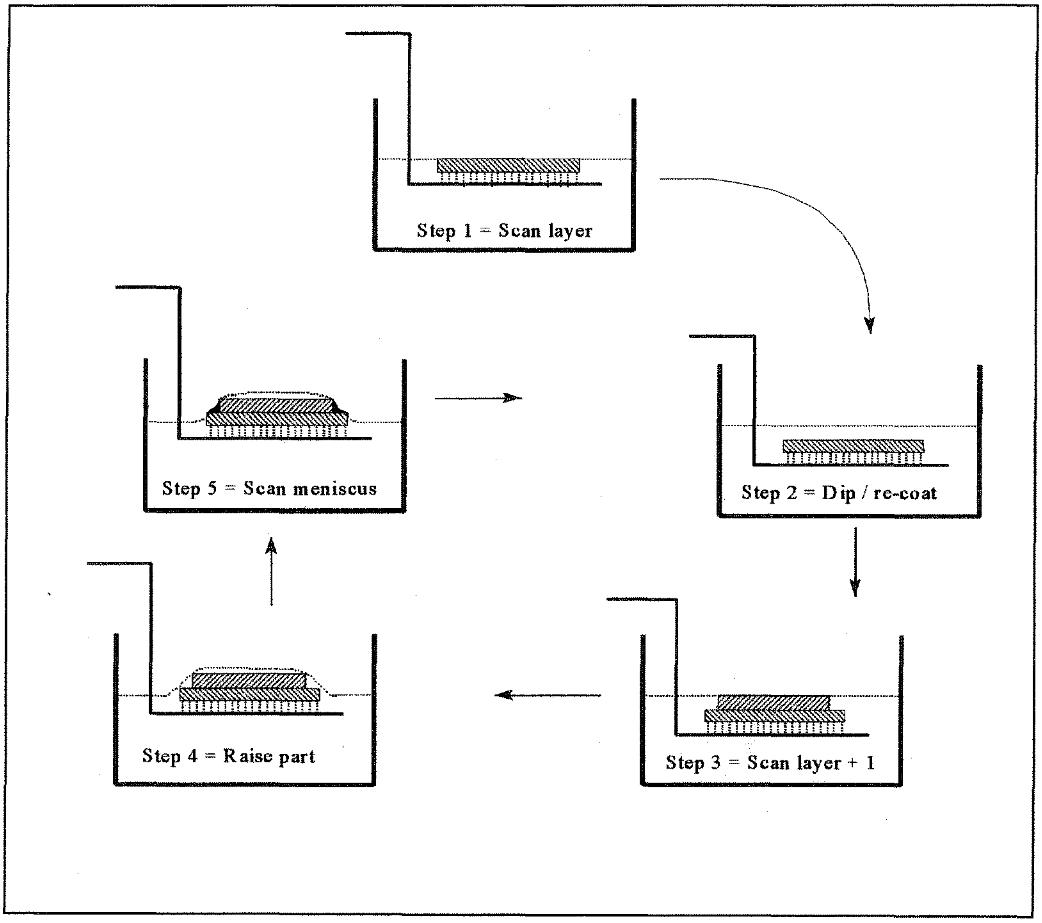


Figure 3 - Lift-up irradiation or Meniscus smoothing

Using a SONY JSC 2000 SL machine, with Japanese Synthetic Rubber company resin JSR 200, Narahara was only successful in smoothing surfaces between 10 and 30-degrees. However, successful meniscus were generated between layers ranging from 100μm to 400μm. Narahara concluded that although lift-up irradiation may provide a suitable method of building smooth parts using thick layers, the process is only suited to very limited geometries. Similar research by 3D Systems has also assessed the use of meniscus between layers. However, although 3D Systems hold patents on meniscus smoothing no practical examples of the technique have been shown by the company. 3D System chief executive Chuck Hill claims that meniscus smoothing is limited to only external surfaces as trapped volumes prevent the generation of meniscus between layers [18]. For this reason 3D Systems have tackled surface smoothing using new thin layer build style [5]. However as previously pointed out, irrespective of layer thickness, stair stepping will always occur unless layer profile is modified. It is the author's opinion that the small range of angled planes found to benefit from Narahara's technique is the result of limited process optimisation. If meniscus smoothing is to be used as a complimentary process alongside print-through, the attributes effecting meniscus shape must be investigated and optimised relative to surface angle.

4.1 Meniscus shape investigation

The shape of a liquid meniscus held between two surfaces is a function of many process attributes, including resin viscosity, temperature, material wetting characteristics and the contact angle of the solid surface interface. All these attributes are however dictated by the SL process and cannot easily be varied during the build cycle. One attribute of meniscus shape, which does vary, is surface angle, which is geometry dependent as shown in Figure 4.

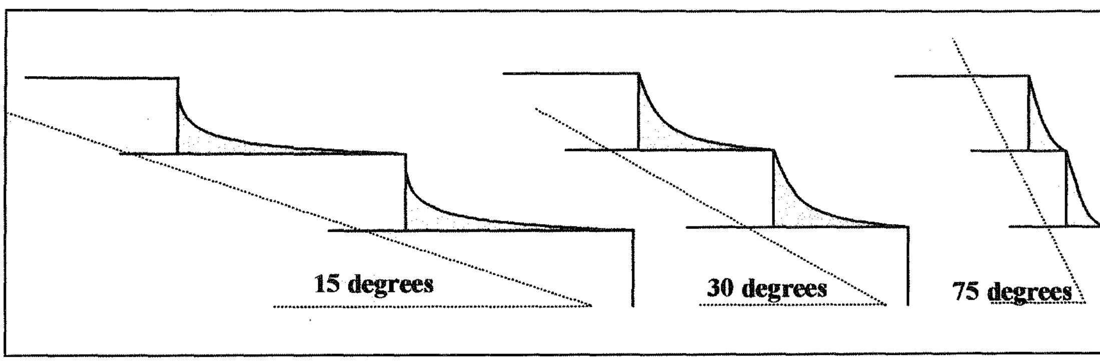


Figure 4 – The effects of surface angle on meniscus shape

In addition to surface angle, the retraction distance used to pull the meniscus above the vat of liquid monomer will also effect the shape of the resulting resin fillet. However, different retraction distances will produce different shaped smoothing fillets on different angled planes, as shown in Figure 5.

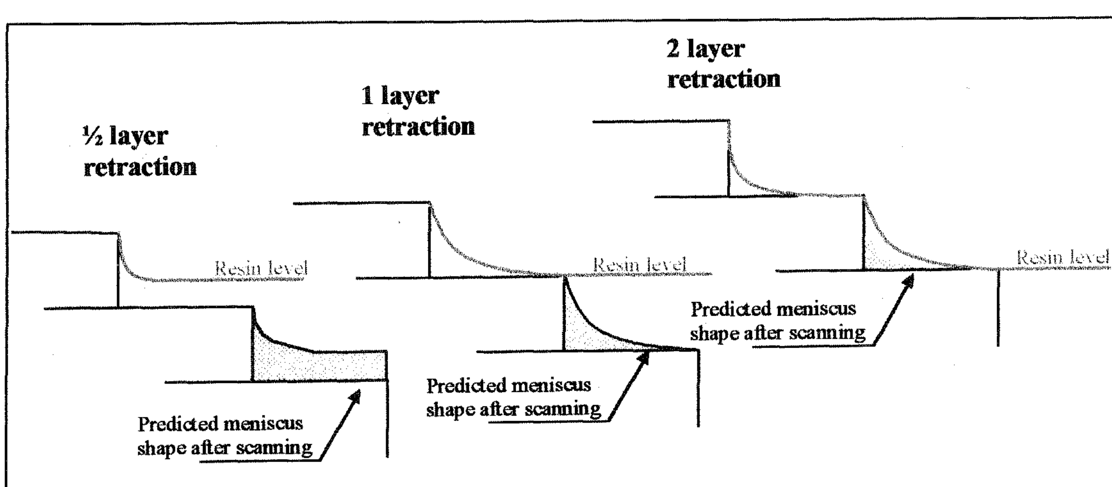


Figure 5 – The effect of retraction distance on meniscus shape

Unfortunately, none of the process attributes effecting meniscus shape can be modified using the current 3D-Systems Build-station™ software. For this reason a new control algorithm has been written to perform the meniscus smoothing cycle detailed in Figure 3. The software has then been run within the operating system of a standard SLA-250/40 machine. Using the new configuration, a series of optimisation experiments were undertaken to assess the effects of different shaped meniscus on different angled planes.

5.0 MENISCUS SMOOTHING RESULTS

Using a test sample with up-facing surfaces ranging between 0 and 90-degrees, in 10-degre increments, a range of 0.15-mm layer, ACES components were produced using the new build algorithm. Using the new control software, retraction distances of ½, 1 and 2-layer thickness were used to produce meniscus over each of the angled planes. Figure 6 shows the measured roughness of each sample relative to surface angle for each of the 3 retraction distances in addition to a standard 3D Systems 0.15-mm layer ACES part.

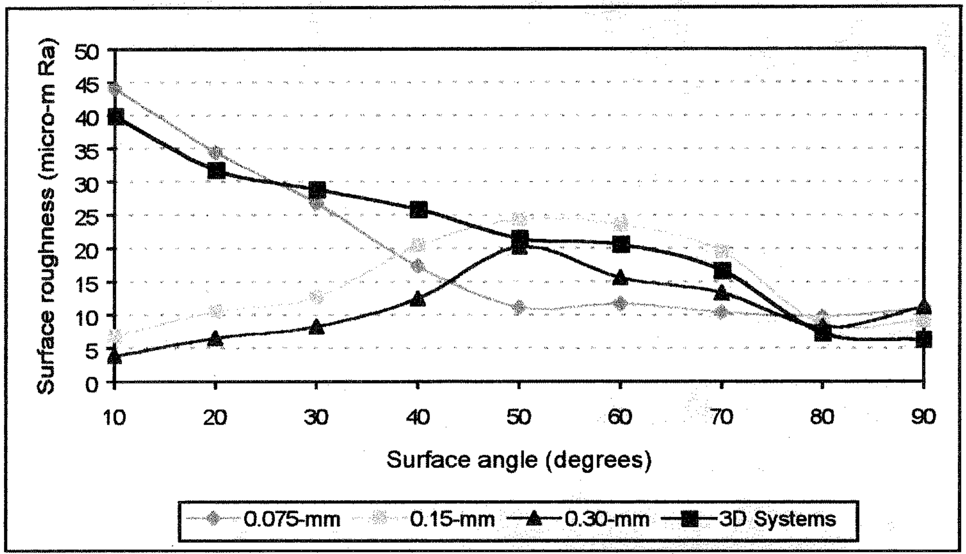
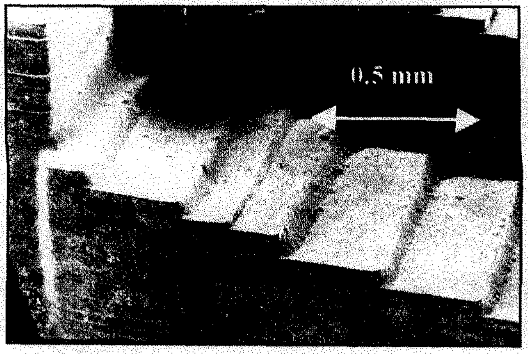
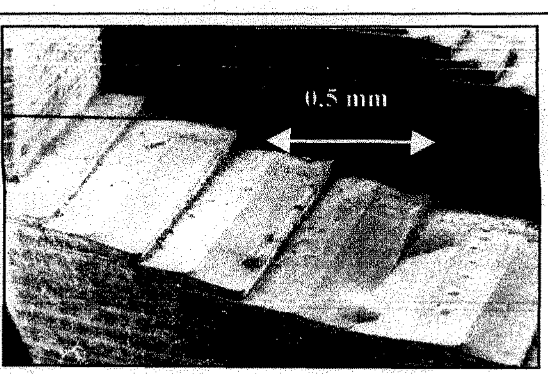


Figure 6 – The effects of meniscus shape on surface roughness

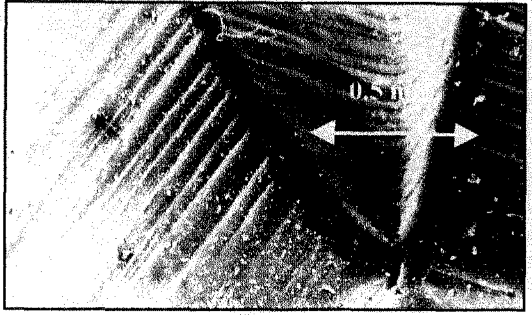
From Figure 6, it can be seen that on a 10-degree manufactured with a 0.3-mm retraction meniscus, surface deviation is below 10% measured on the part manufactured using the standard 3D Systems software. However, as surface angle increases, the effects of meniscus appear less prominent with surfaces between 50 and 70-degrees being reduced by only 60%. Between 80 and 90-degrees meniscus smoothing produces little improvement and can be detrimental in some cases. The effects of different retraction distance on surface deviation can be seen on the micrograph images in Figure 7.



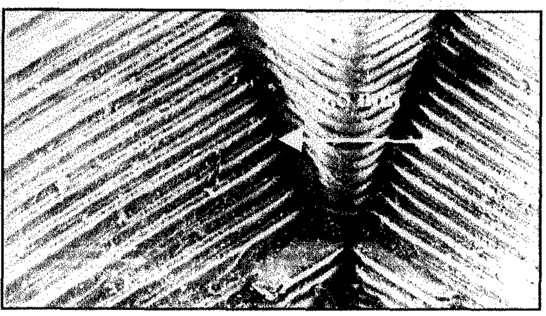
10-Degree surface, 0.075-mm retract



10-Degree surface. 0.3-mm



70-Degree surface, 0.075-mm retract



70-Degree surface, 0.3-mm retract

Figure 7 – The effects of different meniscus shape on 10 and 70-degree surfaces

From Figure 7 it is clearly evident that the 0.3-mm retraction benefits the low angles planes whilst the 0.075-mm retraction is more beneficial to the high angled surfaces. This would suggest that if meniscus smoothing were to be used as a complimentary process in addition to print-though a retraction distance of 0.075-mm would be most suitable as this produces the lowest surface deviation on angled planes between 50 and 100-degree.

6.0 SUMMARY

It is now possible to compare the effects of print-through produced by orientation and the reduction in surface roughness using optimised meniscus smoothing with the surface roughness of part produced using the standard 3D Systems software. Figure 8, shows the surface roughness of a standard 3D Systems 0.15-mm ACES sample over a 90-degree build envelope compared to a 90-degree build envelope produced using the new build strategy.

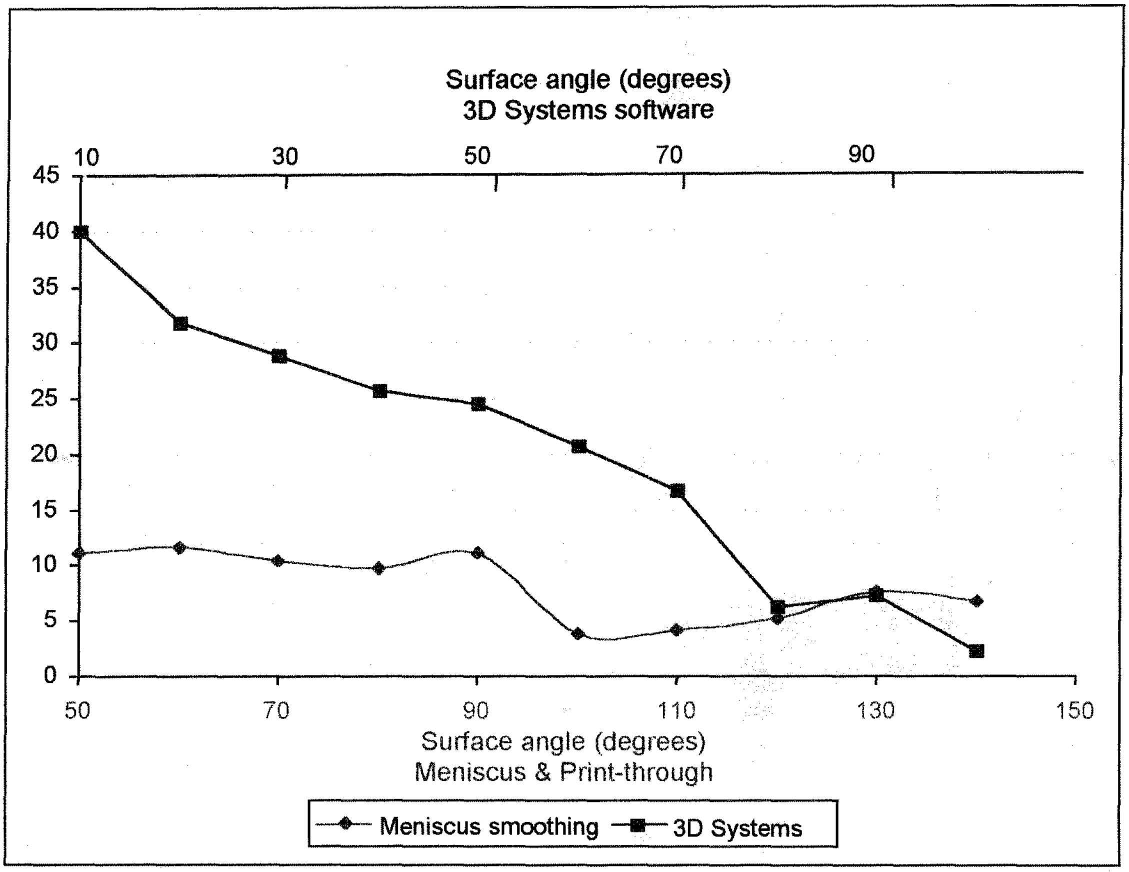


Figure 8 – Roughness deviation of 3D Systems software compared to new algorithm

7.0 CONCLUSIONS

In conclusion it can be said that using the new build strategy a reduction in surface deviation can be achieved on 0.15-mm ACES components of up to 400%. In addition all surfaces within a 90-degree build envelope can be maintained below 10µm Ra, with a uniform roughness distribution. Using the standard 3D Systems software, the difference between the roughest and smoothest surface is 38µm. Using the new build strategy, this is reduced to only 6µm Ra. Hence, for application where a low surface deviation is required, such as tooling, post-process finishing will be less random as all surface on the model now require a similar level of post-processing, if at all.

Although the new smoothing algorithm requires both additional steps within the build cycle and for part be orientating into positions which will inevitable increase built time, it is the authors opinion that such limitations should not detract from the benefits of meniscus smoothing. The speed of the SL process has increased dramatically in recent years from the early 20mW He/Cd laser used on the SLA-1 to the 216mW Solid State Diode Pumped laser used on the new SLA-5000. In addition, the formulation of new resins has made scanning at much higher speeds increasingly possible. However, the cost of skilled labour used to finish parts has also increase, yet the consumer desire for lower price produces necessitates lower cost SL models. Hence, automated in-process finishing is imperative if the process is to develop further into new applications. By further automating meniscus smoothing, many of the process limitation associated with geometries such as trapped volumes and increased build time could be eliminated, resulting in direct parts produced on SL machines which require no post process finishing at all.

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