Finite Element Analysis of Curl Development in the Selective Laser Sintering Process

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Abstract

The work reported within this paper is concerned with the development of analytical procedures which will allow the accuracy of parts generated by selective laser sintering to be predicted. One source of inaccuracy is curl, which results in curved part edges of flat plates manufactured lying horizontally in the part bed. This paper reports on the use of finite element techniques to model the development of curl. The models have been validated through comparison of f.e. results with the results of experimental builds, and extended to allow the influence of "bases" on the development of curl to be examined.

1. Introduction

Curl in selectively laser sintered parts arises mainly from thermal distortion of parts within the build volume during processing. This results in nominally flat surfaces which lie horizontally in the part bed becoming warped. Figure 1 shows schematically how a nominally rectangular 90 x 26 mm, 50 layers thick polycarbonate plate made by SLS will exhibit curl.
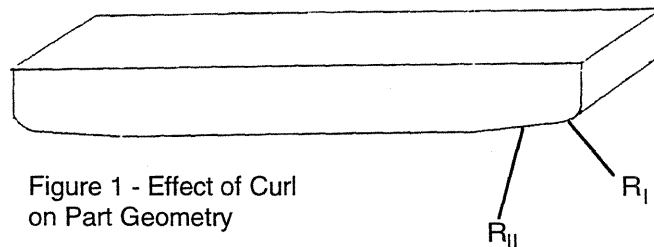

Figure 1 - Effect of Curl on Part Geometry

Previous work [1] has identified different regions of curl within a part. A microscopic amount of curl exists as a result of the definition which can be expected from the process. Thereafter the curl can be divided into two effects. The first of these appears over approximately the 2.5 mm of part closest to the edge of the part and on parts of with the geometry shown in Figure 1 has a radius (R_I in Figure 1) of around 20 mm. The second extends from the end of R_I approximately 10 mm further towards the centre of the part and has a radius (R_{II} in Figure 1) of around 60 mm. R_I curl has been seen to exist from the sintering of the first layer in part build, while R_{II} curl seems to develop as layers are added to the part. This paper reports on the use of the finite element method to analyse the development of R_{II} curl in rectangular polycarbonate plates made by the SLS process on a DTM Sinterstation 2000. One particular area of interest was the localised nature of the curl: previous work had failed to identify any reason why the curl should be confined to the part edges.

Previous work also investigated the effect of bases on R_{II} curl. Figure 2 shows results from an experimental investigation into the effect of the power input to the base, $[P/(Us)]_{base}$, on the resulting R_{II} curl. The graph in Figure 2 suggests that bases have no effect on R_{II} curl until the base is sufficiently dense to offer some restraint, but that thereafter no additional benefit is derived by further increasing the density of the base. The reasons for this were not fully understood and a further aim of the finite element work was an investigation of this effect.
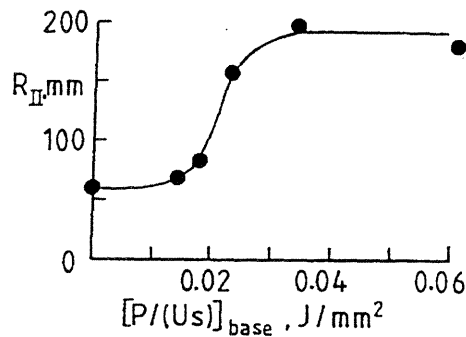

Figure 2 - Effect of Energy Input to Base on R_{II} Curl. From [1].

The finite element method has previously been used by Bugeda et al [2] to study curl development in the stereolithography process. They concluded that curl in stereolithography arose from volumetric shrinkage of the resin when cured. There are seen to be two mechanisms for curl development within selectively laser sintered parts. The first of these is shrinkage as a result of the sintering process, and the second is a thermal strain which results from powder to form the next layer being deposited on the most recently scanned layer. The fresh powder layer is at a lower temperature than the scanned layer, and so will produce some thermal contraction within the scanned layer. Both of these mechanisms result in compressive strains in the layers as they are built. The approach taken within the work reported here has been to use the finite element method to model part build by adding layers of elements to represent the addition of material to a part, and introducing compressive strains into the layers as they are added.

2. Finite Element Model of Part Build

The finite element solver used within the work described here was ABAQUS/Standard [3].

2.1 Geometry

Figure 3 shows the finite element mesh used within the analysis. The mesh represents the first 10 layers of the 90 x 26 mm rectangular polycarbonate plate part described above. All layers excepting the first two have a thickness of 0.125 mm, which was the default layer thickness within the manufacture of the parts. The first layer has a thickness of 0.66 mm, and the second a thickness of 0.25 mm. These thicknesses are based on measurement of layer thickness on one and two layer parts with the same cross sectional area. Further measurements indicated that subsequent layers were the expected 0.125 mm deep. The additional thickness in these first two layers is as a result of "bonus z", whereby additional material is sintered early in the build as a result of large thermal penetration into the part bed. The model was symmetric about the centre of the plate, and so only half the plate has been modelled. 2D analysis was used as it was the distortion along the 90 mm length of the plate that was of interest.
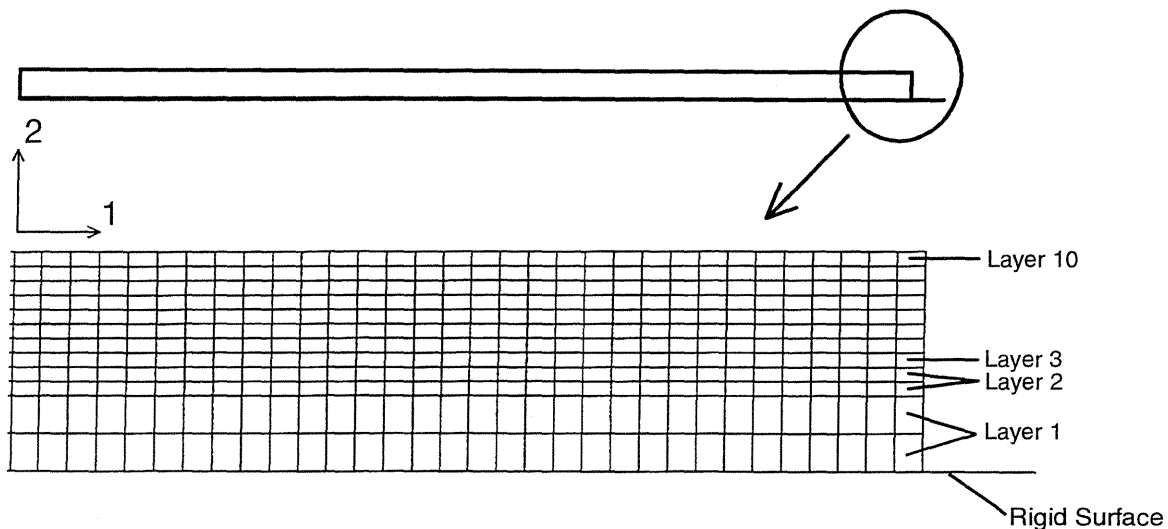
Figure 3 - Finite Element Mesh

The elements used within the analysis were four noded coupled temperature-displacement plane stress elements. Coupled elements allowed for the compressive strain to be introduced to the layers as they were built by artificially lowering the temperature locally within the mesh. The procedure used was to initially define the elements for all ten layers that would be built. The elements for layers two to ten were then removed from the analysis (using the *MODEL CHANGE card within ABAQUS) and re-introduced layer by layer as the analysis progressed.

The part bed has been modelled as a rigid surface. In practice the surface is unlikely to be rigid, but if the part bed is assumed to remain at the same temperature throughout the sintering process it is likely that the bed will be stiff relative to the part.

2.2 Material Properties

The parameters used in building the parts produced parts with a density of 700 kg/m^3. The modulus of the polycarbonate within the analysis was assumed to be 50 MPa, with a Poisson's ratio of 0.4. There is no real scientific basis for the use of an elastic material model, or for its value. In the absence of better material property data a "smeared" elastic response has been assumed in order to evaluate the usefulness of the finite element method in modelling the selective laser sintering process. Further work is planned to gain more information on material property values through the sintering process.

The interaction between the part and the part bed was modelled with a coefficient of friction of 1. This high coefficient of friction value was chosen to reflect the fact that the real surfaces would be quite rough, giving high resistance to relative movement.

2.3 Boundary Conditions and Loading

The first step within the analysis was to analyse the first layer. The only boundary condition applied was to enforce symmetry; the nodes at the centre of the part were therefore constrained not to move in the 1 direction (shown in Figure 3). A gravity load was applied as a body force to

all elements active in the model. The compressive strain was then imposed on the layer by artificially reducing temperature within the model. The strain imposed using this method was 2.6 x 10^{-4}. Initially larger values for the developed strain were used, on the basis of calculations by Childs *et al* reported in [1], but these values were found to overestimate the amount of curl. It may be that initially large strains in the layers may be somewhat relaxed by temperatures developed in a layer while subsequent layers are being scanned. After the first layer has been loaded in this way the elements making up the second layer were introduced, and the gravity load and compressive strain applied to them, with this procedure repeated until all ten layers of the part had been introduced and loaded. Figure 4 shows a detail of the resulting displaced mesh.
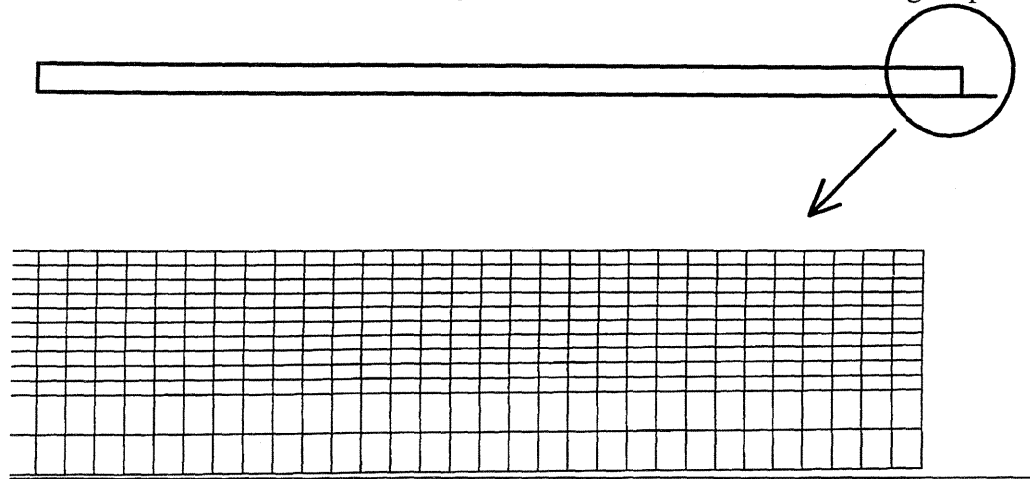

Figure 4 - Displaced Mesh

2.4 Results

In order to validate the analysis the results have been compared with the measurements of experimental builds. Table 1 shows how the results from the finite element model compare with measurements of distortion on two and ten layer parts of the same geometry. The data points used are away from the outer edge of the part to avoid confusion with R_I curl. The results shown in Table 1 were taken as indicating that the distortions predicted by the finite element model were of a similar order to those exhibited by the parts.

The results overall suggested that the combination of gravity loads, the strain induced within layers as they are manufactured, and part/bed interaction leads to R_{II} curl being seen only close to part edges.

Measured displacement in 2 direction 3.25 mm from part edge on two layer part	0.025 mm
FE predicted displacement in 2 direction 3.25 mm from part edge after two layers built	0.011 mm
Measured displacement in 2 direction 5.5 mm from part edge on ten layer part	0.05 mm
FE predicted displacement in 2 direction 5.5 mm from part edge after ten layers built	0.052 mm

Table 1 - Comparison Between FE Predictions and Measurement of Distortion

3. Analysis of the Effect of Bases

Figure 2 shows that the effect of bases on R_{II} curl is dependent on the power input per unit area to the base. The power input effectively defines the density developed within volume being scanned by the laser. It is assumed that the region in Figure 2 where the base has no effect is due to the lightly sintered powder being unable to sustain any load (and therefore acting in the same manner as the powder bed). In order to investigate the results shown in Figure 2 analyses with bases appropriate to $[P/(Us)]_{base}$ values of 0.035 and 0.06 J/mm^2 have been carried out, to try to identify why no further improvement occurs beyond that shown for a $[P/(Us)]_{base}$ value of 0.35 J/mm^2. These two values of $[P/(Us)]_{base}$ would be expected to generate base densities of 580 and 700 kg/m^3 respectively (the higher value being a base with the same density as the part being built).

3.1 Model Development

The mesh used for analysing the effect of a base density of 580 kg/m^3 is shown in Figure 5. The model operated in essentially the same way as that described for part build. The base used in the analysis is four layers thick, corresponding to those used to carry out the measurements shown in Figure 2. The depth of the first two layers in the build (in this case the first two layers of the base) has been changed as the "bonus z" effect increases with sintering power. Measurements on 50 layer parts gave "bonus z" values for a part made with a laser power of 0.035 J/mm^2 as around half of that for a part made with a laser power of 0.06 J/mm^2. The depth of the first two layers was therefore halved. The layer thickness in the model for a base with a density 700 kg/m^3 was the same as for the analysis described in section 2.
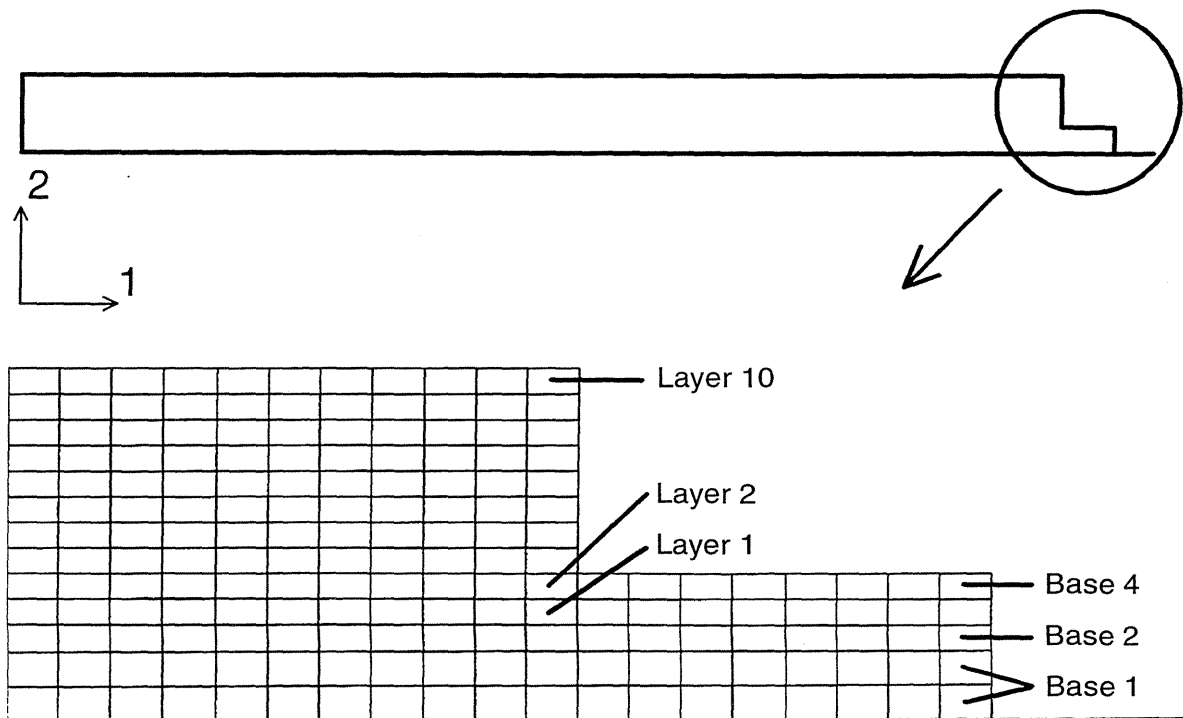

Figure 5 - Finite Element Mesh of Part Build with Base. Base Density 580 kg/m^3.

In both cases the base was extended 2 mm beyond the part in the 1 direction. This is approximately what the radius of the base (which is cylindrical) would have been. The cylindrical shape of the base means that a 3D analysis would have been necessary to reflect the part geometry completely. A 2D analysis was retained for computational efficiency, although this means that the effect of a large area of base material is lost. The effect that the area of the base has on part curl was investigated by carrying out one further analysis with a base which extended 7 mm beyond the part. This analysis was carried out with a geometry and material properties appropriate to a base with a density of 700 kg/m^3.

After the base and two layers of part contained within the base have been completed the addition of subsequent layers deposits powder on top of the protruding part of the base. The effect this has was modelled by applying a pressure load to the top of the elements of the fourth base layer.

When bases are used the layers which occupy space within the base cylinder and the part volume are scanned twice by the laser. The laser first rasters the base layer, with the laser power per unit area appropriate for the base, before rastering the part layer, again with the appropriate laser power per unit area. It has been assumed within the analyses that the second raster causes the strain developed during the first raster to be relieved (initial analyses suggested that if this were not the case the part made with a 700 kg/m^3 density base would curl more than the part made with no base at all). For the 700 kg/m^3 density base it has been assumed that all of the developed strain is relieved by the second raster. For the 580 kg/m^3 base it has been assumed that amount of strain developed during the first raster is proportional to the amount of densification which takes place. When the second raster occurs this strain is assumed to be relieved, but a further strain imposed, as the density of the layer goes from 580 kg/m^3 to 700 kg/m^3. By this reasoning a strain of 1.46 x 10^{-4} is assumed to be developed within layers 1 & 2 in the model of the 580 kg/m^3 base build. The modulus of the 580 kg/m^3 base within the model was 16.7 MPa, experimental measurement of the room temperature elastic modulus of polycarbonate parts made by laser sintering suggested that a 580 kg/m^3 part would have one third of the modulus of a 700 kg/m^3 part. The modulus value for the 580 kg/m^3 dense material was therefore taken as one third of that used for the 700 kg/m^3 dense material. The Poisson's ratio was assumed to be 0.4. To further investigate the effect of the second raster releasing the strain in the layer as sintered one further analysis was carried out. This analysis used the same mesh as for the part built without a base, but assumed that the first two layers were rastered twice. The first two layers were therefore assumed to have no developed strain.

Other than the points mentioned above the analysis procedure, material properties and loading were the same as that for the part without a base described in section 2.

3.2 Results and Discussion

The results from the four analyses can be seen in Figure 6, where the position of the lower surface of the part after two and ten layers have been built within each of the analyses is plotted together with the results obtained for the analysis of a part without a base.
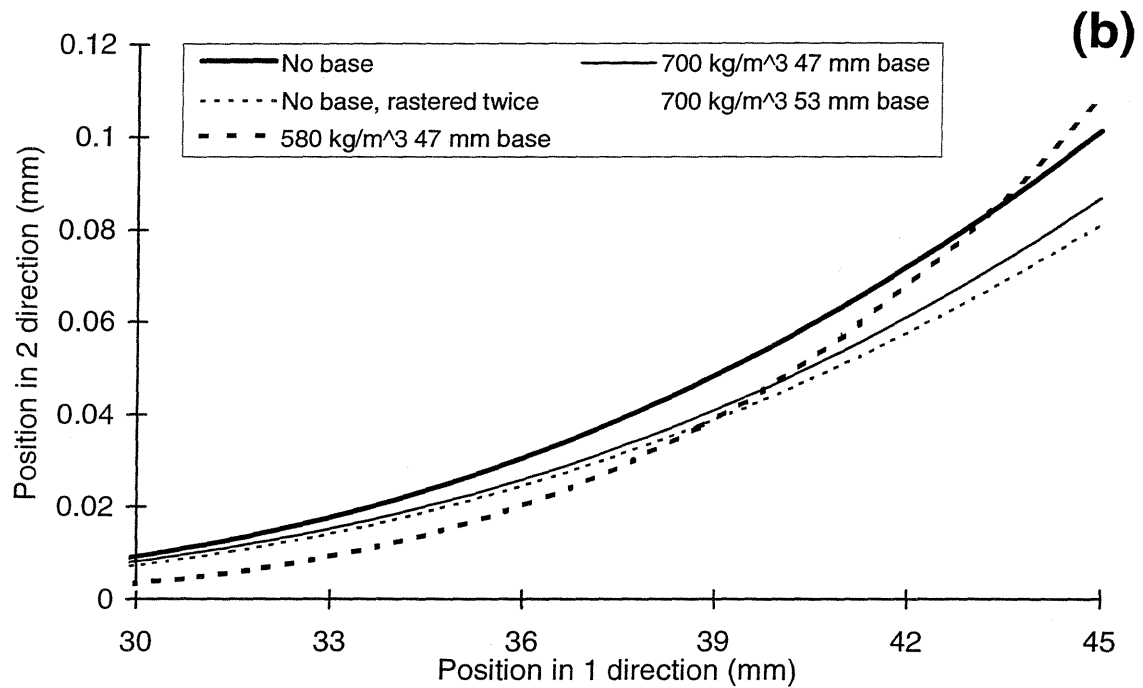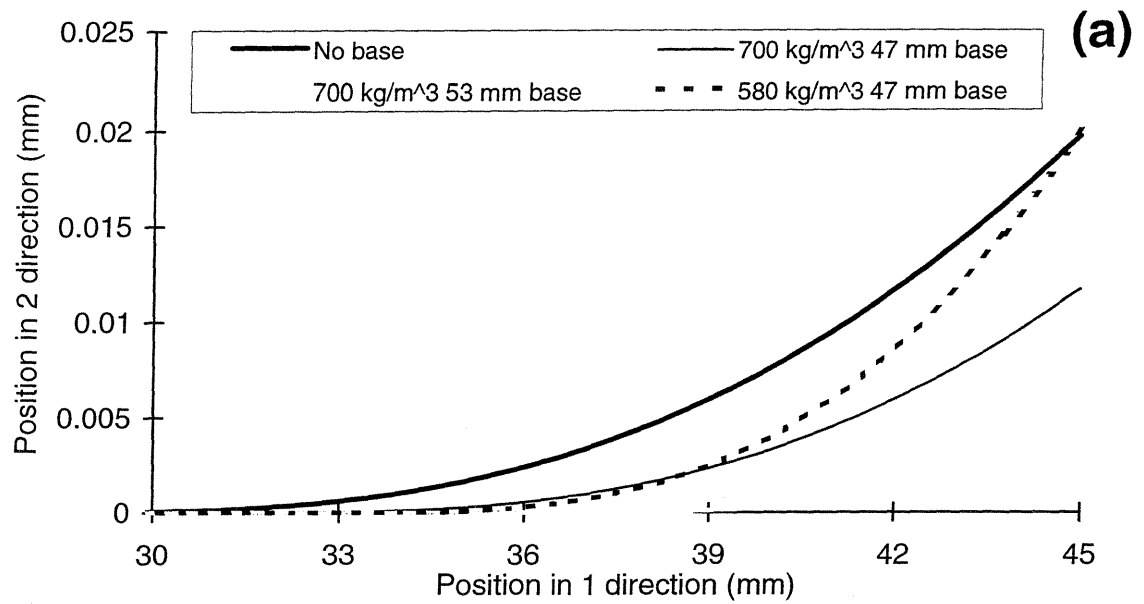
Figure 6 - Predicted Movement of Lower Part Surface Under Various Processing
Conditions After (a) 2 Layers Modelled, and (b) 10 Layers Modelled.
Origin (0,0) at the Centre of the Lower Surface of the Plate.
(No Base, Rastered Twice - 2 Layers Showed No Movement).

Consideration of the results shown in Figure 6 leads to several observations:-

(i) The use of a 2D analysis underestimates the effect the base has on reducing R_{II} curl. The results shown for the analysis of a 700 kg/m^3 density base and a 580 kg/m^3 density base do not

differ significantly from those of the part built without a base. The results for the analysis carried out where an additional 5 mm of base material were added show a significant reduction in the amount of curl generated. This would suggest that the additional area of cylindrical base not taken into account by a 2D model would have an effect on the amount of curl generated.

(ii) The analyses with the 580 kg/m^3 and 700 kg/m^3 density bases show very little difference in terms of the developed R$_{II}$ curl. The residual strain in the first two layers of the part in the case of the 580 kg/m^3 density base is greater than that for the 700 kg/m^3 base, however this seems to be offset by this strain being applied to material with a lower density, modulus and (because of the effect of "bonus z") depth. This provides some insight into the effect shown in Figure 2.

(iii) The results suggest that sintering the first two layers twice to relieve the strain developed in these layers would reduce the amount of curl developed. As the results of the analyses of parts with bases is thought to underestimate the effect that the base has, further work will be required to assess whether or not the benefit derived is as great as that from using a base.

4. Conclusion

The finite element method has been shown to be of value in understanding curl in selectively laser sintered components. The characteristic shape of components exhibiting curl is considered to arise from the interaction of strain developed in the layers of the part during the build process and gravity forces. The effect of bases on R$_{II}$ curl has also been analysed, and qualitative agreement between analysis and experiment shown. The work has made major assumptions with regard to material properties and viscosity, and further work will address these issues.

References

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