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Impact of ironing for improvement of surface finish during fused deposition modeling (FDM) based 3D Printing

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Abstract: Additive Manufacturing is a new innovative way to create parts in multiple layers and allows for the production of complex geometries along with highly customisable components for use in various industries; aerospace, automotive, biomedical, and defence. The popular methods of AM is Fused Deposition Modelling (FDM) due to its practical and cost-effective nature. FDM uses extruded thermoplastic filament to make 3D parts out of a wide range of materials such as Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) with great design freedom. Despite the popularity/ease of use of FDM, there continue to be hurdles to overcome for achieving uniform surface roughness and dimensional accuracy, which are instrumental to functional performance and the industrial acceptance of printed parts. The purpose of this research is to analyse how ironing impacts the surface finish of 3D printed PLA samples using Fused Deposition Modelling (FDM). The research will utilise a RSM based design of experiment (DOE) methodology to prepare 20 samples and the specimens will be manufactured by varying the print speed, layer thickness, and amount of infill during the print process. From surface roughness analysis, it is observed that surface finish enhanced significantly with ironing process by reducing Ra from 3.527 μm to 2.098 μm with an improvement of 40.52 % at 0.13 mm layer thickness. The significant smoothing effect is identified by ironing since average roughness was reduced from 6.000 μm to 4.310 μm. The surface quality improvement is due to the combined heat, pressure, and material redistribution from the ironing processes.

Key words: additive manufacturing, fused deposition modeling, surface finish, ironing

1. Introduction

Additive manufacturing (AM) allows to produce highly intricate customized components layer by layer. This is important for speeding up prototyping cycles, reducing costs associated with tooling and materials, and the reduction of wasted resources within rival industries including aerospace, biomedical equipment, automotive, consumer products.[1-4] AM is broken into seven main technology categories; these categories include Vat Photopolymerization, Material Jetting, Powder Bed Fusion, Binder Jetting, Directed

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Energy Deposition, Sheet Lamination and Material Extrusion (FDM/FFF), and are distinguished by the type of feedstock and the energy type used.[5-7] From above listed technologies, FDM utilizes low-cost machines, readily available filament, a simple operating process, and scalable operations across desktop to production-level machine systems, making FDM the most widely used technology for prototyping and producing functional components.[8-13] FDM providing access, safety, speed of development and freedom of geometric design for end-product applications such as jigs and fixtures, enclosures and covers, biomedical device and model, composite tooling, and consumer goods.[9,14-15] Typical FDM-ready materials include PLA (Excellent printability), ABS (Excellent toughness and resistance to heat), ASA (Excellent UV protection), PETG (Excellent ability to balance other mechanical properties), elastomers such as TPU, and reinforced composites with fiber or particle materials for rigidity and enhanced performance capabilities.[4,7,10] Printing Parameters such as layer height, line width, speed, infill, raster angle, nozzle or bed temperatures, cooling and extrusion flow and their interactions control the quality of the print, as well as bonding/adhesion, dimensional accuracy and top-surface finish that must be optimised systematically to meet the design and performance requirements.[11,13,16-18]

Surface roughness in FDM from factors including staircase geometry, line by line ridging and micro voids which result from discrete paths combined with the cooling process. The size and shape of the surface roughness will vary non-linearly as a function of layer height, speed, temperature, raster angle, infill/cooling and flow rate; additionally, there are significant interactions among variables.[11,13,16-18] Turner *et al*.[13] reported nozzle temperature and layer height to dimensional accuracy and surface roughness by observing that low speeds were capable of overheating/smearing ridges while high speeds may cause under extrusion and preserved valleys . Bakhtiari *et al*.[17] quantified how the compressive properties and Ra of PLA are influenced non-linearly by print speed and temperature. Kalman *et al.*[16] used laser profilometry to assess how outer perimeter geometry has an impact on surface roughness and supporting the influence of both the kinematics and layer height on ridge periodicity and amplitude. Pérez *et al*.[18] demonstrated that the raster angle of the tool path on the down facing surface of a printed part and production platform conditions influence the quality of the top layer consolidation and valley refilling, thus advocating for the result of effectively coordinated parameter tuning. Núñez *et al.*[19] found that smaller layer height and greater infill density will produce better ABS surfaces and maintain better dimensional stability. Pramanik *et al*.[20] found that print speed and hot end temperature had the highest effect on surface roughness for ABS parts. Vyavahare *et al*.[21] demonstrated that the build orientation and layer thickness of the printed part have a significant effect on both surface roughness; the print speed and extruder temperature are also crucial for achieving surface roughness.

There are many options for post-processing FDM to improve surface finishing, but they all have advantages and trade-offs related to cost, safety, dimensional accuracy, and the ability to reach isolated geometries. Chemical vapor polishing allows for rapid and visible reduction of surface roughness and elimination of visible ridges, but may change dimensions of the object, affect some of the mechanical properties of the part, and come with some inherent risks from the solvent being used.[22,23] Abrasives and media-tumbling methods reduce Ra and offer benefits, but these processes often require the ability to reach surfaces to perform the post-processing operations and can also round off sharp features; CNC (computer numerically controlled) machining gives you the ability to have controlled material removal with tight tolerances on accessible surfaces, however, this comes with the drawbacks associated with making fixturing/tool access difficult and being subject to delaminating of the poorly- bonded outer rings.[14,24] Additionally, by filling in the micro-valleys in prints, coatings made from resins or polymers improve the surface texture of the part and allows for more efficient downstream processing operations.[15] Thermal treatments can help strengthen the bond between layers of the printed part and alleviate residual stress, but they have some indirect effects on the uniformity of surface roughness; uncontrolled heating during thermal treatment can re-flow features and shift dimensions of the object.[25,26]

Ironing is a top surface pass that is native to the Slicer, where the heated nozzle makes controlled low flow passes over the finished layer of filament to re-melt material on the top layer, wipe it down, level peaks, and to fill in micro-valleys resulting in a smoother, flatter finish than could normally be achieved through additional external equipment or solvent application. [27,28]

2. Experimental Work

The aim of this research is to evaluate the surface finish (roughness) of FDM-printed items. This includes the methodology, the design of the sample, DOE and data analysis that were done in this study.

2.1. Methodology

The methodology used for experimentation is shown in *Fig.* 1. First, the CAD model of the study sample is designed using CATIA, and RSM DOE L20 array is used to set the experiment parameters. CAD model was sliced with PrusaSlicer software, model printing, measurement of surface roughness, and parameter analysis to determines critical parameter and optimal values.

2.2. CAD Modeling

A CAD model is needed to create a 3D printed object in layers. The CAD model of the object was created using CATIA Software (see *Fig.* 2(a))). The dimensions used to model the object are shown in *Fig*. 2(b)).

2.3. RSM Design of experiments

The use of response surface methodology (RSM) and designed experiments (DOE) enabled researchers to evaluate the effects on the surface quality of parts produced by using fused deposition modelling (FDM), according to three key FDM process parameters: printing speed (PS), layer thickness (LT), and infill density (ID), with the application of the advanced ironing technique to the top surface of parts. The levels of printing speed, layer thickness, and infill density are decided on printer specifications, literature

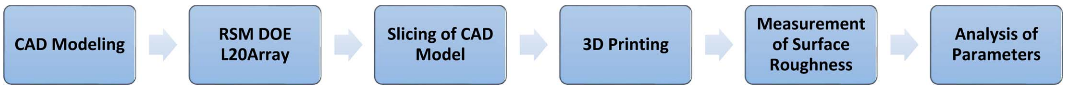
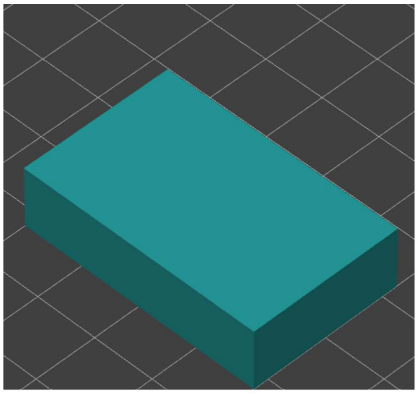
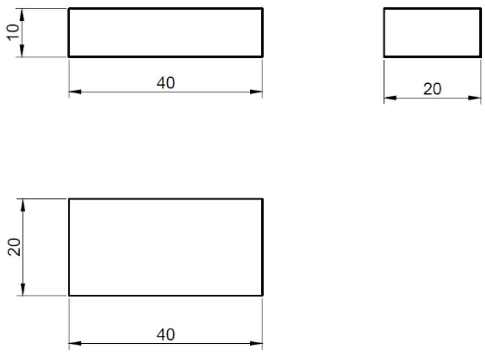


Fig. 1. Methodology of experimentation.



(a)



(b)

Fig. 2. (a) Specimen CAD Model, (b) Specimen Dimensions.

reviews and pilot experiments. A total of 20 experiments were performed. The ranges of the parameters whose effects were evaluated ranged from: PS (86.59 mm/s to 103.41 mm/s), LT (0.13 mm to 0.19 mm), and ID (76.59% to 93.41%).

Table 1. RSM L20 Array

Specimen	Printing Speed (mm/s)	Layer thickness (mm)	Infill density (%)
E1	95.00	0.13	85.00
E2	95.00	0.16	93.41
E3	95.00	0.16	85.00
E4	100.00	0.18	80.00
E5	100.00	0.18	90.00
E6	95.00	0.16	85.00
E7	90.00	0.18	80.00
E8	95.00	0.16	76.59
E9	90.00	0.18	90.00
E10	95.00	0.16	85.00
E11	95.00	0.16	85.00
E12	90.00	0.14	90.00
E13	103.41	0.16	85.00
E14	100.00	0.14	90.00
E15	95.00	0.16	85.00
E16	95.00	0.19	85.00
E17	95.00	0.16	85.00
E18	86.59	0.16	85.00
E19	100.00	0.14	80.00
E20	90.00	0.14	80.00

2.4. Slicing of CAD model

In PrusaSlicer, the 3D model was sliced into layers to generate printer instructions as shown in *Fig.* 3. The ironing technique smooths the top layer by running the nozzle over it again, improving surface finish. This was enabled by activating the ironing top layer option in the print settings before slicing with setting above mentioned parameters Printing Speed, Layer thickness, Infill density. The ironing enabled to all top surface ironing type with 10 % flow rate and 0.05 mm spacing between ironing passes.

2.5. 3D Printing

All 20 specimens were printed by use of Creality 3D CR-X desktop 3D printer. The finalized CAD model was first exported in STL format and then sliced to generate G-code instructions. The printer with 300 mm × 300 mm × 400 mm build volume, utilized filament with nozzle diameter of 0.4 mm as specified by the manufacturer. Printing was performed at 250 °C nozzle temperature and at 60 °C bed temperature. *Fig.* 4 illustrates the printing process and printed specimen with regular and ironing surface finish.

2.6. Measurement of surface roughness

Surface roughness was measured using Surface

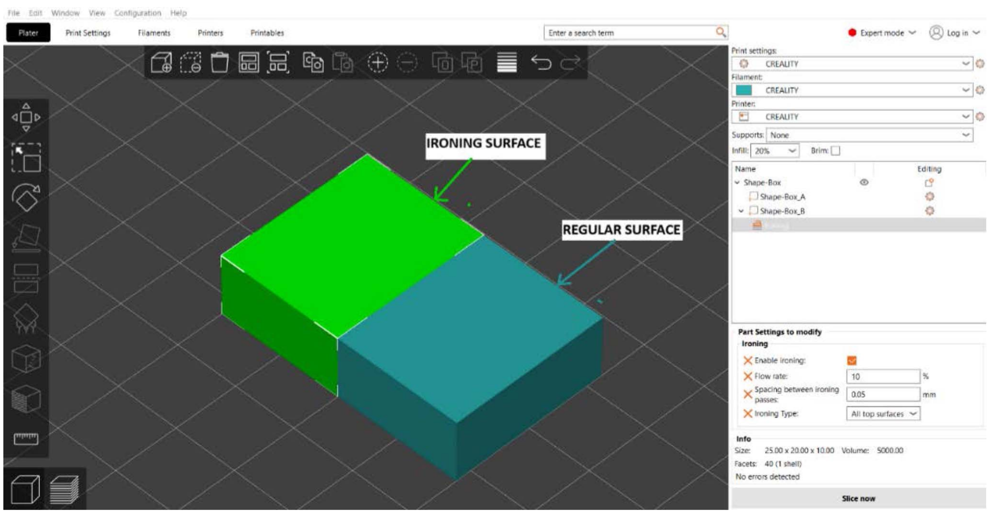


Fig. 3. Slicing of 3D model.

(a)

(b)

Fig. 4. (a) Specimen Printing, (b) Printed Specimen with Ironing and Regular Surface

Fig. 5. Measurement of specimen using surface roughness tester.

roughness tester as shown in *Fig.* 5. The surface roughness values Ra, Rq and Rz were measured. The results were recorded and analysed.

3. Analysis, Results and Discussions

3.1. The main effects plot for surface roughness

Surface roughness measurements were conducted to assess how layer thickness (LT) influences the surface quality of both the standard and ironed surfaces.

Regular surface roughness is at the low end at 3.527 µm for 0.13 mm LT and is at the maximum of 7.233 µm for 0.19 mm LT. Each increment of LT reduces surface roughness and increases from 0.13 mm LT to 0.14 mm LT by 11.38 % and at 0.16 mm, 0.18 mm and 0.19 mm by 46.22 %, 49.42 % and 51.23 %, respectively. From the 0.13 mm LT to the next largest LT, the increase in surface roughness continues to decrease.

When compared to regular surface, the amount of

Table 2. Measurements of 3D printed specimen

Specimen	Parameters			Surface Roughness Ra in µm		% Improvement in surface roughness
	PS mm/s	LT mm	ID %	Regular Printed Surface	Ironing Surface	
E1	95.00	0.13	85.00	3.527	2.098	40.52
E2	95.00	0.16	93.41	6.439	5.240	18.62
E3	95.00	0.16	85.00	6.488	4.621	28.78
E4	100.00	0.18	80.00	6.989	5.289	24.32
E5	100.00	0.18	90.00	6.813	4.613	32.29
E6	95.00	0.16	85.00	6.808	4.987	26.75
E7	90.00	0.18	80.00	7.108	5.148	27.57
E8	95.00	0.16	76.59	6.023	4.596	23.69
E9	90.00	0.18	90.00	6.989	4.681	33.02
E10	95.00	0.16	85.00	6.891	5.128	25.58
E11	95.00	0.16	85.00	6.887	4.568	33.67
E12	90.00	0.14	90.00	3.998	3.125	21.84
E13	103.41	0.16	85.00	6.480	4.586	29.23
E14	100.00	0.14	90.00	3.923	3.113	20.65
E15	95.00	0.16	85.00	6.499	4.985	23.30
E16	95.00	0.19	85.00	7.233	5.146	28.85
E17	95.00	0.16	85.00	6.523	4.687	28.15
E18	86.59	0.16	85.00	6.552	4.365	33.38
E19	100.00	0.14	80.00	3.899	2.546	34.70
E20	90.00	0.14	80.00	4.100	2.687	34.46

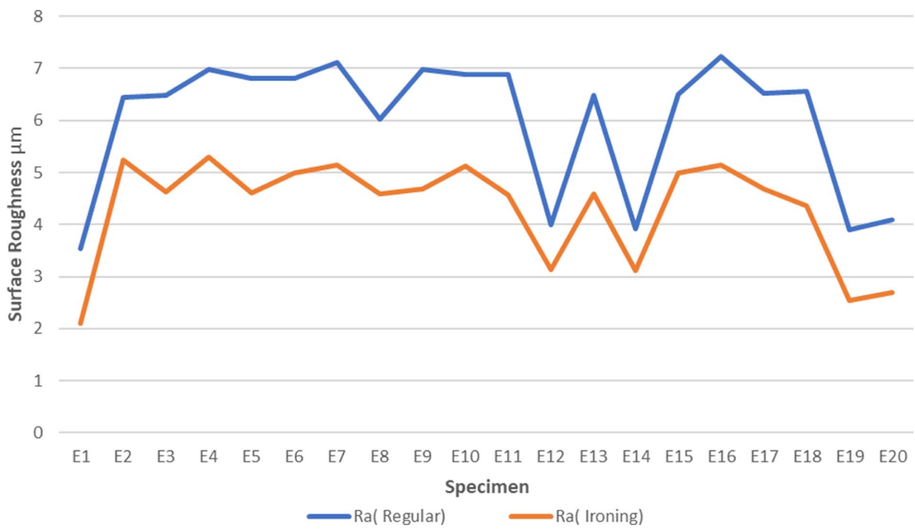


Fig. 6. Comparison between Surface roughness (Ra) for Regular and Ironing surface.

ironed surface roughness is less than regular; ironed LT surface roughness for 0.13 mm is 2.098 µm and 0.19 mm is 5.146 µm. The relationship between surface roughness and LT remains the same as well. The Ra for ironed surface would be a reduction of 26.82 % for the next largest LT from 0.13 mm to 0.14 mm, a reduction of 56.07 % from 0.14 mm to 0.16 mm, a reduction of 57.46 % from 0.16 mm to

0.18 mm and a reduction of 59.23 % from 0.18 mm to 0.19 mm.

The overall conclusion is that the process of ironing provides a significant improvement in the quality of the surface finish. While the average Ra of the standard surface was approximately 6.000 µm, the average Ra of the ironed surface was approximately 4.310 µm; thus, resulting in an 18.60 % to 40.52 % improvement in the overall surface finish consistency. The largest improvement in the Ra measurement occurred at 0.13 mm LT from 3.527 µm to 2.098 µm. This indicates that the process of ironing eliminates layer lines from the surface and optimizes both the quality of the surface finish and the consistency of the surface finish.

The improvement in surface finish during ironing is combined effect of controlled pressure, localized heat and redistribution of material flow on top layer of printed part. During ironing the nozzle of printer moves on a printed surface at reduced speed and during this there is very small filament extrusion, or no extrusion occurs, and this is done at slightly higher temperature as compared to normal FDM printing. These conditions soften the top layer and allow a semi-molten polymer to redistribute and fill the irregularities between adjacent extruded part. During process the pressure of nozzle tip acts like a heated roller which mechanically compresses and flattens surface irregularities.

Mathematically, the surface finish or roughness is average height difference between real surface and ideal flat surface which is mentioned as

$$Ra = \frac{Sum\ of\ height\ differences}{Measured\ Length}$$

During ironing as it redistributes the material on already printed surface and fills the valleys by flattening up the peaks. Therefore, ironing reduces the surface roughness by making surface a continuous surface by reducing the height differences between peaks and valleys.

3.2. Statistical analysis using ANOVA and regression models

To find out significance of process parameters on surface finish of regular and ironed surface regression equations and ANOVA is done.

Table 4. Model summary for regular surface

R-sq	R-sq(adj)	R-sq(pred)
96.91%	94.12%	81.26%

Table 3. Analysis of variance for regular surface

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	30.5722	3.3969	34.81	0.0
Linear	3	24.6494	8.2165	84.19	0.0
PS	1	0.0351	0.0351	0.36	0.562
LT	1	24.6065	24.6065	252.12	0.0
ID	1	0.0078	0.0078	0.08	0.783
Square	3	5.9162	1.9721	20.21	0.0
PS × PS	1	0.2908	0.2908	2.98	0.115
LT × LT	1	5.1212	5.1212	52.47	0.0
ID × ID	1	0.8523	0.8523	8.73	0.014
2-Way Interaction	3	0.0065	0.0022	0.02	0.995
PS × LT	1	0.0	0.0	0.0	0.983
PS × ID	1	0.0006	0.0006	0.01	0.939
LT × ID	1	0.0059	0.0059	0.06	0.811
Error	10	0.976	0.0976	-	-
Lack-of-Fit	5	0.778	0.1556	3.93	0.08
Pure Error	5	0.198	0.0396	-	-
Total	19	31.5481	-	-	-

3.2.1. For regular surface

Tables 3 and 4 indicates ANOVA and Model Summary for Regular Surface respectively.

Regression Equation

$$\text{Ra-Regular} = -171.5 + 1.040\ PS + 660\ LT + 1.663\ ID - 0.00566\ PS^2 - 1765\ LT^2 - 0.00969\ ID^2 - 0.02\ PS \times LT + 0.00034\ PS \times ID - 0.27\ LT \times ID$$

The response surface regression (RSR) analysis and ANOVA are used to determine the effect of PS, LT, and ID on Ra Regular surface. Using this analysis (*Table* 3), we have determined a quadratic model that has an F-value of 34.81 and a P-value of 0.000 for the parameters in the model to be statistically significant; therefore, the parameters are adequate to explain the variability in the surface roughness of the part. The most dominant parameter within the linear portion of the model is LT with a P-value of 0.000. Neither PS or ID had statistically significant linear parameters ($P > 0.05$). Collectively, the quadratic terms were also statistically significant indicating that there are nonlinear relationships between the parameters and Ra Regular surface. Specifically, LT^2 ($P = 0.000$) and ID^2 ($P = 0.014$) were statistically significant; and demonstrate a strong curvature within their respective areas suggesting that there are optimum parameter regions are present; while PS^2 is statistically insignificant. There were no statistically significant interaction effects between PS, LT, and ID; therefore, they act independently. A lack of fit test was insignificant ($P = 0.080$) indicating that the model is acceptable. The model (*Table* 4) also indicated a high R^2 (96.91 %), a high adjusted R^2 (94.12 %), and a high predicted R^2 (81.26 %); demonstrating that the RSR model will reliably predict Ra Regular surface with LT being the most dominant parameter that affects surface roughness.

3.2.2. For ironing surface

Tables 5 and 6 indicates ANOVA and Model Summary for Ironing Surface respectively.

Regression Equation

$$\text{Ra-Ironing} = -156.1 + 1.403\ PS + 757\ LT +$$

Table 6. Model summary for regular surface

R-sq	R-sq(adj)	R-sq(pred)
96.30%	92.97%	80.48%

Table 5. Analysis of variance for ironing surface

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	18.2774	2.0308	28.94	0.0
Linear	3	13.2445	4.4148	62.9	0.0
PS	1	0.0062	0.0062	0.09	0.772
LT	1	13.1728	13.1728	187.69	0.0
ID	1	0.0654	0.0654	0.93	0.357
Square	3	4.449	1.483	21.13	0.0
PS × PS	1	0.5003	0.5003	7.13	0.024
LT × LT	1	4.0733	4.0733	58.04	0.0
ID × ID	1	0.0124	0.0124	0.18	0.684
2-Way Interaction	3	0.5839	0.1946	2.77	0.097
PS × LT	1	0.0064	0.0064	0.09	0.769
PS × ID	1	0.0008	0.0008	0.01	0.917
LT × ID	1	0.5767	0.5767	8.22	0.017
Error	10	0.7018	0.0702	-	-
Lack-of-Fit	5	0.4316	0.0863	1.6	0.31
Pure Error	5	0.2702	0.054	-	-
Total	19	18.9792	-	-	-

$$0.680\ ID - 0.00742\ PS^2 - 1574\ LT^2 - 0.00117\ ID^2 + 0.282\ PS \times LT - 0.00040\ PS \times ID - 2.685\ LT \times ID$$

The response surface regression (RSR) analysis and ANOVA are used to determine the effect of PS, LT, and ID on Ra Ironing surface. According to the results from this study (see *Table* 5), there is a significant quadratic relationship between the parameters of the model with an F value of 28.94 and a P value of 0.000; therefore, the developed model can be considered statistically significant and will help explain variability in ironing surface roughness. In terms of the linear main effects, LT has the greatest influence with a P value of 0.000, and PS and ID

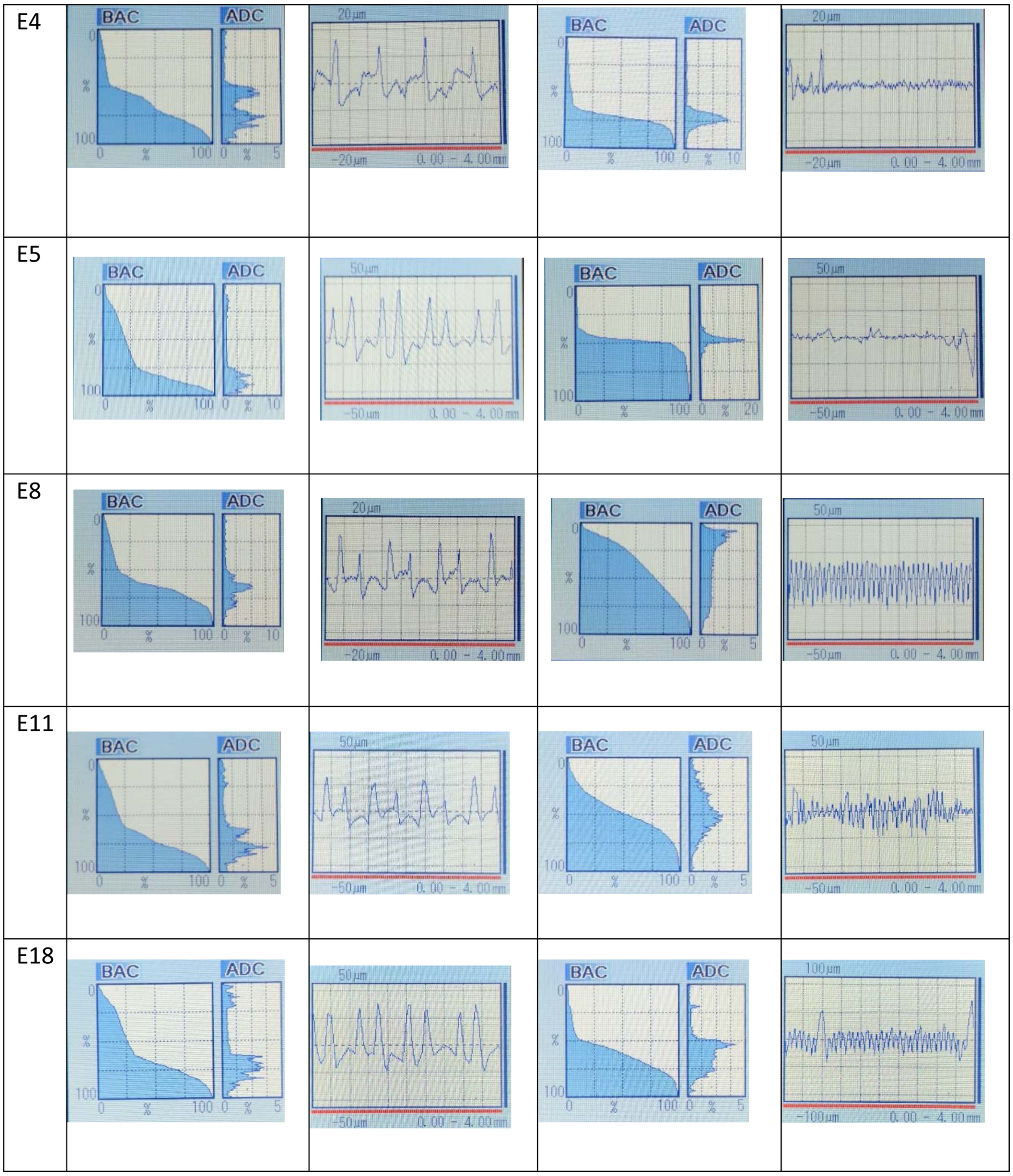


Fig. 7. BAC-ADC and surface roughness profile for regular printing surface and ironing surface.

don't exhibit statistically significant linear relationships with P values greater than 0.05. The quadratic main effects collectively are statistically significant, indicating that there are non-linear relationships between the process parameters and Ra ironing surface; specifically, the quadratic terms, PS^2 (P = 0.024) and LT^2 (P = 0.000), are statistically significant with strong curvature indicating optimum parameter regions, while ID^2 is statistically insignificant. Although there is no overall interaction effect with a P = 0.097 value, there is an interaction effect between LT and ID (P = 0.017) indicating that LT and ID have combined effects on ironing surface roughness. The lack-of-fit test was found to be non-significant (P = 0.310), which indicates that the developed model adequately fits the experimental data. The model summary characteristics (*Table* 6) indicate a high R^2 (96.30%) value, an adjusted R^2 (92.97%) value, and a predicted R^2 (80.48%) value confirming that the developed RSR model can be used reliably to predict Ra ironing surfaces, with LT being the greatest predictor for surface roughness for ironing surfaces.

3.3. Surface topology analysis

Measurements were performed according to ISO 1997 with λc = 0.8 mm and stylus speed = 0.5 mm/s. *Fig.* 7 presents the graphs showing difference between the regular surface and the ironing surface. For the regular surface, the Bearing Area Curve (BAC) drops steeply at the beginning, indicating high surface peaks, and then gradually extends across the full material ratio range from 0 % to 100 %, showing the presence of deep valleys and an uneven profile. The Amplitude Distribution Curve (ADC) is irregular and spread out, with values roughly within 0–5 % in one graph and up to 0–10 % in another, confirming a wide variation in surface heights. In contrast, the ironing surface exhibits a smoother BAC with a less steep slope, indicating reduced peak heights and shallower valleys, resulting in a more uniform material distribution. The ADC is more symmetrical and concentrated, with a narrower spread of values, showing that most surface heights are closely distributed. Overall, the ironing process significantly improves surface quality by reducing roughness and creating a more consistent and uniform surface compared to the regular surface.

The graphs show difference between the regular surface and the ironing surface. For regular surface, the graph shows significant and erratic fluctuation in height in the vertical displacement. High surface roughness and lack of uniformity, due to presence of tall, jagged peaks and deep valleys. Further, the peaks is inconsistent in the horizontal spacing.

For ironing surface, the heights of the peaks are noticeably minimized and the depth of the valleys is reduced, leading to a much lower overall amplitude. The profile maintains a more stable and consistent path across the entire sampling length.

Finaly from the roughness profiles validate that the ironing technique effectively refines the part's exterior. The ironing technique gives superior surface finish than the regular printing.

4. Conclusion

The findings from the present investigation indicate that both layer thickness and the use of ironing affect how well finished the surface is on FDM printed parts. The minimum surface roughness of an FDM printed part, printed with a layer thickness of 0.13 mm, was 3.527 µm under regular printing conditions, indicating that increasing the layer thickness would not produce as favourable of a finished surface. In addition, by using ironing on a printed part with a layer thickness of 0.13 mm, the surface roughness was reduced from 3.527 µm (regular printing) to 2.098 µm, representing an increase in surface finish of approximately 40.52 % compared to normal printing. Overall, the average surface roughness of a printed part that was produced using the regular printing method was reduced from 6.000 µm to 4.310 µm as a result of ironing the part, which translates into an increase in surface finish of 28.17 % improving layer thickness through Ironing. When one compares the effect on surface roughness between printed parts produced at different layer thicknesses from 0.13 mm to 0.19 mm, it is demonstrated that a lower layer thickness produces a smoother surface. It is believed that ironing improves the surface finish due to the combined effect of heat, pressure, and material redistribution that occur during the ironing process, whereby the semi-molten plastic resin enters the voids or valleys of the surface and smooths the peaks or micro-peaks present on the surface. These results illustrate the critical importance of optimising the layer thickness and the ironing parameters utilized to achieve improved surface finish through the reduction in post-processing requirements, the reduction of manufacturing costs and the expanded use of FDM produced components in industry.

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