Response surface method for optimisation of SLA processing parameters

Mahmoud Ahmed El-Sayed*

Arab Academy for Science and Technology and Maritime Transport,
Abu Qir, P.O. Box 1029, Alexandria 21599, Egypt
Email: m_elsayed@aast.edu
*Corresponding author

Nour El-Nakeeb

Sovyen, a Cargil-ADM Joint Venture,
Alexandria, Egypt
Email: I.Shyha@napier.ac.uk

Islam Shyha

Edinburgh Napier University,
Edinburgh EH11-4BN, UK
Email: I.Shyha@napier.ac.uk

Mootaz Ghazy

Arab Academy for Science and Technology and Maritime Transport,
Abu Qir, P.O. Box 1029, Alexandria 21599, Egypt
Email: mootaz.ghazy@aast.edu

Abstract: In the current study, response surface method (RSM) was applied to correlate stereolithography (SLA) process parameters such as layer thickness, hatch overcure, and part orientation to SLA part characteristics such as density, surface finish and ultimate tensile strength (UTS). The results showed that density was directly proportional to the hatch overcure but inversely affecting the layer thickness. Besides, the hatch overcure was shown to have a positive effect on the UTS, while the layer thickness was found to influence the UTS adversely. Furthermore, the relationship between the layer thickness and surface roughness was suggested to be directly proportional. The optimised values of process parameters indicated by the response surface model were 90°, 0.12 mm and 0.1 μm for the part orientation, hatch overcure and layer thickness, respectively. The corresponding predicted density, UTS and surface roughness of an SLA part were 1,098 kg/m3, 42.8 MPa and 5.31 μm, respectively.

Keywords: stereolithography; SLA; additive manufacturing; response surface method; RSM; process parameters; design of experiments; DoEs.

Reference to this paper should be made as follows: El-Sayed, M.A., El-Nakeeb, N., Shyha, I. and Ghazy, M. (xxxx) 'Response surface method for optimisation of SLA processing parameters', *Int. J. Materials and Product Technology*, Vol. X, No. Y, pp.xxx–xxx.

Biographical notes: Mahmoud Ahmed El-Sayed is a Professor of Advanced Manufacturing Techniques at the Department of Industrial and Management Engineering since November 2020. He was graduated from the Department of Production Engineering, Alexandria University in 2001 with an overall grade of Very Good with degree of honour, and then joined the Department of Industrial and Management Engineering, AASTMT in September 2001 as a teaching assistant. He earned his PhD from the University of Birmingham, UK in 2012.

Nour El-Nakeeb is graduated from the Industrial and Management Engineering department at the Araba Academy for Science and Technology and Martiame trasnport. She is currently procurement buyer at Soyven – A Cargill-ADM Joint Venture. HSE is experienced supply chain specialist with a demonstrated history of working in the building materials industry specifically in inventory management and purchasing.

Islam Shyha is a Professor of Manufacturing Engineering and the Head of Mechanical Engineering at Edinburgh Napier University. He has over 20 years of experience in higher education, having worked at Northumbria, Birmingham, and Alexandria universities. He received his higher education practice degree from Northumbria University, PhD from The University of Birmingham, MSc, and BSc from Alexandria University. He has extensive experience in composites machining. His work is supported by the UK Research Council, Innovate UK, and industry. He is a Fellow of the Higher Education Academy, teaches mechanical and manufacturing engineering courses and supervises advanced manufacturing Engineering projects.

Mootaz Ghazy is a Professor of Manufacturing Engineering at Industrial and Management Engineering department at the Arab Academy for Science and Technology and Maritime Transport (AASTMT). He has over 20 years of experience in higher education. He received his PhD degree from Newcastle University, MSc, and BSc from AASTMT University. He has extensive experience in advanced manufacturing and additive manufacturing. he teaches manufacturing engineering courses and supervises advanced manufacturing engineering projects.

1 Introduction

Additive manufacturing (AM) has evolved as frontier technology during the last decades (Al-Ahmari et al., 2019; Haleem et al., 2020; Javaid and Haleem, 2019; Hassanin et al., 2018, 2017; Srivastava et al., 2019). It allows the direct transformation of CAD files into functional prototypes which was found to tremendously reduce the lead time to produce physical prototypes necessary for design verification, fit and functional analysis (Essa et al., 2018; Hassanin et al., 2020a; Mohammed et al., 2020). There have been an increasing number of reports on AM different materials, especially Al-alloys recently, because of the demand from the industrial field for lightweight structures with complex geometries (El-Sayed et al., 2013; Griffiths et al., 2014a, 2014b). Stereolithography

(SLA) is the first AM process in the rapid prototyping family (Essa et al.., 2017). his is not a reference, the statement should be: Since its introduction by Hull in 1984, it has established itself as the main technique for rapid prototyping and manufacturing, especially in the automotive and biomedical industries. The primary layer-based manufacturing mechanism of SLA is built upon a scanning pattern for the entire cross-section of each layer (Hon et al., 2006). The SLA apparatus can produce parts from a 3D CAD model by scanning an ultraviolet laser beam over a resin liquid layer, causing the monomers of the liquid resin to polymerise into a solid (Ghadami, 2014) and joining it to the layer underneath.

The SLA samples' quality depends upon many process parameters such as layer thickness, hatch spacing, hatch overcure, part orientation, angle of the laser beam and post-cure method. These parameters were determined to significantly affect the density, mechanical properties, surface finish, and dimensional accuracy of the fabricated part. Therefore, it is essential to understand how these parameters affect the part properties to achieve a better quality of parts produced by this process (Cotabarren et al., 2019; Karumuri et al., 2021; Kunjan, 2017; Mele et al., 2019; Piedra-Cascón et al., 2021; Seprianto et al., 2020; Shumkov et al., 2020).

Significant research has been conducted in this matter to enhance the SLA process and minimise its setbacks. These investigations showed that layer thickness is the most critical parameter affecting the dimensional accuracy of SLA parts. According to Jacob's research in 1992, the smaller the layer thickness, the less laser exposure it would require during processing. Therefore, less part shrinkage and better dimensional accuracy could be obtained (Ghadami, 2014). Chockalingam et al. (2006) have discussed the effect of layer thickness on the microstructure and mechanical properties of SLA parts such as yield strength, ultimate tensile strength (UTS), impact strength, and residual stresses. To study this effect, three models were constructed under different layer thickness of 0.1, 0.125, and 0.15 mm, respectively. The authors reported that increasing the layer thickness reduced the yield strength, UTS and impact strength. When testing for residual stresses and strain relief rate, it was noted that low residual stresses and high strain relief rate were experienced with 0.125 mm layer thickness. The residual stresses and strain relief rate decreased with increasing the layer thickness above 0.125 mm. Microstructure analysis was also carried out for the specimens using a scanning electron microscope (SEM) and scanning probe image processor (SPIP) software. It was showed that the use of lower-layer thickness decreases the number of voids formed in the SLA part during the photo polymerisation process as well as their sizes, which was found to improve the density and strength of the components. Kazemi and Rahimi (2015) achieved similar results about the effect of layer thickness on the tensile strength. In a recent study by Seprianto et al. (2020), it was concluded that the layer thickness and exposure time (the duration at which the resin is exposed under the light source for each layer) were the most significant factors affecting the impact strength of SLA components. Similar conclusions were reported by Shumkov et al. (2020) about the effect of layer thickness and exposure time on the tensile and compressive properties of photopolymer material SI500.

Lee et al. (2021) also studied the effect of layer thickness on the dimensional accuracy, and the results were in line with Jacob's findings. The same study also suggested that increasing the hatch overcure, from –0.1 to 0.05 mm, will cause dimensional errors to increase. This is because of the increased exposure associated with the larger positive hatch overcure, which results in a larger dimensional error. In contrast, the increase in negative hatch overcure caused the dimensional error to decrease. Thus, to obtain smaller dimensional part errors within a build operating range, small layer thicknesses, negative hatch overcure and medium to large hatch spacing are desirable. In a recent study by Kunjan (2017), the authors reported a significate influence of SLA process parameters, especially hatch overcure and layer thickness, on the geometric tolerance and surface roughness of SLA components made with CIBA TOOL 5530. These conclusions were verified in a very recent review study prepared by Piedra-Cascón et al. (2021).

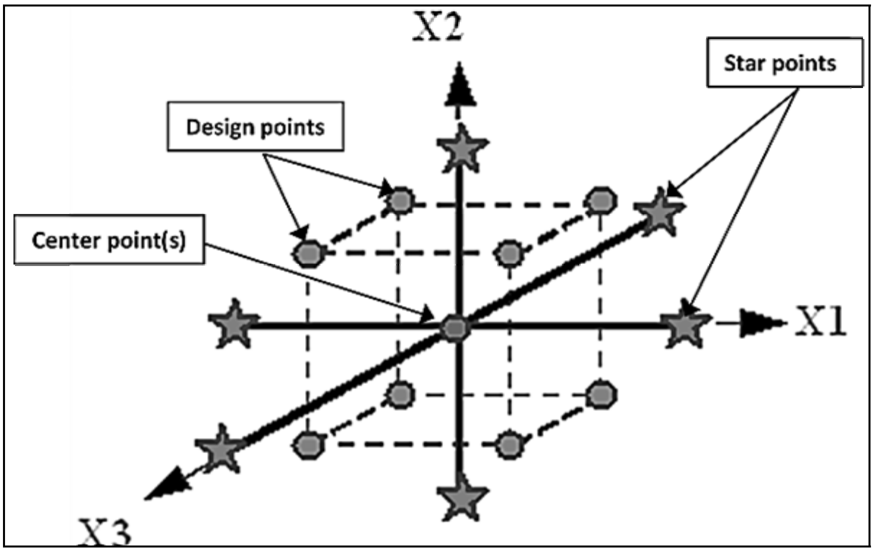
In another study, Salmoria et al. (2009) evaluated the influence of line hatch spacing on the hardness and the degree of cure of SLA parts. Their results showed that lower line hatch spacing would produce a more compactly cured structure that increases the hardness. The results also suggested that the default value of line hatch spacing of 0.10 mm seems to be optimum to build high-performance SLA parts, mainly if a thermal post-cure process is applied.

Since the SLA process builds parts by adding successive layers of the same material, there will inevitably be a stair-stepping effect. Ancau and Caizar (Lee et al., 2001) stated that the staircase effect greatly depends on the layer thickness. The decrease of the layer thickness will decrease the staircase effect and will improve the surface roughness.

Part orientation is also considered one of the most critical process parameters in SLA. A suitable part deposition orientation can improve the mechanical properties (Gowda et al., 2014), the part accuracy and surface finish and reduce production time and support structures needed for building the part (Pandey et al., 2007). In the study conducted by Gowda et al. (2014), three tests were carried out; tensile test, flexural test and impact test. Three different part orientations were used to build the parts for the experiment, namely H_x (0°), VH_{xy} (45°) and V_y (90°). The results showed that at V_y (90°), optimum mechanical properties (maximum strengths) were obtained. In the same study, the authors attempted to analyse the process parameters that influence the strength aspect of the SLA parts. They concluded the following: layer thickness, part orientation, and hatch spacing have the most influence on the strength of SLA prototypes. They also found that the optimal level combination of the process parameters (corresponds to highest tensile, flexural and impact strengths) was as follows: layer thickness: 0.125 mm, orientation: 90° and hatch spacing: 0.15 mm. Among the three process parameters, the layer thickness and part orientation were major contributing parameters for the tensile strength. In addition, part orientation and hatch spacing were major contributing parameters for the flexural strength. Finally, the part orientation was the most significant among all the impact strength parameters (Gowda et al., 2014). Recent research has also suggested that selecting the correct part orientation would improve the accuracy and performance of objects produced using SLA (Cotabarren et al., 2019; Mele et al., 2019).

Design of experiment (DoE) is an inexpensive statistical modelling approach used to analyse the influence of different factors on specific responses of a component or a process. The use of the DoEs procedures such as analysis of variance (ANOVA) and the response surface method (RSM) has demonstrated to be effective in dealing with the impact of many factors and their interactions affecting the measured properties in material processing aiming to optimise the process (Sing et al., 2018; El-Sayed, 2016). RSM approach uses an experimental design to fit a model by using the least squares method. Subsequently, the suitability of the developed model is assessed using the ANOVA (Hader and Park, 1978). Finally, the response surface graphs are used to construct the model surfaces and predict the optimum conditions. One of the widely used RSM tools is the central composite design. Each of the numeric factors under investigation is set into three levels, with +1, 0 and –1, respectively. Two additional axial (face or star) points are also considered for each factor at a distance from the basal (centre) point of $-\alpha$ and $+\alpha$, respectively. A three-factor CCD design is shown in Figure 1. If categorical factors are added, the central composite design will be duplicated for every combination of the categorical factor levels. For many AM processes, RSM was effectively applied to evaluate process parameters' effect on the quality of the components produced (El-Sayed et al., 2019).

Figure 1 A central composite design for three factors



Source: El-Sayed et al. (2020)

Despite the reviewed research, SLA process parameters' effect on the characteristics of Accura Xtreme plastics parts produced is still lacking. Such material can effectively replace traditional polypropylene (PP) and ABS materials. There is an urgent need to study this commercial polymer to report the correct settings of SLA process parameters required to fabricate such material usefully. Accordingly, this paper presents an attempt to understand the relationship between several SLA process parameters such as layer thickness, hatch overcure and part orientation on the quality characteristics of the fabricated components such as density, UTS and surface roughness. DoE using ANOVA and RSM will be adopted to optimise the process parameters in order to fabricate Accura Xtreme plastics parts with appropriate surface finish and improved mechanical properties.

2 Experimental work

2.1 Materials

Accura Xtreme is an ultra-tough, temperature-resistant white plastic that resists breakage and handles challenging functional assemblies has several beneficial properties such as the fast recoating and build times, durability, accuracy, and the aesthetics of moulded PP or ABS. This material has the advantage over other plastics as it can be used in more applications such as snap fit assemblies, enclosures for consumer and electronic products, function prototypes and durable assemblies (Prechtl et al., 2017).

2.2 Design of experiments

In this study, the DoE was carried out using the response surface methodology, which is a statistical technique to generate an experimental design to find a relationship between input and output parameters and to optimise the process responses (e.g., towards a maximum or a minimum). The main objective is to optimise the response surface, which is influenced by various process parameters. The response surface Y can be expressed by a second-order polynomial (regression) equation, as shown in equation (1):

$$Y = b_o + \sum b_i x_i + \sum b_{ii} x_i^2 + \sum b_{ij} x_i x_j \quad (1)$$

where x_i and x_j are the factors input parameters, the terms b_o, b_i, b_{ii}, and b_{ij} are the model coefficients that depend on the main and interaction effects of the process parameters. Design-Expert Software version 7.0.0 (Stat-Ease Inc., Minneapolis, USA) was used to perform the DoE.

The procedure adopted in this study was as the following:

1. Identification of the key process parameters and setting the upper and lower bound for each.
2. Selection of the output response.
3. Developing the experimental design matrix.
4. Carrying out the experiments according to the design matrix and recording the output response.
5. Developing a mathematical model to correlate the process parameters to the output response.
6. Optimising that model using genetic algorithm.

In the current study, three factors (process parameters) were considered: the part orientation, hatch overcure and layer thickness. Due to the technical capabilities of the SLA 5000 machine, the layer thickness could be set at only two levels (0.1 and 0.15 mm). Therefore, the layer thickness was considered as a categorical factor in this study. According to the central composite design, and as described above, each numeric parameter (i.e., part orientation and hatch overcure) was varied over five levels ($-\alpha$, –1, 0, 1 and α). See Figure 1. In this work, α was considered to be 2 in order to change each factor over five equal levels. Table 1 shows the levels of each factor in this investigation. As shown, $-\alpha$ and α represent the minimum and maximum levels respectively, of each factor. Also, a number of centre points [at the 0 level (middle) of all factors (see Figure 1)] were considered. The centre points are used to provide information about the experimental error.

Table 1 The range of matrix building parameters

Parameter	*Units*	*Levels*				
		-α	–1	0	1	α
Part orientation	Degree	0	22.2	45	67.5	90
Hatch overcure	mm	–0.0250	0.0125	0.0500	0.0875	0.1250
Layer thickness	mm	0.1			0.15	

Table 2 Matrix building parameters, density, UTS and surface roughness

Run	*Process variables*			*Measured responses*		
	Orientation (°)	*Hatch overcure (mm)*	*Layer thickness (mm)*	*Density (kg/m^3)*	*UTS (MPa)*	*Ra (µm)*
1	22.5	0.0500	0.10	1044	40.0	2.07
2	90.0	–0.0250	0.10	1014	35.6	2.50
3	45.0	0.0500	0.15	971	14.4	3.27
4	45.0	0.0875	0.10	1067	40.9	2.50
5	45.0	0.0875	0.15	1001	26.0	3.52
6	90.0	0.1250	0.15	1008	27.3	3.71
7	0.0	0.1250	0.15	1009	30.3	3.76
8	0.0	0.1250	0.10	1098	41.8	2.57
9	90.0	–0.0250	0.15	949	6.6	3.82
10	90.0	0.1250	0.10	1125	42.6	2.64
11	45.0	0.0500	0.10	1047	40.1	2.72
12	67.5	0.0500	0.10	1055	40.1	2.72
13	22.5	0.0500	0.15	975	15.1	3.95
14	45.0	0.0500	0.10	1063	40.2	2.84
15	45.0	0.0125	0.10	1038	39.8	2.99
16	67.5	0.0500	0.15	998	21.4	3.95
17	0.0	–0.0250	0.10	1029	36.6	3.03
18	45.0	0.0125	0.15	959	13.4	4.24
19	0.0	–0.0250	0.15	950	9.8	4.28
20	45.0	0.0500	0.15	982	21.4	4.76

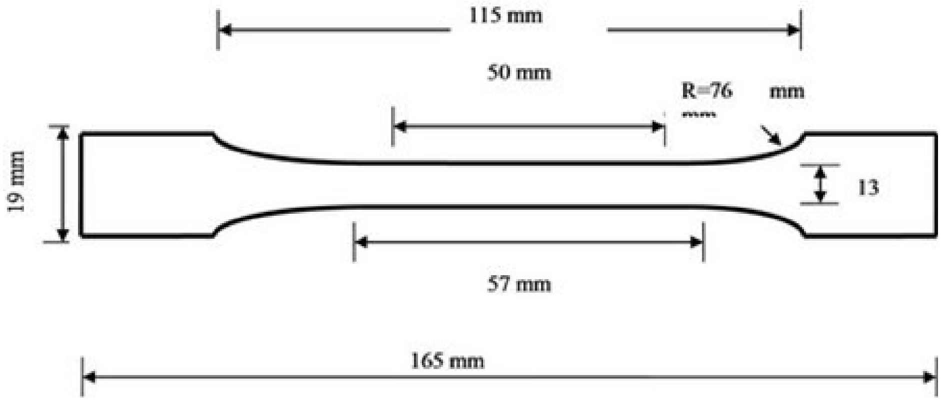
Furthermore, the central composite design related to combining the two numeric factors in the current study was duplicated for each of the layer thickness levels. This resulted in the identification of 20 parametric combinations for testing, as shown in Table 2. Density, UTS, and surface roughness (Ra) represent fabricated samples' quality characteristics.

2.3 Sample build and characterisation

SLA components were fabricated using the 3D system SLA 5000 machine at Science and Technology Center of Excellence (STCE), Cairo, Egypt. The uses a UV laser to cure a vat of photo-reactive resin. The various conditions in pre-processing steps such as STL verification, deposition layer thickness, orientation, building interior structure form, supporting method, and building deposition direction are incorporated employing 3D light year 1.5.2 software provided by 3D systems of Valencia, USA (User Manual, 1988).

Standard tensile test specimens with the shape and dimensions shown in Figure 2 and with a thickness of 7 mm, were produced using the SLA process. As stated above, 20 samples with different parametric combinations were built using a fractional factorial DoE. All samples were fabricated flat concerning the *x*-*y* plane but at different angles to the *x*-axis. The samples were printed over two batches, each of a different layer thickness (i.e., 0.1 and 0.15 mm) and each batch contained ten samples. The build time of the 0.1 mm layer thickness batch and the 0.15 mm layer thickness batch were 8.5 and 7.15 hours, respectively. The values of other parameters were kept constant during fabrication. These include laser power at 94 mW, border speed at 5.5 m/s, hatch speed at 47.6 m/sec, fill speed at 58.9 m/sec and hatch spacing at 0.25 mm.

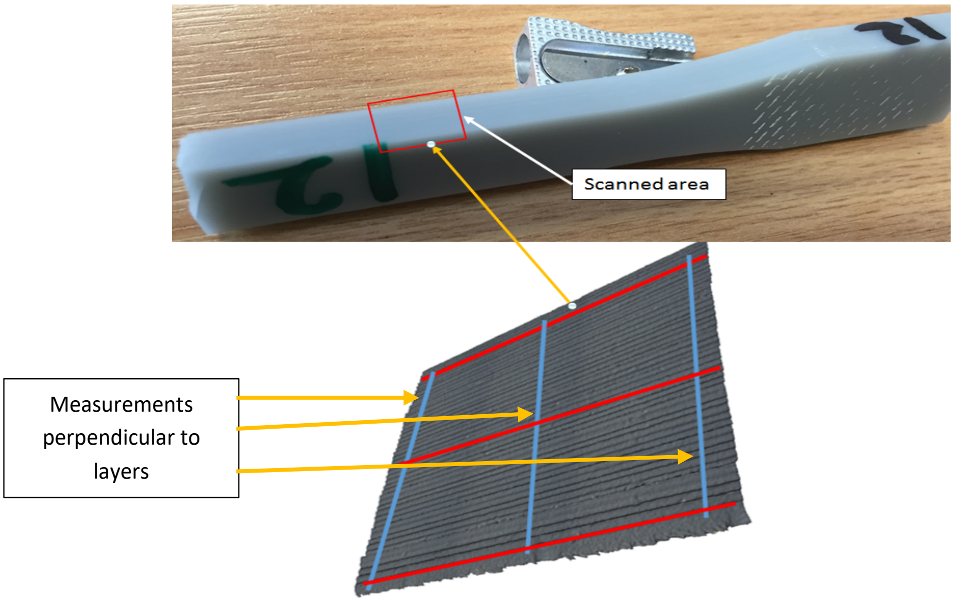
Figure 2 Dimensions of the test bar built using the SLA process



For each sample, the density, surface roughness and UTS were evaluated to study the effect of different process parameters on the part characteristics. The density of the samples was determined through the water immersion Archimedes method.

The average surface roughness (Ra) and profile analysis for the SLA parts were assessed using an Alicona Infinite Focus G4 optical scanner, a resolution down to 200 µm employing ten magnification factors. The scanning area was 8 mm × 7 mm (specimen thickness). Scans were obtained using 599 nm and 5.40 µm vertical (*Z* direction) and lateral (*X* and *Y*) resolutions, respectively. All measurements confirmed to ISO 4287 and ISO 4288 using 0.8 mm cut-off and evaluation length of 7.5 mm and 6 mm parallel and perpendicular to the layers, respectively. Three measurements were taken perpendicular to the direction of the layers, as shown in Figure 3. For each sample, the average surface roughness (Ra) of the three parallel measurements and three perpendicular measurements was considered a response. Finally, a tensile test was carried out on each sample using a MecmesinMultiTest 5-Xt tensile testing machine, with a 5 mm/min strain rate.

Figure 3 Location of surface roughness measurement and scanned profile (see online version for colours)



3 Results and discussion

The measured values of density, UTS and surface roughness, along with the parametric combinations, are presented in Table 2. The response surface of the UTS was suggested to be represented as a two-factor interaction (2FI) model of the parameters of the SLA process [i.e., orientation (*O*), hatch overcure (*H*) and layer thickness (*T*)], that could be given as shown in equation (2). In addition, density and surface roughness were linear functions of the three parameters, expressed in equation (3).

$$Response = b_o + b_1(O) + b_2(H) + b_3(T) + b_4(OH) + b_5(OT) + b_6(HT) \quad (2)$$

$$Response = b_o + b_1(O) + b_2(H) + b_3(T) \quad (3)$$

where b_o is the average response, and b_1, b_2, …, b_6 are the model coefficients that depend on the main and interaction effects of the process parameters. Least squares fitting, which is a mathematical procedure for finding the best-fitting curve to a given set of points by minimising the sum of the squares of the offsets of the points from the curve, was applied to analyse the data presented in Table 2 and to determine the constant coefficients (Hassanin et al., 2020b). The values of the coefficients for the response surface of the density, UTS and surface roughness are shown in Table 3. The coefficient of correlation (R^2) of the models describing the relationship between the process parameters and the density, UTS and surface roughness were 0.95, 0.88 and 0.80, respectively.

Table 3 Response surface model coefficients for the density, UTS and surface roughness

Coefficient	*Density model*	*UTS model*	*Surface roughness model*
b_o	+1019.13	+29.17	+3.29
b_1	+2.86	–0.37	–0.071
b_2	+37.13	+6.70	–0.17
b_3	–38.87	–10.60	+0.63
b_4	0	+0.24	0
b_5	0	–0.34	0
b_6	0	+3.87	0

Table 4 shows the ANOVA *p*-values for each of the parameters and parameter interactions for each of the density, UTS and surface roughness. In statistical significance testing, the *p*-value is the probability of obtaining a test statistic at least as extreme as the one that was observed, assuming that the null hypothesis is correct. The null hypothesis (which assumes that all parameters have no significant effect) is rejected when the *p*-value is less than the predetermined significance level, which is 0.05 (95% confidence level). This means that any factor with a *p*-value less than 0.05 is considered a significant model parameter (Carter et al., 2015; Hassanin et al., 2016). In this study, the ANOVA indicated that the most significant factors influencing both the density and UTS were the hatch overcure and layer thickness within the investigated range of parameters. Also, the interaction between both factors was suggested to affect the UTS of SLA parts. Finally, the surface roughness of an SLA component was mainly influenced by the layer thickness only.

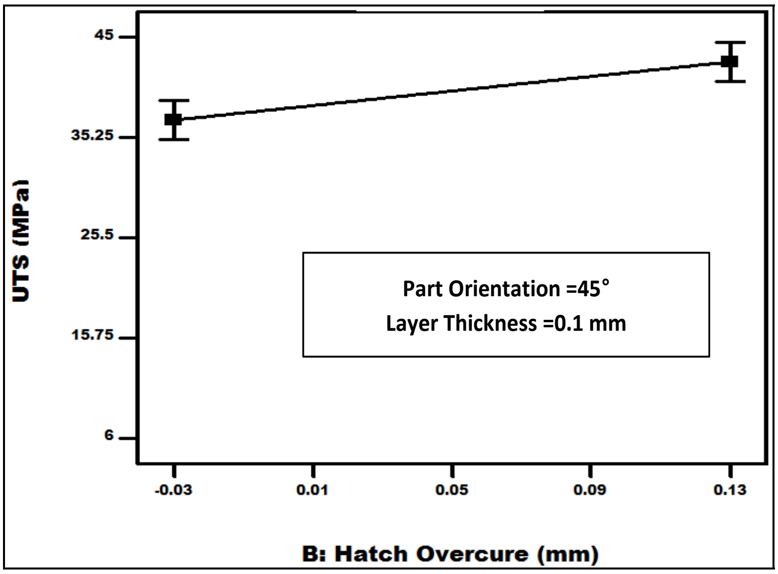
Table 4 ANOVA *p*-values for each of the parameters and parameter interactions for the density, UTS and surface roughness

Model parameter	*P-value*		
	Density	*UTS*	*Ra*
O	0.4624	0.6254	0.5538
H	*< 0.0001*	*< 0.0001*	0.1634
T	*< 0.0001*	*< 0.0001*	*< 0.0001*
OH	NA	0.7615	NA
OT	NA	0.6505	NA
HT	NA	*0.0002*	NA

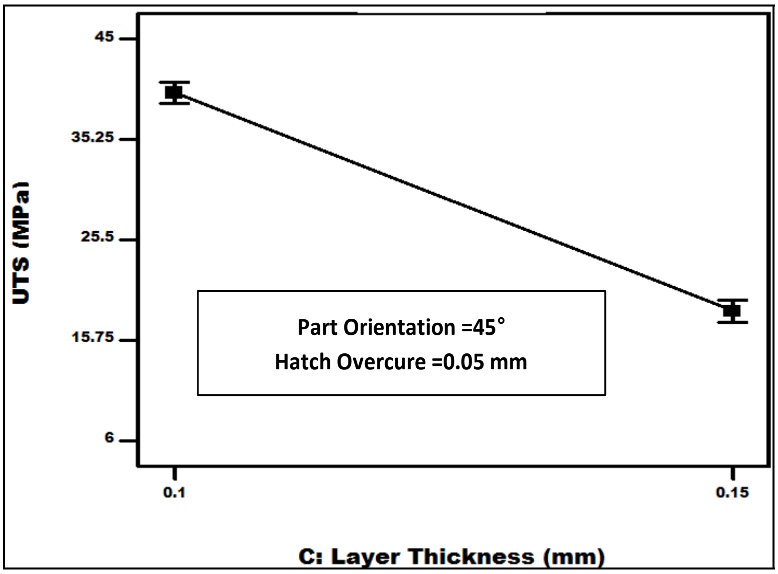
Note: Italic values indicate statistically significant process parameters (p-value < 0.05)

Figures 4(a) and 4(b) show the UTS response surface model prediction against hatch overcure and layer thickness, respectively. It was shown that the UTS of the SLA component increased consistently with either increasing the hatch overcure and/or decreasing the layer thickness. These findings were in agreement with the results by Seprianto et al. (2020), who reported that the main factor that had the most influence on the impact strength of the SLA test specimens from 3D UV Resin Anycubic material was the layer Thickness factor with a percentage contribution of 52%. Besides, and as indicated by the model, it seems that the interaction between the hatch overcure and layer thickness is also significant, as shown in Figure 4(c). At larger layer thickness, the effect of hatch overcure on the UTS is more considerable. Conversely, the influence of layer thickness is more significant at smaller values of hatch overcure.

Figure 4 Response surface plot showing the effect of (a) hatch overcure, (b) layer thickness and (c) the interaction between hatch overcure and layer thickness on the UTS (see online version for colours)

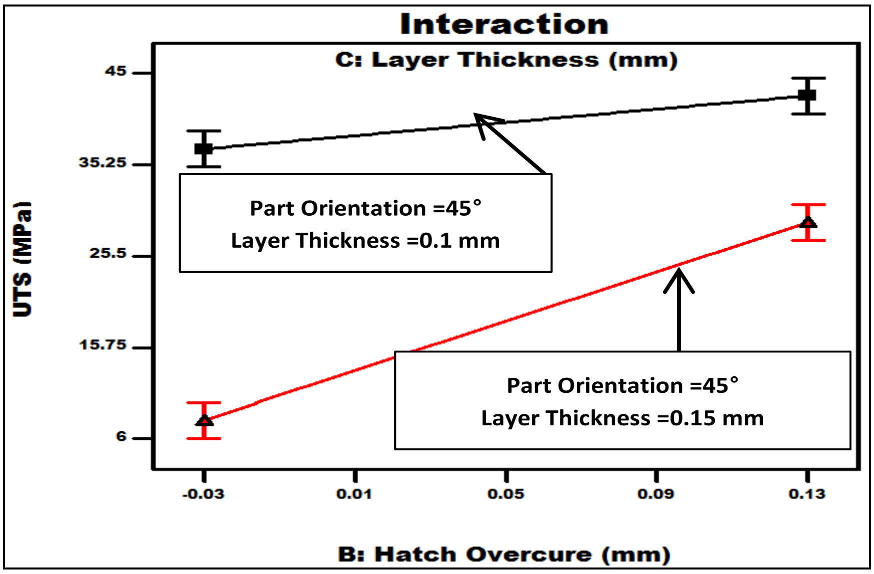


(a)



(b)

Figure 4 Response surface plot showing the effect of (a) hatch overcure, (b) layer thickness and (c) the interaction between hatch overcure and layer thickness on the UTS (continued) (see online version for colours)



(c)

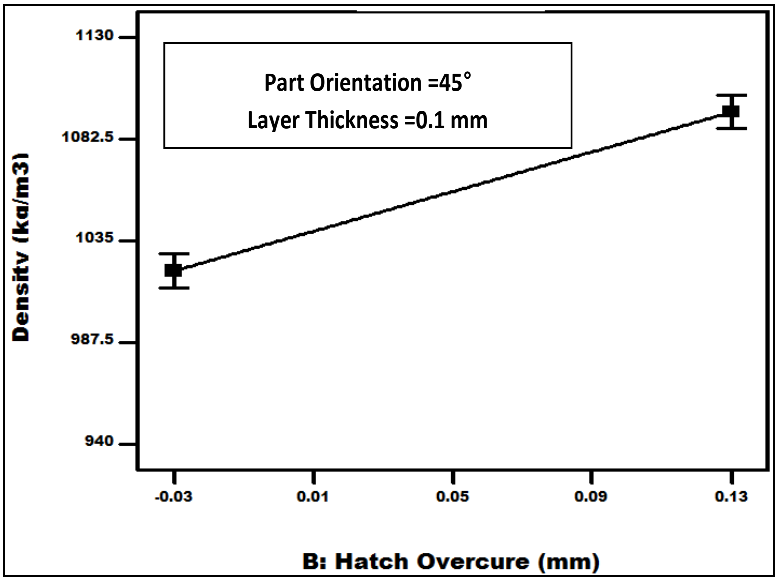
Both the hatch overcure and layer thickness were found to directly affect the density of SLA parts. As shown in Figure 5(a), a larger hatch overcure was found to enhance the density. The same effect was observed when adopting a smaller layer thickness value, as could be inferred from Figure 5(b).

Lee et al. (2001) stated that manufacturing SLA parts using a positive hatch overcure requires more laser exposure than when a negative hatch overcure is considered. This increase in exposure leads to higher densities of SLA parts and was also suggested to improve the mechanical properties. On the other hand, Ghadami (2014) suspected that adopting smaller values of hatch overcure would reduce the amount of laser exposure, which subsequently resulted in less shrinkage and improved dimensional accuracy.

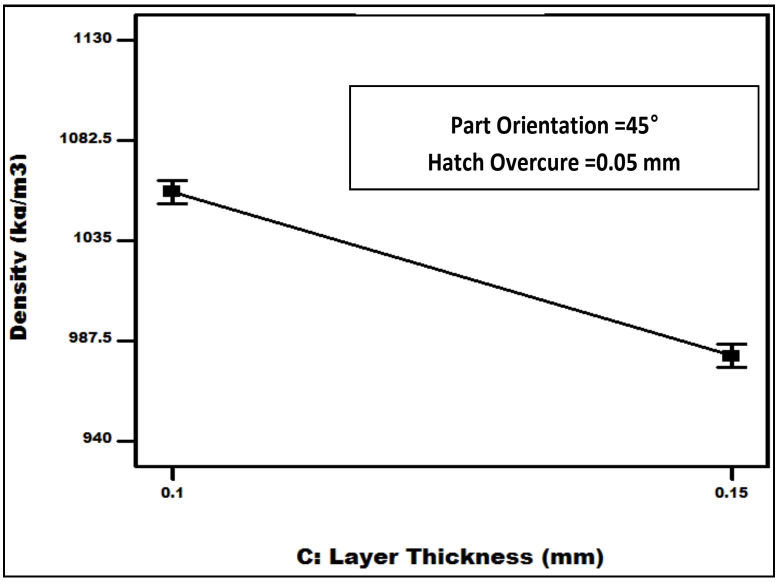
In another study on the effect of layer thickness on the microstructure of SLA parts, it was reported that the use of a lower layer thickness decreased the number of voids formed during the photo polymerisation process, as well as their sizes, resulting in a higher density of SLA parts (Chockalingam et al., 2006). On the contrary, larger size voids were observed with larger layer thickness. These larger voids formed during fabrication were shown to reduce the component's density and, accordingly, result in lower SLA components' strength.

In the current work, both the hatch overcure and layer thickness influence the part density. At constant values of part orientation and layer thickness of 45° and 0.1 mm, increasing the hatch overcure from –0.03 to 0.13 mm increased the density of an SLA part from 1,020 to 1,095 kg/m^3, as shown in Figure 5(a). Similar enhancement in the density can be obtained by decreasing the layer thickness from 0.15 to 0.1 mm, while the part orientation and hatch overcure cure are kept at 45° and 0.05 mm, respectively. See Figure 5(b). These results could confirm earlier results reported by Shumkov et al. (2020), who suggested an increase in the exposure time (related to the rise in hatch overcure), improved photopolymer material density SI500 and higher mechanical properties were obtained.

Figure 5 Response surface plot showing the effect of (a) hatch overcure and (b) layer thickness on the density



(a)

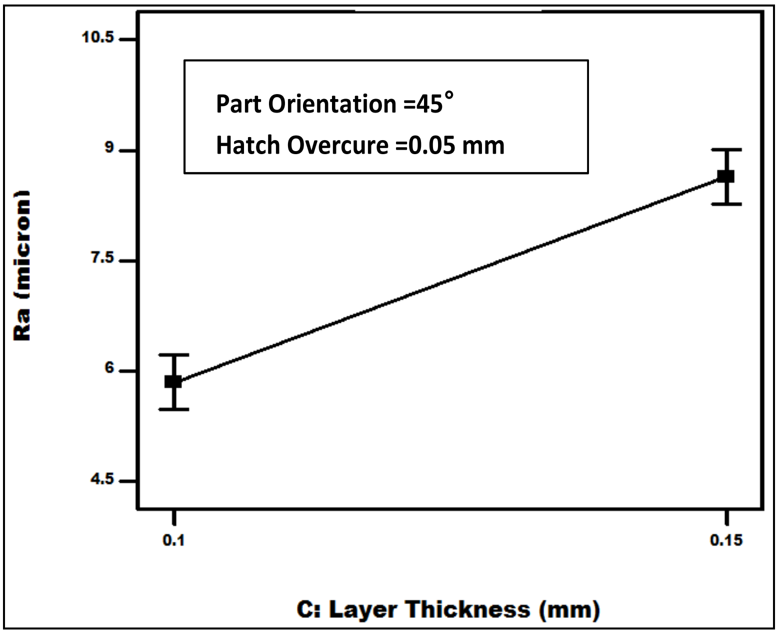


(b)

In addition, it was shown that the UTS of an SLA part could be increased by either increasing the hatch overcure and/or reducing the layer thickness. As shown in Figure 4(a), at 45° part orientation and 0.1 mm layer thickness, increasing the hatch over cure from –0.03 to 0.13 mm caused an increase in the UTS from 37 to 43 MPa. In addition, decreasing the layer thickness from 0.15 to 0.1 mm increased the UTS of an SLA part from 18 to 40 MPa (at constant part orientation and hatch overcure of 45° and 0.05 mm, respectively). This was expected, as shown above, that increasing the hatch overcure and/or decreasing the layer thickness would increase the density of an SLA part and accordingly, the mechanical properties of the SLA components. The current study's results could confirm the previous results obtained by Raju et al. (2014) and Chockalingam et al. (2006), who reported that the layer thickness was the most contributing parameter affecting the mechanical properties in SLA. They reported that increasing the layer thickness reduced both the yield strength and UTS of an SLA part.

Finally, the surface roughness of SLA components was suggested by the model to be directly proportional to the layer thickness, as indicated in Figure 6. At constant values of the part orientation and hatch overcure of 45°and 0.05 mm, reducing the layer thickness from 0.15 to 0.1 mm was associated with a decrease of the surface roughness from 8.6 to 5.8 µm.

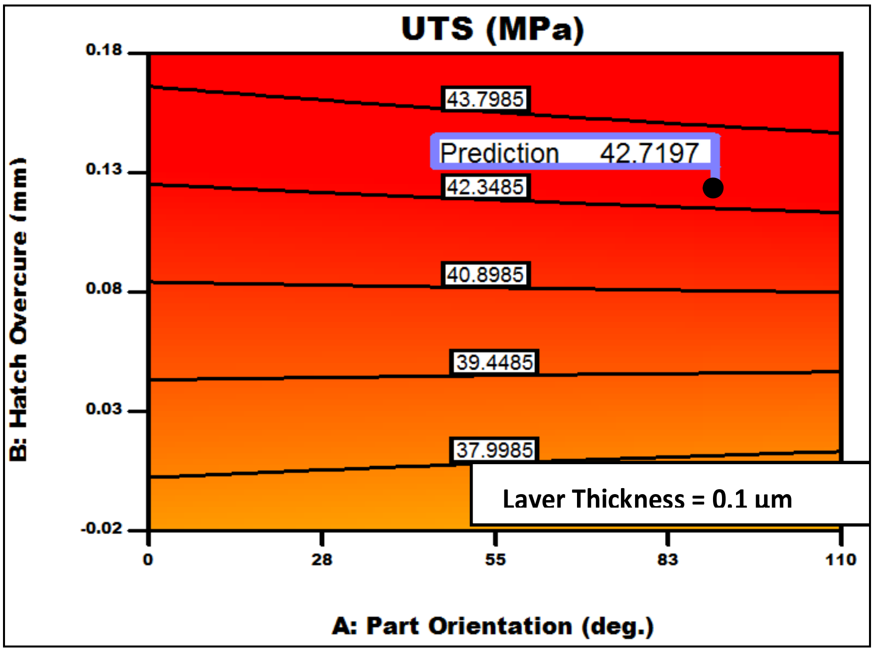
Figure 6 Response surface plot showing the effect of layer thickness on the surface roughness



Ancau and Caizar (Lee et al., 2001) stated that the staircase effect depends mainly upon the layer thickness. The decrease of the layer thickness would decrease the staircase effect and improve the surface finish. Kim and Lee (2005) also stated that the stair-stepping impact is one of the significant factors affecting an SLA component's surface roughness. They suggested that the simplest method for reducing surface roughness was to reduce a slice's layer thickness. This reduction would result in the better surface quality of finished parts but increased the build time and required a new recoating mechanism. In another study by Kunjan (2017), it was also reported that the layer thickness has a significate impact on the surface roughness of SLA components. These results by Kim and Lee (2005) and Kunjan (2017) were in agreement with those obtained in the current investigation that showed a 33% reduction in the surface roughness of an SLA part corresponding to a 33% decrease in the layer thickness. See Figure 6.

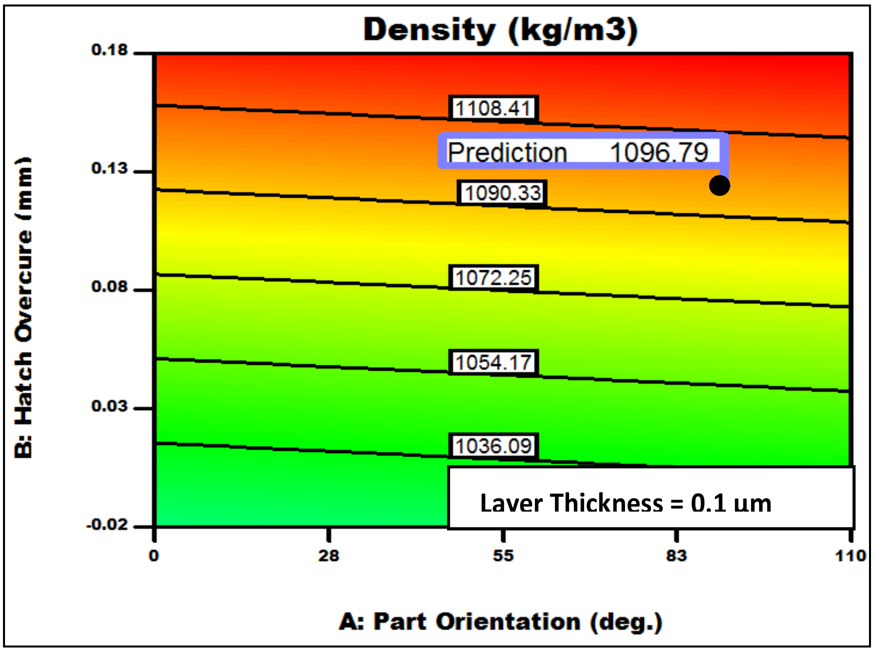
An optimisation study was carried out to explore the optimum processing parameters at which the desirable density, UTS and surface finish of an SLA part can be achieved. The objective function was set to maximise both the density and UTS while achieving minimum possible corresponding surface roughness. The experimental data were analysed by design-expert software, and the genetic algorithm was used to predict the process parameters based on the objective function. The response equations describing both the porosity and surface roughness in terms of the key process parameters [shown in equations (2) and (3) and the related coefficients listed in Table 3] were solved simultaneously. The results by design-expert software are shown in Figure 7 which shows the contour plot for the optimisation function to obtain the highest density and UTS, and the lowest surface roughness, for a range of part orientation and hatch overcure. The model suggested that the process parameters' optimised values would be 90°, 0.12 mm and 0.1 µm for the part orientation, hatch overcure and layer thickness, respectively. At these values of process parameters, the predicted density, UTS and surface roughness of an SLA part would be 1,098 kg/m^3, 42.8 MPa and 5.31 µm, respectively.

Figure 7 Predicted optimum part orientation, hatch overcure and layer thickness corresponding to (a) maximum UTS, (b) maximum density and (c) minimum surface roughness (see online version for colours)

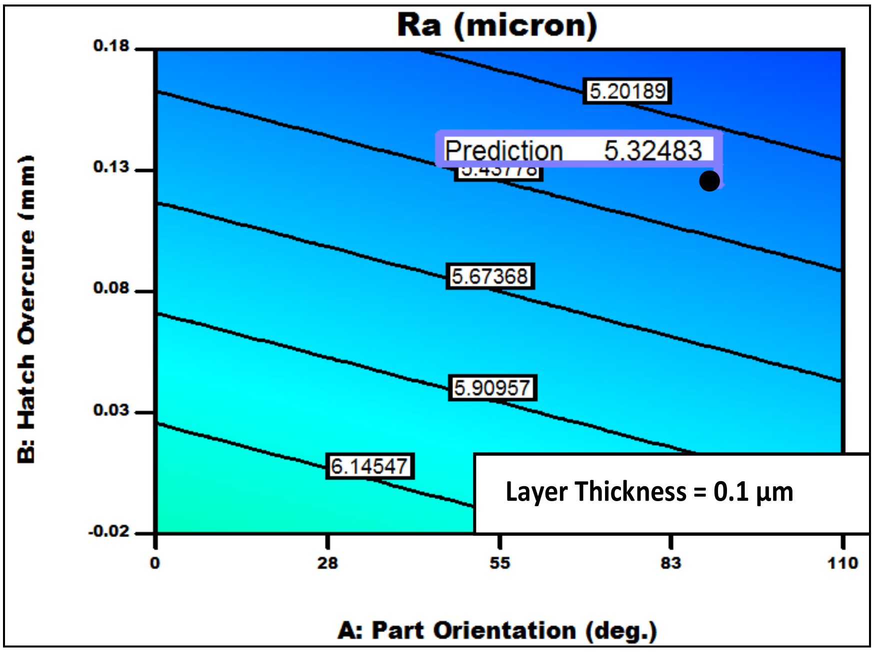


(a)

Figure 7 Predicted optimum part orientation, hatch overcure and layer thickness corresponding to (a) maximum UTS, (b) maximum density and (c) minimum surface roughness (continued) (see online version for colours)



(b)



(c)

It should be emphasised that the part orientation was found to be an insignificant factor in this study. The statistical model indicated that there was no effect of the part orientation on SLA part characteristics. This might be because all samples were fabricated parallel to the *x*-*y* plane but at different angles to the *x*-axis, which means that the orientation of different layers (or layer-to-layer interfaces) with respect to an SLA component was the same for parts fabricated in this study. This was in agreement with results by Quintana et al. (2010) and Hague et al. (2004). They suggested that changing the position (angle) of the part regarding any of the *x*, *y* or *z* axes had no significant effect on the mechanical properties of SLA parts as the samples had identical sample layer interfaces and therefore were isotropic parts.

4 Conclusions

This research aimed to study the effect of SLA process parameters on part characteristics fabricated using Accura Xtreme material. In this study, 20 standard test specimens were manufactured using SLA 5000 machine. Three tests were then performed on each specimen to evaluate the part properties, and the results were recorded and analysed. The DoEs was then used to correlate the process parameters with the part characteristics, and the conclusions were as follows:

1. The density was directly proportional to the hatch overcure but inversely proportional to the layer thickness. Increasing the hatch overcure from –0.03 to 0.13 mm increased the SLA part's density from 1,020 to 1,095 kg/m^3. The same increase in the density was obtained by decreasing the layer thickness from 0.15 to 0.1 mm.
2. For the UTS, the hatch overcure and layer thickness were the most significant model terms. As the hatch overcure increased from –0.03 to 0.13 mm, the UTS also increased from 37 to 43 MPa. As the layer thickness increases from 0.1 to 0.15 mm, the UTS decreased from 40 to 18 MPa.
3. The relationship between the layer thickness and surface roughness was directly proportional. Increasing the layer thickness from 0.1 to 0.15 mm, the surface roughness (Ra) also increased from 5.8 to 8.6 µm. This was reasoned to the increase of the stair-stepping effect associated with the increase of layer thickness.
4. The model suggested that the predicted density, UTS, and surface roughness of an SLA part would be 1,098 kg/m^3, 42.8 MPa and 5.31 µm, respectively at the predicted optimum values of the process parameters, which were 900, 0.12 mm and 0.1 µm for the part orientation, hatch overcure and layer thickness, respectively.

References

Al-Ahmari, A., Ashfaq, M., Mian, S.H. and Ameen, W. (2019) 'Evaluation of additive manufacturing technologies for dimensional and geometric accuracy', *International Journal of Materials and Product Technology*, Vol. 58, Nos. 2–3, pp.129–154.

Carter, L.N., Essa, K. and Attallah, M.M. (2015) 'Optimisation of selective laser melting for a high temperature Ni-superalloy', *Rapid Prototyping Journal*, Vol. 21, No. 4, pp.423–432.

Chockalingam, K., Jawahar, N. and Chandrasekhar, U. (2006) 'Influence of layer thickness on mechanical properties in stereolithography', *Rapid Prototyping Journal*, Vol. 12, No. 2, pp.106–113.

Cotabarren, I., Palla, C.A., McCue, C.T. and Hart, A.J. (2019) 'An assessment of the dimensional accuracy and geometry-resolution limit of desktop stereolithography using response surface methodology', *Rapid Prototyping Journal*, Vol. 25, No. 7, pp.1169–1186.

El-Sayed, M., Ghazy, M., Youssef, Y. and Essa, K. (2019) 'Optimization of SLM process parameters for Ti6Al4V medical implants', *Rapid Prototyping Journal*, Vol. 25, No. 3, pp.433–447.

El-Sayed, M., Salem, H.G., Kandeil, A-R. and Griffiths, W.D. (2013) 'A study of the behaviour of double oxide films in Al alloy melts', in *Materials Science Forum*, Trans Tech Publications Ltd.

El-Sayed, M.A. (2016) 'The behaviour of bifilm defects in cast Al-7Si-Mg alloy', *PloS One*, Vol. 11, No. 8, p.e0160633.

El-Sayed, M.A., Essa, K., Ghazy, M. and Hassanin, H. (2020) 'Design optimization of additively manufactured titanium lattice structures for biomedical implants', *The International Journal of Advanced Manufacturing Technology*, Vol. 119, No. 9, pp.2257–2268.

Essa, K., Modica, F., Imbaby, M., El-Sayed, M.A., ElShaer, A., Jiang, K. and Hassanin, H. (2017) 'Manufacturing of metallic micro-components using hybrid soft lithography and micro-electrical discharge machining', *The International Journal of Advanced Manufacturing Technology*, Vol. 91, Nos. 1–4, pp.445–452.

Essa, K., Sabouri, A., Butt, H., Basuny, F.H., Ghazy, M. and El-Sayed, M.A. (2018) 'Laser additive manufacturing of 3D meshes for optical applications', *PloS One*, Vol. 13, No. 2, p.e0192389.

Ghadami, F. (2014) 'Process parameters optimization to improve dimensional accuracy of stereolithography parts', *International Journal of Advanced Design and Manufacturing Technology*, Vol. 7, No. 1, p.59.

Gowda, R.B.S., Udayagiri, C.S. and Narendra, D.D. (2014) 'Studies on the process parameters of rapid prototyping technique (stereolithography) for the betterment of part quality', *International Journal of Manufacturing Engineering*, Vol. 2014, pp.1–11, DOI: 10.1155/2014/804705.

Griffiths, W., Caden, A. and El-Sayed, M. (2014a) 'The behaviour of entrainment defects in aluminium alloy castings', in *Proceedings of the 2013 International Symposium on Liquid Metal Processing and Casting*, John Wiley & Sons, Inc.

Griffiths, W.D., Caden, A. and El-Sayed, M. (2014b) 'An investigation into double oxide film defects in aluminium alloys', in *Materials Science Forum*, Trans Tech Publications Ltd.

Hader, R. and Park, S.H. (1978) 'Slope-rotatable central composite designs', *Technometrics*, Vol. 20, No. 4, pp.413–417.

Hague, R., Mansour, S., Saleh, N. and Harris, R. (2004) 'Materials analysis of stereolithography resins for use in rapid manufacturing', *Journal of Materials Science*, Vol. 39, No. 7, pp.2457–2464.

Haleem, A., Javaid, M., Khan, S. and Khan, M.I. (2020) 'Retrospective investigation of flexibility and their factors in additive manufacturing systems', *International Journal of Industrial and Systems Engineering*, Vol. 36, No. 3, pp.400–429.

Hassanin, H., Abena, A., El-Sayed, M.A. and Essa, K. (2020a) '4D printing of NiTi auxetic structure with improved ballistic performance', *Micromachines*, Vol. 11, No. 8, p.745.

Hassanin, H., Alkendi, Y., El-Sayed, M., Essa, K. and Zweiri, Y. (2020b) 'Controlling the properties of additively manufactured cellular structures using machine learning approaches', *Advanced Engineering Materials*, Vol. 22, No. 3, p.1901338.

Hassanin, H., Al-Kinani, A.A., ElShaer, A., Polycarpou, E., El-Sayed, M.A. and Essa, K. (2017) 'Stainless steel with tailored porosity using canister-free hot isostatic pressing for improved osseointegration implants', *Journal of Materials Chemistry B*, Vol. 5, No. 47, pp.9384–9394.

Hassanin, H., El-Sayed, M.A., ElShaer, A., Essa, K. and Jiang, K. (2018) 'Microfabrication of net shape zirconia/alumina nanocomposite micro parts', *Nanomaterials*, Vol. 8, No. 8, p.593.

Hassanin, H., Modica, F., El-Sayed, M.A., Liu, J. and Essa, K. (2016) 'Manufacturing of Ti-6Al-4V micro-implantable parts using hybrid selective laser melting and micro-electrical discharge machining', *Advanced Engineering Materials*, Vol. 18, No. 9, pp.1544–1549.

Hon, K.K.B., Han, C. and Edwardson, S.P. (2006) 'Investigations on new scanning pattern for stereolithography', *CIRP Annals – Manufacturing Technology*, Vol. 55, No. 1, pp.217–220, DOI: 10.1016/s0007-8506(07)60402-8.

Javaid, M. and Haleem, A. (2019) 'Using additive manufacturing applications for design and development of food and agricultural equipments', *International Journal of Materials and Product Technology*, Vol. 58, Nos. 2–3, pp.225–238.

Karumuri, R.T., Dave, H.K., Rajpurohit, S.R. and Prajapati, A.R. (2021) 'Study on compression properties of ABS and FPU parts printed using SLA', in *Advances in Manufacturing Processes*, Springer, pp.319–328.

Kazemi, M. and Rahimi, A. (2015) 'Supports effect on tensile strength of the stereolithography parts', *Rapid Prototyping Journal*, Vol. 21, No. 1, pp.79–88.

Kim, H-C. and Lee, S-H. (2005) 'Reduction of post-processing for stereolithography systems by fabrication-direction optimization', *Computer-Aided Design*, Vol. 37, No. 7, pp.711–725, DOI: 10.1016/j.cad.2004.08.009.

Kunjan, C. (2017) 'Development of process model for optimal selection of process parameters for geometric tolerances and surface roughness in stereolithography', *ADMT Journal*, Vol. 9, No. 3, pp.103–113.

Lee, S., Park, W., Cho, H., Zhang, W. and Leu, M-C. (2001) 'A neural network approach to the modelling and analysis of stereolithography processes', *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Vol. 215, No. 12, pp.1719–1733.

Mele, M., Campana, G., Lenzi, F. and Cimatti, B. (2019) 'Optimisation of build orientation to achieve minimum environmental impact in stereo-lithography', *Procedia Manufacturing*, Vol. 33, pp.145–152.

Mohammed, A., Elshaer, A., Sareh, P., El-Sayed, M. and Hassanin, H. (2020) 'Additive manufacturing technologies for drug delivery applications', *International Journal of Pharmaceutics*, Vol. 580, pp.119245–119269.

Pandey, P.M., Reddy, N.V. and Dhande, S.G. (2007) 'Part deposition orientation studies in layered manufacturing', *Journal of Materials Processing Technology*, Vol. 185, Nos. 1–3, pp.125–131, DOI: 10.1016/j.jmatprotec.2006.03.120.

Piedra-Cascón, W., Krishnamurthy, V.R., Att, W. and Revilla-León, M. (2021) '3D printing parameters, supporting structures, slicing, and post-processing procedures of vat-polymerization additive manufacturing technologies: a narrative review', *Journal of Dentistry*, p.103630, DOI [online] https://doi.org/10.1016/j.jdent.2021.103630.

Prechtl, C., Kraut, M., Franzreb, M., Brenner-Weiß, G. and Dittmeyer, R. (2017) 'Membrane-supported multichannel microfluidic solvent extraction system', *Chemical Engineering & Technology*, Vol. 40, No. 4, pp.670–677.

Quintana, R., Choi, J-W., Puebla, K. and Wicker, R. (2010) 'Effects of build orientation on tensile strength for stereolithography-manufactured ASTM D-638 type I specimens', *The International Journal of Advanced Manufacturing Technology*, Vol. 46, Nos. 1–4, pp.201–215.

Raju, B.S., Shekar, U.C., Venkateswarlu, K. and Drakashayani, D.N. (2014) 'Establishment of process model for rapid prototyping technique (stereolithography) to enhance the part quality by Taguchi method', *Procedia Technology*, Vol. 14, pp.380–389, DOI: 10.1016/j.protcy.2014.08.049.

Salmoria, G.V., Ahrens, C.H., Beal, V.E., Pires, A.T.N. and Soldi, V. (2009) 'Evaluation of post-curing and laser manufacturing parameters on the properties of SOMOS 7110 photosensitive resin used in stereolithography', *Materials & Design*, Vol. 30, No. 3, pp.758–763, DOI: 10.1016/j.matdes.2008.05.016.

Seprianto, D., Sugiantoro, R. and Erwin, M. (2020) 'The effect of rectangular parallel key manufacturing process parameters made with stereolithography DLP 3D printer technology against impact strength', *Journal of Physics: Conference Series*, Vol. 1500, No. 1, pp.012028–012035, IOP Publishing.

Shumkov, A., Ablyaz, T., Muratov, K. and Sidhu, S. (2020) 'Prediction of the properties of photopolymer prototypes', in *IOP Conference Series: Materials Science and Engineering*, IOP Publishing.

Sing, S.L., Wiria, F.E. and Yeong, W.Y. (2018) 'Selective laser melting of lattice structures: a statistical approach to manufacturability and mechanical behavior', *Robotics and Computer-Integrated Manufacturing*, Vol. 49, pp.170–180.

Srivastava, M., Rathee, S., Maheshwari, S. and Kundra, T. (2019) 'Estimating percentage contribution of process parameters towards build time of FDM process for components displaying spatial symmetry: a case study', *International Journal of Materials and Product Technology*, Vol. 58, Nos. 2–3, pp.201–224.

User Manual, O. (1988) *3D Systems*, Editor, Valencia, Fla, USA.