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Philip E Reeves and Richard C Cobb

SL Surface Finish: the cause, the effect and a hands-free solution

Abstract
The use of Stereolithography (SL) can produce accurate prototype models with complex internal and external features. However, a major problem to commercial use is the poor surface finish caused mainly by "stair stepping" which is inherent in layer manufacturing.Models are often finished by hand but this is labour intensive, highly selective and causes inaccuracies in the model geometry.
A three-year research project has been undertaken to address these issues and to investigate a range of possible post process solutions applicable to the model-making community. The paper gives a detailed explanation of the factors affecting surface roughness, and describes a methodology for surface finishing using additive and abrasive finishing techniques.
Initial findings of the research show that additive coatings can improve surface geometry and roughness by up to 50%. A combination of additive and abrasive techniques, using specialist barrel tumbling equipment can however result in a 80% reduction in surface roughness on complex surfaces. The process needs only limited manual intervention and results in parts with only a small loss in model accuracy.

Introduction

Rapid Prototyping (RP) can in many cases produce parts faster and more economically than by conventional techniques. The processes are best suited to parts which are generally complex in design with freeform curves and re-entrant features, possessing only a limited percentage of plane surfaces. However, a major problem to commercial use is the poor surface finish caused mainly by "stair stepping" which is inherent in layer manufacturing.

When finishing Stereolithography models best results are obtained following multiple stagehand finishing in the cured state, with a series of grades of abrasive paper [1]. Current surface finishing techniques are highly selective, with finishing of fine detail and internal features often omitted. In many cases finishing of models is neglected as it is labour intensive and not cost effective.

With the introduction of new resins and build styles, Stereolithography part accuracy and surface finish has increased almost six fold in as many years, with the Accurate Clear Epoxy Structure (ACES®) build style resulting in parts with a Roughness average (Ra) of less than 0.28 μm on up-facing planes [2]. The introduction of the new Quick-cast® 1.1 build style makes possible roughness values of 0.25 - 0.5μm Ra for parts used as sacrificial patterns for investment casting [3]. However, research into these new build styles has addressed only the problems associated with vertical and horizontal planes. Analysis of the overall surface roughness of SL parts suggests that the surface roughness on angled planes therefore requires fundamental research.

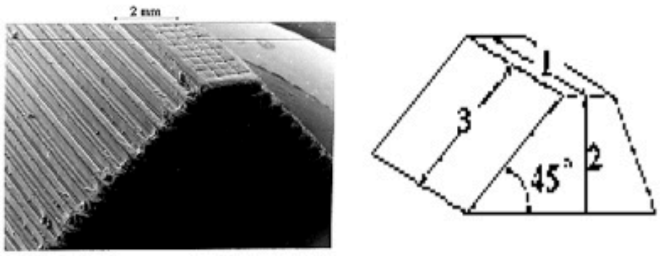

Figure 1a: Acrylic Star-Weave® sample with 0.125mm layers
1. Horizontal plane 0.22μm Ra
2. Vertical plane 4.2μm Ra
3. 45° plane 24μm Ra

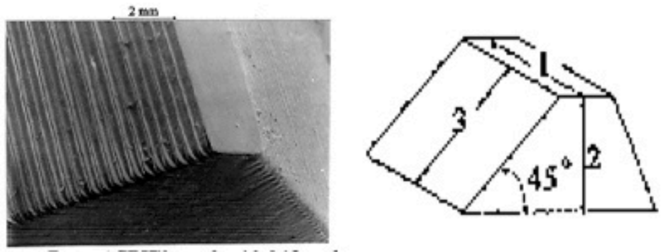

Figure 1b: Epoxy ACES® sample with 0.15mm layers
1.Horizontal plane 4.61μm Ra
2. Vertical plane 8.34μm Ra
3. 45° plane 37.1μm Ra

Work has been undertaken to reduce surface roughness on complex planes and features,using part orientation software prior to slicing [4]. The Computer Aided Design (CAD) representation of the geometry is oriented about its axis in such a way that layering will be reduced on planes perpendicular to the "Z" axis, hence reducing "stair stepping" [5]. With many complex parts however, software orientation can only reduce "stair stepping" on a limited number of surfaces, and additional post process finishing is still required. Given the rough texture of SL parts, and the limitations of manual finishing, research has been undertaken to establish faster more consistent finishing techniques, using conventional mass finishing technology. The Brite-Euram INSTANTCAM project [6] investigated a number of SL components using "traditional" abrasive flow tumble peening and sandblasting equipment. Work at the University of Nottingham applied acrylic SL parts to a range of automated finishing equipment including barrel tumbling, vibratory finishing, ultrasonic abrasion and abrasive flow blasting [7]. In both cases, as with work undertaken at the GINTIC institute [8], the abrasive systems employed were developed for the finishing of metallic components using harsh ceramic media. Some encouraging results were observed but many of the component were found to have excessive damage, with loss of material along both edges and at sharp corners.

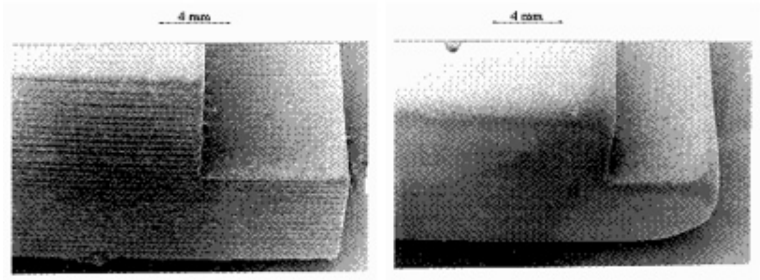

Figure 2: An as-received SL component, and the same following 6 hours tumbling

Research Methodology

Given the limitation of current SL finishing techniques, the University of Nottingham has undertaken a three year research project to define a Non selective system for the surface finishing of SL parts. The aims being to achieve a reduction in surface roughness with minimal manual intervention and loss to the intended part geometry. Some of the initial findings using coating materials for additive processing will be reported in this paper, in addition to a new process termed "dual" finishing.

Surface Deviation: the cause & effect

In order to fully understand the principles of surface processing an examination of the factors affecting the resolution of SL parts is required, as each factor has a cumulative effect on the resulting component surface. Three groups of factors have been identified within the SL process. The factors being either user defined variable or fixed by the limits of SL technology. The factors fall in to the pre-build, build and post-build stages of model manufacture.

• Pre-build factors include, the interpretation of curved surfaces by the CAD software and the facets generated by the Stereolithography Transfer software (STL) used to represent the CAD geometry in the RP environment (see Figure 3). The quality of the STL file replication can be improved by increasing the number of surface facets, this however increases the volume of computer data resulting in increased process time. For complex components and those exhibiting features such as shallow radius planes small tessellations must be used in order to prevent heavily faceted surfaces being produced (see Figure 4).

• Other pre-build factors include, the orientation of the STL data prior to slicing and the position of any support structure required during the model generation. Due to factors such as spacial constraints on the build platform it may not be possible to orientate a component in to a stable build position, hence support structure may be required in order to provide model stability. The support structure will however results in a series of witness marks on the component surface requiring additional post process finishing.

• One other major consideration over surface resolution is the slice thickness defined at the pre-build stage, as this will have a direct effect on surface roughness (see Figure 5). Layer thickness being set at either 0.067mm or 0.125mm for the acrylic resin and 0.15mm or 0.25mm for the epoxy resin.

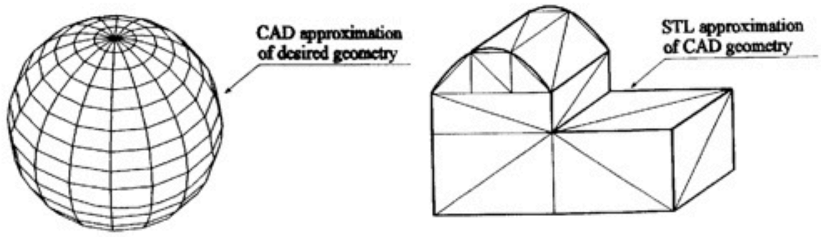

Figure 3: CAD approximation and STL tessellation

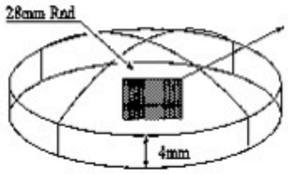

Figure 4: SL tessellation on shallow angles and curves

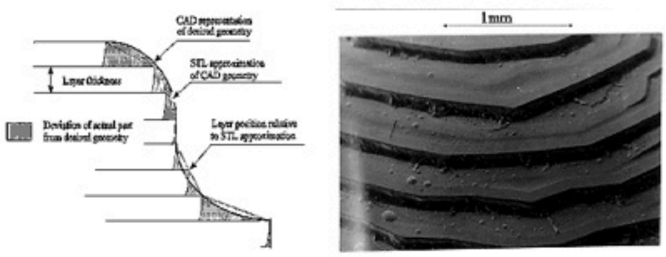

Figure 5: Schematic of CAD, STL and layer thickness at the PRE_BUILD stage

• Build factors include the effects of temperature on resin viscosity, as viscosity affects the "settling" characteristics of resin within the build environment. Deviation in resin viscosity has been found to result in variable layer thickness during the build cycle[9]. Other build factors affecting layer continuity include fluctuations in laser power, the effects of trapped volumes causing increased layer thickness and the positioning of the skin fill hatching at the layer boundary (Figure 6). The major cause of surface deviation during the build cycle is however the effect of layer profile, and the undercut generated by the parabolic profile of the laser beam used to initiate photo-polymerisation of the resin (see Figure 7). The undercut generated in effect increased the deviation of the SL model from the desired geometry, hence increasing the surface roughness.

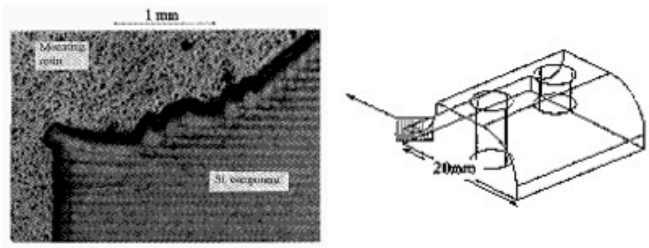

Figure 6: Variable layer thickness and skin fill integrity generated at the BUILD stage

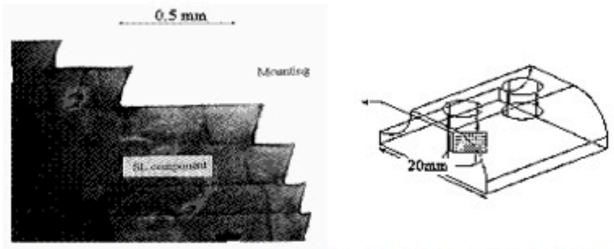

Figure 7: Undercut layer profile generated by parabolic scanning laser

Post-build factors are dependent on the level of manual processing applied to the "green-state" model prior to Ultra-Violet (UV) post curing. One post build factor found to effect part integrity is the time the model is left in the green state prior to curing. Green state models are known to under go swelling if exposed to liquid SL resin for prolonged periods, hence excess resin in contact with the cured polymer should be removed as rapidly as possible following the build cycle to prevent part expansion [10].

The most notable post process factor seen to affect surface deviation is the level of excess resin removed in the un-cured green state, known as "part stripping". Insufficient part stripping results in a loss to geometric integrity and resulting in additional manual finishing of the part in the fully cured state (Figure 8). A degree of excess resin on the surface of the model may however be beneficial for reducing surface deviation, as this can partially fill the build steps caused by layer manufacturing. Other factors effecting surface deviation incurred at the post-build stage, include damage to the soft partially cured resin during removal of any support structure.

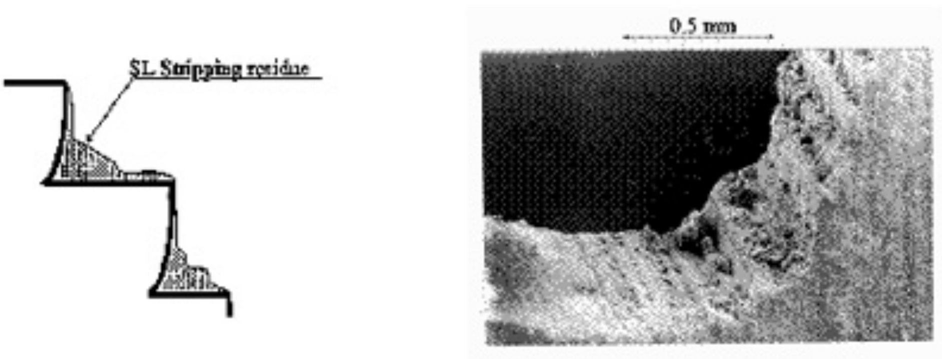

Figure 8: The effects of resin stripping residue on surface profile

The final surface deviation of the model can therefore be considered to be the cumulative effect of factors occurring during the pre-build, build and post-build stages of model manufacture.

Additive Processing

Given that all SL models are at present best only stepped, and at worst badly faceted, some level of surface refinement is imperative to achieve an acceptable surface finish. Given the geometric and time limitations of manual finishing the goal of the work is to achieve a rapid post process finish method to reduce the cumulative surface deviation produced during the three stages of model manufacture.

Epoxy Primer Coatings

Initial trials at the University of Nottingham [11] [12] have shown that resin coatings can reduce surface roughness, provided that the coating thickness which is a function of the initial viscosity, can be defined and controlled. Hence, a range of coatings with good wetting and adhesion characteristics were investigated.

A commercially available three part epoxy loaded primer coating has been chosen. This is used in the manufacture of glass fibre composites as a filling agent for the surface of damaged gel coats.

A series of experiments were undertaken to apply both concentrated and thinned epoxy primer to SL parts by painting, spraying and dipping. Figure 9 shows an SL test sample with complex small scale features clearly revealing the approximation to an intended 1mm radius.The coating can be used in its concentrated state and can reduce surface deviation by up to70%. However, as the sectional view in Figure 10 illustrates this is at the expense of the part geometry.

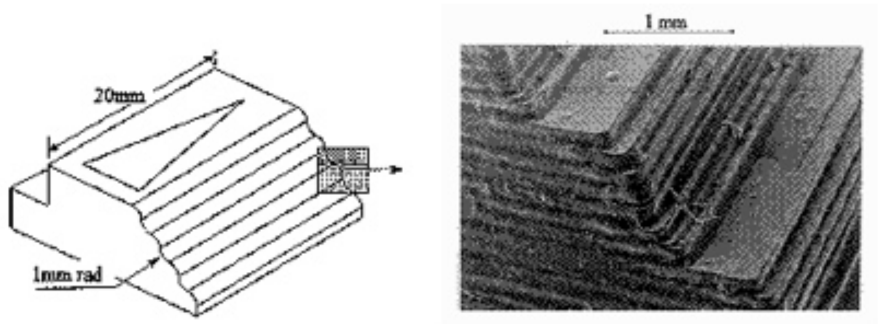

Figure 9: Intended CAD geometry and actual SL part, showing approximation to fine detail

At a lower viscosity using a 50% thinned solution it was necessary to apply multiple coatings in order to reduce surface roughness by significant levels. At the thinned viscosity, multiple layers applied by dipping and painting were found to result in a thick enough deposition to reduce surface deviation by up to 60% on all surfaces. The effect as seen in Figure 11 was not only a reduction in the Ra value of the component surfaces, but also improved geometry of the Stereolithography model nearer to the intended CAD profile. In summary the epoxy primer is capable of reducing surface roughness on parts of limited complexity with only minimal blocking of holes and features, although the time taken to build up sufficient coating thickness needs to be reduced.

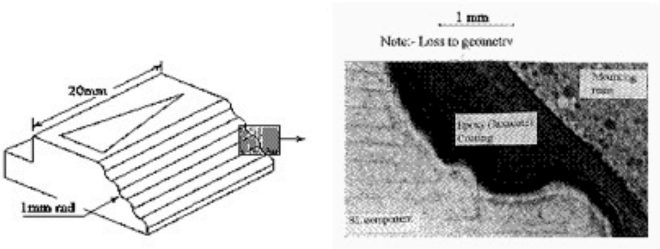

Figure 10: SL sample coated in one later of concentrated epoxy primer, applied by dripping

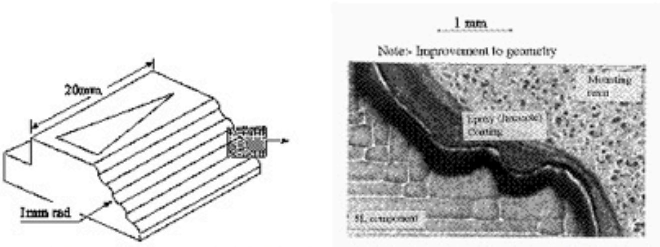

Figure 11: SL sample coated in two layers of 50% thinned epoxy primer, applied by dripping

Dual Processing: a hands free solution

In order that additive coatings can be used successfully as a method of reducing surface deviation without loss to geometric integrity, coatings must be carefully applied at the right viscosity and layer thickness. This method of solely using additive coating has therefore proved to be a time consuming solution to the problem of SL surface finishing.

One alternative method of reducing the lengthy "manual" finishing time for SL models is by automated abrasive finishing. For 20 years thermosetting plastic object manufactured from polymers such as ABS, acrylics, polyvinyl but ride and impact styrene have been "mass finished" in automatic systems to remove excess material such as lugs, flash and machining marks [13]. However, previous attempts to finish Stereolithography parts [6][7][8] have shown that conventional "mass finishing systems" cause considerable damage. In each case however, a "ceramic finishing medium" and systems intended for the abrasion of ferrous and Non-ferrous metals have been used, this would appear to be too harsh for the polymer material.

The system used within the University of Nottingham is a barrel finishing or "rumbling" machine run at approximately half conventional speed, with a hardwood lining to prevent part damage. The medium used is a "solution" of fine ceramic "silica" powder (0.25μm mesh) bonded using a resin agent to a carrying medium. Carrying media can take the form of either natural hardwood or polyester moulded preforms [14] ranging in size dependent on the application.

Current research has established a range of optimum process parameters for the barrel finishing of both acrylic and epoxy parts, the results of which will be presented at a later stage. In addition to the barrel finishing of un-treated components, a number of parts have also been coated in a thick 150μm layer of concentrated epoxy and subjected to the barrel finishing process. The aim of the "dual" coating, abrasive process, is to build up a rapid sacrificial layer of epoxy on to the surface, filling both the layer stepping and covering any imperfections generated during the three stages of model manufacture. An abrasive medium is then used to remove excess material from "outside" the build step. Due to the medium geometry however, the coating will not be removed from within the layer step as the abrasive medium is too large to penetrate the corner of the build.

Test were carried out using eight epoxy Quick-cast® aero-engine turbine blades, which were used to assess the effectiveness of the coating and finishing treatment on "real" industrial components. Following coating, the 150μm layer of epoxy was cured at ambient temperature for 4 hours. The coated parts were then barrel finished in the system for 6 hours total process time, following which an analysis of both geometry (Figure 12) and the surface roughness using a Taly-surf were undertaken (Figure 13).
Analysis of the surface has shown that by "dual" processing it is possible to reduce surface deviation on a complex component by up to 88 % over the total surface area, with minimal damage to the part geometry. Trials with coated parts not barrelled showed a marked reduction in surface deviation however there was a general loss to the part geometry and definition without additional tumbling. Abrasion of un-coated components showed little improvement to the overall surface roughness, this being attributed to the harness of the cured SL resin being greater than that of the epoxy coating. The abrasive system can therefore be considered suitable for the abrasion of the epoxy coating without significant damage to the SL substrate.

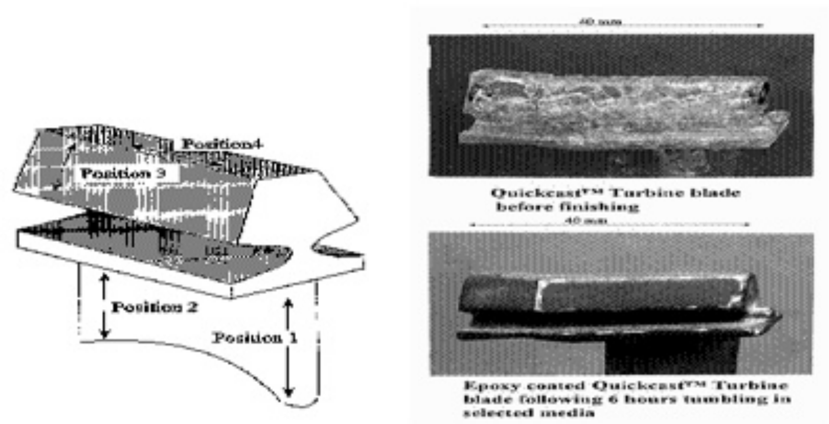

Figure 12: Quickcast® turbine blade before finishing, and after 6 hours tumbling in selected media

	Surface roughness of supplied blade(μM Ra)	Surface roughness of blade following tumbling(μM Ra)	Surface roughness of 150μM coated blade(μM Ra)	Surface roughness of dual processed blade(μM Ra)
Position 1	6.38	5.5	2.3	1.8
Position 2	5.36	5.2	1.9	1.25
Position 3	11.6	11.1	3.6	1.6
Position 4	25.7	24.8	3.4	1.29
Average 0.25 S1-4	12.26	11.65	2.8	1.49
reduction in Ra	N/A	5%	77%	88%

Figure 13: Surface roughness of turbine blades following processing

Conclusions

In conclusion it can be stated that, a thorough understanding of the causes of surface deviation within the Stereolithography process has been obtained. This has directed a research program towards both additive and abrasive finishing techniques, given that the component has been sliced and orientated in the most suitable way.

The epoxy primer has been shown to be an excellent coating for SL components, either as abase for other coatings or as a method of surface finishing. With the application of thinned primer by dipping it is possible to reduce surface deviation rapidly with minimal change to the part geometry.

"Dual" additive and abrasive finishing has been seen to reduce surface deviation on more complex models by up to 88%, with minimal change to the part geometry. It is intended through further research to optimize the abrasive medium and process to result in a fast, Non-selective finishing system capable of reducing surface deviation to a better quality and more economically than current finishing techniques.

Acknowledgements

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Philip E Reeves, Richard C Cobb
Centre for Rapid Prototyping in Manufacturing
Department of Manufacturing Engineering and Operations Management
University of Nottingham
University Park, Nottingham, NG7 2RD