Generalization of profile texture parameters for additively manufactured surfaces

To cite this article: L Pagani et al 2018 J. Phys.: Conf. Ser. 1065 212019

View the article online for updates and enhancements.
Generalization of profile texture parameters for additively manufactured surfaces

L Pagani¹, F Zanini², S Carmignato², X Jiang¹ and P J Scott¹
¹ EPSRC Future Metrology Hub, University of Huddersfield, Huddersfield, UK
² Department of Management and Engineering, University of Padua, Vicenza, Italy
E-mail: l.pagani@hud.ac.uk

Abstract. Additive manufacturing technologies allow the production of highly complex parts. The surface topography of such parts often presents micro-scale and freeform-shaped re-entrant features. These features cannot be measured completely using optical or tactile techniques, without sectioning the sample. Therefore, X-ray computed tomography has recently started to be used for topographical measurement of additively manufactured surfaces, as it is capable of acquiring also re-entrant features of the surface when a sufficiently high spatial resolution is achieved. However, profile texture parameters described in the standard ISO 4287 are not suited to characterise the aforementioned profiles, due to the possible re-entrant features. This paper proposes a new definition of texture parameters optimised for additively manufactured surface profiles with the presence of re-entrant features, measured by means of X-ray computed tomography.

Keywords: Additive manufacturing; Computed tomography; Surface roughness; Freeform profile; Re-entrant features.

1. Introduction
The increasing interest in modern advanced manufacturing processes, such as additive manufacturing (AM) and other laser based technologies, lead to new challenges in the surface characterisation field. The manufactured surface (which can be external or internal) can have a complex freeform shape and its texture can consistently vary depending on the adopted AM technology and on the building direction and may include the presence of micro-scale and freeform-shaped re-entrant features [1, 2].

The most commonly used techniques for topography measurements (i.e. contact probing and optical techniques) do not allow such re-entrant features as well as internal surfaces to be accessed, providing only a limited description of the actual surface morphology.

X-ray computed tomography (CT) has recently started to be considered as a viable alternative technique capable of obtaining topographical measurements at micro-scale, including non-accessible surfaces and re-entrant features [3] when a sufficiently high structural resolution is achieved [4]. Moreover, metrological CT systems are currently available to perform accurate measurements [5]. The CT measurement procedure consists in (i) acquiring a number of radiographic projections at different angular positions of the scanned object, (ii) reconstructing a volumetric grey scale model of the sample and (iii) determining its surface by setting a threshold or by applying some advanced edge-detection algorithm, such as the level set method [6].
In Townsend et al. [7], the authors proposed a procedure for performing topographic measurements using the CT reconstructed dataset. In particular, they simulated the measurement done with an optical device by projecting the CT surface points on a regular rectangular grid to resemble the measurements done with optical devices. As stated above, surfaces and cross-sectional profiles extracted from CT data can include also re-entrant features.

The most commonly used profile texture parameters are defined in the standard ISO 4287 [8], while the texture parameters based on areal measurement are available in the ISO 25178-2 [9]. These parameters were initially designed for measurement performed using stylus or optical devices [10], so the re-entrant features and complex freeform nominal shape are not taken into account. This paper focuses only on the profile texture parameters.

In this paper, a number of profile texture parameters are re-defined in order to be suited to characterize complex AM surface profiles including re-entrant features. The paper is structured as follow: in section 2 the conventional profile texture parameters are extended to a general profile, section 3 presents a case study of a cross-sectional profile obtained from the CT scan of a Ti6Al4V part produced via selective laser melting and in section 4 conclusions and future developments are given.

2. Roughness parameters definition
Let $\gamma : I \to \mathbb{R}^2$, $I \in [t_0, t_1]$ ($r(t) = \gamma$) be a measured profile, the primary parameters are computed after removing the reference (form) profile $r_F(t) = \gamma_F$. The decomposition can be expressed by

$$r(t) = r_F(t) + r_{res}(t)$$

where $r_{res}(t)$ represents the difference between the measured and the reference profiles, i.e. the primary profile. For simplicity, the following equality is now introduced

$$r_{res}(t) = r_{res}(t) \cdot n_F(t).$$

where $n_F(t)$ is the normal of the reference profile.

The height parameters can be computed as the integral of a scalar field on the reference profile. For a complete description on the integration of scalar field on parametric curves see do Carmo [11]. The arithmetical mean deviation of the assessed profile can be computed as

$$Pa = \frac{1}{L_F} \int_{\gamma_F} |r_{res}(t)| \, dl$$

where $dl = ||r_F'(t)|| dt$ is the infinitesimal arc length element and $L_F = \int_{\gamma_F} dl$ is the length of the measured profile projected on the reference one. The other height parameters can be computed as

$$Pq = \sqrt{\frac{1}{L_F} \int_{\gamma_F} r_{res}^2(t) \, dl} \quad Psk = \frac{1}{L_F Pq^3} \int_{\gamma_F} r_{res}^3(t) \, dl \quad Pku = \frac{1}{L_F Pq^4} \int_{\gamma_F} r_{res}^4(t) \, dl$$

$$Pp = \max_t r_{res}(t) \quad Pv = \min_t r_{res}(t) \quad Pt = \max_t r_{res}(t) - \min_t r_{res}(t)$$

The root mean square slope on a general profile can be computed as

$$Pdq = \sqrt{\frac{1}{L_F} \int_{\gamma_F} \left( \frac{r_{res}'}{(r_F'(t))^2} r_F'(t) \right)^2 \, dl} = \sqrt{\frac{1}{L_F} \int_{\gamma_F} \left( \frac{r_{res}'}{(r_F'(t))^2} \right)^2 \, dl}$$

where

$$r_{res}'(t) = \frac{d(r_{res}(t) \cdot n_F(t))}{dt} = r_{res}'(t) \cdot n_F + r_{res}(t) \cdot n_F'(t)$$

2
It should be noted that if the form profile is parametrised according to the arc length \[11\]

\[
l_F(t) = \int_{t_0}^{t} \|r_F'(u)\| \, du
\]

the speed of the curve is constant and equal to one, so the proposed parameters correspond to the parameters described in the ISO 4287 standard.

A useful parameter for the characterisation of AM products can be the portion of the reference profile with re-entrant features. This parameter can be defined as

\[
P_{r_f} = \frac{L_F - L_S}{2L_S}
\]

where \(L_S\) is the length of the shadow of the measured profile on the reference one, i.e. \(L_F\) after subtracting the length of the re-entrant features. Let \(\vartheta\) be the angle between \(n(t)\) (normal of the measured profile) and \(n_F(t)\) and

\[
k(t) = \begin{cases} 
1 & \text{if } -\frac{\pi}{2} \leq \vartheta \leq \frac{\pi}{2} \\
-1 & \text{otherwise}
\end{cases}
\]

the length of the shadow of the measured profile on the reference profile can be computed as

\[
L_S = \int_{\gamma_F} k(t) \, dl.
\]

In order to compute the parameters the reference profile is approximated linearly interpolating between the measured points. The residual scalar field is approximated by linear interpolation. The numerical integration is performed, for each segment of the reference profile, using the Gaussian quadrature rule.

3. Case study

A Ti6Al4 specimen produced by selective laser melting was scanned using a metrological X-ray CT system (Nikon Metrology MCT225), with voxel size equal to 4 \(\mu\)m. The reconstructed volume was elaborated using the analysis and visualization software VGStudio MAX 3.1 [12]: after applying a median filter with a window of 3 x 3 voxels, the sample surface was determined using the local adaptive algorithm. The spatial coordinates of one cross-sectional profile taken as an example were then extracted. This profile is represented as a black line in Figure 1, together with the estimated reference straight line (blue line) and the difference between the two profiles, translated for visualization purpose (\(r_{res}(t)\), red line). The reference profile was computed using the principal component analysis method and the residual were computed using the orthogonal projection of the measured points onto the reference line. The analysis profile presents both re-entrant features and an unequally spacing between the measured points. Table 1 shows the parameters measured on the primary profile (P-parameters) using the definitions proposed in Section 2. It is possible to observe that 2\% of the measured AM profile is characterise by re-entrant features.

![Figure 1. Measured profile and estimated reference line](image-url)
Table 1. Roughness parameters

|    | \( Pa \) (\( \mu m \)) | \( Pq \) (\( \mu m \)) | \( Psk \) | \( Pku \) | \( Pp \) (\( \mu m \)) | \( Pv \) (\( \mu m \)) | \( Pt \) (\( \mu m \)) | \( Pdq \) | \( Prf \) (%) | \( L_P \) (mm) | \( L_F \) (mm) | \( L_S \) (mm) |
|----|------------------------|------------------------|----------|----------|------------------------|------------------------|------------------------|----------|--------------|--------------|--------------|--------------|
|    | 10.89                   | 14.28                  | 0.97     | 4.91     | 57.37                  | 29.75                  | 87.12                  | 1.44     | 2.19         | 4.85         | 3.95         | 3.78         |

4. Conclusions and future developments

A new definition was proposed for a set of profile texture parameters that are able to characterise freeform profiles with re-entrant features. If the reference profile is re-parametrised according to the arc length, the proposed set of parameters corresponds to the analogous parameters described in the standard ISO 4287. Moreover, a new parameter for characterising the amount of the re-entrant features was proposed as well. The introduction of the proposed set of parameters brings some new challenges such as the development of filters to compute the waviness (W) and roughness (R) parameters and the computation of the correlation index of a profile.

Acknowledgements

LP, XJ and PJS gratefully acknowledge the UKs Engineering and Physical Sciences Research Council (EPSRC) founding the grants Ref. EP/K037374/1 and EP/P006930/1. FZ and SC gratefully acknowledge the University of Padova founding the projects Nr. CPDA151522/15 and BIRD167853/16.

References

[1] I. Gibson, D. W. Rosen, and B. Stucker. *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing*. 1st. Springer Publishing Company, Incorporated, 2009.

[2] A. Townsend et al. “Surface texture metrology for metal additive manufacturing: a review”. In: *Precision Engineering* 46 (2016), pp. 34–47.

[3] F. Zanini et al. “Accuracy of surface topography measurements performed by X-ray computed tomography on additively manufactured metal parts”. In: *euspen’s 18th conference*. Venice, Italy, 2018.

[4] F. Zanini and S. Carmignato. “Two-spheres method for evaluating the metrological structural resolution in dimensional computed tomography”. In: *Meas. Sci. Technol.* 28.11 (2017).

[5] S. Carmignato, W. Dewulf, and R. Leach. *Industrial X-Ray Computed Tomography*. 1st. Springer International Publishing, 2018.

[6] S. Osher and R. Fedkiw. *Level Set Methods and Dynamic Implicit Surfaces*. 1st. Springer-Verlag New York, 2003.

[7] A. Townsend et al. “Factors affecting the accuracy of areal surface texture data extraction from X-ray CT”. In: *CIRP Annals* 66.1 (2017), pp. 547–550.

[8] ISO 4287, *Geometrical product specification (GPS) - Surface texture: Profile Method - Terms, definitions and surface texture parameters*. ISO 4287. 1998.

[9] ISO 25178-2, *Geometrical product specification (GPS) - Surface texture: Areal - Part 2: Terms, definitions and surface texture parameters*. ISO 25178-2. 2012.

[10] D. Whitehouse. *Handbook of Surface and Nanometrology, Second Edition*. Taylor & Francis, 2010.

[11] M. P. do Carmo. *Differential Geometry of Curves and Surfaces*. Prentice-Hall, 1976.

[12] GMbH, Volume Graphics. “VGStudio MAX”. 2016.