1 INTRODUCTION

1.1 Background

Rapid prototyping (RP) or layer manufacturing is the third phase in the evolution of prototyping after manual and virtual prototyping. The term rapid immediately suggest speedy fabrication of sample part for demonstration, testing and evaluation. Rapid prototyping is used to fabricate a three-dimensional object of any shape directly from a CAD model by a quick, highly automated and totally flexible process. Without the existence of CAD, rapid prototyping system could not be possible.

There are many ways in which one can classify the numerous rapid prototyping system in the market, one of the better way is to classify rapid prototyping system broadly by the initial form of its material, i.e., the material that the prototype or part is built with. In this manner, all rapid prototyping systems can be easily categories into (1) liquid-based, (2) solid-based and (3) powder-based.

Figure 1: Example of Rapid Prototyping Product

Liquid based RP systems have the initial form of its material in liquid state. Through a process commonly known as curing, the liquid is converted to solid state. The following RP systems fall into this category;3D System's Stereolithograpy Apparatus (SLA), Cubital's Solid Ground Curing (SGC), Sony's Solid Creation System (SCS), CMET's Solid Object Ultraviolet-Laser Printer (SOUP), Autostrade's E-Darts and Teijin Seiki's Soliform System.

Except for powder, solid- based RP system are meant to encompass all forms of material in the solid state. In this context, the solid form can include the shape in the form of wire, a roll, laminates and pellets. The following RP systems fall into this category; Stratasys' Fused Deposition Modelling (FDM), Cubic Technologies' Laminated Object Manufacturing (LOM) and Kira Corporation's Paper Lamination Technology (PLT).

In a strict sense, powder is by and large in the solid state. However, it is intentionally created as a category outside the solid-based RP systems to mean powder in grain-like form. The following RP systems fall into this category; 3D System's Selective Laser Sintering (SLS) and EOS's EOSINT System3D System's

Selective Laser Sintering (SLS) falls under powder-based categories and is one of the leading commercial rapid prototyping (RP) process. Due to ability to process various materials such as polymers, metals, ceramic and composites, SLS is one of the most rapidly growing rapid prototyping processes [8]. In spite of its potential use in various areas of materials, the used of SLS is limited, since the dimensional accuracy of its product is still inferior to that of conventional machining processes [15]. Therefore, improving the accuracy is a vital means for further generalizing SLS technology.

Part inaccuracy is mainly result from the material shrinkage during the sintering process. The shrinkage result in deformation of built part which is cause by nonuniform internal stress. To minimize shrinkage and to improve the accuracy, the process parameters have to be tuned by an appropriate method. Therefore, understanding the process parameters will allow users to produce parts with desired physical characteristics. Thus this paper attempts to make an effort to understand the relationship between the process parameters and shrinkage and to obtain the optimum model of SLS process parameters.

1.2 Problem Statement

SLS Rapid prototyping and other types of rapid prototyping is all use to make prototypes. Prototypes represent the actual product, so if the prototypes have a flaw so thus the actual product. Due to lack of identifying the effect of process parameters prototypes manufactured are lack of part accuracy.

1.3 Objective

The objectives of this project are to analyze the effect of process parameters on the part accuracy and to produce the optimal model of process parameters that result in less shrinkage. In this project, the scope of study is to produce optimal model of process parameters that can give a better result of product manufactured. Furthermore, students need to study the process done by rapid prototyping in producing prototypes.

1.4 Feasibility Of The Project Within The Scope And Time Frame

It is an obligatory for mechanical engineering students to complete final year project within 2 semesters. The project commences with research work in first semester (FYP 1) following by progress work in second semester (FYP 2). It will be assumed that the project is feasible within the scope and time frame.

2 LITERATURE REVIEW

Rapid prototyping is advanced manufacturing technology commercialized in the middle of 1980s [12].Since the mid-eighties a variety of rapid prototyping technologies have been developed, including the Stereolithograpy (SLA), the selective laser sintering (SLS), the fused deposition modelling (FDM), the laminated object manufacturing (LOM) and the three deposition printing [2].

Compare to all rapid prototyping technologies, SLS technology has attracted much attention because it can produce rapid prototyping product with a wide range of materials. Available material that can be used in SLS include; polycarbonate (PC), nylon, nylon/glass composition, wax, ceramics, true form ™, elastomeric and metal-polymer powders [3].

The SLS process can be divided into two steps (see Fig. 2). At first, the laser beam selectively scans the powder surface according to the information contained in the CAD files. Under the radiation, the powder partially melts. The liquid formed by the molten material binds the surrounding powder and solidifies when the laser beam is switched off or is guided to another point of the powder bed. Once the scanning is finished, a new layer of powder is deposited and the scanning starts again. The final part has a rigid but porous structure. The loose powder can be removed and recycled. (Boillat et al. (2004))

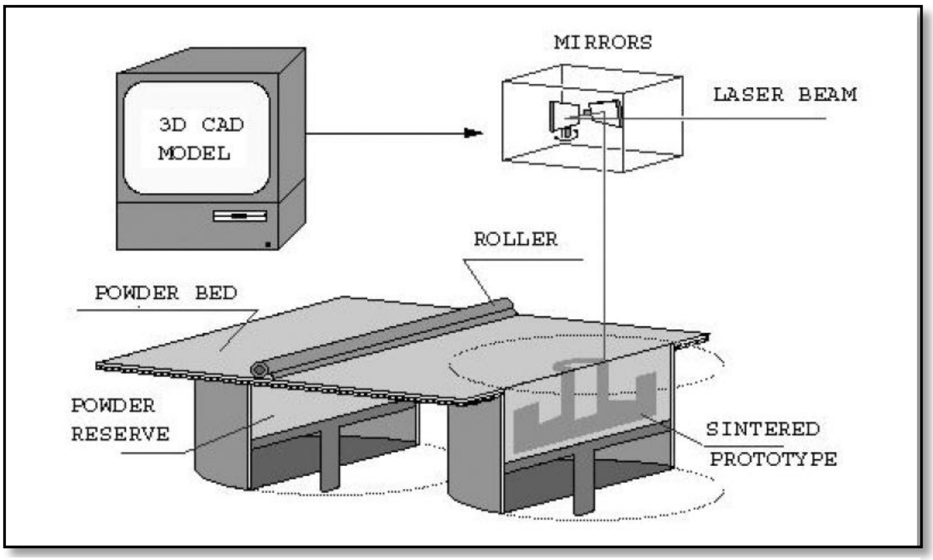

Figure 2: Schematic picture of SLS rapid prototyping

Regarding the characteristics of the SLS process, the shape inaccuracy caused by phase change during the sintering process is larger than that caused by other rapid prototyping processes. Several research have been done on process parameters and also on phenomenon of distortion and control for SLS rapid prototyping process.

Choi et al.(2002) states that rapid prototyping process parameters can be classified into nuisance, constant and control. Nuisance parameters include age of the laser, beam position accuracy, humidity and temperature, which are not controlled in the experiment analysis but may have some effect on the part. Constant parameters normally include beam diameters, laser power and material properties. The control process parameters will affect the output of the process and controllable in a run for example, hatch space, layer thickness and hatch length.

Child et al. (1999) reported on the thermal and powder densification modelling of the selective laser sintering of amorphous polycarbonate. there strategies were investigate: analytical, adaptive finite mesh difference and fixed finite mesh element. A comparison between the three strategies and the experiment result was used to reliably evaluated their ability to predict the behaviour of the physical process. The analysis showed that the densification and linear accuracy due to sintering were mostly sensitive to changes in the activation energy and heat capacity of the polymer. as secondary factor of the linear accuracy, the powder bed density and the powder layer thickness is include. The author also showed that simulations of manufacturing hollow cylinder and T-shapes features distortions due to the excessive depth of sintering at the downward-facing surfaces in the powder bed.

Boillat et al. (2004), developed a three-dimensional finite element model of the selective laser sintering process to study the effect of process parameters on density of the manufactured part. Dong et al. (2008), developed transient three-dimensional finite element model to simulate the phase transformation during the selective laser sintering process; taking into account the thermal and sintering phenomena involved in this process. Dong et al, (2008) also studies effect of the process parameters to the desired outcome such as temperature and density distributions.

1. Effect of scanning speed

The accumulated energy on the powder bed surface transmitted from the laser beam decrease with the increase of the beam speed, result in temperature decreasing

2. Effect of intensity of the laser (laser power)

Simulation is conducted at two speeds, low and high. Maximum temperature as a function of laser power. The increase of laser power improves the sintered depth of the powder but this improvement is accompanied but increasing temperature on the surface of the powder which leads to degradation of the sintered material

3. Effect of pre-heating temperature

Same laser speed and same laser power. The temperature in the powder bed increases with pre-heating temperature. The preheating temperature influences the rate of the heat diffusion and the sintering process.

4. Effect of the spot size of the laser beam

Same laser power and same laser speed. The increase of the laser radius reduces the maximal intensity of the laser beam which results in significant decrease of the powder bed surface temperature.

Raghunath and Pandey analyse several process parameters such as laser power, beam speed, hatch spacing, part bed temperature and its effect on shrinkage of part manufactured by SLS process. From the analysis Raghunath and Pandey discovered that laser power and scan length influence shrinkage in X-direction. Along Y-direction laser power and beam speed are important parameters and along Z-direction beam speed, hatch spacing and part bed temperature are found significant.

Based on studies of selective laser sintering, Prakash and Singh investigates the effect of process parameters on two different quality characteristic namely density and part distortion. Process parameters include laser power, scan spacing and scan velocity. It has been observed that the density of the parts produced in SLS systems is directly related with the energy density to which the part is exposed. Prakash and Singh define energy density (ED) as:

ED = P/HD.LS (1)

Where P is laser power, HD is hatching distance and LS is laser speed during hatching. Prakash and Singh analyse the quality using S/N and ANOVA analysis based on the result of FEM simulation. Based on the above analysis regression equation for density and part distortion is obtain in term of process parameters which are laser power, scan spacing and scan velocity.

Kolossov et al. (2004) developed a thermal model of selective laser sintering (SLS) using 3D finite element analysis. The temperature evolution and the formation of the sintered part were observed. The FE mesh used in this work is a quasi-regular mesh with two types of cells. The result of the model are presented and validated experimentally.

Choi et al. (2002) propose a Virtual Reality (VR) system. This system involves modelling and simulation of RP in a virtual system, which visualize and testing the effects of process parameters on the part quality. Same as finite element method this system also require mathematical model that incorporates the behaviour of RP process. For this study, the mathematical model defines as below:

1. $$\text{Velocity}\ (v) = \frac{P_\ell(1-R)}{\rho d_b \ell_m [C_p(T_m - T_b) + kL_h]} \qquad (2)$$
2. $$\text{Scan time}\ (T_\ell) = \frac{L_d}{L_v} \qquad (3)$$
3. $$\text{Build-time of a part} = \sum_{i=1}^{N_\ell} T_{\ell i} + T_s N_\ell \qquad (4)$$
4. $$\text{Orientation efficiency}\ (n) = \frac{\sum_{i=1}^{N_p} V_{pi}}{h_m A_w} \qquad (5)$$

Ning et al. (2004) study the relationship between the hatch length and the part quality. The experiment was conducted on different types of material and the microstructure change is observed using scanning electron microscopy (SEM). Yang et al.(2002) studied the shrinkage compensation of SLS by using Taguchi method.

The accurate rate of shrinkage is measure with the reduction of curling that is obtained from the adjustment of the building orientation.

Wang et al. (2008) study the process parameters in order to determine the best process parameters for SLS by minimizing the shrinkage. The process parameters are layer thickness, hatch spacing, laser power, scanning speed, work surrounding temperature, interval time and scanning mode. Wang used genetic algorithm based on the neural network model to developed optimum process parameters.

Bacchewar et al.(2006) developed central rotatable composite design (CCD) experiment to study the effect of process parameters, namely laser power, build orientation, layer thickness, beam speed and hatch spacing on surface roughness. Analysis of variance was used to study the significance of process variable on surface roughness.Literature review shows evident that many researchers concentrated on studying the analysis of process parameters on SLS process either by finite element analysis or by suggesting a factor in X, Y and Z directions for scaling up STL file. So this present project aims to finding out the effect of parameters namely laser power, beam speed, hatch spacing, part bed temperature and hatch length on shrinkage for better accuracy.

Before analysing all those five process parameters, we need to know what are those process parameters is actually means. Part bed temperature is the temperature at which the powder in the part cylinder is controlled. before the laser scanners move, powder in the part cylinder will be heated to part bed temperature [12].

Laser power is the power available from the laser beam at part bed surface. this parameters should be set to ensure that the powder at part bed surface will be heated closed to melting temperature during scanning [12]. Choi et al [7] mention that hatch spacing refers to the distance between the parallel vectors used to solidify the layer surface. Katz et al [13] states that beam speed or laser scanning speed is the speed at which the laser spot travels along the surface of the powder during operation.

3 METHODOLOGY

3.1 Process Flow Diagram

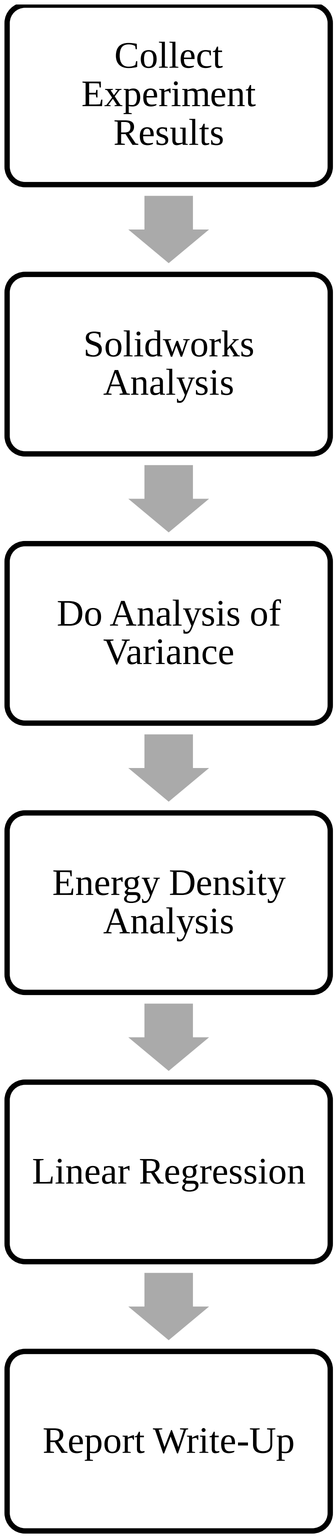

Figure 3: Methodology Process Flow

3.2 Gather Experiment Results

In order to do analysis of process parameters, result is required. Results is obtained from the experiment done by Raghunath et al.[6]. All the experiment data and results is presented in Table 1, Table 2, Table 3 and Table 4.

3.3 Solidworks Simulation Analysis

Solidworks simulation is used to shows shrinkage effect due to temperature distribution in X and Z direction for different hatch length.

3.4 Do Analysis of Variance (ANOVA)

The purpose of analysis of variance (ANOVA) is to investigate which process parameters significantly affect the quality characteristic of the material. So, the contribution percentage of each process parameter can be determined using this ANOVA analysis. Below are the equation used in this ANOVA analysis base on order of the calculation:-

i) Total Sum of Squares, $$T_{SS} = \sum_{i=1}^{N}\left(y_i^2\right) - \frac{T^2}{2} \quad (6)$$

Where, N= number of trials

y_i = value at i the observation

T = sum of all observation

ii) Sum of squares $$SS = \sum_{i=1}^{k_A}\left(A_i / n_{A_i}\right) - \frac{T^2}{n} \quad (7)$$

Where, k_A= number of levels for process parameter A

A_i = sum of observations under A_i level

N_{Ai}= number of observations under A_i levels

iii) Variance or Mean square $= Sum\,of\ \ squares/DOF$ (8)

iv) Error Sum of Squares, $E_{SS} = T_{SS} - (SS_A + SS_B + ...+ S_i)$ (9)

v) F-Ratio $= Sum\,of\ \ squares/E_{SS}$ (10)

vi) Percentage Contribution $= (Sum\,of\ \ squares / T_{SS}) \times 100$ (11)

3.5 Energy Density Analysis

To study the relationship of the process parameters that is the function of energy density and how it is related to the shrinakge

3.6 Linear Regression to derive Empirical Models

Based on the ANOVA results, linear regression is perform to obtain standard models to produce less shrinkage prototype for each directions. Linear regression is to model the relationship between a scalar variable y and one or more variables denoted as x.

3.7 Gantt chart

Detail of fyp schedule throughout this semester is shown in the gantt chart in the Appendix III.

3.8 Important information throughout this project regarding the hatch length and hatch spacing, Refer to Appendix IV.

4 RESULT AND DISCUSSION

4.1 Preliminary Data before Experiment

Table 1 and 2 show the preliminary table and orthogonal array that been construct base on the earlier research information. The L_{16} orthogonal array shown in Table 2 was constructed base on five process parameter for the experiment trial purpose. To select an appropriate orthogonal array, total degrees of freedom need to be computed. The degrees of freedom are the number of comparisons to be made between designed parameters. Each process parameter is assigned to a column with sixteen process parameter combination being available. Therefore, only sixteen experiments are required to study in determine the contribution for each process parameter.

Table 1: Rapid Prototyping Process Parameters and Levels [6]

Symbol	Parameters	Level of each Parameter			
		Level 1	Level 2	Level 3	Level 4
A	Laser power (W)	24	28	32	36
B	Beam speed (mm/s)	3000	3500	4000	4500
C	Hatch spacing (mm)	0.22	0.24	0.26	0.28
D	Part bed temperature (°C)	175	176	177	178
E	Hatch length (mm)	30	45	60	75

Table 2: Taguchi L16B Orthogonal Array [6]

Experiment No.	A	B	C	D	E
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	1	4	4	4	4
5	2	1	2	3	4
6	2	2	1	4	3
7	2	3	4	1	2
8	2	4	3	2	1
9	3	1	3	4	2
10	3	2	4	3	1
11	3	3	1	2	4
12	3	4	2	1	3
13	4	1	4	2	3
14	4	2	3	1	4
15	4	3	2	4	1
16	4	4	1	3	2

4.2 Result from Each Experiment

Table 3: Shrinkage (%) for each experiment in X, Y and Z Direction [6]

						X-direction	Y-direction	Z-direction
Ex No.	A	B	C	D	E	Average Shrinkage (%)		
1	1	1	1	1	1	0.79167	0.65833	2.65
2	1	2	2	2	2	0.72778	0.95	2.93333
3	1	3	3	3	3	0.775	1.31667	3.63333
4	1	4	4	4	4	0.66667	1.5	4.01667
5	2	1	2	3	4	0.37	0.60833	3.25
6	2	2	1	4	3	0.47917	0.85	3.18333
7	2	3	4	1	2	0.45556	0.54167	2.95
8	2	4	3	2	1	1.13333	1.15833	3.46667
9	3	1	3	4	2	0.56667	0.75833	3.29167
10	3	2	4	3	1	0.90833	1.19167	3.1
11	3	3	1	2	4	0.39667	0.64167	3
12	3	4	2	1	3	0.55833	1.09167	3.11667
13	4	1	4	2	3	0.39583	0.38333	2.84167
14	4	2	3	1	4	0.30667	0.63333	2.98333
15	4	3	2	4	1	0.78333	0.875	3.09167
16	4	4	1	3	2	0.61667	0.61667	3.325

Table 4: S/N Ratio for each experiment in X, Y and Z Direction [6]

						X-direction	Y-direction	Z-direction
Ex No.	A	B	C	D	E	S/N ratio		
1	1	1	1	1	1	1.9856	3.6123	-8.4658
2	1	2	2	2	2	2.725	0.3595	-9.3486
3	1	3	3	3	3	2.1814	-2.4069	-11.2063
4	1	4	4	4	4	3.5019	-3.5486	-12.0804
5	2	1	2	3	4	8.5817	4.1927	-10.256
6	2	2	1	4	3	6.1966	1.3767	-10.0582
7	2	3	4	1	2	6.806	5.2489	-9.3982
8	2	4	3	2	1	-1.0965	-1.2809	-10.8053
9	3	1	3	4	2	4.8655	2.3471	-10.3493
10	3	2	4	3	1	0.8208	-1.5288	-9.8275
11	3	3	1	2	4	8.0208	3.8166	-9.5467
12	3	4	2	1	3	5.0515	-0.7828	-9.8779
13	4	1	4	2	3	7.9948	8.3039	-9.0737
14	4	2	3	1	4	10.2626	3.8195	-9.4947
15	4	3	2	4	1	2.0528	1.1429	-9.8045
16	4	4	1	3	2	4.1754	4.1329	-10.4374

For this 16 experiments, all parameters are varies dependent to level assign which is show in Table 1. However laser spot size and layer thickness has been keep fixed and same as 0.6mm and 0.15mm. [6]

4.3 Analysis of the result collect

4.3.1 Analysis using Solidworks Simulation

Hatch length is one of the process parameters that need to be study. For the hatch length process parameter, only x direction and z direction is to be analyse. In order to understand more, Solidworks simulation analysis is performed. Material used for Solidworks Simulation is a Polyamide (PA type 6). Table 5 shows material properties of polyamide.

Table 5: Polyamide material properties

Quantity	Value	Unit
Young's modulus	2300 - 2500	MPa
Tensile strength	48 - 85	MPa
Elongation	100 - 320	%
Compressive strength	46 - 90	MPa
Fatigue	31 - 31	MPa
Bending strength	110 - 120	MPa
Impact strength	0.44 - 3	J/cm
Yield strength	35 - 40	MPa

This simulation is perform on two different hatch length which are 30mm and 60mm and on two different direction which is X and Z. Result of the simulation process is shown in the Figure 5-8.

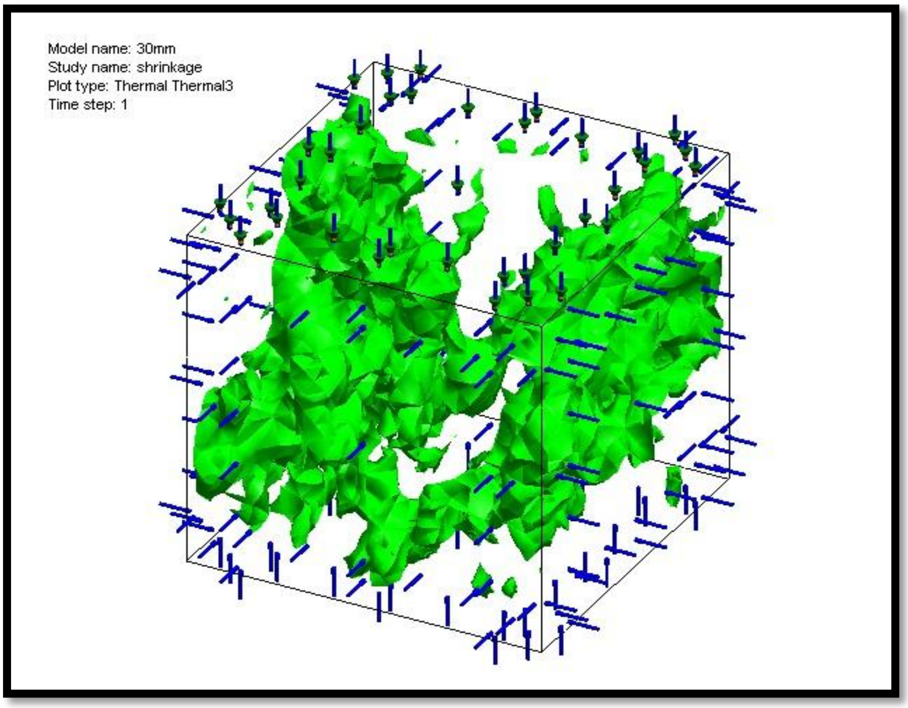

Figure 5: Temperature Distribution in X (30mm)

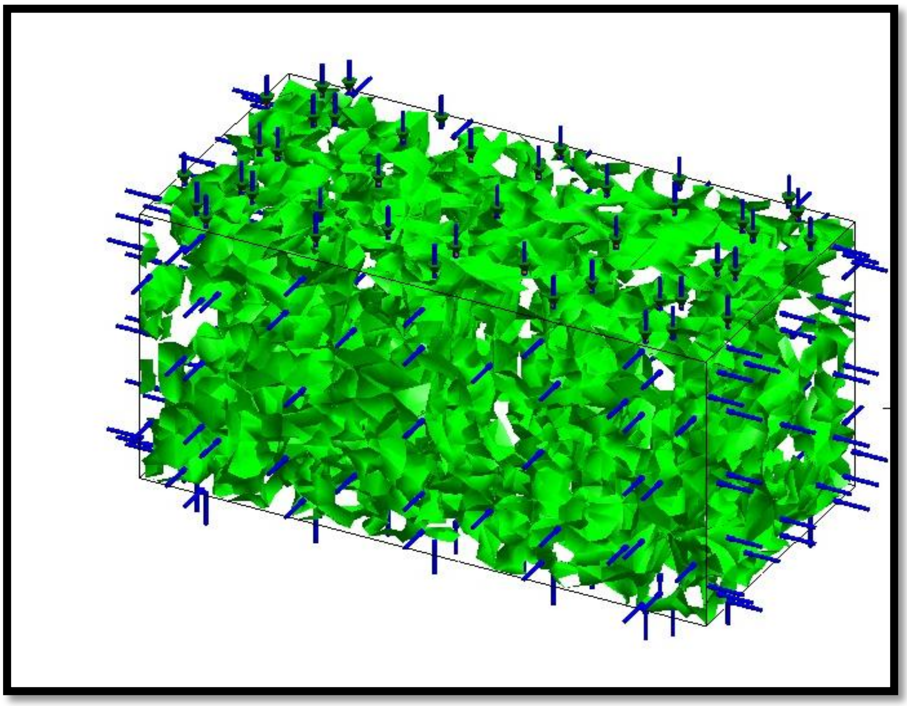

Figure 6: Temperature Distribution in Z Direction (60mm)

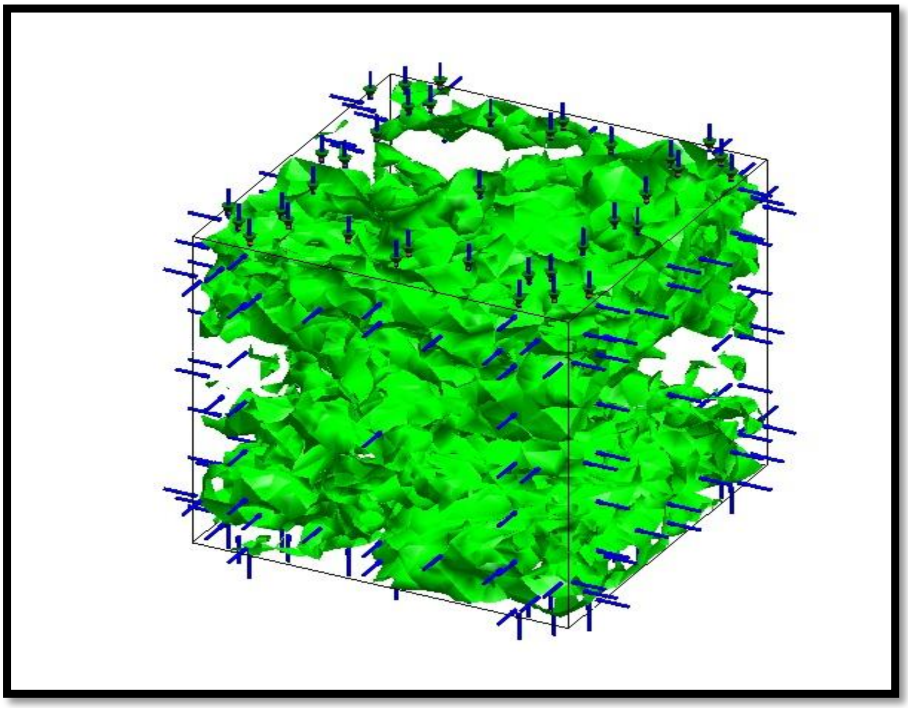

Figure 7: Temperature Distribution in Z Direction (30mm)

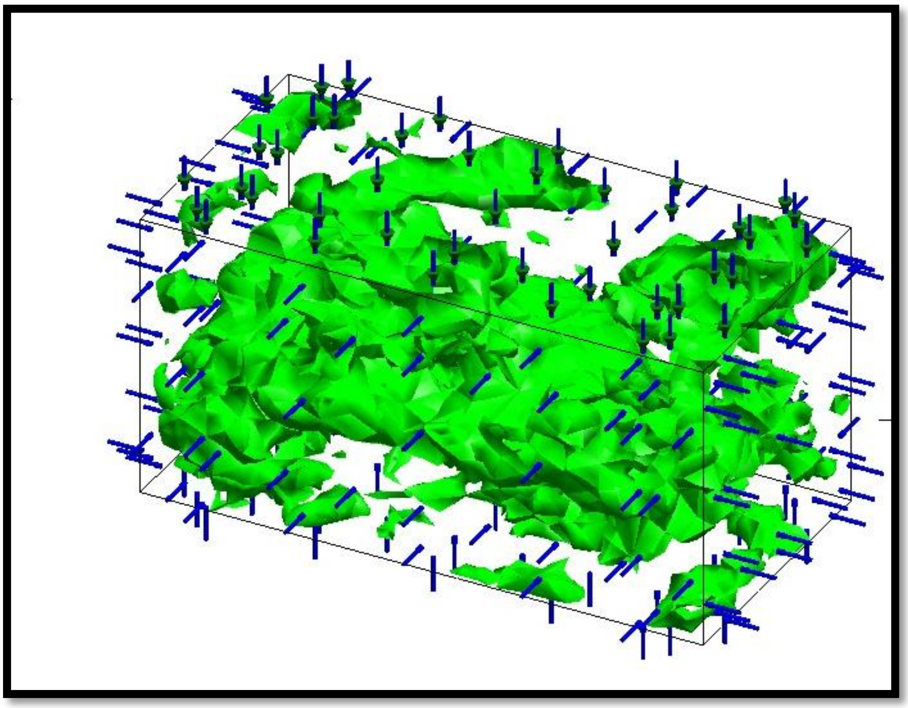

Figure 8: Temperature Distribution in Z Direction (60mm)

Figure 5 and 6 represent the temperature distribution in X direction. 30mm shows less temperature distribution compare to 60mm, Ning et al (2004) states that when the scan length is small, the sintered powder does not have sufficient time to cool as it absorbs energy transferred from the neighbouring scan lines. William and Deckard [16] also mention that large thermal gradient occur for short scan line length. The thermal gradient decay with increasing scan line length. The decrease in the thermal gradient for long scan lengths may be due to longer time periods in which cooling occurs between successive laser exposures.

Therefore based on analysis and literature review, we can say that low cooling rate cause the increase in shrinkage which is increasing hatch length reduce the shrinkage effect, but this only applicable to X direction. Raghunath et al (2007) states that shrinkage is not identical along X and Z direction because laser scanning is done along X direction and the part is built along Z direction. Based on Raghunath statement, it is clear why Solidworks simulation shows contradict result for axis X and Z direction

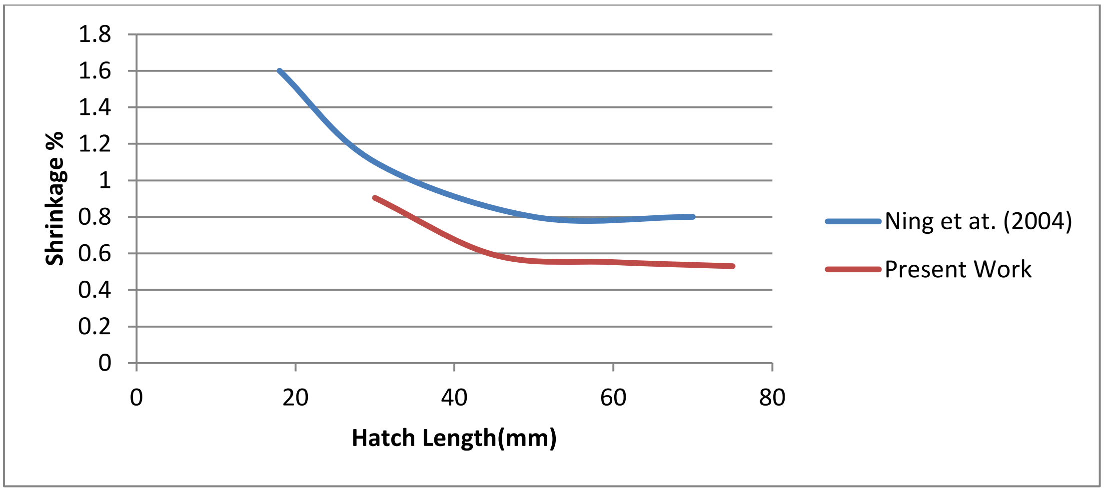

Figure 9: Shrinkage % with different Hatch Length

Figure 9 shows the graph of shrinkage percentage varies with different hatch length. Present work is based on data calculated in Table 3. When we compare present work graph with the graph plot based on the data from Ning et al. (2004), same trend was found. It shows that the present work of hatch length analysis shows good agreement with literature review.

4.3.2 Analysis of Variance for 5 Process Parameters

ANOVA is used to analyse each process parameters in all direction X, Y and Z. Calculation for ANOVAs analysis was performed by Microsoft Excel 2010. Analysis result of ANOVA shows that different parameters give different significant effect in each direction. For more clear view, refer to Figures 10-12. In order to decide which parameters are consider significant in each direction, F-distribution is define. Based on the degree of freedom of the parameters, F-value above 3.01 is consider significant affecting shrinkage in each direction. This limit of F-value is define based on the [18]. Table 6, 7 and 8 shows the result from the overall calculation of analysis of variance. For the overall calculation of anova, please refer to Appendix II.

Table 6: ANOVA Table in X Direction

FACTOR	DOF	SS	MS	F	CONTRIBUTION
Laser Power	**3**	**26.388**	**8.796**	**3.34**	**0.176**
Beam Speed	3	18.506	6.169	2.34	0.124
Hatch Spacing	3	2.288	0.763	0.29	0.015
Part Bed Temperature	3	10.803	3.601	1.37	0.072
Hatch Length	**3**	**91.642**	**30.547**	**11.60**	**0.612**
Total, SS_{Total}	15	149.625			
Error, SS_E	12	31.596	2.633		

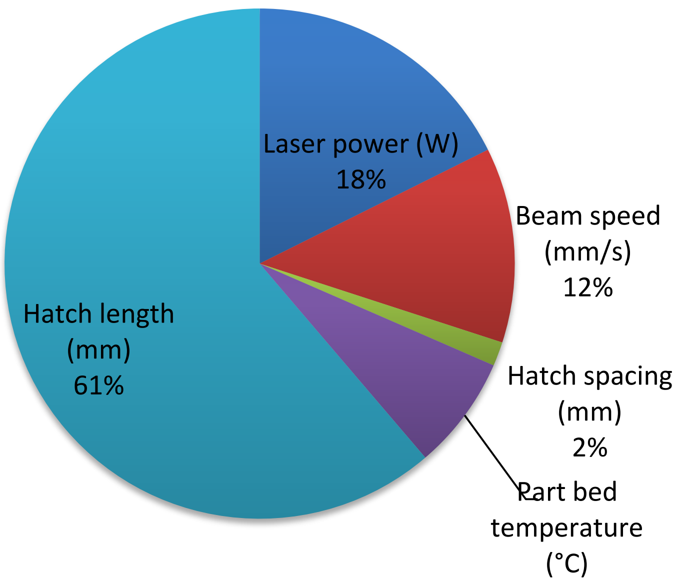

Figure 10: ANOVA Pie Chart in X Direction

Table 7: ANOVA Table in Y Direction

FACTOR	DOF	SS	MS	F	CONTRIBUTION
Laser Power	**3**	**51.259**	**17.086**	**4.19**	**0.334**
Beam Speed	**3**	**53.115**	**17.705**	**4.34**	**0.346**
Hatch Spacing	3	15.520	5.173	1.27	0.101
Part Bed Temperature	3	20.139	6.713	1.65	0.131
Hatch Length	3	13.294	4.431	1.09	0.087
Total, SS_{Total}	15	153.327			
Error, SS_E	12	48.953	4.079		

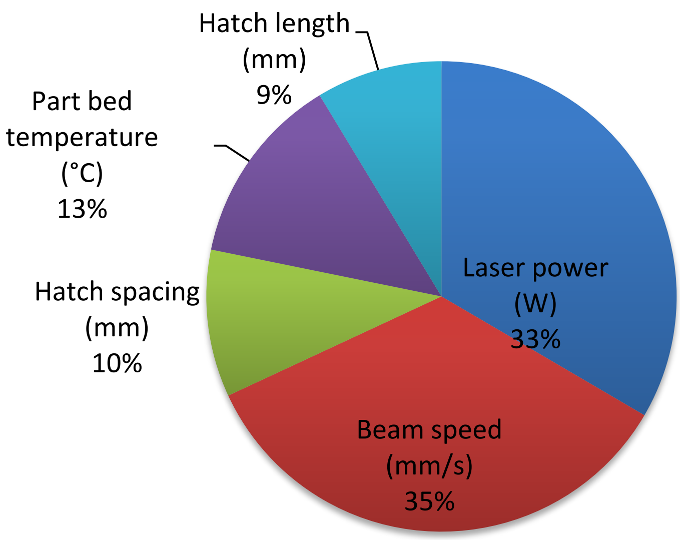

Figure 11: ANOVA Pie Chart in Y Direction

Table 8: ANOVA Table in Z Direction

FACTOR	DOF	SS	MS	F	CONTRIBUTION
Laser Power	3	0.764	0.255	1.90	0.067
Beam Speed	**3**	**3.826**	**1.275**	**9.54**	**0.337**
Hatch Spacing	**3**	**1.580**	**0.527**	**3.94**	**0.139**
Part Bed Temperature	**3**	**4.344**	**1.448**	**10.83**	**0.383**
Hatch Length	3	0.841	0.280	2.10	0.074
Total, SS_{Total}	15	11.356			
Error, SSE	12	1.605	0.134		

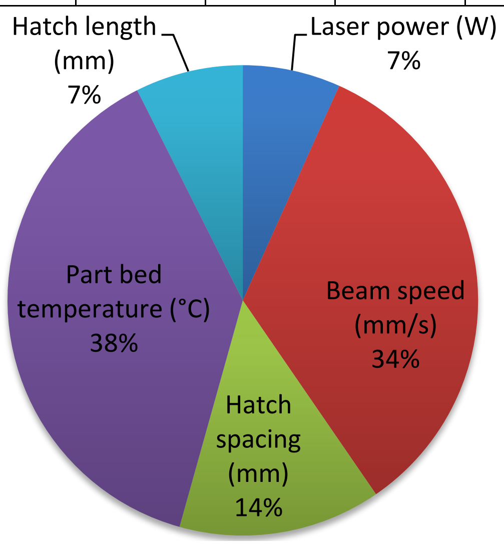

Figure 12: ANOVA Pie Chart in Z Direction

Based from the Pie Chart and from the f-value in all tables, it shows that hatch length and laser power are the most influences parameters for shrinkage in X direction. In Y direction beam speed and laser power are parameters the most influencing the shrinkage effect. However in Z direction there are three significant parameters that influence shrinkage effect which are part bed temperature, beam speed and hatch spacing.

4.3.3 Analysis of Variance for 3 Process Parameters

Previously, ANOVA is done on 5 process parameters. This ANOVA for 3 process parameters is only for laser power, beam speed and hatch spacing. This theree process parameters are choose because this is the function of energy density. Energy density analysis will be discuss later in part 4.3.4. In order to decide which parameters are consider significant in each direction, F-distribution is define. Based on the degree of freedom of the parameters, F-value above 3.11 is consider significant affecting shrinkage in each direction. This limit of F-value is define based on the [18]. Table 9, 10 and 11 shows the result from the overall calculation of analysis of variance. For the overall calculation of anova, please refer to Appendix I.

Table 9: ANOVA Table in X Direction

ANOVA in X					
FACTOR	DOF	SS	MS	F	CONTRIBUTION
Laser Power	2	64.102	32.051	4.33	0.408
Beam Speed	2	44.376	22.188	3.00	0.282
Hatch Spacing	2	48.687	24.344	3.29	0.310
Total, *SSTotal*	8	157.165			
Error, *SSE*	6	44.376	7.396		

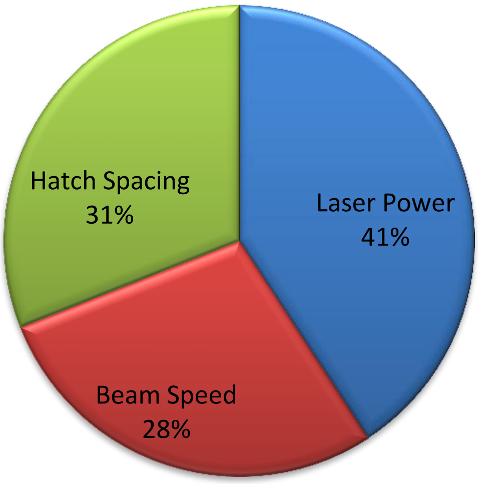

Figure 13: ANOVA Pie Chart in X Direction

Table 10 : ANOVA Table in Y Direction

ANOVA in Y					
FACTOR	DOF	SS	MS	F	CONTRIBUTION
Laser Power	2	17.141	8.570	3.31	0.143
Beam Speed	2	18.760	9.380	3.63	0.156
Hatch Spacing	2	15.498	7.749	3.00	0.129
Total, *SSTotal*	8	51.399			
Error, *SSE*	6	15.498	2.583		

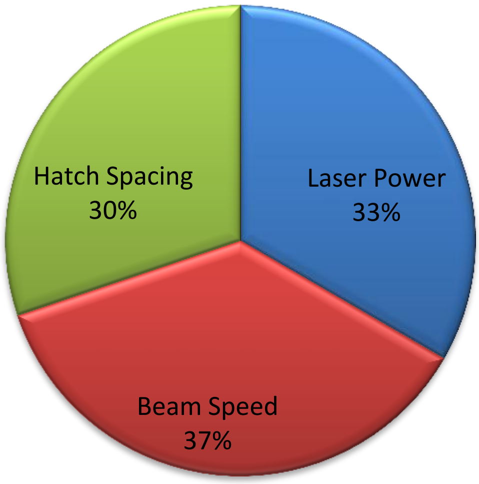

Figure 14: ANOVA Pie Chart in Y Direction

Table 11: ANOVA Table in Z Direction

ANOVA in Z					
FACTOR	DOF	SS	MS	F	CONTRIBUTION
Laser Power	2	163.093	81.546	3.00	0.328
Beam Speed	2	163.181	81.591	3.00	0.328
Hatch Spacing	2	170.818	85.409	3.14	0.344
Total, *SSTotal*	8	497.093			
Error, *SSE*	6	163.093	27.182		

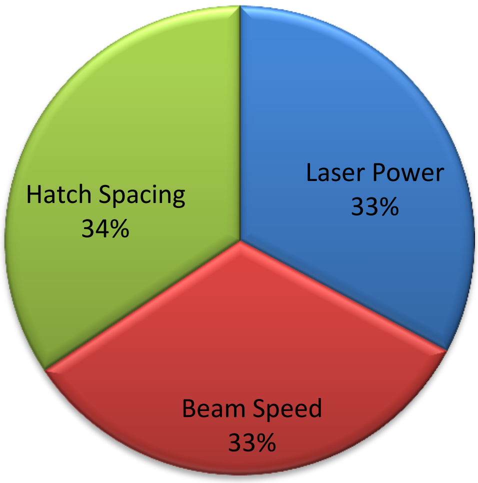

Figure 15: ANOVA Pie Chart in Z Direction

Based from the Pie Chart and from the f-value in all tables, it shows that hatch spacing and laser power are the most influences parameters for shrinkage in X direction. In Y direction beam speed and laser power are parameters the most influencing the shrinkage effect. However in Z direction there is only one significant parameters that influence shrinkage which is hatch spacing.

4.3.4 Energy Density Analysis

The reason we calculate anova for 3 parameters is mention before is because those theree parameter are the function of energy density. Prakash and Singh (2010) indicated in their finding that the result for shrinkage was observed to be decrease with increasing in energy density value. Therefore, energy density for all experiment in Table 2 is calculate based on the formula (1). Table 12 shows all result of energy density calculation.

$$E = \frac{\mathrm{P}}{\mathrm{V} \times HS}$$

Table 12: Energy density for all 16 experiment

Experiment No.	Energy Density	Experiment No.	Energy Density
1	0.019	9	0.036
2	0.023	10	0.036
3	0.024	11	0.036
4	0.025	12	0.038
5	0.029	13	0.039
6	0.03	14	0.04
7	0.033	15	0.041
8	0.036	16	0.043

Based from the result in Table 12 and Table 3, a graph of shrinkage versus energy density for all direction is plotted.

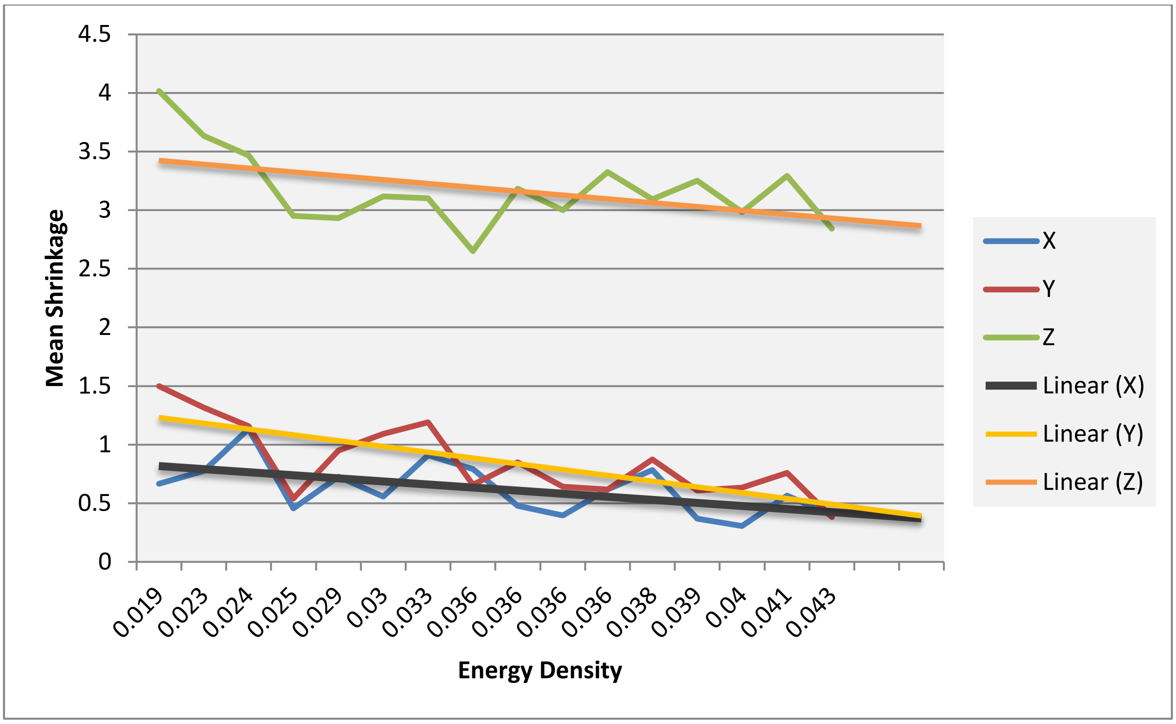

Figure 16: Mean Shrinkage with respect to energy density

Figure 16 shows the pattern of present work on mean shrinkage with increasing energy density. Even though the graph pattern is not constant but we can summaries based on the linear X, Y and Z. From that, we can see that the pattern is gradually decrease thus shows that as the energy density increase the mean shrinkage percentage decrease. Result of present work is compare with the result from the simulation process by Singh et al. (2010).

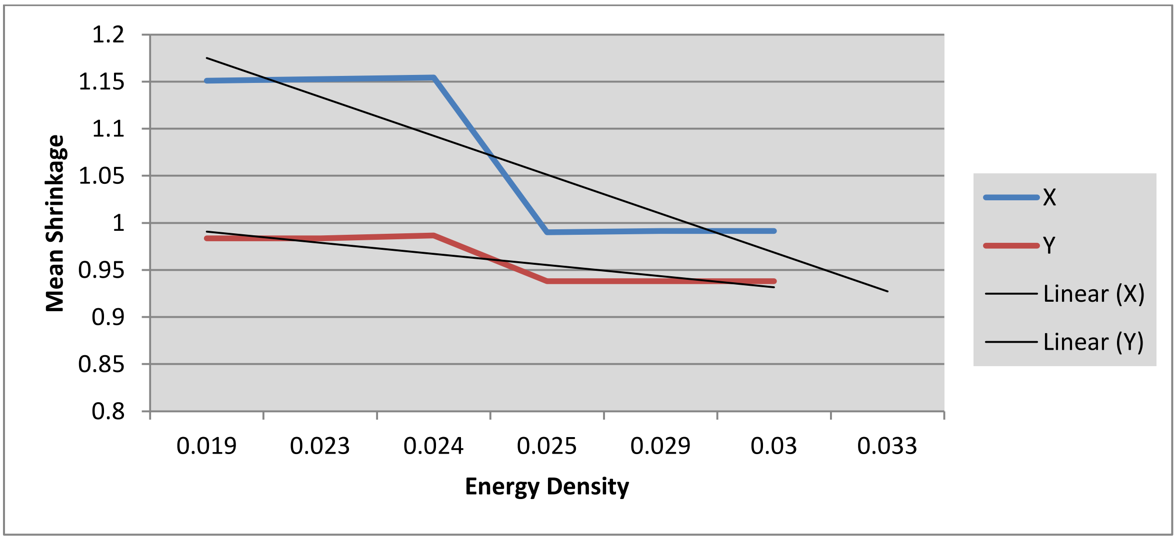

Figure 17: Mean Shrinkage with respect to different energy density[LR]

Figure 17 shows result from the simulation process by Singh et al. (2010). Compare with the graph plot for this present work, Figure 19, the trend observed is similar which is decreasing as energy density increase. Since present result for energy density shows good agreement with result from the literature review, we can say that the higher energy density the better.

From the shrinkage percentage value given in the Table 3, mean shrinkage for 3 process parameter by level can be calculated. This calculation is to get optimum value of thos 3 process parameters. Let's take laser power in X-direction as our process parameter example. Level 1 average shrinkage is calculated by adding all value of level 1 of laser power divide by the total number of sample size that used laser power value at level 1.

$$\frac{0.79167 + 0.72778 + 0.775 + 0.66667}{4} = 0.74028\ dB$$

Table 13, 14 and 15 in the shows all calculation data on mean shrinkage percentage in all direction. Data is calculated using Excel formula.

Table 13: Mean percentage Shrinkage in X-Direction

Symbol	Parameters	Mean Shrinkage			
		Level 1	Level 2	Level 3	Level 4
A	Laser power (W)	0.740	0.610	0.608	0.526
B	Beam speed (mm/s)	0.531	0.605	0.603	0.744
C	Hatch spacing (mm)	0.571	0.610	0.695	0.607
D	Part bed temperature (°C)	0.528	0.663	0.695	0.624
E	Hatch length (mm)	0.904	0.592	0.552	0.530

Table 14: Mean percentage Shrinkage in Y-Direction

Symbol	Parameters	Mean Shrinkage			
		Level 1	Level 2	Level 3	Level 4
A	Laser power (W)	1.106	0.790	0.921	0.627
B	Beam speed (mm/s)	0.602	0.906	0.844	1.092
C	Hatch spacing (mm)	0.692	0.881	0.967	0.904
D	Part bed temperature (°C)	0.731	0.783	0.933	0.944
E	Hatch length (mm)	0.971	0.717	0.910	0.846

Table 15: Mean percentage Shrinkage in Z-Direction

Symbol	Parameters	Mean Shrinkage			
		Level 1	Level 2	Level 3	Level 4
A	Laser power (W)	3.308	3.213	3.127	3.060
B	Beam speed (mm/s)	3.008	3.050	3.169	3.481
C	Hatch spacing (mm)	3.040	3.098	3.344	3.313
D	Part bed temperature (°C)	2.925	3.060	3.327	3.396
E	Hatch length (mm)	3.077	3.125	3.194	3.313

Based from the data, we can plot graphs for better understanding. The entire graph plotted is shown in the Figures 18-20. Based from the graph, optimum value for 3 process parameters can be identified. For example, In X Y and Z direction, Mean shrinkage for laser power is less in level 4 which is 36W. Full optimum parameters result is represent in Table 16.

Table 16: Optimum Process Parameters

Parameters	Value
Laser Power (W)	36
Beam Speed (mm/s)	3000
Hatch Spacing (mm)	0.22

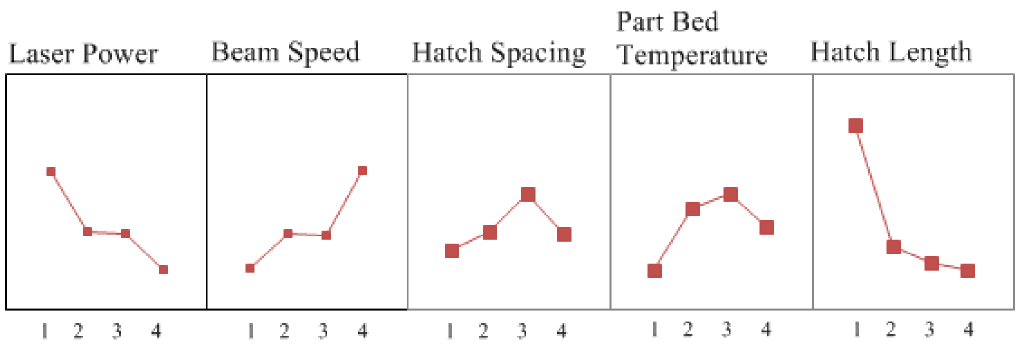

Figure 18: Shrinkage (%) in X direction

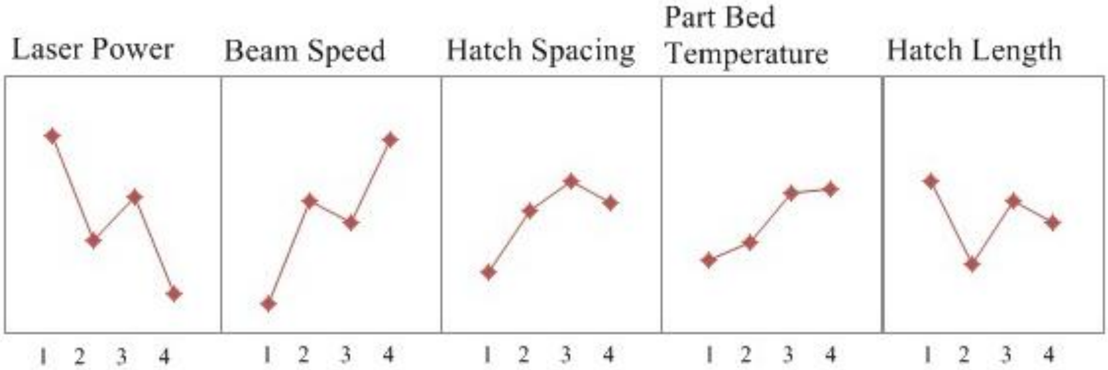

Figure 19: Shrinkage (%) in Y direction

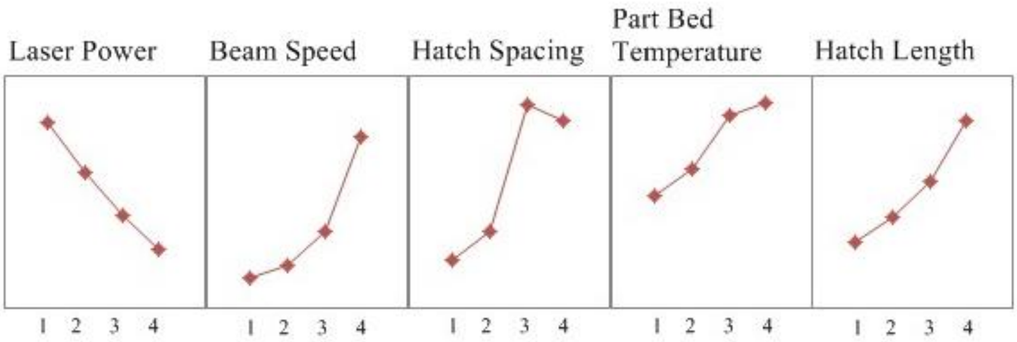

Figure 20: Shrinkage (%) in Z direction

**X-axis: level of process parameters*
**Y-axis: level of shrinkage (%)*

Figure 18-20 shows how shrinkage varies in different direction for every process parameters. In x-direction, shrinkage percentage is less at level 4 for laser power and hatch length, level 1 for beam speeds, hatch spacing and part bed temperature. For Y direction, laser power also results in less shrinkage percentage at level 4. Beam speed, hatch spacing and part bed temperature in y direction also got less shrinkage percentage at level 1. Results for less shrinkage remain the same for Z direction for every process parameters. So what we can conclude here is high laser power and low beam speed, hatch spacing and part bed temperature result in less shrinkage.

For this present project based on the data gather from the [6], energy density is calculated for optimum process parameter. Energy density is calculated based on the formula (1);.

$$E = \frac{\mathrm{P}}{\mathrm{V} \times HS}$$

E is energy density J/mm², *P* is laser power in W, and *V* is beam speed in mm/s and *H*s is hatch spacing in mm. [6].

Energy Density of optimum process parameter

$$E = \frac{36\mathrm{W}}{3000\mathrm{mm/s} \times 0.22mm} = 0.054$$

In order to get less shrinkage we have to ensure energy density is high. To increase *E*, we increase *P* and reduce *V* and *H*s therefore optimum process parameters for those 3 parameters is the highest value of Laser Power and the lowest value of hatch spacing and beam speed. Comparison of energy density for optimum process parameter that we calculate above with the entire energy density for all 16 experiments shows that the optimum process parameters have the highest value since based on the Table 12, the highest value is only 0.043. Therefore, it is clear that the highest energy density the better less of shrinkage effect.

4.3.5 Building Empirical Model with Linear Regression for 5 Parameters

For this project, there are several process parameters that are related to shrinkage effect for each directions and the mechanistic model relating these parameters is unknown. Therefore, it is necessary to build a model relating the parameters on observed data which is data from s/n ratio data in Table 4 and ANOVA done in previous analysis. The calculation to obtain empirical model is based on this formula [18]:

$$\eta\beta_0 + \beta_1\sum x_1 + \beta_2\sum x_2 = \sum y$$

$$\beta_0\sum x_1 + \beta_1\sum x_1^2 + \beta_2\sum x_1 x_2 = \sum x_1 y$$

$$\beta_0\sum x_2 + \beta_1\sum x_1 x_2 + \beta_2\sum x_2^2 = \sum x_2 y \qquad (12)$$

Table 17: Multiple Regression data in X direction

No	Y	X1	X2	Y²	X1²	X2²	X1X2	X1Y	X2Y
1	0.79167	24	30	0.626741	576	900	720	19.00008	23.7501
2	0.72778	24	45	0.529664	576	2025	1080	17.46672	32.7501
3	0.775	24	60	0.600625	576	3600	1440	18.6	46.5
4	0.66667	24	75	0.444449	576	5625	1800	16.00008	50.00025
5	0.37	28	75	0.1369	784	5625	2100	10.36	27.75
6	0.47917	28	60	0.229604	784	3600	1680	13.41676	28.7502
7	0.45556	28	45	0.207535	784	2025	1260	12.75568	20.5002
8	1.13333	28	30	1.284437	784	900	840	31.73324	33.9999
9	0.56667	32	45	0.321115	1024	2025	1440	18.13344	25.50015
10	0.90833	32	30	0.825063	1024	900	960	29.06656	27.2499
11	0.39667	32	45	0.157347	1024	2025	1440	12.69344	17.85015
12	0.55833	32	30	0.311732	1024	900	960	17.86656	16.7499
13	0.39583	36	30	0.156681	1296	900	1080	14.24988	11.8749
14	0.30667	36	45	0.094046	1296	2025	1620	11.04012	13.80015
15	0.78333	36	30	0.613606	1296	900	1080	28.19988	23.4999
16	0.61667	36	45	0.380282	1296	2025	1620	22.20012	27.75015
16	**9.93168**	**480**	**720**	**6.919828**	**14720**	**36000**	**21120**	**292.7826**	**428.276**

Based from the anova result, it shows that laser power and hatch length is the most significant parameters that influence the shrinkage. Therefore, empirical model to minimize shrinkage effect in X direction, derived from data in Table 17 and from the formula given above is shown below:

$$S_X = 1.930 - 0.0299L_P - 0.009167H_L \qquad (13)$$

Table 18: Multiple Regression data in Y direction

No	Y	X1	X2	Y^2	$X1^2$	$X2^2$	X1X2	X1Y	X2Y
1	0.65833	24	3000	0.433398	576	9000000	72000	15.79992	1974.99
2	0.95	24	3500	0.9025	576	12250000	84000	22.8	3325
3	1.31667	24	4000	1.73362	576	16000000	96000	31.60008	5266.68
4	1.5	24	4500	2.25	576	20250000	108000	36	6750
5	0.60833	28	3000	0.370065	784	9000000	84000	17.03324	1824.99
6	0.85	28	3500	0.7225	784	12250000	98000	23.8	2975
7	0.54167	28	4000	0.293406	784	16000000	112000	15.16676	2166.68
8	1.15833	28	4500	1.341728	784	20250000	126000	32.43324	5212.485
9	0.75833	32	3000	0.575064	1024	9000000	96000	24.26656	2274.99
10	1.19167	32	3500	1.420077	1024	12250000	112000	38.13344	4170.845
11	0.64167	32	4000	0.41174	1024	16000000	128000	20.53344	2566.68
12	1.09167	32	4500	1.191743	1024	20250000	144000	34.93344	4912.515
13	0.38333	36	3000	0.146942	1296	9000000	108000	13.79988	1149.99
14	0.63333	36	3500	0.401107	1296	12250000	126000	22.79988	2216.655
15	0.875	36	4000	0.765625	1296	16000000	144000	31.5	3500
16	0.61667	36	4500	0.380282	1296	20250000	162000	22.20012	2775.015
16	**13.775**	**480**	**60000**	**13.3398**	**14720**	**2.3E+08**	**1800000**	**402.8**	**53062.52**

Based from the anova result, it shows that laser power and beam speed is the most significant parameters that influence the shrinkage. Therefore, Empirical model to minimize shrinkage effect in Y direction, derived from data in Table 18 and formula given is shown below:

$$S_y = 0.786 - 0.0327L_P - 0.0002813B_S \qquad (14)$$

Table 19: Multiple Regression data in Z direction

No	Y	X1	X2	X3	Y²	X1²	X2²	X3²	X1X2	X1Y	X2Y	X3Y
1	2.65	0.22	3000	175	7.02	0.05	9.00E+06	30625	660	0.58	7950.0	463.8
2	2.93	0.24	3500	176	8.60	0.06	1.23E+07	30976	840	0.70	10266.7	516.3
3	3.63	0.26	4000	177	13.20	0.07	1.60E+07	31329	1040	0.94	14533.3	643.1
4	4.02	0.28	4500	178	16.13	0.08	2.03E+07	31684	1260	1.12	18075.0	715.0
5	3.25	0.24	3000	177	10.56	0.06	9.00E+06	31329	720	0.78	9750.0	575.3
6	3.18	0.22	3500	178	10.13	0.05	1.23E+07	31684	770	0.70	11141.7	566.6
7	2.95	0.28	4000	175	8.70	0.08	1.60E+07	30625	1120	0.83	11800.0	516.3
8	3.47	0.26	4500	176	12.02	0.07	2.03E+07	30976	1170	0.90	15600.0	610.1
9	3.29	0.26	3000	178	10.84	0.07	9.00E+06	31684	780	0.86	9875.0	585.9
10	3.10	0.28	3500	177	9.61	0.08	1.23E+07	31329	980	0.87	10850.0	548.7
11	3.00	0.22	4000	176	9.00	0.05	1.60E+07	30976	880	0.66	12000.0	528.0
12	3.12	0.24	4500	175	9.71	0.06	2.03E+07	30625	1080	0.75	14025.0	545.4
13	2.84	0.28	3000	176	8.08	0.08	9.00E+06	30976	840	0.80	8525.0	500.1
14	2.98	0.26	3500	175	8.90	0.07	1.23E+07	30625	910	0.78	10441.7	522.1
15	3.09	0.24	4000	178	9.56	0.06	1.60E+07	31684	960	0.74	12366.7	550.3
16	3.33	0.22	4500	177	11.06	0.05	2.03E+07	31329	990	0.73	14962.5	588.5
16	**50.83**	**4**	**60000**	**2824**	**163.1**	**1.008**	**2.30E+08**	**498456.0**	**15000**	**12.74**	**192162.53**	**8975.44**

Based from the anova result, it shows that hatch length, beam speed and part bed temperature is the most significant parameters that influence the shrinkage. Therefore, Empirical model to minimize shrinkage effect in Z direction, derived from data in Table 19 and formula given is shown below:

$$Sz = -28.6 + 0.00031Bs + 4.042H_S + 0.168T_B \qquad (15)$$

4.3.6 Building Empirical Model with Linear Regression for 3 Parameters

Previously, we developed empirical model for 5 process parameters based on the anova for 5 process parameter. This time, we develop empirical model based on the result of anova for 3 parameters. The calculation to obtain empirical model is based on this formula [18]:

$$\eta\beta_0 + \beta_1\sum x_1 + \beta_2\sum x_2 = \sum y$$
$$\beta_0\sum x_1 + \beta_1\sum x_1^2 + \beta_2\sum x_1x_2 = \sum x_1y$$
$$\beta_0\sum x_2 + \beta_1\sum x_1x_2 + \beta_2\sum x_2^2 = \sum x_2\, y \qquad (16)$$

However for z direction, this formula is apply [18];

$$\eta\beta_0 + \beta_1\sum x_1 = \sum y$$
$$\beta_0\sum x_1 + \beta_1\sum x_1^2 = \sum x_1y \qquad (17)$$

Table 20: Multiple Regression data in X direction

No	Y	X1	X2	Y^2	$X1^2$	$X2^2$	X1X2	X1Y	X2Y
1	0.79167	24	0.22	0.6267414	576	0.0484	5.28	19.00008	0.1741674
2	0.72778	24	0.24	0.5296637	576	0.0576	5.76	17.46672	0.1746672
3	0.775	24	0.26	0.600625	576	0.0676	6.24	18.6	0.2015
4	0.66667	24	0.28	0.4444489	576	0.0784	6.72	16.00008	0.1866676
5	0.37	28	0.24	0.1369	784	0.0576	6.72	10.36	0.0888
6	0.47917	28	0.22	0.2296039	784	0.0484	6.16	13.41676	0.1054174
7	0.45556	28	0.28	0.2075349	784	0.0784	7.84	12.75568	0.1275568
8	1.13333	28	0.26	1.2844369	784	0.0676	7.28	31.73324	0.2946658
9	0.56667	32	0.26	0.3211149	1024	0.0676	8.32	18.13344	0.1473342
10	0.90833	32	0.28	0.8250634	1024	0.0784	8.96	29.06656	0.2543324
11	0.39667	32	0.22	0.1573471	1024	0.0484	7.04	12.69344	0.0872674
12	0.55833	32	0.24	0.3117324	1024	0.0576	7.68	17.86656	0.1339992
13	0.39583	36	0.28	0.1566814	1296	0.0784	10.08	14.24988	0.1108324
14	0.30667	36	0.26	0.0940465	1296	0.0676	9.36	11.04012	0.0797342
15	0.78333	36	0.24	0.6136059	1296	0.0576	8.64	28.19988	0.1879992
16	0.61667	36	0.22	0.3802819	1296	0.0484	7.92	22.20012	0.1356674
16	9.93168	480	4	6.9198281	14720	1.008	120	292.78256	2.4906086

Based from the anova result, it shows that laser power and hatch spacing is the most significant parameters that influence the shrinkage. Therefore, Empirical model to minimize shrinkage effect in X direction, derived from data in Table 20 and formula given is shown below:

$$Sx = 0.865 - 0.01615LP + 0.912HS \qquad (18)$$

Table 21: Multiple Regression data in Y direction

No	Y	X1	X2	Y^2	$X1^2$	$X2^2$	X1X2	X1Y	X2Y
1	0.65833	24	3000	0.4333984	576	9000000	72000	15.79992	1974.99
2	0.95	24	3500	0.9025	576	12250000	84000	22.8	3325
3	1.31667	24	4000	1.7336199	576	16000000	96000	31.60008	5266.68
4	1.5	24	4500	2.25	576	20250000	108000	36	6750
5	0.60833	28	3000	0.3700654	784	9000000	84000	17.03324	1824.99
6	0.85	28	3500	0.7225	784	12250000	98000	23.8	2975
7	0.54167	28	4000	0.2934064	784	16000000	112000	15.16676	2166.68
8	1.15833	28	4500	1.3417284	784	20250000	126000	32.43324	5212.485
9	0.75833	32	3000	0.5750644	1024	9000000	96000	24.26656	2274.99
10	1.19167	32	3500	1.4200774	1024	12250000	112000	38.13344	4170.845
11	0.64167	32	4000	0.4117404	1024	16000000	128000	20.53344	2566.68
12	1.09167	32	4500	1.1917434	1024	20250000	144000	34.93344	4912.515
13	0.38333	36	3000	0.1469419	1296	9000000	108000	13.79988	1149.99
14	0.63333	36	3500	0.4011069	1296	12250000	126000	22.79988	2216.655
15	0.875	36	4000	0.765625	1296	16000000	144000	31.5	3500
16	0.61667	36	4500	0.3802819	1296	20250000	162000	22.20012	2775.015
16	13.775	480	60000	13.3398	14720	230000000	1800000	402.8	53062.515

Based from the anova result, it shows that laser power and beam speed is the most significant parameters that influence the shrinkage. Therefore, Empirical model to minimize shrinkage effect in Y direction, derived from data in Table 21 and formula given is shown below:

$$Sy = 0.786 – 0.0327L_P – 0.0002813B_S \qquad (19)$$

Table 22: Multiple Regression data in Z direction

No	Y	X1	Y^2	$X1^2$	X1Y
1	2.65	0.22	7.02	0.05	0.58
2	2.93	0.24	8.60	0.06	0.70
3	3.63	0.26	13.20	0.07	0.94
4	4.02	0.28	16.13	0.08	1.12
5	3.25	0.24	10.56	0.06	0.78
6	3.18	0.22	10.13	0.05	0.70
7	2.95	0.28	8.70	0.08	0.83
8	3.47	0.26	12.02	0.07	0.90
9	3.29	0.26	10.84	0.07	0.86
10	3.10	0.28	9.61	0.08	0.87
11	3.00	0.22	9.00	0.05	0.66
12	3.12	0.24	9.71	0.06	0.75
13	2.84	0.28	8.08	0.08	0.80
14	2.98	0.26	8.90	0.07	0.78
15	3.09	0.24	9.56	0.06	0.74
16	3.33	0.22	11.06	0.05	0.73
16	50.83	4	163.1	1.008	12.74

Based from the anova result, it shows only hatch spacing significant influence the shrinkage. Therefore, Empirical model to minimize shrinkage effect in Z direction, derived from data in Table 22 and formula given is shown below:

$$Sz = 2.1625 + 4.0625HS \qquad (20)$$

DISCUSSION

Ragunath did the study on 5 process parameters which is laser power, beam speed, hatch spacing, part bed temperature and hatch length in his study on process parameters. From the analysis of the solidworks simulation, small hatch length lead to increase in shrinkage, however its only apply for x direction, based from the anova analysis of 5 process parameter, in x direction hatch length is one of the significant process parameters that need to control in order to reduce the shrinkage effect.

For part bed temperature, anova analysis for 5 process parameters shows that this parameters only significant in z direction. Z direction in SLS rapid protoyping is the direction of the part build. Based from the figure 18, 19 and 20 part bed temperature result in less shrinkage when the value is at level 1 which is 175 degree. This is because, when the temperature increase, low cooling rate is reduce thus lead to increasing crystalline which increase the shrinkage effect. However its depend on the material used, this analysis is based on the polyamide type 6 thus optimum process parameter for part bed temperature is 175. Different material result in different value of part bed temperature.

Analysis of variance is then focus only on 3 process parameters which are laser power, beam speed and hatch spacing. Based from research studies on literature review it shows that those process parameters is a function of energy density. Based on the energy density analysis, reduction in shrinkage occur when the energy density is increase, compare with the experiment result done by Singh et. al(2010), good agreement is found.

Gibson et al. (1997) states that tensile strength and part density increase with decreasing beam speed, hatch spacing and increasing laser power. So, high energy density can have high tensile strength and large part density for SLS parts.

Thus shows that energy density is significant function that contribute to the reduction in shrinkage. Therefore, empirical model is develop based on the anova of 3 process parameters.

5 CONCLUSION & RECOMMENDATIONS

Based on the results obtained, the objective of this project which are to analyze the effect of process parameters on the part accuracy and to produce the optimal model of process parameters that result in less shrinkage is satisfied.

Shrinkage percentage give a significant effect on the part accuracy of the prototype produced. From the analysis done throughout this project, several process parameter such as laser power, beam speed, hatch spacing, part bed temperature and hatch length are contribute to the occurrence of the shrinkage. However certain process parameters are significant to shrinkage effect at different direction of the prototype.

The most important process parameters are laser power, beam speed and hatch spacing. thus empirical model that minimize the effect of shrinkage is develop based on this parameters using the linear regression formula. Below are the summaries of the optimum model obtain.

$$Sx = 0.865 – 0.01615LP + 0.912HS \quad (18)$$

$$Sy = 0.786 – 0.0327LP – 0.0002813Bs \quad (19)$$

$$Sz = 2.1625 + 4.0625HS \quad (20)$$

For the future studies regarding the process parameters of SLS rapid prototyping. It is recommended that more process parameters are taken into consideration such as part build orientation and layer thickness, Besides, for more understanding research work should be extended for developing a multi objective model that consider various other quality objectives such as surface roughness.

With the integration of SLS rapid prototyping, manufacturing systems can be developed to a state in which the design and process planning has a high level of intelligence that can greatly shorten design-manufacturing cycle time.

REFERENCES

1. Boillat, E., Kolossov, S., Glardon, R. Et al. (2004). *Finite element and neural network models for process optimization in selective laser sintering*
2. Childs, T.H.C., Berzins, M., Ryder, G.R., Tontowi, A.E.,(1999). *Selective laser sintering of an amorphous polymer simulation and experiments.*
3. Kolossov,S., Boillat,E.,Glardon, R. Et al. (2003). *3D FE simulation for temperature evolution in the selective laser sintering process*.
4. Singh,A.K., Prakash R.S (2010). *Simulation based multi-objective optimisation model.*
5. Dong,L., Makradi, A., Ahzi,S. Et al. (2009). *Three-dimensional transient finite element analysis of the selective laser sintering process*
6. Raghunath, N., Pandey,P. M (2007). *Improving accuracy through shrinkage modelling by using Taguchi method in selective laser sintering*.
7. Choi, S.h., Samavedam, S.(2002). *Modelling and optimisation of rapid prototyping*
8. Bacchewar,P.B., Singhal,S.K., and Pandey, P.M (2006). *Statistical modelling and optimization of surface roughness in the selective laser sintering process*
9. Chua,C.K., Leong,K.F., Lim,C.S., (2010) *THIRD EDITION, Rapid Prototyping; Principle and Application.*
10. Rahul B. Patil, Vinod Yadava (2007). *Finite element analysis of temperature distribution in single metallic powder layer during metal laser sintering.*
11. Gabriel and Lombera,G., (1999). *Numerical prediction of temperature and density distributions in selective laser sintering processes.*
12. Gibson, I., Dongping Shi (1997). *Material properties and fabrication parameters in selective laser sintering process.*
13. Katz. Z and Smith P E S (2001). *On process modelling for selective laser sintering of stainless steel.*
14. Ning. Y, Wong Y.S, Fuh. J.Y.H (2004) *Effect of control of hatch length on material properties in the direct laser sintering process.*
15. Wang R.J, Li X.H, Wu Q.D, Wang L (2009). *Optimization process parameters for selective laser sintering based on neural network and genetic algorithm.*

16. John D. William and Carl R. Deckard (1998). *Advances in modelling the effect of selected parameters on the SLS process.*

17. Yang. H.J, Hwang. P.J, Lee. S.H (2002). *A study on shrinkage compensation of the SLS process by using the Taguchi Method.*

18. Montgomery, Runger & Hubele. *2007, Engineering Statistics, Wiley.*

19. Patri. K, Venuvinod. *2004, Rapid Prototyping- Laser beam and other technologies, Kluwer Academic Publishers.*

APPENDIX I

ANOVA(3parameters) Z direction

Laser Power

	1	2	3	total	average
24	-8.4658	-9.3486	-11.2063	-29.0207	-7.25518
28	-10.256	-10.0582	-9.3982	-29.7124	-7.4281
32	-10.3493	-9.8275	-9.5467	-29.7235	-7.43088
				-88.4566	-5.52854
		SS_T	163.0929		

Beam Speed

	1	2	3	total	average
3000	-8.4658	-10.256	-10.3493	-29.0711	-7.26778
3500	-9.3486	-10.0582	-9.8275	-29.2343	-7.30858
4000	-11.2063	-9.3982	-9.5467	-30.1512	-7.5378
				-88.4566	-5.52854
		SS_T	163.1814		

Hatch Spacing

	1	2	3	total	average
0.22	-8.4658	-10.0582	-9.5467	-28.0707	-7.01768
0.24	-9.3486	-10.256	-9.8779	-29.4825	-7.37063
0.26	-11.2063	-10.8053	-10.3493	-32.3609	-8.09023
				-89.9141	-5.61963
		SS_T	170.8184		

ANOVA(3parameters) Y direction

Laser Power

	1	2	3	total	average
24	3.6123	0.3595	-2.4069	1.5649	0.391225
28	4.1927	1.3767	5.2489	10.8183	2.704575
32	2.3471	-1.5288	3.8166	4.6349	1.158725
				17.0181	1.063631
		SS_T	17.14072		

Beam Speed

	1	2	3	total	average
3000	3.6123	4.1927	2.3471	10.1521	2.538025
3500	0.3595	1.3767	-1.5288	0.2074	0.05185
4000	-2.4069	5.2489	3.8166	6.6586	1.66465
				17.0181	1.063631
		SS_T	18.76029		

Hatch Spacing

	1	2	3	total	average
0.22	3.6123	1.3767	3.8166	8.8056	2.2014
0.24	0.3595	4.1927	-0.7828	3.7694	0.94235
0.26	-2.4069	-1.2809	2.3471	-1.3407	-0.33518
				11.2343	0.702144
		SS_T	15.49802		

ANOVA(3parameters) in X Direction

Laser Power

	1	2	3	Total	Average
24	1.9856	2.725	2.1814	6.892	1.723
28	8.5817	6.1966	6.806	21.5843	5.396075
32	4.8655	0.8208	8.0208	13.7071	3.426775
				42.1834	2.636463

SS_T 64.10161

Hatch Spacing

	1	2	3	total	average
0.22	1.9856	6.1966	8.0208	16.203	4.05075
0.24	2.725	8.5817	5.0515	16.3582	4.08955
0.26	2.1814	-1.0965	4.8655	5.9504	1.4876
				38.5116	2.406975

SS_T 48.68734

Beam Speed

	1	2	3	total	average
3000	1.9856	8.5817	4.8655	15.4328	3.8582
3500	2.725	6.1966	0.8208	9.7424	2.4356
4000	2.1814	6.806	8.0208	17.0082	4.25205
				42.1834	2.636463

SS_T 44.37618

APPENDIX II

ANOVA(5parameters) in X direction

laser power	1	2	3	4	Total	Average
24	1.9856	2.725	2.1814	3.5019	10.3939	2.598475
28	8.5817	6.1966	6.806	-1.0965	20.4878	5.12195
32	4.8655	0.8208	8.0208	5.0515	18.7586	4.68965
36	7.9948	10.2626	2.0528	4.1754	24.4856	6.1214
					74.1259	4.632869
					SST	26.38763

beam speed	1	2	3	4	total	average
3000	1.9856	8.5817	4.8655	7.9948	23.4276	5.8569
3500	2.725	6.1966	0.8208	10.2626	20.005	5.00125
4000	2.1814	6.806	8.0208	2.0528	19.061	4.76525
4500	3.5019	-1.0965	5.0515	4.1754	11.6323	2.908075
					74.1259	4.632869
					SST	18.50558

hatch spacing	1	2	3	4	total	average
0.22	1.9856	6.1966	8.0208	4.1754	20.3784	5.0946
0.24	2.725	8.5817	5.0515	2.0528	18.411	4.60275
0.26	2.1814	-1.0965	4.8655	10.2626	16.213	4.05325
0.28	3.5019	6.806	0.8208	7.9948	19.1235	4.780875
					74.1259	4.632869
					SST	2.287867

part bed temperature	1	2	3	4	total	average
175	1.9856	6.806	5.0515	10.2626	24.1057	6.026425
176	2.725	-1.0965	8.0208	7.9948	17.6441	4.411025
177	2.1814	8.5817	0.8208	4.1754	15.7593	3.939825
178	3.5019	6.1966	4.8655	2.0528	16.6168	4.1542
					74.1259	4.632869
					SST	10.80259

hatch length	1	2	3	4	total	average
30	1.9856	-1.0965	0.8208	2.0528	3.7627	0.940675
45	2.725	6.806	4.8655	4.1754	18.5719	4.642975
60	2.1814	6.1966	5.0515	7.9948	21.4243	5.356075
75	3.5019	8.5817	8.0208	10.2626	30.367	7.59175
					74.1259	4.632869
					SST	91.64161

ANOVA(5parameters) in Y direction

laser power	1	2	3	4	total	average
24	3.6123	0.3595	-2.4069	-3.5486	-1.9837	-0.49593
28	4.1927	1.3767	5.2489	-1.2809	9.5374	2.38435
32	2.3471	-1.5288	3.8166	-0.7828	3.8521	0.963025
36	8.3039	3.8195	1.1429	4.1329	17.3992	4.3498
					28.805	1.800313
					SST	51.25897

beam speed	1	2	3	4	total	average
3000	3.6123	4.1927	2.3471	8.3039	18.456	4.614
3500	0.3595	1.3767	-1.5288	3.8195	4.0269	1.006725
4000	-2.4069	5.2489	3.8166	1.1429	7.8015	1.950375
4500	-3.5486	-1.2809	-0.7828	4.1329	-1.4794	-0.36985
					28.805	1.800313
					SST	53.11497

hatch spacing	1	2	3	4	total	average
0.22	3.6123	1.3767	3.8166	4.1329	12.9385	3.234625
0.24	0.3595	4.1927	-0.7828	1.1429	4.9123	1.228075
0.26	-2.4069	-1.2809	2.3471	3.8195	2.4788	0.6197
0.28	-3.5486	5.2489	-1.5288	8.3039	8.4754	2.11885
					28.805	1.800313
					SST	15.52008

part bed temperature	1	2	3	4	total	average
175	3.6123	5.2489	-0.7828	3.8195	11.8979	2.974475
176	0.3595	-1.2809	3.8166	8.3039	11.1991	2.799775
177	-2.4069	4.1927	-1.5288	4.1329	4.3899	1.097475
178	-3.5486	1.3767	2.3471	1.1429	1.3181	0.329525
					28.805	1.800313
					SST	20.13912

hatch length	1	2	3	4	total	average
30	3.6123	-1.2809	-1.5288	1.1429	1.9455	0.486375
45	0.3595	5.2489	2.3471	4.1329	12.0884	3.0221
60	-2.4069	1.3767	-0.7828	8.3039	6.4909	1.622725
75	-3.5486	4.1927	3.8166	3.8195	8.2802	2.07005
					28.805	1.800313
					SST	13.29397

ANOVA(5parameters) in Z direction

laser power	1	2	3	4	total	average
24	-8.4658	-9.3486	-11.2063	-12.0804	-41.1011	-10.2753
28	-10.256	-10.0582	-9.3982	-10.8053	-40.5177	-10.1294
32	-10.3493	-9.8275	-9.5467	-9.8779	-39.6014	-9.90035
36	-9.0737	-9.4947	-9.8045	-10.4374	-38.8103	-9.70258
					-160.031	-10.0019
					SST	0.763617

beam speed	1	2	3	4	total	average
3000	-8.4658	-10.256	-10.3493	-9.0737	-38.1448	-9.5362
3500	-9.3486	-10.0582	-9.8275	-9.4947	-38.729	-9.68225
4000	-11.2063	-9.3982	-9.5467	-9.8045	-39.9557	-9.98893
4500	-12.0804	-10.8053	-9.8779	-10.4374	-43.201	-10.8003
					-160.031	-10.0019
					SST	3.826335

hatch spacing	1	2	3	4	total	average
0.22	-8.4658	-10.0582	-9.5467	-10.4374	-38.5081	-9.62703
0.24	-9.3486	-10.256	-9.8779	-9.8045	-39.287	-9.82175
0.26	-11.2063	-10.8053	-10.3493	-9.4947	-41.8556	-10.4639
0.28	-12.0804	-9.3982	-9.8275	-9.0737	-40.3798	-10.095
					-160.031	-10.0019
					SST	1.58035

p.b.temperature	1	2	3	4	total	average
175	-8.4658	-9.3982	-9.8779	-9.4947	-37.2366	-9.30915
176	-9.3486	-10.8053	-9.5467	-9.0737	-38.7743	-9.69358
177	-11.2063	-10.256	-9.8275	-10.4374	-41.7272	-10.4318
178	-12.0804	-10.0582	-10.3493	-9.8045	-42.2924	-10.5731
					-160.031	-10.0019
					SST	4.344201

hatch length	1	2	3	4	total	average
30	-8.4658	-10.8053	-9.8275	-9.8045	-38.9031	-9.72578
45	-9.3486	-9.3982	-10.3493	-10.4374	-39.5335	-9.88338
60	-11.2063	-10.0582	-9.8779	-9.0737	-40.2161	-10.054
75	-12.0804	-10.256	-9.5467	-9.4947	-41.3778	-10.3445
					-160.031	-10.0019
					SST	0.841403

APPENDIX III

No	Detail/week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Project work continue								Midterm break								
2	Submission of Progress report																
3	Project work continue																
4	Pre-EDX																
5	Submission of Draft report																
6	Submission of Dissertation (Soft bound)																
7	Submission of Technical Paper																
8	Oral Presentation																
9	Submission of Dissertation (Hard bound)																

APPENDIX IV

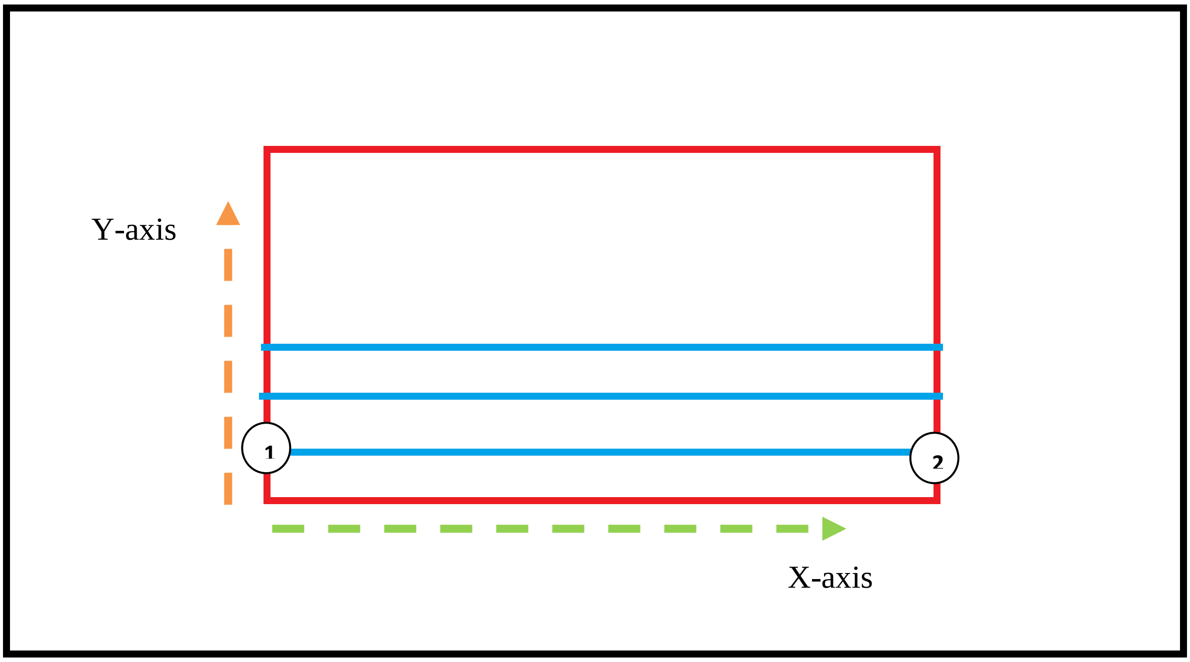

Figure above shows example drawing of powder surface in 2D view.

- Black rectangle shows the plan view of powder surface
- Red rectangle shows plan view of product that want to be build
- Blue line indicated the hatch length
- Space between the blue line indicated the hatch spacing
- Dash green line indicate the X-axis
- Dash orange line indicated the Y- axis
- The sintering process is occur along the x-axis from 1 until 2