THE FINISHING OF STEREOLITHOGRAPHY MODELS USING RESIN BASED COATINGS

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

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 surface coatings and mechanical finishing processes applied to SL models. This paper describes some initial findings using resin coatings applied to both cured and uncured SL parts.

Initial findings suggest that excess resin retained after part stripping can result in a lower surface roughness than parts thoroughly cleaned prior to post curing. Through the addition of photocurable and epoxy based resins to parts in both the un-cured, green and cured states, surface roughness has been seen to be reduced by up to 50% on complex parts.

INTRODUCTION

Rapid Prototyping can 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 stage hand finishing in the cured state, with a series of grades of abrasive papers[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 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]. Quick-cast™ 1.1 uses triple up-facing layers to reduce deviation by applying additional layers of material to the part, covering any deviation caused by previous layers. 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 requires fundamental research (*Figure 1*).

Work has been undertaken at the CAD stage to reduce surface roughness on complex planes and features using part orientation software prior to slicing[4]. The CAD representation is oriented about its axis in such a way that stepping will be reduced on planes perpendicular to the 'Z' axis, hence reducing the 'stair stepping' effect. However, the effects of trapped volumes, delamination, build time and the working envelope must also be considered and can prevent build of a part in an optimum orientation. With many complex parts, software orientation can only reduce 'stair stepping' on a limited number of surfaces and additional post process finishing is still required.

Recent research has been undertaken to establish suitable finishing techniques for StereoLithography models using a number of conventional mass finishing systems. The INSTANTCAM project[5] during 1992 addressed the problem of SL surface roughness using tumble peening and sandblasting in addition to spray painting. Work at the University of Nottingham applied SL components to conventional mass finishing equipment including barrel tumbling, vibratory finishing, ultrasonic abrasion and blasting[6]. The resulting acrylic components were found to have excessive damage, with loss of material at both edges and corners *(Figure 2)*. In both work programs and in work undertaken at the GINTIC institute[7] on SL abrasion, the abrasive systems employed were developed for the mass finishing of metallic components using harsh ceramic media.

RESEARCH ACTIVITIES

Given the need for an economic method for StereoLithography part finishing, the University of Nottingham has undertaken a three year research project to define a non selective system for the surface finishing of SL models, with minimal manual intervention and loss to the intended part geometry. A three phase approach to surface finishing has been defined (*Figure 3*), dependent on the part geometry.

- Chemical machining of SL parts using acids and solvents to remove excess material from steps defined by the CAD geometry.

- Abrasive finishing systems including barrel, vibratory and ultrasonic machining using specially selected finishing media to remove material from the steps defined by the CAD geometry.

- Additive processing of SL parts applying coating materials to reduce surface deviation by filling the steps within the CAD geometry.

Some of the initial findings using coating materials for additive processing will be reported in this paper.

In order to define the most appropriate processing techniques for the models an understanding of the factors affecting the resolution of SL parts is required. The factors which affect the overall resolution of a part include resin type, resin temperature and viscosity, part stripping residue, build orientation, CAD and STL representation and the parabolic curing profile of the SL resin in addition to the defined layer thickness. Layer thickness or *step height* is the major contributory factor in the generation of surface roughness but present resin and machine technology prevents proctical reduction in layer thickness, in addition to the increased build time associated with thinner layers.

Research into surface roughness suggests that in addition to layer thickness, excess resin within the build step will result in a change to the surface profile, and hence the surface roughness. The effects of this excess material or 'part stripping residue' can be assessed if a series of part surfaces are compared to the surface defined by the CAD data. To do this a mathematical representation of a layer manufactured surface can be derived assuming that the layer profile is at right angles, as opposed to parabolic (*Figure 4*). From this mathematical representation, it is possible through the measurement of a series of SL samples to plot both the mathematical and 'actual' roughness average values for a given layer thickness *(Figure 5)*.

A series of test samples were constructed with incline planes ranging from 10 to 90 degrees, in 10 degree increments, with a measurement of surface roughness average taken at 10 points on the plane surface (*Figure 6*). As it can be seen the actual surface roughness measured across a range of surface planes give lower Ra values than mathematically predicted. The effects of the parabolic curing profile should in theory increase the surface roughness however, analysis suggests that excess resin not removed during part stripping results in a reduction in surface Ra (*Figure 7*).

PHOTOCURABLE RESIN COATINGS

Additional material within the build step can therefore be considered to result in SL parts with lower Ra values than those thoroughly cleaned prior to post curing. This has directed research towards establishing a series of coating materials to further reduce the surface roughness values of SL parts. StereoLithography resin has already been seen to reduce Ra values when not fully stripped during the build step. Initial experiments were thus conducted on both acrylic and epoxy parts by applying SL resin as a coating to both cured and un-cured 'green' state models. This resulted in parts with excessive loss of geometry, due to the high viscosity of the resin coatings. A thinning agent was therefore used to reduce the working viscosity of SL resin. At the lower viscosity, thinner coatings could be applied to parts without excessive loss to part geometry. Low viscosity coatings could then be built up until sufficient material remains in the build step to reduce the overall part Ra, this being a function of the layer thickness and the coating viscosity *(Figure 7)*.

The use of StereoLithography resin as an additive coating will result in parts which are both mechanically and visually as near to 'virgin' SL part as possible. The 'bench-mark' of the project is to reduce the roughness average of SL models to below 1.5μm on all surface, without loss to the initial part geometry. A number of diluent agents were also added to both epoxy XB5170 and acrylic XB5149 resins. A series of standard geometries were selected with vertical, horizontal and stepped faces, and the solution was applied to both cured and un-cured 'green state' components by dipping and painting. Applying resins to green state models has potential benefits as it could reduce the overall processing time of prototype manufacture, since UV curing need only be performed once following additive coating.

Hexandiol-diacrylate was found to be the most successful diluent when applied to both acrylic and epoxy resins, as other diluents were seen to cause rapid coagulation. On exposure to UV post curing it was found that due to the separation of the monomer chains within the dilute solution, cross polymerisation was not possible. The SL parts remained tacky irrespective of both curing temperature and time exposure to intense UV. The percentage mix of diluent was reduced from 50% by volume to 25% by volume, resulting in coagulation of the epoxy resin. Painting and dipping of parts was carried out with the acrylate solution however photopolymerization remained unsuccessful. Unfortunately due to the 'tackiness' of the coating following curing, it was not possible to measure coating thickness.

A number of parts coated with the 25% thinned SL solution were also placed in a nitrogen enriched environment, and subjected to UV post curing. It was found that with the inhibition of oxygen during curing, full photopolymerization occurred, resulting in a fully cured components. The coating was capable of reducing surface roughness over a complex geometry although the viscosity of the coating resulted in blocked holes and features resulting in a loss of part geometry. Nitrogen curing with lower viscosity 50% diluent was not successful. Further research is now being carried out to establish a suitable diluent resulting in full photopolymerization, yet maintaining a suitably low solution viscosity.

EPOXY PRIMER COATINGS

The initial trials showed that resin coatings had potential for reducing the surface roughness provided that the coating thickness which is a function of the initial viscosity, can be defined and controlled, hence alternative coatings possessing good wetting and adhesion characteristics were investigated.

Jaxacote 22.22 is a commercially available three part epoxy loaded primer coating used in the manufacture of glass fibre composites as a filling agent for the surface of damaged gel coats. The coating contains both a filler and a low temperature exothermic agent, in addition to a thinning agent which can be added up to 75% by volume to reduce the coating viscosity. The coating is formulated to have excellent wetting and adhesion to epoxy substrates, resulting in a high sheen finish. It can also be abraded following curing, to give a sub-micron surface roughness.

A series of experiments were undertaken to apply both concentrated and thinned epoxy primer to acrylic and epoxy SL parts by painting, spraying and dipping, with the intention of reducing surface deviation yet retaining or improving part geometry *(Figure 8)*. Initial findings showed that the coating in its concentrated state can reduce surface deviation by up to 70% when applied by dipping, but the coating viscosity led to significant loss to part geometry (*Figure 9*). Due to the high viscosity in the concentrated state spraying was not possible. Geometric definition can be improved by brush application however surface roughness is accentuated by the effects of 'brush' markings and more importantly individually painting the parts will increase the overall processing time.

Following investigation with the concentrated solution, a 50% thinned coating was applied to both acrylic and epoxy samples by dipping, painting and spraying. At the lower viscosity it was necessary to apply multiple coatings in order to reduce surface roughness by significant levels. On vertical and horizontal planes coatings applied by spraying were found to result in Ra values of 1.6µm and 2.2µm Ra, this being a reduction from 2.1µm and 5.6µm respectively. However, due to the thickness of the coating applied no significant difference was seen on stepped surfaces. At the thinned viscosity multiple layers of the epoxy primer applied by both dipping and painting were found to result in surface reduction of up to 50% on stepped planes. After two layers applied by dipping vertical and horizontal planes were reduced from 5.1µm and 2.1µm to 1.2µm and 0.6µm Ra respectively *(Figure 10)*. The effect of the epoxy primer as seen in *Figure 10* 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. These results show that thinned epoxy primer (Jaxacote) 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.

CONCLUSIONS

In conclusion it can be stated that, a number of positive directions for future research have been established. The use of thinned SL resin as an additional coating, will if successful, result in near transparent SL models requiring no other post process finishing, yet retaining their intended geometry. The epoxy primer (Jaxacote) has been shown to be an excellent coating for SL components, either as a base 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.

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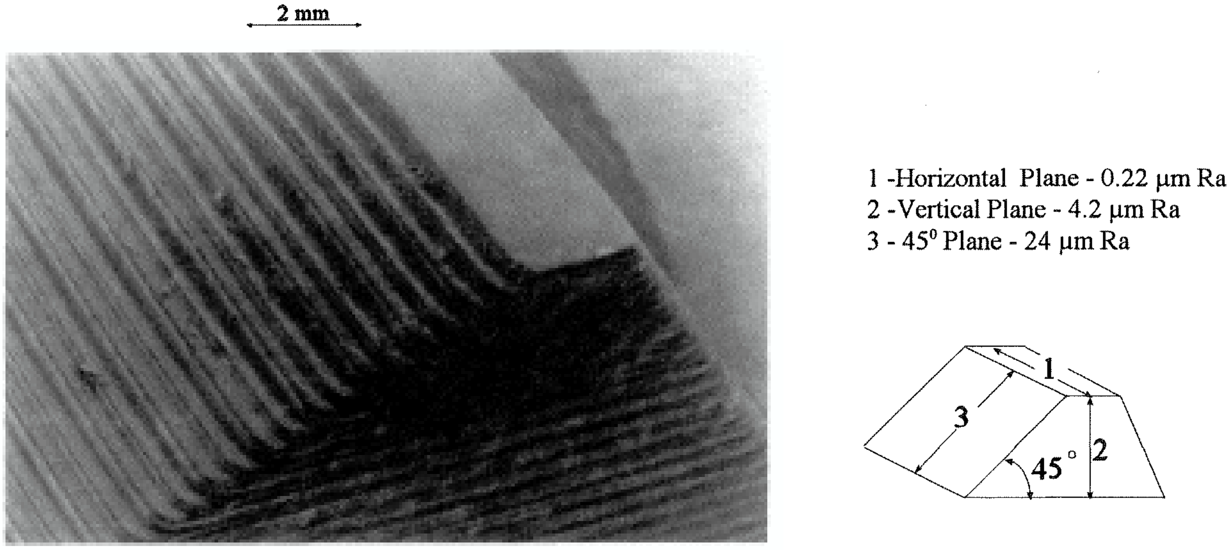
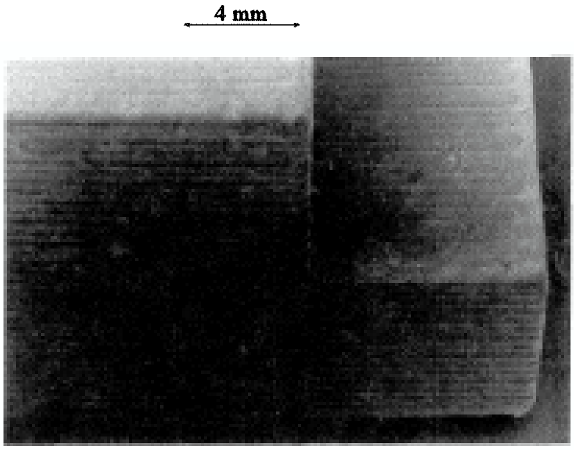


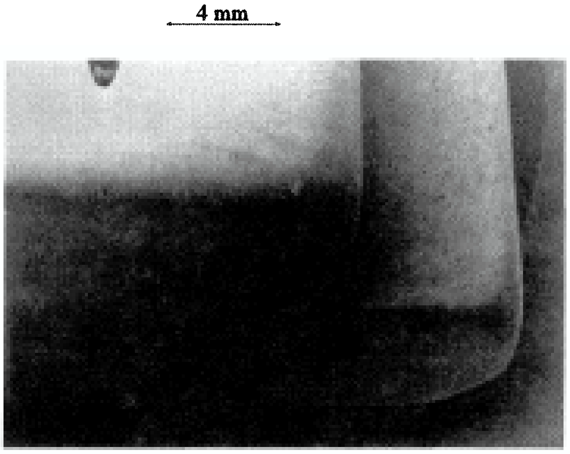
1 -Horizontal Plane - 0.22 μm Ra
2 -Vertical Plane - 4.2 μm Ra
3 - 45° Plane - 24 μm Ra

Accurate Clear Built Epoxy Structure part (ACES™), showing Vertical, Horizontal & 45° Stepped planes with 0.25mm layers.

Figure 1

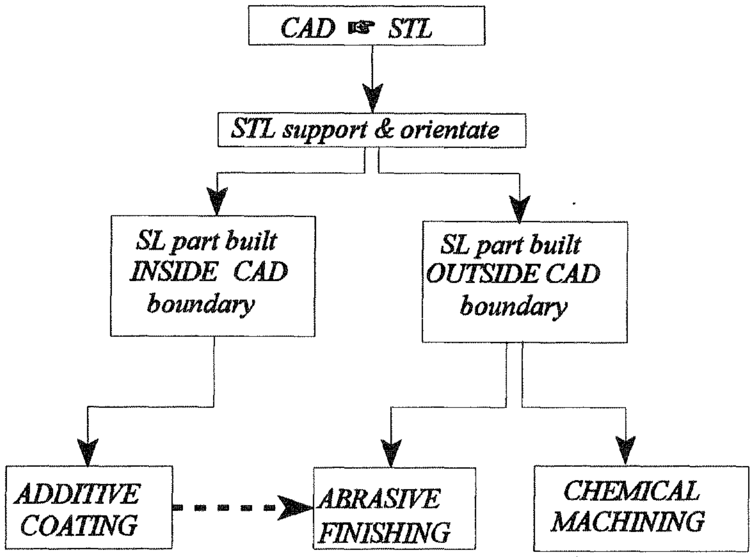


Acrylic Star Weave™ SL component



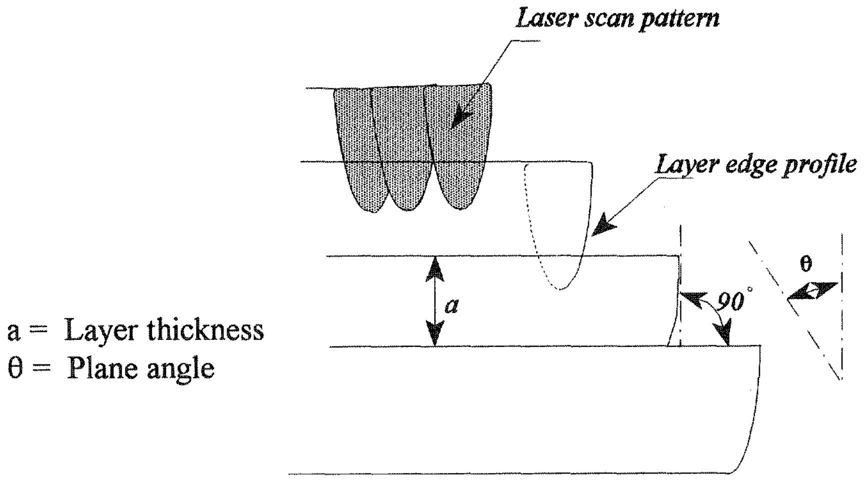
Acrylic Star Weave™ SL component following 4 hrs tumbling with ceramic media in a metallic finishing system.

Figure 2



Three phase approach to the post process surface finishing of SL components

Figure 3

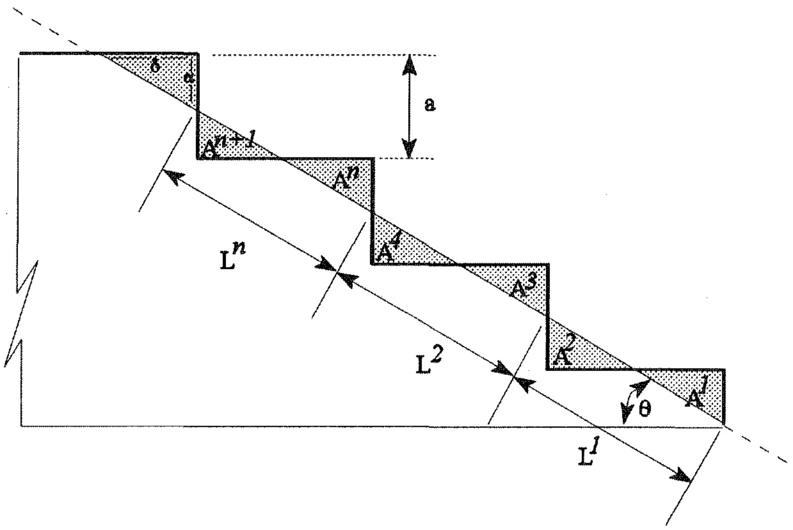


Parabolic curing profile of SL layer edges

Figure 4

Roughness Average - $Ra = \frac{\Sigma A}{L}$

Where A is the area of profile above and below the line of the arithmetic mean, and L is the sample length taken along the line of the arithmetic mean.



Let:- A^n = An individual unit of area above or below the arithmetic mean line.
L^n = The sample length taken parallel to the surface plane.

a = Layer thickness of SL build.
θ = Angle of surface plane.

$$\alpha = \tfrac{1}{2} a \qquad \delta = \frac{\tfrac{1}{2} a}{\tan \theta}$$

$$A^n = \tfrac{1}{2}\, \alpha\, \delta \qquad A^n = \frac{a^2}{8 \tan \theta}$$

For a given sample length L^n two unit areas must be considered $A^n + A^{n+1}$

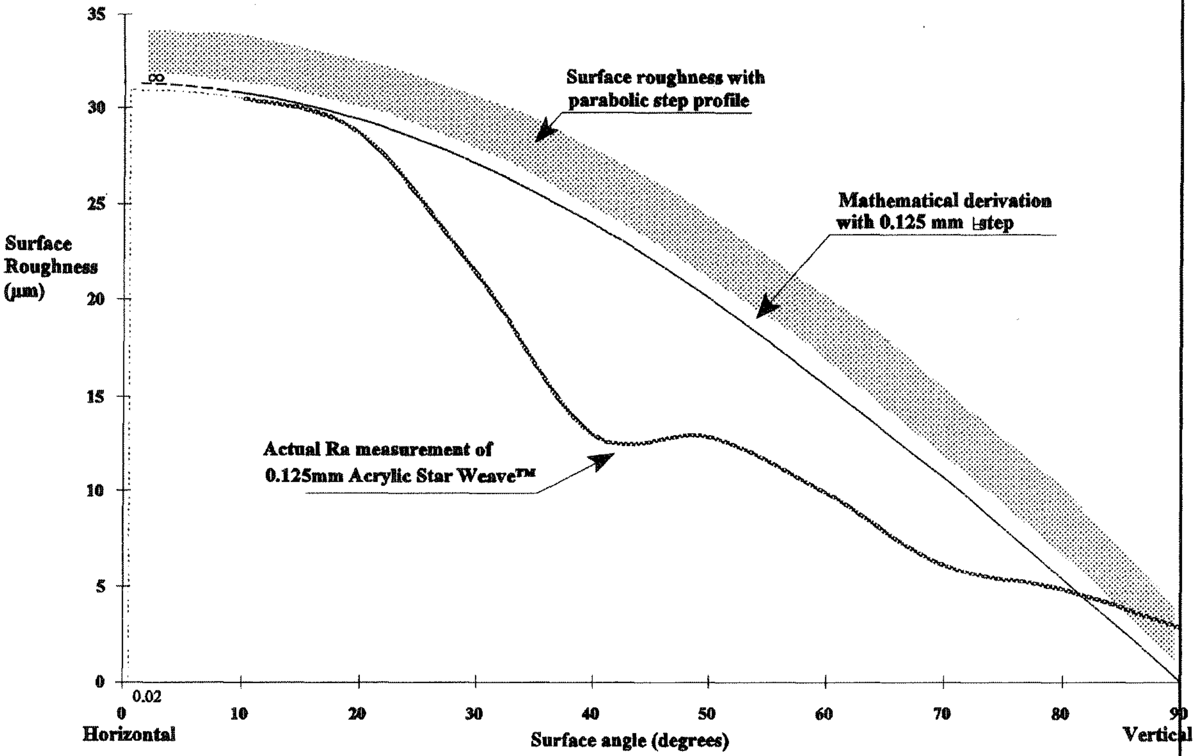
$$L^n = \frac{a}{\sin \theta}$$

Therefore :- $$Ra = \frac{2 A^n}{L^n}$$

$$Ra = \frac{a \sin \theta}{4 \tan \theta}$$

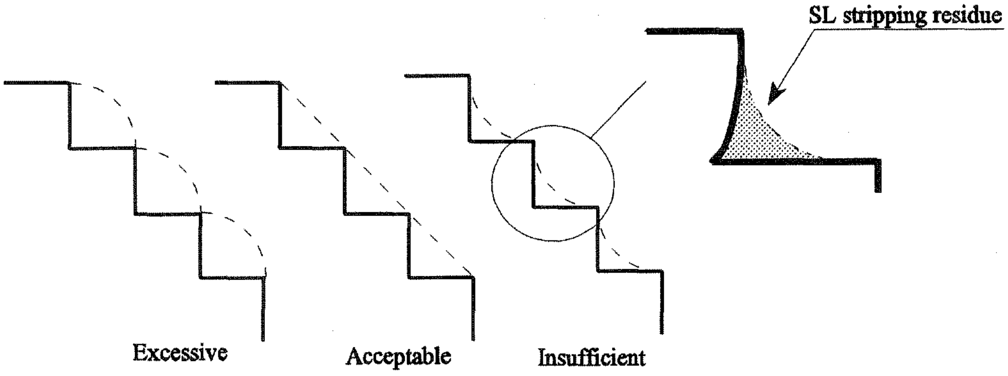
Derivation of surface Roughness average (Ra) for a stepped plane

Figure 5



Comparison of mathematical and actual surface roughnesses

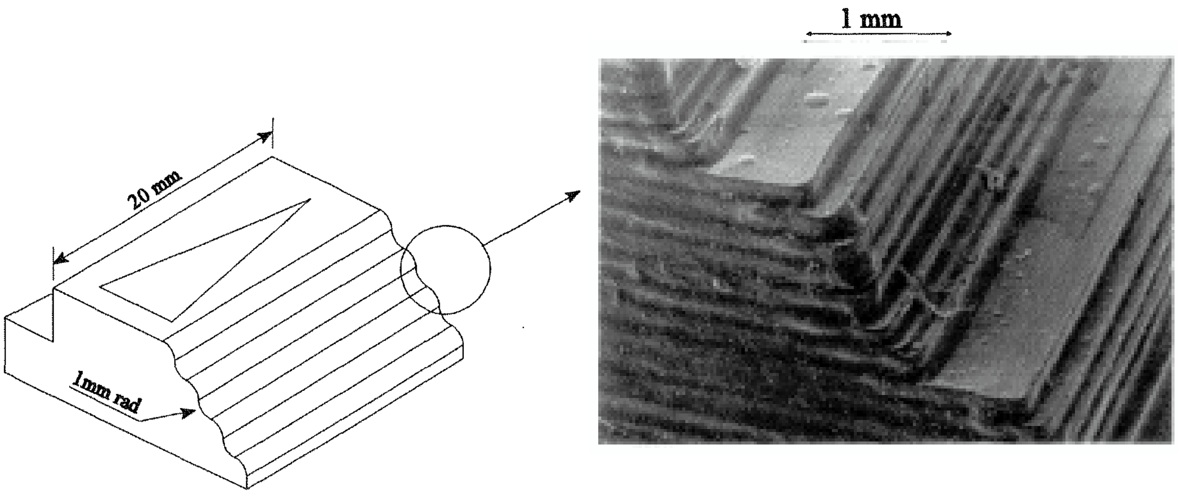
Figure 6



Meniscus level is a function of :- Resin viscosity, layer thickness, surface angle, step profile & manual part stripping.

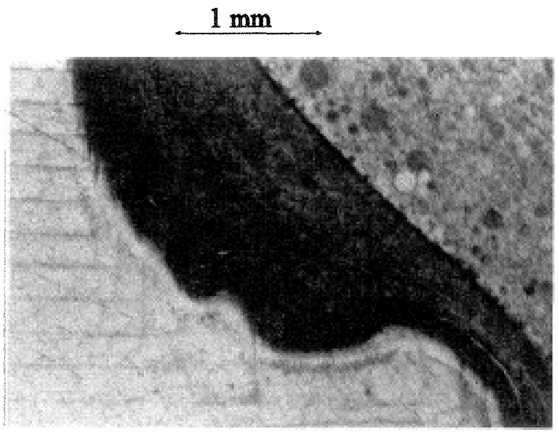
The effects of resin stripping residue on surface profile

Figure 7



Intended CAD geometry & 'actual' SL part, showing approximation to fine detail

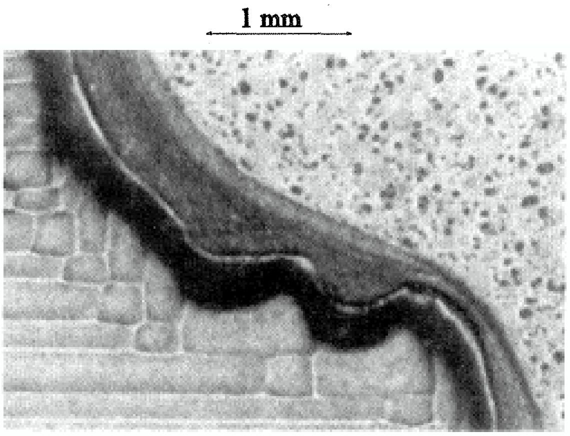
Figure 8



Note:- Loss to geometry

SL sample coated in 10 layer of concentrate epoxy primer, applied by dipping.

Figure 9



Note:- Improvement to geometry

SL sample coated in 2 layers of 50% thinned epoxy primer, applied by dipping.

Figure 10