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Topography characterization of fused deposition modelling surfaces

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Abstract
Deemed as one of the established additive manufacturing technique, fused deposition modelling (FDM) is commonly used for creating functional prototypes. Additive manufacturing, in general, generates surfaces that are different compared to conventional manufacturing and consists of features that are either not well-defined or satisfactorily characterized using the existing surface standards. The generated surfaces vary with respect to different techniques, materials, geometries and process parameters Additive manufacturing boosts of manufacturing individualized parts and as claimed, product with complex design can be easily manufactured but the problem lies in manufacturing it with highest surface quality or produce a well-defined robust surface.
The aim of the study is to characterize the FDM surfaces generated at different process settings using areal surface parameters. The experimental study includes surface measurements of study sample build at different orientation and layer thickness. A general statistical methodology is implemented to identify the deterministic features on the manufactured surface. The results include topography characterization using the significant features and detailed study on the influence of geometry and process settings on FDM surfaces.

Additive manufacturing (AM), Fused Deposition Modelling (FDM), Surface Topography, Areal surface parameters, Power Spectral Density (PSD)

1. Introduction

Additive manufacturing is a rapid manufacturing technique which reduces multiple processing steps of conventional manufacturing and requires less material, less processing time, less energy on generating products with complex geometries. Considering AM's huge prospect in producing cost-effective, light-weight complex components, especially related to aerospace and medical applications, the technique is continuously improved to serve the function of a part in a better way. So it is important to study the topography of AM surfaces which helps to develop a fundamental understanding of the process and the functional behaviour of the component and later can be used to optimize the design.

This research concerns the surfaces produced by Fused Deposition Modelling (FDM) where the melted material from the filament is extruded and deposited in layered fashion as in the CAD model. This layer by layer manufacturing causes a stair-case effect and greatly influences the surface quality [1][2]. Most of the studies on FDM have focused on optimizing the process parameters and as mentioned in [1], the key success of additive manufacturing lies in proper selection of process parameters. Selecting the optimum parameters ensures better quality and dimensional precision of products. In this study, the effects of build angle and layer thickness on the surface topography are investigated.

Due to the dominant lay of FDM surfaces, most of the investigations and models are developed to study the surfaces using two-dimensional profiles. But three-dimensional surface topography will provide more information required to understand the surface and its functional behaviour. This study specifically deals in identifying the significant features and to numerically characterize the FDM surfaces using set of robust areal surface parameters. For the surface characterization, these significant parameters and PSD analysis are used to determine the dominant features and wavelength respectively for certain inclination and layer thickness.

2. Methodology

The modified truncheon artefacts, as shown in figure 1, are printed in Zortrax M200 with the thermoplastic polymer ABS (Acrylonitrile-Butadiene-Styrene) material at build inclination varying from 0^{o} to 90^{o} with step of 10^{o}. The study samples are built at high print quality with layer thickness of 0.09mm, 0.19mm & 0.29mm.

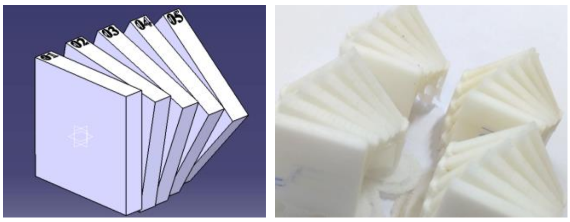


Figure 1. CAD model and FDM print of modified truncheon study artefacts

2.1. Surface evaluation

The sample's surfaces are evaluated using three-dimensional measurements from contact profilometer. The instrument used for measurements was the Taylor Hobson stylus profilometer. Measurement area of 2.5mm X 2.5mm is considered for the study. The captured surfaces are analysed using Mountains Map software wherein a string of operators performed to remove the influence of form. The areal surface parameters, defined by ISO 25178-2:2012 [3], are used to evaluate the surfaces generated by different layer thickness and build angle.

2.2. Identifying significant features

The surface parameters vary in the randomness of surface features at different scale of measurements. While comparing multiple surfaces at a particular scale, it is not imperative to characterize all the features present on the surface. Hence dominant features that are comparative and deterministic are identified and analysed using power spectral density and regression analysis.

The Power Spectral Density (PSD) analysis Fourier transforms the topography data in order to obtain the contribution at different lateral scales. This technique offers a means of representing the properties of all wavelengths, or spatial sizes, of the features of surface texture. Those properties of PSD were used in study in order to compare and characterize the printed surfaces.[4]

The Multiple regression analysis helps to identify the significant surface parameters based on the coefficient of determination (R^2), Significance F and P-value of the regression coefficients. Higher the R^2, higher the variability of the surface parameter readings explained with respect to the layer thickness and build angle. The significance F (for $\alpha=0.05$) suggest the non-randomness in the data and the P-value (confidence interval of 95%) helps to determine the significant influence of individual process variable.

3. Results and Discussions

The ploughing effect was observed as result of measurements, but ploughing effect was insignificant compare to overall roughness of measured topography. It needs to be pointed that surfaces printed in 0^o inclination need to be analysed separately due to the difference in printing procedure. The surface is deposited on a single plane in raster orientation, as shown in figure 2, unlike at other build inclination where the surfaces are combination of layers deposited.

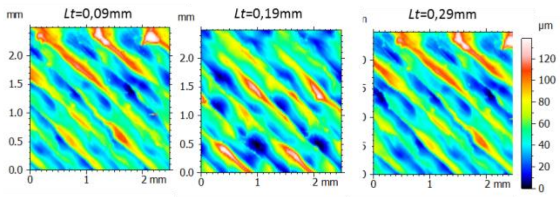


Figure 2. Overview of surface topography for samples printed with different layer thickness with 0^o inclination.

Figure 3 shows the example of variation of surface topography due to the changing of printing inclination.

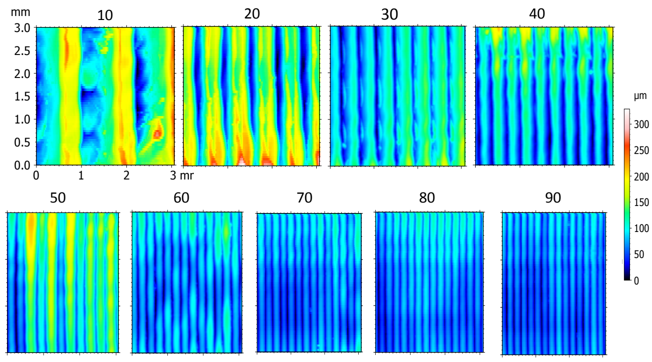


Figure 3. Visualization of surface topography variation correspondently to changing of printing inclination. (Layer thickness, Lt=0,19mm).

For the PSD analysis, three dimensional PSD was calculated for each inclination. Later the PSD curvature that describes the surface behaviour in profile and printing direction was extracted from the 3D PSD plot. The combination of PSD for profile directions and inclination from 10 to 90 degrees are combined to one plot for the demonstration of array of wavelength that describes the measured surfaces. From PSD plots for profile direction dominant wavelength for each inclination were determined. It was found that this wavelength can be correlated to the layer thickness used for printing of the sample.

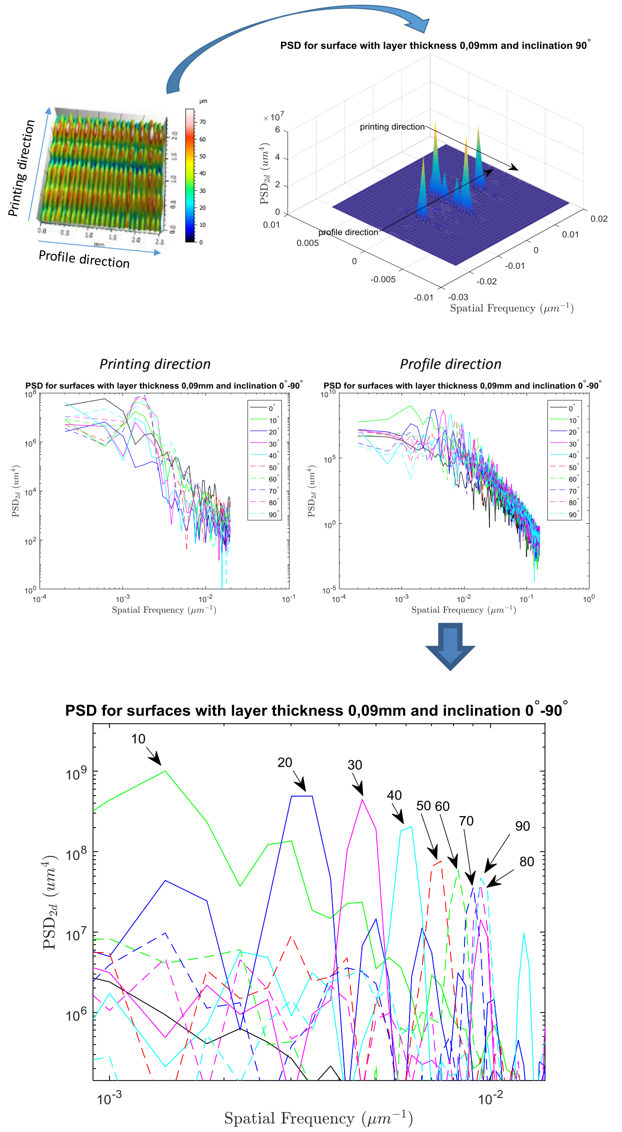


Figure 4. Methodology for determination of dominant wavelength for samples printed with layer thickness *Lt*=0.09mm

Figure 4 demonstrate the stepwise calculation procedure from topography measurement to waviness determination from the PSD plot.

The simple equation below describes the dependencies.

$$Lt = W * \sin \alpha \tag{1}$$

where, *Lt*-layer thickness; *W*-dominant wavelength determinate from PSD plot; α-angle of inclination.

Accordingly to the PSD calculations, the discrepancies from the thickness layer chosen as printing parameter was detected and presented in Table 1.

Table 1. Determination of thickness layer from dominant wavelength calculated from PSD for profile direction.

Lt- layer thickness, SPF -spatial frequency from PSD, $Lt_{theoretical}$- Layer thickness calculated from equation 1						
Print parameter	**Lt=0.09mm**		**Lt=0.19mm**		**Lt=0.09mm**	
Inclination (°)	**SPF (1/µm)**	**$Lt_{theoritical}$ (µm)**	**SPF (1/µm)**	**$Lt_{theoritical}$ (µm)**	**SPF (1/µm)**	**$Lt_{theoritical}$ (µm)**
10	0.0014	124	0.0006	289	0.0006	289
20	0.0032	107	0.0017	201	0.001	342
30	0.0046	109	0.0021	238	0.0015	333
40	0.0061	105	0.003	214	0.0021	306
50	0.00725	106	0.0034	225	0.0025	306
60	0.0082	106	0.0041	211	0.0027	321
70	0.009	104	0.0045	209	0.0029	324
80	0.0094	105	0.0047	210	0.003	328
90	0.0096	104	0.0047	213	0.003	333
Average *Lt* (µm)		106		215		324
Difference (µm)		16		25		34
Difference (%)		17		13		12

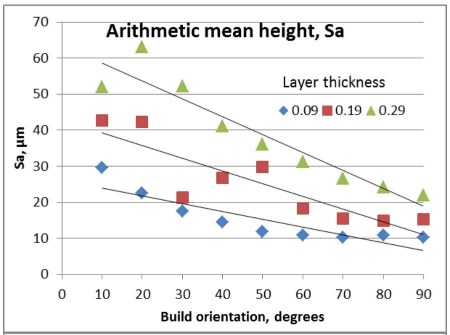
Results from Table 1 shows that calculated printed layer thickness is higher than correspondent parameter from printer set up.

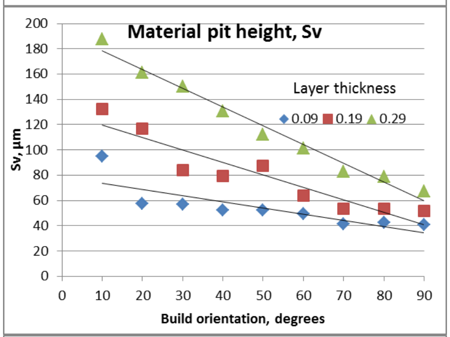
From the regression analysis, the surface parameters with coefficient of determination (R^2) above 0.80 are considered as significant. The significant surface parameters are listed in table 2.

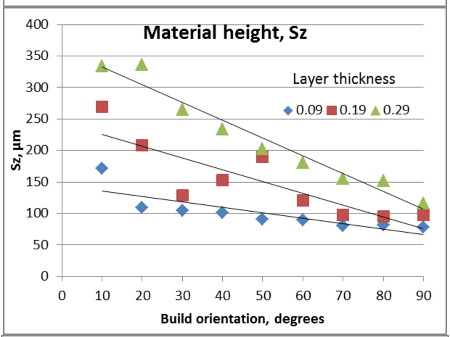
Table 2. Significant surface parameters

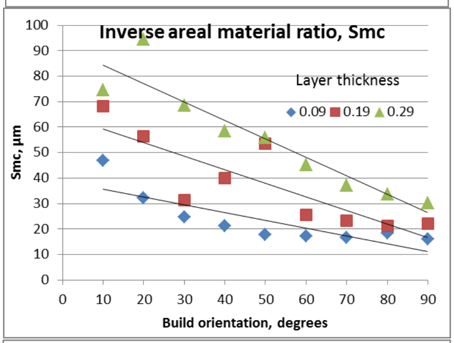
Significant Surface parameters	**R^2**	**Significance F**	**P-value**	
			Layer thickness	**Build angle**
Maximum pit height, Sv	0.88	1.18E-11	1.52E-09	3.15E-09
Maximum height, Sz	0.84	3.60E-10	4.05E-08	5.01E-08
Arithmetic mean height, Sa	0.86	3.98E-11	4.62E-09	9.10E-09
Inverse areal material ratio, Smc	0.83	7.11E-10	1.09E-07	6.12E-08
Void volume, Vv	0.81	7.61E-10	1.11E-07	6.70E-08
Core material volume, Vmc	0.86	5.82E-11	3.72E-09	2.36E-08
Core void volume, Vvc	0.81	2.86E-09	4.46E-07	1.65E-07
Pit void volume, Vvv	0.88	7.76E-12	9.93E-11	4.96E-08

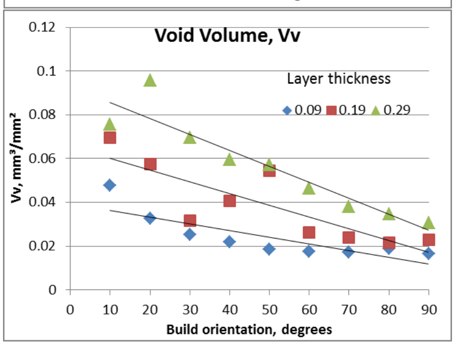
These significant areal surface parameters are considered for characterizing the surfaces printed at different angles and layer thickness.











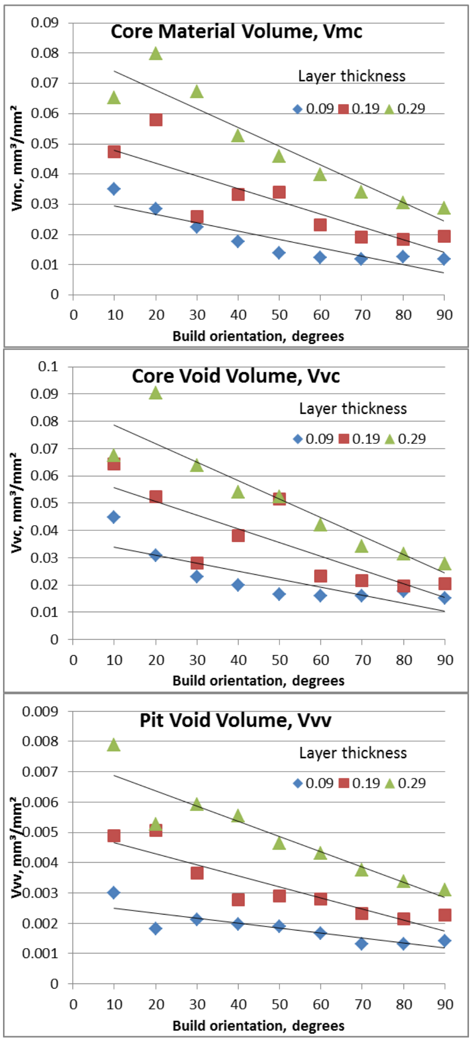


Figure 5. Measurements of significant areal surface parameters varying with respect to different build angles and layer thickness.

All the significant parameters follow a similar trend with respect to different layer thickness and build angle. From figure 5, it is evident that:

1. The surface parametric readings increase with increase in layer thickness.
2. The parametric readings are lower for surfaces build at higher build angle.

5. Conclusions

The FDM surfaces printed at different process settings and inclination are characterized using areal surface parameters and 3D power spectral density. The methodology helps to identify the dominant features on the surface.

From the surface measurement and analysis, it is found that the significant features characterized by PSD and regression analysis are found to decrease with increase in inclination and increases with increase in layer thickness. Further from PSD analysis, difference in the theoretical layer thickness and printed layer thickness is identified.

Future work: As 3D topography measurement shows the waviness in printing direction further investigation on PSD plot for printing direction need to be done to verify the surface quality in print direction. Further investigations on surfaces printed with 0^{o} inclination and influence of printed layer thickness are to be done.

References

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[4] Jacobs T, Junge T and Pastewka L, 2017 Quantitative characterization of surface topography using spectral analysis, *Surface Topography: Metrology and Properties*, **5**, **1.**