Extraction of Process Signature Features from Additive Manufactured Metal Surfaces

S. Lou[1], W. Sun[2], W. Zeng[1], H. S. Abdul-Rahman[1], X. Jiang[1], P. J. Scott[1]
[1]EPSRC Centre for Innovative Manufacturing in Advanced Metrology, University of Huddersfield, Queensgate, Huddersfield, HD1 3DH, UK
[2] National Physical Laboratory, Engineering Measurement Division, Hampton Road, Teddington, Middlesex, TW11 0LW, UK

E-mail: s.lou@hud.ac.uk

Keywords: surface texture, additive manufacturing, roughness, waviness, filtration, segmentation

Abstract While additive manufacturing (AM) technology offers a number of advantages over conventional subtractive manufacturing techniques, many technical barriers still hinder its full commercialisation. One major issue is that AM processes are not robust enough, which consequently brings various shortcomings that are commonly seen in AM products, such as poor as-built surface finish, low quality and large variance between components. These issues lead to the awareness that AM requires measurement methods to control its process [1].

The complex nature of AM processes tends to produce components with surfaces that have a roughness ranging from a few micrometres to several hundred micrometres. Current industry practice to inspect the AM surface quality follows traditional roughness evaluation, which was more suitable for machined surfaces presenting random surface textures. However this conventional surface evaluation method does not consider the specific characteristics of AM surface topography that are related to the AM manufacturing process signature. A strong quantitative evaluation of the relationship between the mechanisms that contribute to surface texture and surface parameters must be investigated [2-8].

Measured machined surfaces with form removed can be decomposed by filtration techniques into three spatial frequency components, i.e. roughness, waviness and form error, such that the characterisation of these various frequency components can provide an indication of corresponding machining faults, e.g. tool wear and machine vibration. These spatial components as well as other significant process signature features should also be well defined to reflect the characteristics of AM process. Figure 1 illustrates the surface topography of a top inclined surface produced by Electron Beam Melting (EBM). The process signature features used in this work are defined below:

- Roughness: surface asperity in micro scale, mainly generated by the physical interaction between the laser beam/electron beam melting process and metal powder particles.
- Waviness: wave-like features reflecting the shape of the molten tracks, which are formed by the Marangoni flow of molten metal liquid [9].
- Form error: shape distortion mainly caused by thermal effect.
- Globules in various sizes: spherical protrusion features. They can be either small size unmolten/partial molten particles adhered to the underlying surface, or medium size spatters originated from the metal liquid ejection due to molten pool overheat [10], or large size ballings due to insufficient laser energy input or fast laser scanning speed [11].

The characterisation of AM surfaces is more challenging due to their complex topography. It should take into full consideration the effect of geometry of AM process signature features, e.g. molten tracks and globules. A specific surface analysis toolbox is developed to extract these features.

The robust Gaussian regression filter is applied first to extract the waviness component. The polynomial regression can suppress the distortion of surface form on linear Gaussian filtration, while the robust statistical estimator can render the insensitivity to globules. See Figure 2 for the extracted waviness component. The L-filter cut-off wavelength is elaborately set to 0.2 mm, which reflects the smallest width of the molten tracks. The resulting residual surface, taking out the waviness component from the original measured surface, comprises the roughness with the globules (see Figure 3). The enhanced watershed segmentation method is then applied to extract the globules from the underlying roughness surface (see Figure 4 and 5). The parametric characterisation of these extracted features is listed in Table 1-3.

In summary, by extracting and characterising various signature features of AM surfaces, it enables the establishment of an accurate link between AM surface topography and its production mechanism and therefore contributes to the optimisation of AM process for improved manufacturing reliability and precision.

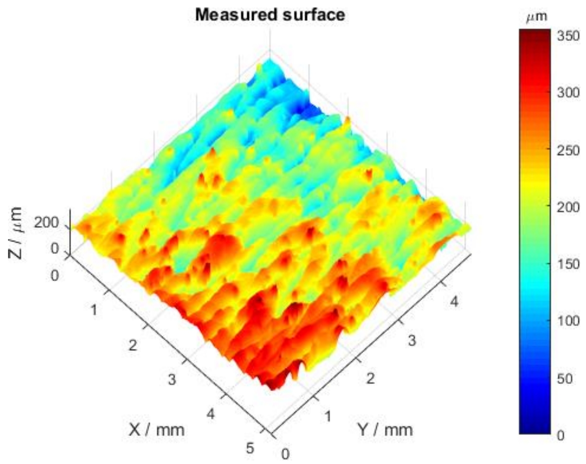

Figure 1. Raw measured surface from the top of an EBM produced part.

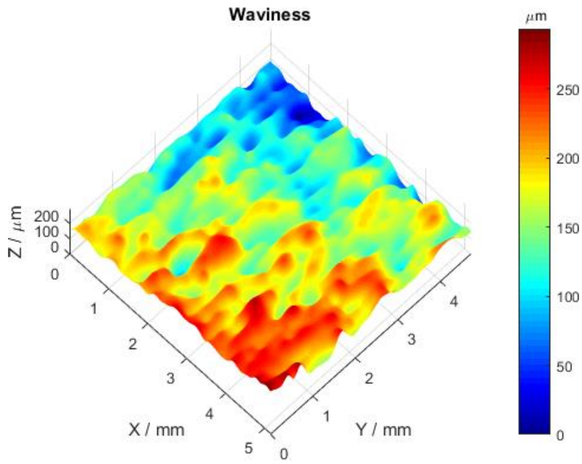

Figure 2. Waviness surface obtained by applying the first order robust Gaussian regression filter (L-filter cut-off wavelength 0.2 mm).

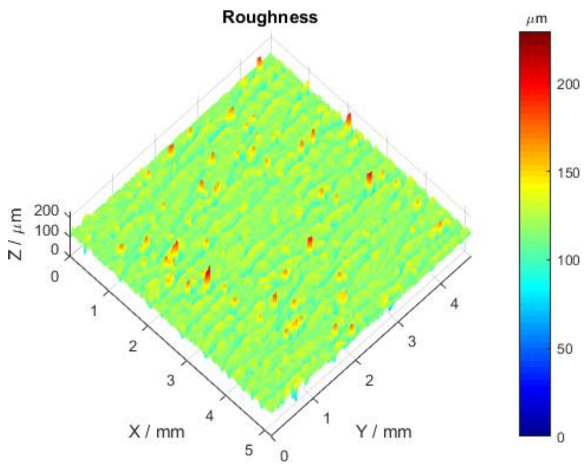

Figure 3. Roughness surface obtained by subtracting the waviness surface from the raw surface.

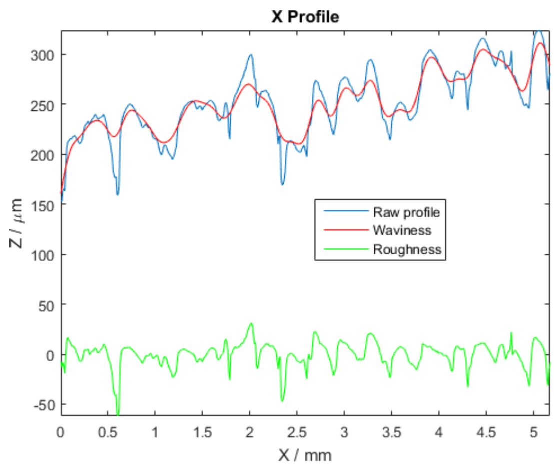

Figure 4. A raw measured profile with corresponding waviness profile and roughness profile in X direction.

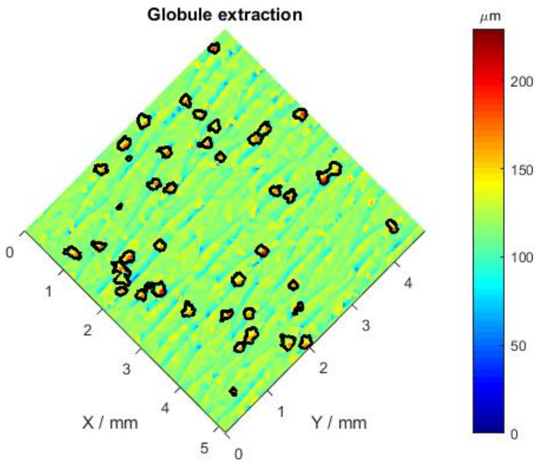

Figure 5. Globules extracted by applying the enhanced watershed segmentation (height thresholding 160 µm).

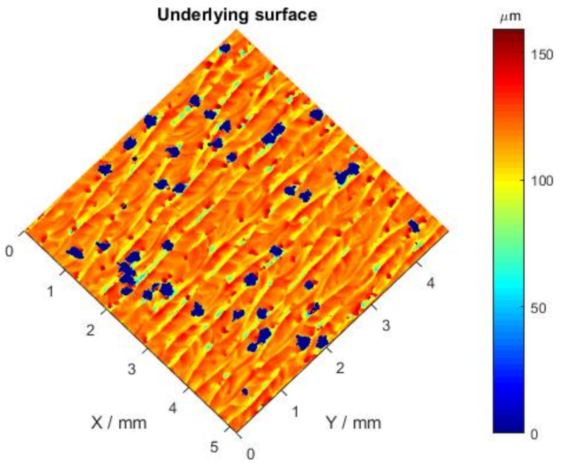

Figure 6. Underlying surface after exclusion of globules.

Table 1. Comparison of surface texture characterisation of surface **roughness** components.

	Roughness surface obtained by linear Gaussian filter (L-filter cut-off wavelength 0.2 mm)	Roughness surface obtained by the first order robust Gaussian filter (L-filter cut-off wavelength 0.2 mm)	Roughness surface after exclusion of globules
Sa	8.9 µm	8.7 µm	8.5 µm
Sq	12.6 µm	12.4 µm	11.3 µm

Table 2. Surface texture characterisation of surface **waviness** component.

Sa	Sq	Autocorrelation length (average width of molten tracks)
39.1 µm	48.7 µm	0.595 mm

Table 3. Characterisation of globule features.

Total globule areas	globule area percentage to the whole surface	Total globule volume
1.21 mm^2	5.0%	0.16 mm^3

Acknowledgement

The authors would like to thank Prof. Iain Todd & Dr. Martin Highett from the Mercury Centre (part financed by the European Union), Department of Materials Science and Engineering, University of Sheffield for supplying the AM samples.

References

[1] Innovate UK (2012) Shaping our national competency in additive manufacturing: a technology innovation needs analysis, https://connect.innovateuk.org/documents/2998699/3675986/UK+Review+of+Additive+Manufacturing+-+AM+SIG+Report+-+September+2012.pdf/a1e2e6cc-37b9-403c-bc2f-bf68d8a8e9bf

[2] Whitehouse D J (2003) Surface metrology in manufacture, In: Handbook of surface and nanometrology, IoP, pp 674-748

[3] Lou S, Townsend A, Jiang X, Blunt L, Zeng W, Scott P J (2016) On characterising surface topography of metal powder bed fusion additive manufactured parts, *euspen's 16th Int Conf.*pp 137-138

[4] Townsend A, Senin N, Blunt L, Leach R, Taylor J (2016) Surface texture metrology for metal additive manufacturing: a review, *Precis. Eng.* **46** pp 34-47

[5] Thompson A, Senin N, Leach R (2016) Towards an additive surface atlas, Surface finish metrology of additive-manufactured components, *Proc. ASPE Summer Topical* pp 156-161

[6] Reese C Z, Taylor J S, Evans C J (2016) Surface finish metrology of additive-manufactured components, *Proc. ASPE Summer Topical* pp 50-54

[7] Jason C F, Shawn P M, Brandon M L (2016) Preliminary study toward surface texture as a process signature in laser powder bed fusion additive manufacturing, *Proc. ASPE Summer Topical* pp 169-173

[8] Adam C L, Matthew P M, Joseluis A V, Christopher A B (2016) On the Metrology of Surfaces Produced by Laser Melting of Powders, *Proc. ASPE Summer Topical* pp 174-179

[9] Niu H J, Chang T H (1999) Instability of scan tracks of selective laser sintering of high speed steel powder, *Scripta Mater.*, **41** pp 1229-1234

[10] Simonelli M, Tuck C, Aboulkhair NT, Maskery I, Ashcroft I, Wildman RD, et al. (2015) A study on the laser spatter and the oxidation reactions during selective laser melting of 316L stainless steel, Al-Si10-Mg, and Ti-6Al-4V, *Metall. Mate.r Trans. A*, **46** pp 3842-3851

[11] Kruth J P, Froyen L, Van Vaerenbergh J, Mercelis P, Rombouts M, Lauwers B (2004) Selective laser melting of iron-based powder, *J. Mater. Process Technol.* 149 pp 616-622