Optimising Build Parameters and Hatch Style for Part Accuracy in Stereolithography

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Abstract: A detailed study of the effects of layer thickness, hatch spacing, hatch overcure depth, and hatch fill cure depth on the quality of the StereoLithography (SL) product was carried out using acrylic based resin. Taguchi Method was used for analysing all experimental results. The ANOVA and the Signal-to-noise ratio (S/N) results were used to select the optimum parameters and the appropriate factor levels for further experiments. A new hatch style with an optimum layer thickness is proposed for the build process with minimum geometrical distortion.

1.0 INTRODUCTION

The activity of manufacturing has been practiced by mankind for thousands of years with a ceaseless drive towards improvement and innovation. Manufacturing industries are one of the key makers of a successful economy. All nations in the world are striving towards a strong manufacturing base capable of changing to the needs of fluctuating markets. Manufacturing creates wealth and opportunity bringing with it an increased quality of life which can be a direct result of the consumption of goods or the production of goods. A strong manufacturing base is the key to economic success which is achieved with increased efficiency and productivity. Very few technologies have offered as much as rapid prototyping technologies (RPT) have in the last few years. One of such important new tool in RPT is Stereolithography (SL), a technology that let us transform digital designs into 3-dimensional solid objects for production of machine parts, models, prototypes, and moulds Components can now be produced in a fraction of the time that was required previously with the added benefits of reduced costs and more design iterations. Designers have been released from old constraints with new tools from the array of RPT. Managers must take on new business practices, designers must understand the power at their fingertips , process engineers need know of the new process routes and marketing personnel must be aware of their new found ability to react quickly to market changes. Without doubts, products with outstanding quality, satisfying a market niche, are pre-requisites for a successful company.

The main process stages involved in fabricating parts are common to most systems, but the mechanisms by which the individual layers are created obviously depends on the particular system. A schematic for SL is as shown in **figure 1.**

2.0 RESEARCH RATIONALE

One of the most challenging goals of Rapid Prototyping is the generation of accurate and dimensionally stable parts. The ultimate dimensions of a part built on a layer by layer basis depend on many factors that must be carefully balanced to produce accurate parts . **Laslie et al (1991)** concluded that the inability to understand and control these parameters has leads to many problems including post-cure shrinkage, swelling, cantilever curl distortion, vertical wall post-cure distortion and horizontal slab distortion. In their work, **Murphy et al,. (1988),** concluded that an unfortunate fact of acrylate polymerisation is shrinkage and the attendant residual stresses which reside in the cured parts. This stresses often result in the distortion of the work piece.

The problem of dimensional and form accuracy, and surface finish has been discussed by several authors and a number of ways to minimise it have been proposed. What is required for industrial applications are functional metal prototypes. These components are often needed early in a project to determine not only form and fit but function as well.

Despite significant advancement in build styles and material properties, there has been no such perfect part. **Dickens (1995),** commented that all the commercial Rapid Prototyping Systems can only produce for now in materials that are not suitable for production tooling. But he agrees that the emphasis has changed over the year from Rapid Prototyping to Rapid Tooling.

Previous investigations **(Gargiulo, 1992)** have shown that it is not only important to observe the overall shrinkage (liquid to solid transition) to achieve good part accuracy but also the polymerisation dynamics which influence both the mechanical properties and the shrinkage are significant. In some related works, **(Wiedemann et al 1995; Konig et al 1994)** the use of hatch strategies has been proposed. Hatch strategies are understood to mean the specific configuration in terms of duration and location of individually polymerised lines to describe the respective cross-sectional area on the resin surface. So the use of hatch strategies is intended to reduce or compensate the accumulation of internal stress resulting from polymerisation shrinkage.

Konig et al. concluded that when layers are scanned in only one direction, shrinkage forces occur mainly in the scanning direction which results in one-sided curling of the parts. An alternating exposure of the layers resulting in a more homogeneous structure of residual stress in the part and to a higher part stability was therefore proposed. Based on this proposal, the *Divergent STAR-WEAVE* (DSW), shown in **figure 2** was developed. This development is based on the hypothesis that if alternating the exposure of the layer will homogenised the residual stress structures, starting the hatching from the middle of the part and alternating it will normalise the residual stress to give a more uniform distribution of the stress. This will result in a more accurate and dimensionally stable parts.

In this research work, the effects of the parameters shown in **table 1** on the product quality will be experimentally determined. The definition of these factors are as follows:

1. ***Layer thickness:*** The three-dimensional objects are sliced into series of constant thickness, two-dimensional layers to be solidified by the UV laser. Each two-dimensional layer is solidified on the photopolymer surface with a specific hatch style selected by the user.

2. ***Hatch style***: Hatching or printing is the process of solidifying the cross section of a layer of the model to be built.
3. ***Hatch spacing***: Hatch spacing is the distance between parallel vectors used to hatch the interior of the part. If the hatch spacing is very small, the solidifying vectors will overlap causing a completely solid layer. Large hatch spacing allow liquid polymer to be trapped in the part to be solidified in the postcuring operation.
4. ***Hatch overcure***: Hatch overcure is the depth that one cured vector string pierces into the lower adjacent layer. This is what keeps the individual layers connected together to form a complete part.
5. ***Hatch fill cure depth***: Fill cure depth is the depth of the solid layers formed on the upper and lower faces of the solid. This holds the remaining liquid inside the part for subsequent post-curing.

In this type of experiment, the Taguchi method for full and fractional factorial is most suitable according to **Box, et al (1978).** Hence, the Taguchi method was used for the selection of the experimental parameters. By using Taguchi method therefore, a full factorial experiment with an L8 array is required (i.e. 2^3) giving a total of eight experimental runs. However, an L4 array - fractional factorial as shown in **table 1** and **table 2** which satisfies the conditions proposed by Taguchi in **Box, (1978**), were used.

In this work, the hatch style chosen is the STAR-Weave™. This is because as stated above it is the most advanced build style by the systems' vendor which gives the best dimensional accuracy and surface finish with the acrylic resin. Apart from the STAR-Weave™ the other hatch style developed for this study is the DSW and the scanning technique is done as shown in **figure 2.** In this technique, the scanning is commenced from the middle of the part in such a way that half of the part is first scanned from the middle to one end and the other half is then scanned from the middle to the other end. This process is repeated in either x or y-direction as done in STARWEAVE™.

3. EXPERIMENTAL METHODS

The following equipment were used in this investigation: Sun Sparc 10 and Silicon Graphics Indigo Workstations, 3D Systems StereoLithography Apparatus SLA - 250 series 40, and Post Curing Unit (PCU). The entire investigation was conducted in the Rapid Prototyping Centre and all dimensional measurements were taken from a Mitutoyo BHN-706 CNC Co-ordinate Measuring Machine (CMM) with an accuracy of ±5μm. As for the surface finish measurements, a Taylor-Hobson Talysurf model surtronic-3 was used with a wavelength cut-off of 2.5 mm. The experimental part as shown in **figure 3,** was designed in DUCT5.

4.0 RESULTS AND DISCUSSIONS

Figure 4 shows the flatness of the experimental models for the two hatch styles and the experimental runs for the 0.125 mm layer thickness. The flatness is calculated from the measurement taken at different points on the surface of the models. This is the XY-plane ABCD shown in **figure 3.** The SW hatch style gives the least average values of 0.388 mm for the flatness. This is the third experimental run (R_3). The smaller the flatness the better for a flat part. From ANOVA, R_3 consistently gives the highest S/N values for all the four runs and also the least sensitive values. This implies that for a flat part, the SW hatch style is more robust than DSW hatch style. The three factors are also consistently statistically significant in all the states of the model (i.e. green, cured or detached).

As for the DSW hatch style in the green state, all the three factors are statistically significant while factor C is not statistically significant in the cured and detached state. In addition, the percentage contribution of factor B is significantly higher than the percentage contributions of the other two factors in either green, cured or detached state of the part. This suggests that for the DSW hatch style, controlling factor B will significantly affect the flatness of the part. The significant effect of factor B may be due to the mechanics of curing which is dependent on the hatch style. It was discovered that R_1 which has a higher value of overcure depth, consistently gives higher S/N values than all the other runs. Hence factor B can be said to significantly affect the quality of a flat SLA model. In the confirmation experiment, R_2 of DSW or R_1 of SW may be used for the confirmation experiment.

For the layer thickness of 0.190 mm, the average flatness value does not follows a similar pattern as observed in the results for the 0.125 mm layer thickness where the SW hatch style gives the minimum average flatness. From **figure 5** which is a plot of the flatness for the 0.190 mm layer thickness and the two hatch styles, the DSW hatch style gives the minimum average flatness value. This suggests that hatch method and the layer thickness do significantly affect the flatness of a part. From ANOVA data, R_4 gives the combination for the optimum condition for the DSW hatch style while in SW hatch style is R_3. Factors A and B are consistently significant for all the hatch styles in all the runs. Where factor C is significant it is at level 1 and its percentage contribution is least and this seems to suggest that for DSW hatch style, the flatness is determined by the effect of factors A and B. In DSW hatch style the percentage contribution of factor B is the second highest but it is least sensitive to variability. For further experiments as to confirm which combination of factors and at what level will give the optimum value, DSW hatch style will be used with R_4 or R_3 combination. This is because R_4 and R_3 with DSW hatch style gives the minimum value of flatness and this is more robust.

For the layer thickness of 0.250 mm, there seems not to be a similar pattern to what was observed in the flatness results for the 0.190 mm layer thickness. However, it is similar to what was observed in the results of the 0.125 mm layer thickness where SW hatch style gives the least value of flatness as shown in **figure 6** for 0.250 mm layer thickness. This suggests that both the hatch style and the layer thickness affect the flatness of the model.[ref] From the ANOVA data, R_4 gives the optimum combination for SW hatch style while for DSW hatch style it is R_1 hatch style. Factor C is consistently significant for SW hatch style in all the stages while factor A is only significant in the cured state. As for DSW hatch style all the three factors are significant but the percentage contribution of factor A is higher than the other two factors while the percentage contribution of factor C is the least. Since factor C deals with the surface, it should be better to contribute more and this may explained why the flatness is least is SW hatch style where factor C is not only statistically significant but also the percentage contribution is the highest of the three factors. As for the DSW hatch style it is more robust with factor A at level 2, factor B at level 2 and factor C at level 1. Hence changing the factors A and B levels may give a very robust design. It will therefore be a good idea to carry out further experiment with R_2 of SW hatch style or R_2 of DSW hatch style to confirm these findings.

5.0 CONFIRMATION EXPERIMENT

For the confirmation experiment, R_3 with DSW was used after considering other factors and their effect on the process mean. **Figure 7** shows the flatness of the part for the three different layer thicknesses. The chart shows that there is a significant improvement in the flatness as a result of the optimum factor combination which has been used. There is about 15% improvement in the flatness of the part for the 0.125 mm, 64% for the 0.190 mm and 80% for the 0.250 mm layer thickness. These low values of the flatness confirms that the optimum combination is in line with Taguchi philosophy of the smaller-the-best.

	Level 1 (mm)	Level 2 (mm)	Level 3 (mm)
Layer thickness	0.125	0.190	0.250
Hatch spacing (A)	0.210	0.200	
Hatch overcure (B)	-0.04	-0.035	
Hatch fill cure depth (C)	0.250	0.200	

Table 1 List of experimental parameters and their factor levels.

		FACTOR/LEVEL		
		A	B	C
No.1	R_1	1	1	1
No.2	R_2	1	2	2
No.3	R_3	2	1	2
No.4	R_4	2	2	1

Table 2 Experimental Runs and Level Combination.

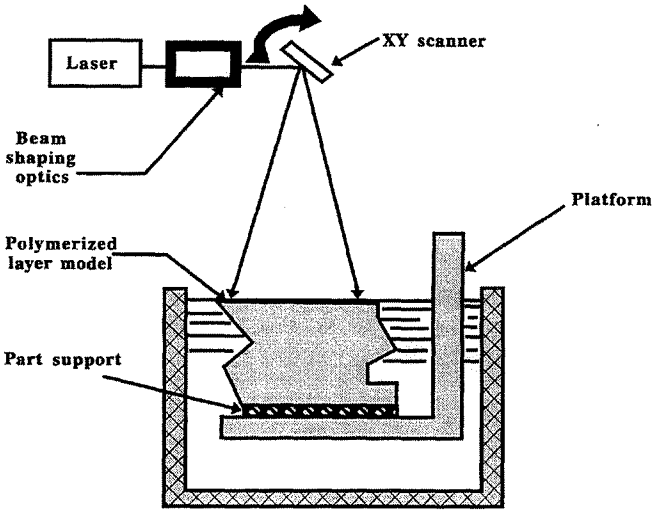

Figure 1 Schematics of Stereolithography.

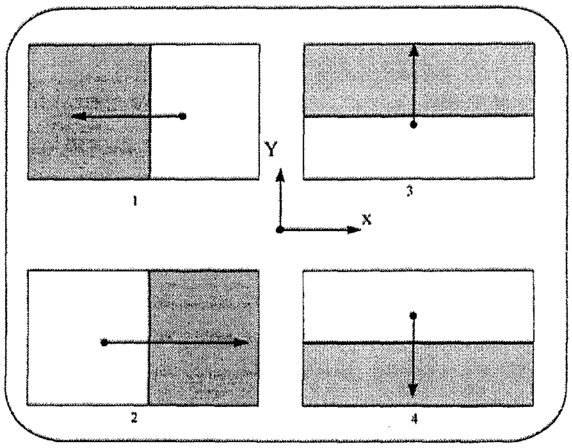

Figure 2 Schematic of DSW hatch style.

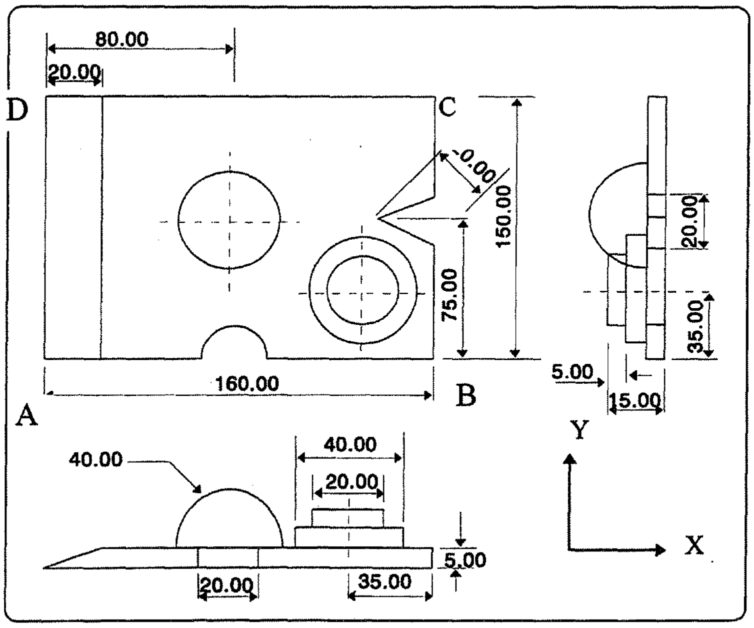

Figure 3 The Experimental Model.

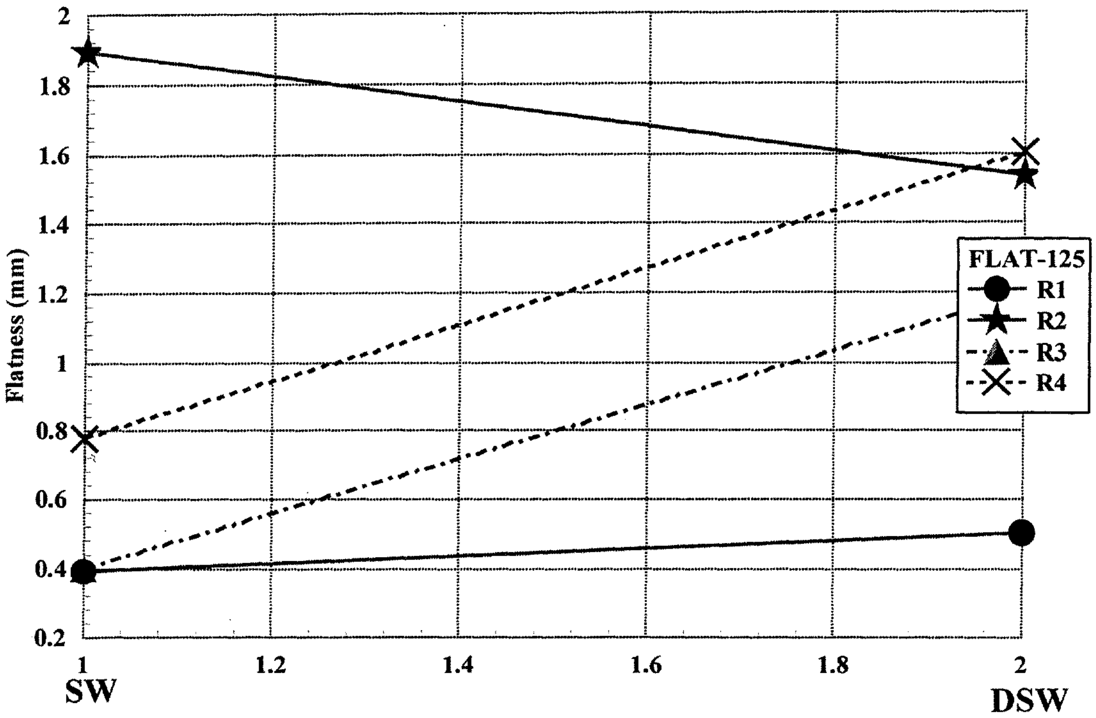

Figure 4 Average flatness values for the 0.125 mm layer thickness.

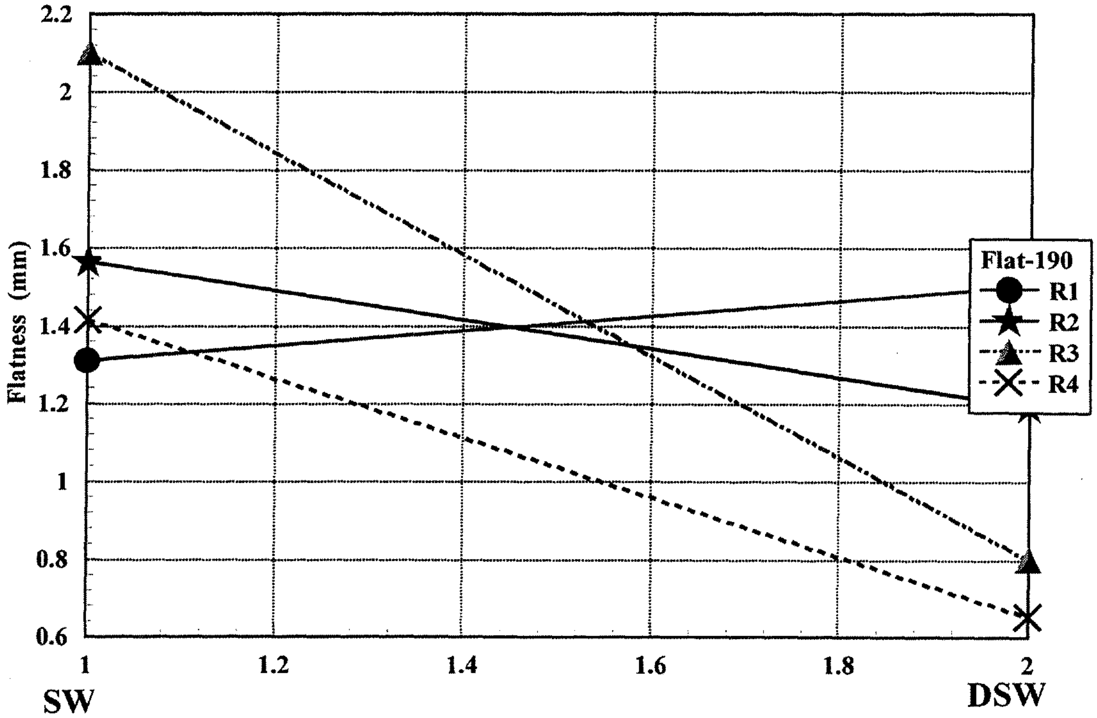

Figure 5 Average flatness values for the 0.190 mm layer thickness.

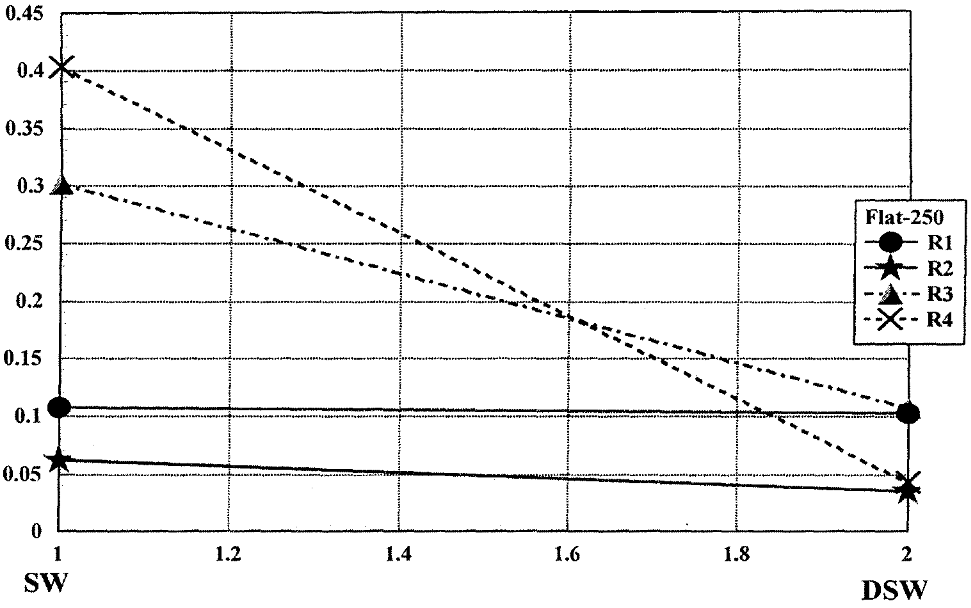

Figure 6 Average flatness values for the 0.250 mm layer thickness.

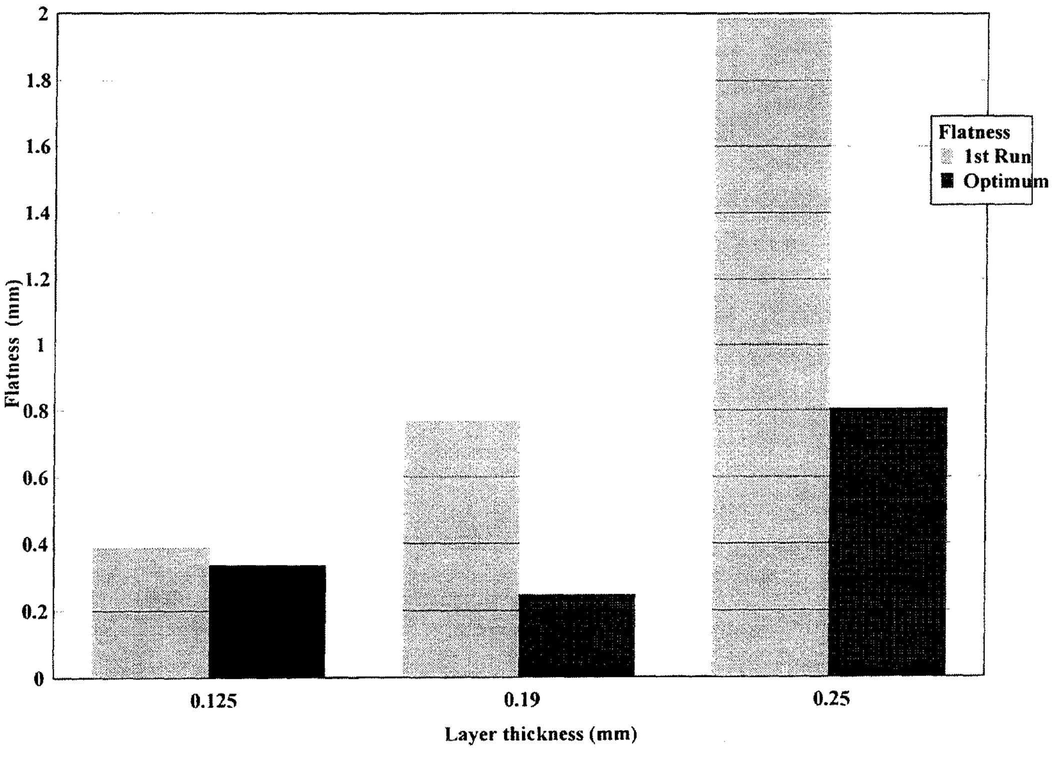

Figure 7 First run and confirmation experiment values for the flatness.