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Optimal FDM Parameters Setting in Enhancing Impact Strength of PP/UHMWPE composite Using Fractal Factorial Design

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ABSTRACT

This paper aims to account a comprehensive study on the effect of Fused Deposition Modelling (FDM) parameters towards impact strength of Polypropylene/Ultra-High Molecular Weight Polyethylene (PP/UHMWPE) (90/10) composite using Fractal Factorial Design (FFD). The current study converged the investigation on five parameters namely; layer thickness (LT), number of shells (NOS), extrusion temperature (T), raster angle (RA), and infill speed (IS). The impact strength samples were manufactured according to the FFD recommended runs, which take two levels for every parameter into account. Scanning electron microscope (SEM) analysis was done to explore the effect of parameters setting on the samples' microstructure and insight on the correlation between samples' impact strength and parameters setting. The outcomes from the experiment revealed a significant effect for all investigated parameters but in various levels including some of the 2-factor interactions. Layer thickness has dominating effect as compared to single effect parameters, followed by infill speed. Layer thickness and number of shells interaction has the highest effect of all the parameters interactions. The best parameters setting has improved the impact strength of PP/UHMWPE composite by 61.5% compared with the worst setting results. Output of this study provides distinct insight into the effect of FDM parameters on the impact strength of PP/UHMWPE (90/10) composite. SEM investigation revealed the details behind altering the impact strength as result of process parameters changing.

Keywords: Fused Deposition Modeling, Impact Strength, process parameters, Factorial Design

I. INTRODUCTION

Fused Deposition Modeling (FDM) is based on layers building strategy that places a semi-molten plastic filament onto a platform in consecutive layers from bottom to top [1]. The extrusion nozzle follows the precise details of the object's cross section in every consecutive layer. The process is safe, clean, and free from toxic materials making it ideal for medical applications [2]. FDM imports the design in STL format file which includes multi slices to explicate the details of the object. The machine keeps the building area in heated envelope to guarantee good bounding between adjacent layers [3].

On account of the building process strategy, overall product quality may deteriorated in different phases including part depreciation of mechanical properties [4], increased surface roughness [5], dwindling of dimensional accuracy and repeatability [6], increasing building time and material consumption [7], or even amassing a number of them. FDM process parameters such as build orientation, raster angle, layer thickness, deposition temperature, deposition velocity, infill density and others has intensely influence the quality of the process [8]. "Ref. [9] reported that the properties of FDM parts are strongly dependent on process parameters as they affect the meso-structure and the strength of filament-filament bound [9]. Right selection of these parameters can improve the quality of FDM products, at which investigation of the effect of these variables on the process response is auspicious in specifying the best setting of these parameters. Design of experiment (DOE), Factorial design are subsequently used as a statistical tool to find out the best setting of the process parameters that optimize the process responses in forms of maximizing or minimizing based on the natural of the process response [10].

Preceding efforts have been made towards optimization the FDM-responses due to investigation of the effect of the process parameters choosing the optimal setting of these parameters. "Ref. [11] demonstrated that improving tensile and flexural strength of FDM-parts made of acrylonitrile butadiene styrene (ABS P400) by maintaining thickness layer at lower level, whereas at higher level to improve the impact strength [11]. Thickness of the layers subsequently caused two issues which are temperature gradient toward the bottom and circumvents the formation of voids between adjusted raster. Thin layers resulting increase in the number of layers which in turn raises the temperature gradient toward the bottom and consequently increase the diffusion between adjacent layers as well as limits the forming the voids. This will eventually improve the tensile and flexural strength. Whereas, thick layers results reducing in total number layers and then reduce heating/cooling cycles consequent reduce layer deformation and stress formation. Furthermore, thick

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layers provide more strain as compared to thin layers, and consequently has more tendency to absorb the impact of energy, as reported by "Ref. [12]. As for raster angle and raster width it is found that it was better when it is set at higher levels to improve all responses [13, 14,15]. That's attributed to the alignment of the raster to part loading direction as the alignment between them increases the loading ability. Whereas, increment of the raster width leads to decreasing of the number of raster required in performing one layer, that reduces the total joint area required along one layer, thenceforth enhance the overall mechanical properties. Air gap does not play significant role in improving the impact strength, however it has substantial effect on tensile and flexural strength when set at higher and medium range respectively [11]. This can be explained by the presence of positive gap between rasters which allowing the melted material to flow through and form joint points with adjusted lower layer; this in turn has enhances the bonding between layers, subsequently enhance over all material strength.

A study by "Ref. [9] conforms the previous research, as they institute that the tensile strength of the FDM parts made of ABS are strongly influenced by the setting values of part orientation, raster angle, raster width, and air gap [16]. "Ref. [17] reported that the air gap is the more dominant single variable that influence the tensile properties of FDM made from Polycarbonate (PC) parts as compared with the effect of other tested parameters namely; raster width, and raster angle. They found that by changing the default parameters setting has provided 20% improvement in the tensile strength, and they noticed that this improvement is equivalent to 80% of injection moulded and extruded PC parts strength, which anchorages to use as functional parts [17]. For the same material, "Ref. [18] reported that the layer thickness acquired highest effect on the impact strength of the FDM parts as compared with build orientation, raster angle and raster width which are included in the research. The optimal setting of these parameters which specified by Taguchi Design Method, resulting in three folds of improvement in impact strength as compared with un-optimized specimens [18]. "Ref. [19] found that deposition velocity and screw driving velocity (controls the amount of the material extruded) in bioextruder bring about the highest effect in terms of road width and consequently on the porosity and mechanical properties of the produced structure [19]. For two different grades of Polypropylene, "Ref. [20] revealed that 0° raster angle provide the highest ultimate tensile strength and Young's modulus, in contrast with the worst tensile properties which cross 45° building mode [20]. This result is mainly attributed by the alignment of loading direction with the raster length direction, and they didn't reliant on the bonding points between the rasters in loading applied forces as occurred in the other cases. Furthermore, the layer thickness showed less significant effect on the process responses. However, the selected range of layer thickness was quite narrow and it is observed that effect is clearer if the range start from 0.1 mm rather than 0.2 to 0.35 mm. "Ref. [21] investigated the effect of layer thickness, infill orientation, and the number of shell perimeters on the ultimate tensile strength and normal strain at break for polylactic acid (PLA). The results revealed significant decrease in the ultimate tensile strength as the infill orientation approaches to 90° and an increase as the number of shells increase. It is due to the loading direction issue, where the case becomes worst if the loading based on the bounding points between layers as occur in 90° fill orientation. Owing to the shell rasters positioned in alignment with the loading direction, the increase in their number subsequently provides stronger supports (compared with bounding points between adjacent layers). The study presented the increase in ultimate tensile strength and reaches the peak at layer thickness of 0.18mm, then decrease over this limit. Furthermore, the study reported the effect of the combination of the layer thickness and number of shells on the elastic modulus, where it reached the maximum value at the minimum value of the layer thickness and four perimeters. Infill orientation and number of shell perimeters interaction pushes the elastic modulus to peak at lower and higher levels respectively [21]. "Ref. [22] showed statistically that layer thickness has a dominant effect (89.44% effect contribution) on flexural force for the FDM samples made from PLA (Polylactic Acid), followed by the interaction between deposition angle and infill in modest contribution (4%) [22].

Based on results of the previous work for the same research group, 90/10 (PP/UHMWPE) Polypropylene/Ultra High Molecular Weight Polyethylene composite achieved the highest impact strength along the whole tested range (UHMWPE content from 10% to 50 %) [22]. The present study has attempted to enhance the impact strength of this composite (90/10) by exploring the best setting of five control variables which includes; layer thickness, number of shells, deposition temperature, raster angle, and infill velocity. Fractal Factorial design has been used to find out the best setting for these parameters.

II. EXPERIMENTAL

A. Materials

PP/UHMWPE (90/10) composite has been used in the study. The UHMWPE used was GUR 1020 (Ticona, United Kingdom) and supplied in a powder form $Mw = 3.5 \times 10^6$ g/mol with a density of $0.93 g/cm^3$. Polypropylene Impact Copolymer grade SM240 was supplied in a gradual form, melt flow rate at 230 C° is 25g/10 min, density $0.9 g/cm^3$.

B. Sample Preparation

Sample preparation starts with blending the 90/10 PP/UHMWPE using internal mixer (Model: Brabender) at 190 C°, 40 rpm for 10 min, resulted blend passes to crasher to transform it to granule form. Single type extruder set at; 140, 160, 190, and 190 °C from inlet to die temperature using 240 rpm and 10 rpm screw and roller pulley speed, respectively. 1.7±0.5mm filament diameter produced based on FDM raw material specifications. Next, the Flashforge Dual Extrusion 3D Printer, equipped with; build envelope (225 × 145 × 150 mm), nozzle diameter 0.4

mm was used to produce five impact test samples for each experiment run which suggested by Fractal Factorial Design. Impact test sample dimensions were specified according to ASTM D6110-10 notched charpy impact standard.

III. **Experimental Design**

The current study stipulated five important control factors [21, 24, 25] namely; layer thickness (A), Number of shells (B), Raster angle (C), Deposition temperature (D), and Infill speed (E) to investigate their effects on the impact strength of FDM-parts made from PP/UHMWPE. Other factors are holed at machine default values. Tables 1&2 exhibit the levels of control and fixed process parameters respectively.

Table. 1 independent FDM-parameter and their levels

FDM Parameters	code	Unit	Low level (-1)	Mid level (0)	High level (+1)
Layer thickness	A	mm	0.10	0.20	0.30
No. of shells	B	--	1	3	5
Deposition temperature	C	ºC	200	220	240
Raster angle	D	º	0	30	60
Infill speed	E	mm/s	30	45	60

Table. 2 fixed FDM-parameters

No	FDM-parameters	Unit	Value
1	Nozzle diameter	mm	0.4
2	Platform temperature	C°	120
3	Infill density	%	100
4	1th layer speed	mm/s	30
5	Orientation	x-y plane	horizontal

Fractal Factorial Design (FFD) was employed to design the experiment runs in order to investigate the effect of process parameters, interactions, establish empirical model, and find best setting for process parameters to maximize the process response (Impact strength). With the aim of reducing the number of experiment runs, half factorial 2^5 unblocked design having 16 factorial runs which are able to estimate main effects, two-factor interaction effects, and three-factor interaction effects [26]. Experimental runs randomization is necessary to eliminate the external disturbance or noise factors and reduce the effect of experiment bias [27]. In the current study, the experiment runs have been randomized based on the factorial method suggestion to prevent the effect of out of control factors such as machine parts situation along the working time.

Factorial design in MINITAB R17 with α=0.05 and maximizing the response strategy has been employed to analysis the experimental data in terms of response regression model to forecast the future responses and specify the right factors setting that could optimize the response function. Table-3 presents the experiment runs and response values.

Table. 3 Experiment runs design and response values

Trail no.	Std. order	Independent variables					Response Impact strength KJ/m^2
		Layer thickness mm	No of Shells	Deposition Temp. C°	Raster angle °	Infill speed mm/s	
1	4	0.1	1	200	0	60	4.84
2	10	0.3	1	200	0	30	5.27
3	12	0.1	5	200	0	30	4.88
4	6	0.3	5	200	0	60	7.12
5	7	0.1	1	240	0	30	5.37
6	16	0.3	1	240	0	60	4.66
7	2	0.1	5	240	0	60	4.10
8	1	0.3	5	240	0	30	7.51
9	14	0.1	1	200	60	30	5.11
10	3	0.3	1	200	60	60	4.59
11	11	0.1	5	200	60	60	3.70
12	13	0.3	5	200	60	30	8.35
13	5	0.1	1	240	60	60	7.10
14	15	0.3	1	240	60	30	4.88
15	9	0.1	5	240	60	30	4.42
16	8	0.3	5	240	60	60	4.95

IV. **RESULTS AND DISCUSSION**

Analysis of variance (ANOVA) presented in table (4) is used to proof the significant of the model variables in terms of P-value related to model, variables, and variable interactions. According to the F-calculated = 8393.89 is much greater than F-tabulated $=F_{(\alpha,\ dfm,\ dfd\ )} = F_{(\alpha,P\text{-}1,N\text{-}P)} = F_{(5\%,5,10)} = 4.74$, means reject the null hypothesis ($\beta_1 = \beta_2 = \beta_3 = \beta_n = 0$). Thus, it can be ratified that the model is suitable to represent the available data and any variable out of the model is insignificant [28]. Figure-1 shows the distribution of the experiment data is approximately normal.

Table-4 Analysis of variance (ANOVA)

Source	DF	Adj. SS	Adj. MS	F-value	P-value
Model	13	26.89	2.06	3893	0.000
Linear	5	5.92	1.18	2231	0.000
Interaction	8	20.96	2.62	4932	0.000
Error	2	0.0011	0.005		
Total	15	26.89			

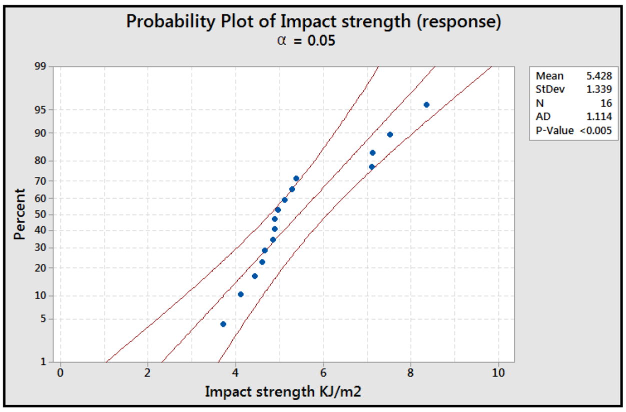


Figure. 1 Probability plot of the response (impact strength)

Pareto chart figure-2 presents briefly the significant variables after excluding insignificant variables. Layer thickness (LT), infill speed (IS), number of shells (NOS) have stronger effect than the deposition temperature (T) and raster angle (RA), raster angle is the lowest effect in all parameters group. Layer thickness has zealous positive

effect on response followed by infill speed that results in negative effect. Number of shells came third with positive effect. Residual parameters showed little negative effect as presented in main effects plot figure (3). This result is consistent with “Ref. [18]” results, which indicated that the layer thickness is the dominating effect on impact strength of Polycarbonate. As well “Ref. [11] reported that the optimal layer thickness which provides maximum impact strength (0.2531mm) was garter than those required to get maximum tensile and flexural strength (0.1318 & 0.1278 mm respectively), which implies that impact resistance is required to set the layer thickness at elevated level which is consistent with current result.

Decreasing the effect of extrusion temperature and raster angle is attributed to decreasing the effect of tested temperature range on the composite fluidity which in turn effects on the degree of layer joints and between adjacent rasters. As for decrement of raster angle effect, it is deduced that there is no relationship between direction of raster angle changing and applied load direction.

LT/NOS interaction is found to be the stronger effect in contrast with the significant difference in the intersected relations slop in figure-4. NOS/IS, LT/T, NOS/T, LT/IS, NOS/RA brought about high effect on process response, and it is noteworthy to maximize the impact strength. “Ref. [21]” reported decrease in ultimate tensile strength as infill rasters direction approaches to 90°, however noticed increase again as the number of shells increase. Current study exhibited lower effect of RA/NOS interaction particularly at prominent level of RA. This is in total contrast with cases which attributed to the relation between applied load and infill rasters direction. In “Ref. [21] case, the load is applied along the specimen length and changing the raster angle will subsequently specify the percentage of applied load which only action bounding points between layers. At the angle of 90° the load will be completely sustained by joints points between layers, and then increase in the number of shells consequently becomes significant. Whereas in the current study case, the applied load cross the infill raster direction, then changing its angle does not make big sense.

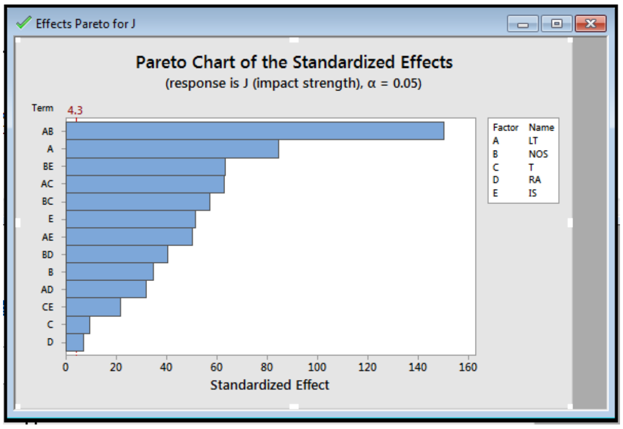


Figure.2 FDM parameters and interactions effect on response (impact strength)

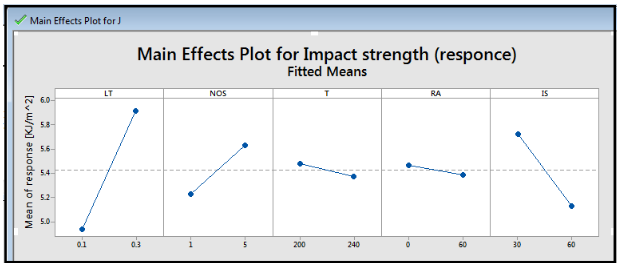


Figure. 3 main effects plot for response

It is also observed that T & RA both exhibited the lowest effect as compared with the interactions. Nevertheless, the interactions of these variables with others such as LT&T and NOS&RA have higher effect as compared to the variables itself. This proved that it is important to note that some variables do not showed significant effect individually however they provide a substantial effect with others. This result is strongly consistent with argument mentioned by “Ref. [22]” .

Prediction model presented in equation-1 constructed to predict future response based on fitted variables value. The regression model was built with R2=100%, R2 (adj)=99.79%, and R2 (pred.) =99.75%. According to model response optimizer, optimal independent variables setting were specified as presented in figure-5, the impact strength value predicted as 9.26 KJ/m^2

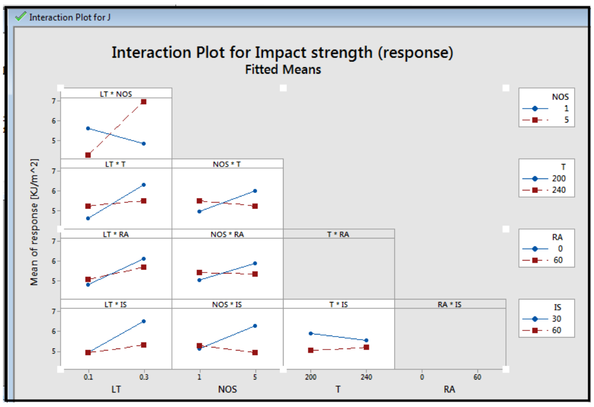
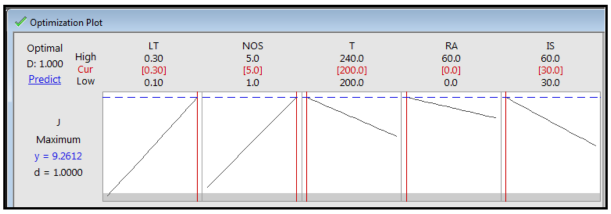


Figure-4 Intersection effects plot for response


Optimization Plot

Optimal
D: 1.000
Predict

	LT	NOS	T	RA	IS
High	0.30	5.0	240.0	60.0	60.0
Cur	[0.30]	[5.0]	[200.0]	[0.0]	[30.0]
Low	0.10	1.0	200.0	0.0	30.0

J
Maximum
y = 9.2612
d = 1.0000

Figure-5 Response optimization

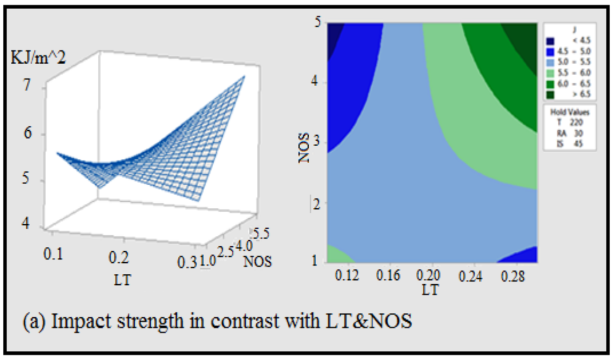
$$J=-5.123 + 42.253\,A + 1.7113\,B + 0.03952\,C + 0.02251\,D - 0.0356\,E + 4.328\,A{*}B - 0.1809\,A{*}C - 0.0610\,A{*}D - 0.19375\,A{*}E - 0.008234\,B{*}C - 0.00385\,B{*}D - 0.012188\,B{*}E + 0.000415\,C{*}E \qquad (1)$$

To test model reliability FDM parameters set to the optimal values presented in figure-5; layer thickness = 0.3 mm, number of shells = 5, extrusion temperature = 200 °C, raster angle = 0°, infill speed = 30 mm/sec. The impact strength of the five manufactured samples using the outlined settings are presented in Table 5. The impact strength (maximum) according to prediction model is presented in Equation (4.3) = 9.612[Mpa].

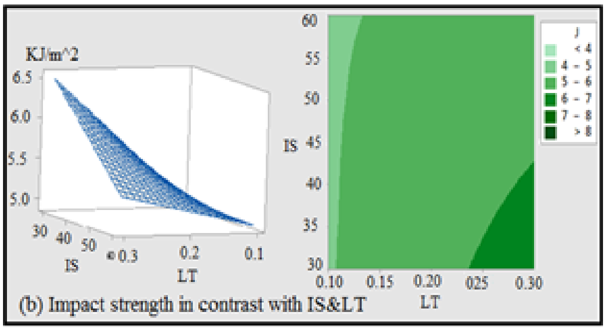
Table 5 Predicted and experimental results of impact strength

Run No.	Prediction value [Mpa]	Experimental values [Mpa]	Model reliability
1	9.26	9.03	--
2		9.32	--
3		9.12	--
4		9.11	--
5		9.00	--
Mean		9.12	98.4 %

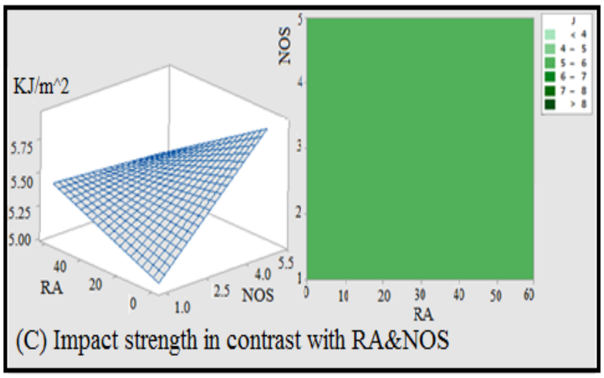
The distinct changes in process response guided by the changing in independent variables can be observed in the previous plots as well as the surface and counter plots of variables interaction presented in figure-6. Similarly, it can be visibly observed that layer thickness and number of shells interaction has dominating effect the process response. Response peak was reached at the high levels of the both LT and NOS as shown in figure-6-a. Whereas, in IS & LT interaction (figure-6-b) shows the response peak at low level of the IS and high level of the LT in narrow changing range of the response (5.0 to 6.5KJ/m2). Limited response changing range (5.0 to 5.75 KJ/m2) is observed in RA & NOS interaction which justified the low effect of this interaction.



(a) Impact strength in contrast with LT&NOS



(b) Impact strength in contrast with IS&LT



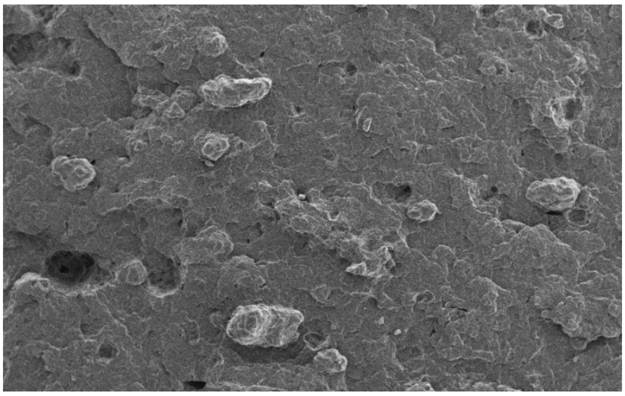
(C) Impact strength in contrast with RA&NOS

Figure. 6 Surface and counter plots for the variables interaction

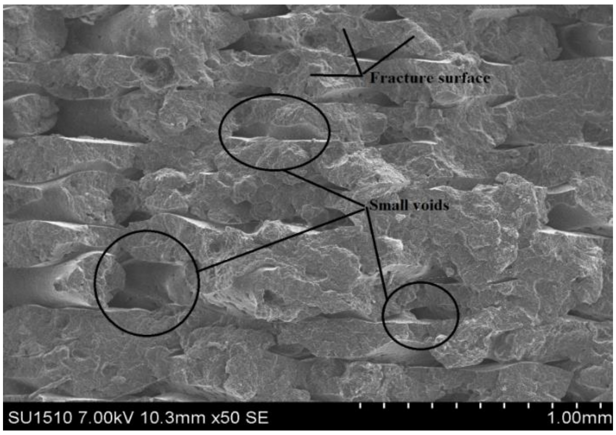
To understand the natural effect of the process parameters, scanning electron microscope (SEM) images were captured for selected runs samples which represent the high, mid, and low response. Complete diffusion between adjusted rasters and between adjusted layers for high impact sample (run-12, table 3) is observed as presented in figure-7-a. This diffusion is attributed to printing with low level of infill speed at high level of layer thickness, which caused the nozzle to be more stable and laying the rasters perfectly and do not leave the opportunity to form voids. Complete diffusing between adjusted rasters and layers strongly increase the adhesive strength between layers consequentially strengthens the mechanical behavior of the part as reported by “Ref. [11]”. and “ Ref. [17]”. Furthermore, by taking figure-6-b as reference (interaction between infill speed and layer thickness), it can be clearly discerned that the manufacturing the sample under this setting will provide maximum level of the impact strength.

Mid-impact strength sample is presented in figure-7-b (run-4, table 3) revealed excellent diffusion between adjusted rasters and between adjusted layers, however, some small voids appeared along the captured area. The parameters setting for this sample were medially between high and low strength samples cases. High level for both infill speed and layer thickness leads to moderate level of impact strength as presented in figure-6-b because of the formation of voids. However, high level of shells (5 perimeters) included in this sample setting has enhances the process response to substantial level.

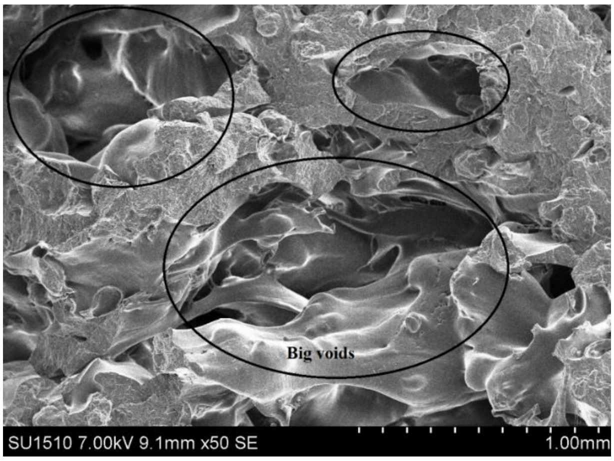
Low impact strength sample presented in figure-7-C (run-7, table 3) shows several large voids which spread along the captured area. This sample was fabricated with low level of layer thickness and high level of infill speed. By referring to figure-6-b it can be discern that the resulted impact strength under these parameters values will provide minimum strength level. The printing by high level of infill speed at low level of layer thickness definitely result in many voids and then deteriorate the sample strength.



(a) High impact strength sample



(b) Mid impact strength sample



(C) Low impact strength sample

Figure-7 scanning electron microscope images for impact samples

V. Conclusion

Fractal factorial design 2^5 has been used to investigate the effect of FDM parameters includes; layer thickness, number of shells, extrusion temperature, raster angle, and infill printing speed on the behaviour of impact strength of PP/UHMWPE (90/10) composite.

Analysis of the results showed that of all the single effects, layer thickness has dominant effect on the process response followed by infill speed and number of shells, whereas remaining parameters showed moderate effect. Layer thickness and number of shells interaction both at high level has strongly maximize the process response. Extrusion temperature and raster angle both has low single effect. However, they showed significant effect as they interact with other variables.

Scanning Electronic Microscopce images for high, mid, and low impact strength samples were consistent with the Fraction Factorial Design analysis results. Forming the voids through sample material is strongly related to the parameters setting values. Increasing the infill speed at low level of layer thickness has inevitably leads to formation of several big voids and subsequently depreciates the material impact strength.

The experiment design disclosed that changing the parameter setting has highly affected the FDM process. Impact strength of PP/UHMWPE (90/10) composite was altered from 3.7 KJ/mm^2 to 8.35KJ/mm^2 as a result of the changing of process parameters. The improve in impact strength is due to the parameters changes which is corresponding to 55.6% estimates the value of parameters affected on process response. Best parameters setting is as specified by FFD analysis result leads to increases of the impact strength of composite samples to 9.612 KJ/m^2 which is equivalent to 61.5% improvement as compared with worst setting.

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