ACCURACY EFFECTS OF SHELLING A PART IN THE SLS PROCESS

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Abstract

In order to reduce SLS process time in the manufacture of a mould insert, the idea of shelling the geometry of the insert has been tested. Some shelling strategies have been successful with the RapidTool^{TM} process, proving the feasibility of the idea. It has been observed in the tests, for both polymer and RapidSteel2.0^{TM} materials, that size accuracy, particularly of small features in the scanning (X) direction, depends on vector length (VL). When a sudden change in VL occurs, this leads to steps on the sintered surface. This paper presents both experimental observations of this and simulation results from a finite element model.

Introduction

Although Selective Laser Sintering (SLS) is one of the technologies known as 'rapid', if the part to be manufactured is a mould insert, a long time can be expended in the processing. This is observed mainly because a mould insert is usually a solid part, in contrast with most plastic parts, which are like a shell. To reduce process time, it was suggested to shell the geometry of the insert, reducing mainly the volume of material to be fine/normally processed [1]. The indirect rapid tooling process called RapidTool^{TM}, using RapidSteel2.0^{TM} (RS2), was used to test this idea.

One of the shelling strategies tested successfully required, however, using a thin shell (thickness equal to or less than 2mm) and, in this range, a side effect on accuracy of the insert was observed. Basically, steps appeared on the walls perpendicular to the X direction, which is the main laser moving direction in a raster scanning strategy (Figure 1). In the particular case of Figure 1, a shell of 2mm presented well-defined steps up to 0.1mm inwards (undersize). In other tests using 4.5mm shell thickness, the steps were outwards (oversize). Although the size of the steps seems small, they are undesirable and will demand extra work during the surface finishing stage. If not removed, the steps can be mirrored onto the moulding or create undercuts that will make moulding ejection difficult.

The steps occurred exactly where the vector length (VL - scan line length with laser on), changes from a long to a short one, and vice-versa, shown schematically in Figure 2. Shelling an insert causes a large variation of VL all over the part geometry and this variation seems to have a negative effect on accuracy. In order to have a better understanding of the VL influence on part accuracy of small features in the SLS process, two approaches have been used. Firstly, two experimental parts were designed specially to check this effect on two different materials. Secondly, a 2D SLS finite element model was used to analyse in more details the alteration in the process conditions caused by the VL changes. The main objective of this work is to present some initial findings of this study.

Influence of Geometry Changes on SLS Processing Conditions

The influence of the geometry (*i.e.* VL) on part properties, mainly density and strength, has been studied and discussed by other researchers [2,3,4]. The main point observed is that geometry variation is responsible for changing thermal gradients in the part.

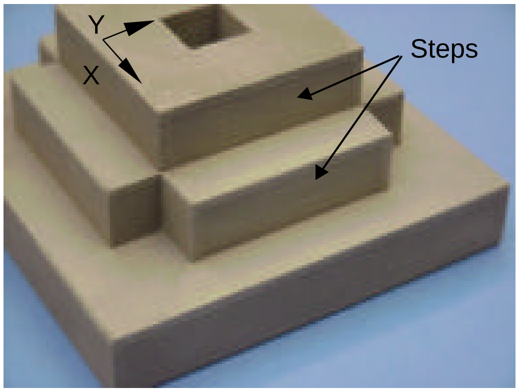

Figure 1 - Steps on some part walls for an insert with shell of 2mm

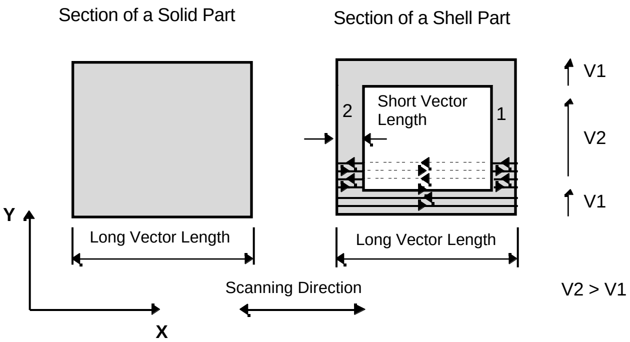

Figure 2 - VL analysis in solid and shell section schematically

The energy stored at the surface of the layer during the interaction period between the laser and the powder is usually referred to as energy density or Andrew number.

$$A_N = \text{Laser Power(P)}/[\text{Beam Speed(BS)} * \text{Scan Spacing(SS)}] \quad [\text{Joules/mm}^2] \qquad (1)$$

Williams and Deckard [4] stated that this equation represents the energy stored at the surface given constant geometry of the part. They pointed out however that the time between successive exposures (delay), which is determined by the VL and beam speed on a raster strategy, should also be considered.

$$\text{Delay} = \text{VL/BS} \qquad [\text{Seconds}] \qquad (2)$$

During this dwell period, energy is lost due to conduction into the powder bed and radiation and convection at the surface of the powder bed. The influence of this delay period on density and part strength are associated with the difference in maximum temperature reached when varying the delay period [4]. A longer VL means more cooling and heat lost from the material being processed and, as a consequence, lower temperature attained. Higher temperature is associated with shorter VL.

Other effects of geometry variation are the possibility of non-uniform shrinkage and growth. Growth is defined as sintering of powder outside the desired part boundary, caused by heat transfer from the processed material to the surrounding support powder [2]. The shrinkage of the RS2 is very small (an overall amount of $\approx$0.2%) and the growth is normally considered constant and compensated together with the beam spot radius, via the offset parameter.

However, in our experimental tests of the shelling idea, the geometry was the only parameter altered in the SLS processing. Therefore, it seems to be the cause of a variation in the growth in the section, resulting in development of steps on some walls. As can be seen in Figure 2, shelling causes a significant alteration of the geometry of the section to be processed. This observation lead to a study in more detail of the accuracy of the SLS process, mainly when processing small feature in the X direction, either in pairs (typical of a shell or hollow part) or single features (typical of metal or plastic parts).

Influence of VL on Part Accuracy - Experimental Study

The experimental study was carried out using two parts specially designed to check the dimensional variation of the small features positioned in the X direction – the main direction of interest in this work (Figure 3). The part used to test single features (left) was divided into two STL files (one with the base and the features AA and the other with BB), so that, although some of these features are positioned on the same X line, they are processed individually. The X dimensions of the small features are 0.25, 0.5, 0.75, 1, 2, and so on up to 9mm. The part on the right was used to study small features when processed in pairs. This design was applied for features of 1, 2, 3 and 4mm thickness, which represent the range of interest for the shelling idea [1]. The distance between the paired features was also considered, starting from 5, 10, 20 and so on up to 100mm, for 1 and 2 mm features, and the same variation for 3 and 4mm, but starting from 10mm (external distance). All the features in both parts have the same size in Y (5mm) and Z (3mm) direction. Also, all test parts have the same base design, which was used to check accuracy of larger dimensions, not reported in this work.

The parts were built using a DTM Sinterstation 2000, without beam offset or scaling. The processing parameters used for RS2 were P=20Watts, SS=0.08mm, BS=1257.3mm/s and layer thickness (LT) 0.076mm. Also, the same experiments were carried out with a nylon-12 polymer, Duraform (DF), in order to compare the behaviour of the two materials under similar geometry conditions. The processing parameters used for DF were P=5.2Watts, SS=0.15mm, BS=1257.3mm/s and LT=0.1mm.

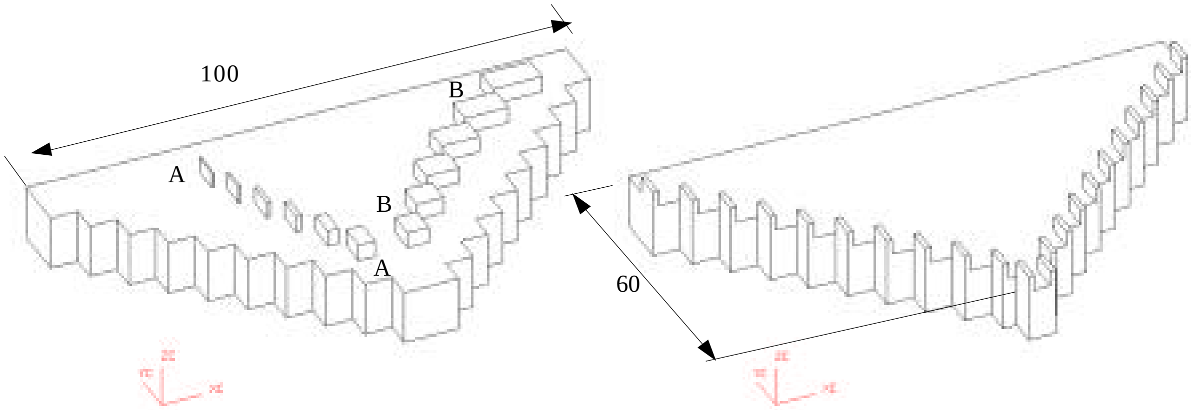

Figure 3 – Geometry of the test parts – single features (left) paired features (right)

Measurement Results

All the parts were measured using a Coordinate Measuring Machine (CMM) and the results are presented in graphs for each material. The parts were measured in the green stage (after SLS processing) for RS2. Dimensional error is usually considered as deviation of measured dimensions from the desired or nominal dimensions. We used a similar approach in this work, but we define 'Error' as the difference between measured dimension and VL, due to the specific objective of this study. This is what error represents in the graphs that follow. The same graphs can be plotted against delay between exposures using equation (2).

Figure 4 shows the results in the X direction for small features single processed according to VL for RS2. The error in the Y direction is also presented according to VL: however it is important to remember that all features have the same 5mm Y-dimension (Figure 5). Figure 6 presents the results for pairs of features and in addition, to help the analysis, the results for single features were plotted together. The large number of points for the features processed in pairs accounts for all the distances measured. The results for the paired features are also presented in Figure 7, but according to the distance that each feature of the pair is positioned apart. Figures 8, 9, 10 and 11 present the same sequence of measurement results for DF.

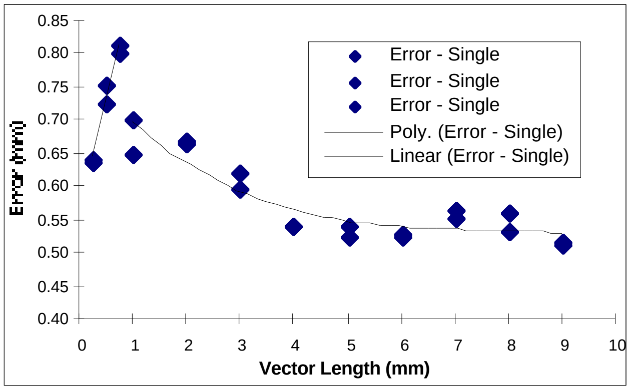

Figure 4 - Error of the RS2 single features – X direction

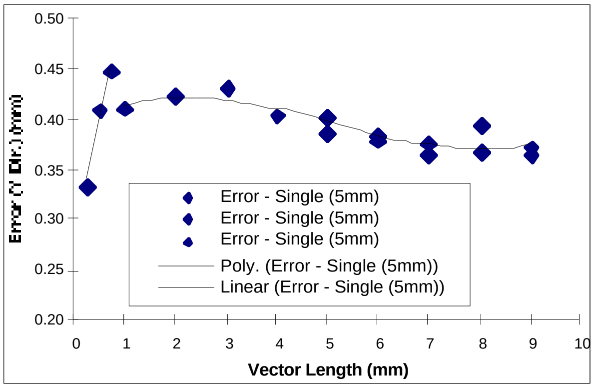

Figure 5 - Error of the RS2 single features – Y direction

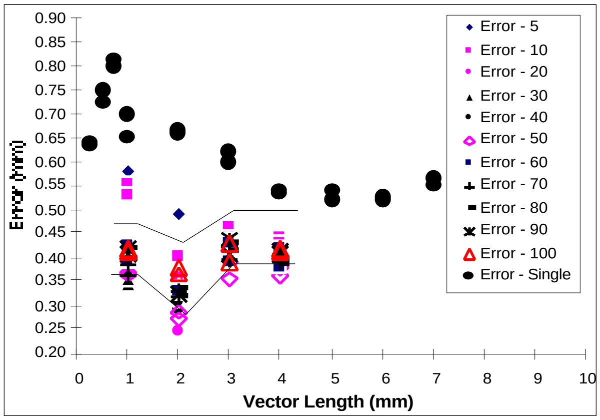

Figure 6 - Error of the RS2 paired and single features – X direction

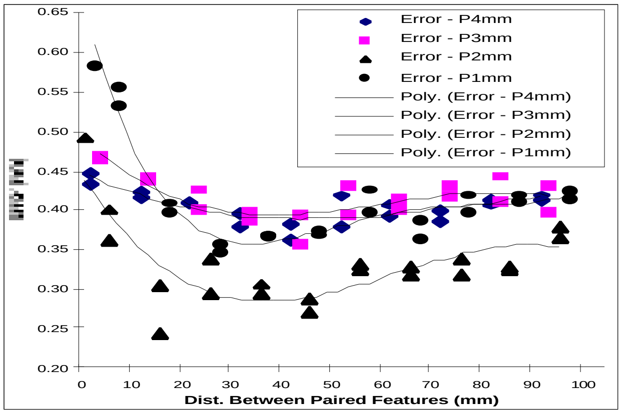

Figure 7 - Error according to the distance between the RS2 paired features – X direction

Discussion

Figures 4 and 5 show that, considering the low shrinkage of RS2, the growth does increase as the feature dimension decreases (at least for VL>1mm), or in other words, as the delay between exposures reduces. The variation is mainly observed in the X direction, and is almost negligible for the Y direction. A significant difference in growth was observed for features of the same size, but processed in pairs and singly (see Figure 6). The single features presented much more growth than the ones processed in pairs.

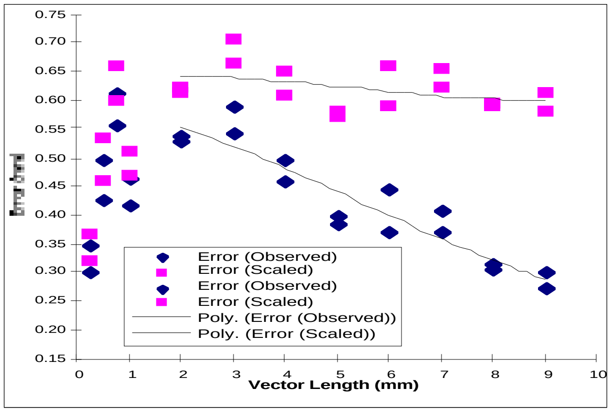

Figure 8 - Error of the DF single features – X direction

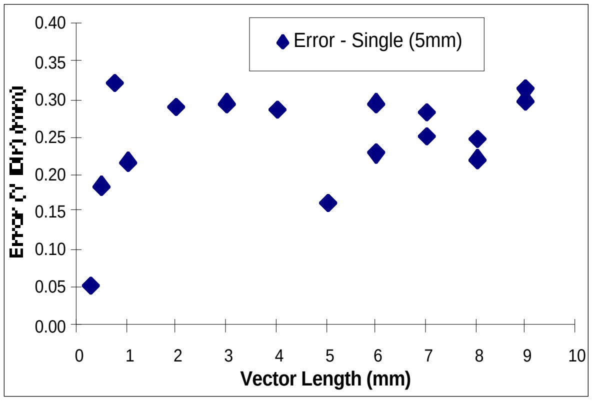

Figure 9 - Error of the DF single features – Y direction

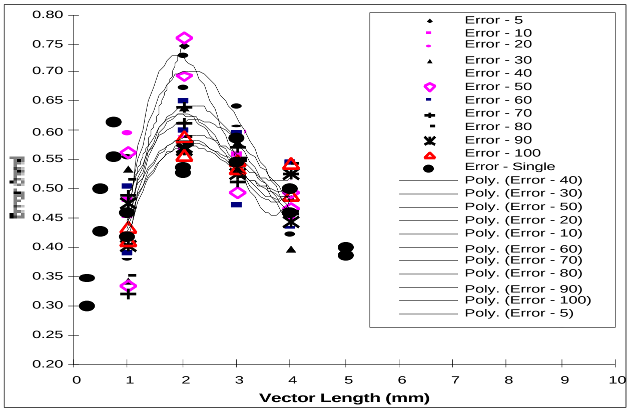

Figure 10 - Error of the DF paired and single features – X direction

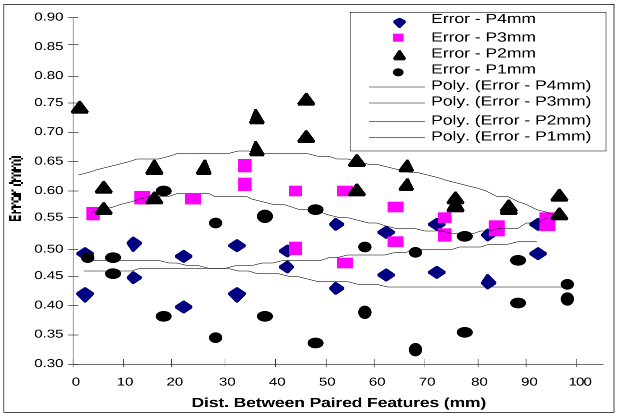

Figure 11 - Error according to the distance between the DF paired features – X direction

Figure 7 shows that the growth in paired features increases when they are positioned close together. This is more clearly observed for features of 1 and 2mm. It can be seen that for 1mm paired features, positioned 5mm apart, the error is converging to the value for 1mm single features. It seems that after around 20-30mm apart, the error is not much affected by the distance between the paired features. One thing that catches the attention is that the 2mm paired features seem to have less error than the others do, by a rather constant difference. This effect can also be seen in the overall shape of the curves for paired features (VL=2mm) in Figure 6. This observation is in line with the undersize steps observed in the strategy using 2mm-shell thickness (Figure 1), but an explanation has not yet been found.

The results for DF should be analysed taking into account that there is higher shrinkage associated with this material (≈ 3.4% in X direction). In Figure 8, X-errors are plotted in two ways: as observed and after a scaling to allow for shrinkage. The growth does not increase very much with small features and even presents a reduction around 1mm. It seems that the growth does not vary in the Y direction (Figure 9), except perhaps for VL<1mm. There was also not a significant variation in growth of the features processed in pairs and singly (Figure 10), and the influence of the distance between the paired features on the error values is not clear (Figure 11). It is possible however to see that the 2mm features presented, in general, the highest error of the features analysed, which is exactly the opposite of what was observed in the RS2 tests.

An odd trend can be detected in the error results for the three smallest single features (0.25, 0.5 and 0.75mm), in both direction and materials. As can be seen in Figures 4,5,8 and 9, the error increases in a quite linear way from 0.25 to 0.75mm, having a peak in 0.75mm (highest value in the experiments), and dropping rather sharply towards 1mm. It seems unlikely that this effect is due to processing changes, but it might have been caused by some systematic error of the scanner in our machine. It is worth mentioning however that a dimension of 0.75mm would correspond, because of the usual offset and shrinkage, to a nominal dimension of ≈1.17mm for RS2 or ≈1.3mm for DF, values that can be found in real parts.

Study Using a SLS Numerical Model

A sintering model developed at the University of Leeds [5,6] was used to study the changes in the SLS processing conditions due geometry variation. The model uses the finite element method to solve heat transfer equations and calculate temperature rise caused by a transient moving heat source. The temperature/time history that is calculated is linked to a sintering law to calculate the density changes in the bed. These density changes are used to calculate powder shrinkage in the Z direction using mass conservation. From the density profile it is possible to evaluate the size accuracy of the part. The model is developed in 2D, limiting the accuracy analysis only to the Y direction, but allowing good insight in terms of temperature and density variation in the part. Details of the model can be found in [5,6,7]. As there is not a model defined for RS2, the model for crystalline polymer was used for this study, more specifically for DF.

The model was used to simulate SLS processing of single features and also pairs of features, positioned at different distance between them. The latter was achieved by assuming a VL that induces the same delay for a single VL as for twice the feature size, plus the distance between the paired features. The fast speed set in our machine to move the mirror when the laser is off for DF is 5080mm/s. The processing parameters were the same as used in the experimental tests.

As the model does not calculate the shrinkage that occurs when the material cools down from processing temperature to room temperature, the error presented should be analysed as being only due to growth.

Numerical Results

Figures 12, 13 and 14 present respectively the maximum temperature achieved at the top surface of the layer, the average density attained and the corresponding error values for single features in the Y direction according to VL. Finally, Figure 15 presents the error according to the distance between the paired features.

Discussion

The results confirm an increase in the maximum temperature reached and density as the VL decreases. In this small range of VL the temperature gradient does not seem very significant, causing little increase in growth (Figure 14). However, in an extended analysis, with VL up to 100mm, the variation can reach 0.17mm. The error predicted is smaller than the experimental results (Figure 9) by a value around 0.2mm. The model also predicts a slight growth variation according to the distance between the paired features (Figure 15).

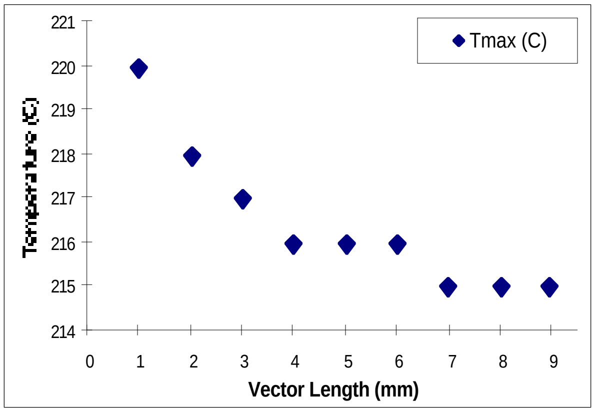

Figure 12 - Maximum temperature according to VL for single features –Y dir.

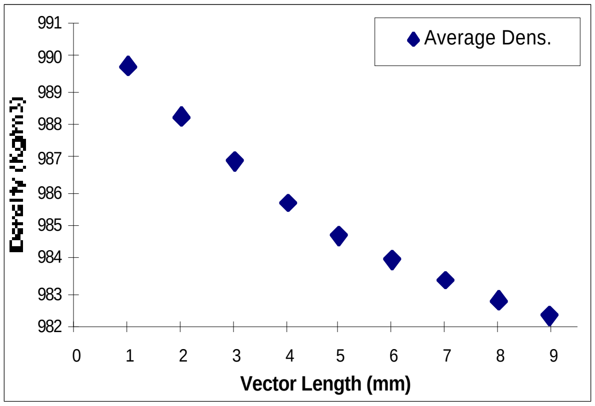

Figure 13 - Average density according to VL for single features –Y dir.

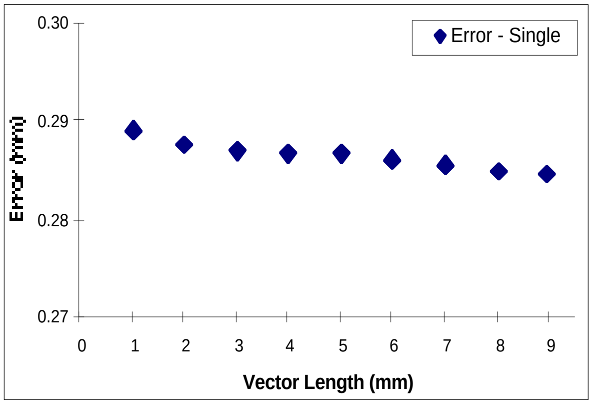

Figure 14 - Error for single features according to VL –Y dir.

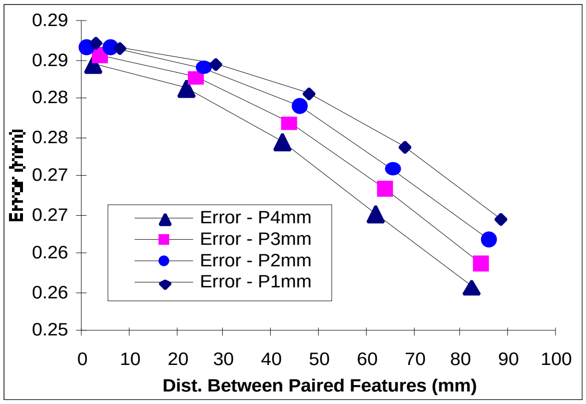

Figure 15 - Error according to the distance between the paired features –Y dir.

Further Work

The 2D model does not allow an accuracy study in the X direction. Therefore, a 3D model is under development using the same 2D principle. As the variation of the growth seems more evident in RS2 than in DF, a SLS model adapted to this material might help to understand this behaviour.

Conclusions

As well as the influence of VL on part densification and strength, its effect on accuracy is also relevant to further improve SLS accuracy. The experimental results showed that for small features the growth should not be considered constant and this is more critical for the X than for Y direction.

The influence of the part geometry on accuracy/growth is dependent on the material being processed and also on the arrangement of features (as tested here by processing features singly and in pairs). These influences seem much more relevant for RS2 than for DF.

Although the study originated from an observation of a particular case, the shelling idea to save time in the RapidTool process, it is important to mention that geometry variation is likely to be found in most plastic or metal parts, which reinforces the importance of a better control of its effects.

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