AREAL SURFACE TEXTURE PARAMETERS ON SURFACE

L. Pagani[1], P.J. Scott[1]
[1]**EPSRC Centre for Innovative Manufacturing in Advance Metrology, Centre for Precision Technologies (CPT), School of Computing and Engineering, University of Huddersfield, Huddersfield, HD13DH, UK**

INTRODUCTION

Additive manufacturing (AM) techniques enable the manufacture of components with free-form geometries and complex internal and external features. X-ray computed tomography (CT) is increasingly being used to inspect internal features of AM parts. An advantage of the CT process, compared to optical and stylus instruments with limited acquisition slope angles, is the ability to reconstruct reentrant features (undercuts). Processing reentrant features provides an advantage in the computation of surface parameters. If the surface includes many reentrant features, their elimination can lead to a biased estimation of parameters related to the height or the area of the scale limited surface. A unified framework capable of handling free-from surfaces, with generic form surface, reentrant features and unevenly spaced points, such as those from CT reconstruction, will be proposed. Standard software instruments employed for roughness parameter require evaluation of height data on a rectangular grid. This allows the computation of areal parameters based on discrete methods with good approximation, dependent upon the sample size. The reconstruction from CT volume to mesh allows performance of an adaptive meshing based on the maximum allowable distance between the implicit function (implicit surface defined by a constant grey value) and the final triangular mesh [1]. With irregular meshes it is not possible to perform the integral with the discrete approximation and a bias on the parameters computation can arise. In this paper an approach that approximates a generic mesh based on locally refined (LR) B-spline is proposed [2]. The approach can be applied to a generic form surface because the local stretching of the surface is taken into account. Mesh parameterisation enables to handle undercuts, each acquired point is described as a function of two abstract parameters. In this paper the proposed method will be compared with the discrete (ISO 25178-2 compliant [3]) method implemented in standard software packages [4]. Since filtering techniques based on a general mesh are not yet defined in the standard, the primary surfaces, the surface after removing the form, will be analysed. The areal parameters of a Rubert sample (casting plate 334, nominal *Ra* of 25 µm) measured with a focus variation (FV) instrument will be evaluated. Two form surfaces will be taken into account: plane and cylinder. Robustness of the discrete method will be finally evaluated with the mesh reconstructed from two CT measurements: the Rubert sample and an AM part.

PARAMETER COMPUTATION

In this paper it is assumed that a manufactured surface can be described with a regular parametric surface $\Sigma \subset \mathbb{R}^3$ as

$$\boldsymbol{r}(u,v) = \begin{cases} x = x(u,v) \\ y = y(u,v) \\ z = z(u,v) \end{cases} \tag{1}$$

with $\boldsymbol{u} = (u,v)^T$ and $U \subset \mathbb{R}^2$. U is called the parameters space and it is usually described with a square of unitary edge. Suppose that it is possible to decompose the surface in two parts

$$\boldsymbol{r}(u,v) = \boldsymbol{r}_{form}(u,v) + \boldsymbol{r}_{res}(u,v) \tag{2}$$

where $\Sigma_{form} : \boldsymbol{r}_{form}(u,v)$ represents the form and $\Sigma_{res} : \boldsymbol{r}_{res}(u,v)$ the residual surface. If a total least squares approach is implemented the last term can be rewritten as

$$\boldsymbol{r}_{res}(u,v) = r_{res}(u,v)\,\boldsymbol{n}(u,v) \tag{3}$$

where $r_{res}(u,v)$ is the distance between $\boldsymbol{r}(u,v)$ and its projection on the form surface $\boldsymbol{r}_{form}(u,v)$ and $\boldsymbol{n}(u,v)$ is the surface normal. $r_{res}(u,v)$ can be interpreted as a scalar field on the surface $\boldsymbol{r}_{form}(u,v)$. If it is possible to describe the value of the surface $r_{res}(u,v)$ on the form surface without stretching and if no reentrant features appear on the residual surface, the parameters can be computed with the definition of the ISO 25178-2 norm [3]. When the form surface cannot be described by a developable surface, but it is a general free-form surface, the local stretching must be taken into account [5]. Form surfaces developable to a plane are all the surfaces where the gaussian curvature is null everywhere [6], such as cylinder. Let $\boldsymbol{r}_{form,i}$ the partial derivative along the dimension i, the parameters on the primary surface can be computed weighting the "height" values with the infinitesimal surface area

$$d\sigma_{form} = \|\boldsymbol{r}_{form,u}(u,v) \times \boldsymbol{r}_{form,v}(u,v)\| \, du \, dv.$$

According to the previous definition the arithmetic mean of the absolute value of the height can be computed as

$$Sa = \frac{1}{A} \iint_{\Sigma_{form}} |r_{res}(u,v)| \, d\sigma_{form} \tag{4}$$

where A is the area of the form surface, the root mean square error as

$$Sq = \sqrt{\frac{1}{A} \iint_{\Sigma_{form}} r_{res}^2(u,v) \, d\sigma_{form}} \tag{5}$$

the skewness as

$$Ssk = \frac{1}{A\,Sq^3} \iint_{\Sigma_{form}} r_{res}^3(u,v) \, d\sigma_{form} \tag{6}$$

and the kurtosis as

$$Sku = \frac{1}{A\,Sq^4} \iint_{\Sigma_{form}} r_{res}^4(u,v) \, d\sigma_{form}. \tag{7}$$

SURFACE APPROXIMATION

In order to estimate the parameter of the LR B-spline, a parameterisation of the reconstructed mesh is firstly computed. Stretch minimising approach proposed in Yoshizawa et al. [7, 8] will be employed because it minimise the area distortion, it is therefore a good candidate for the surface reconstruction. This parameterisation will be used as a common parameterisation for all the surfaces involved. The form surface is then estimated with a total least squares (TLS) approach. Plane and cylinder form surfaces will be analysed, but the proposed method does not depend on a specific form surface. The differences between the point cloud and the projections on the form surface are firstly computed. Both the two point clouds, form and residuals, are then approximated with the LR algorithm. The height areal parameters (Sa, Sq, Ssk and Sku) of the primary surface can be computed as the integral of a scalar field, represented by the residuals, on the form surface. Since both the involved surfaces, $\boldsymbol{r}_{form}$ and r_{res}, share the parameters domain, the integration can be performed with a numerical quadrature rule. The numerical integration is performed with the h-cubature method implemented in Johnson [9]. This method recursively partition the integration domain into smaller sub-domains, the quadrature rule is applied to each, until a convergence criterion is reach.

EXPERIMENTAL RESULTS

Parameters' computation with the proposed method will be compared with the discrete method implemented in standard software packages. Two surfaces were measured: a Rubert sample with nominal *Ra* equal to 25 µm and an AM manufactured part. The Rubert plate was measured both with a focus variation (FV) instrument and with a CT device, while only the CT data of the AM part will be analysed. The FV dataset will be firstly considered to verify the error of the surface approximation. The primary surface will be added to a portion of cylinder to evaluate the stability of the proposed method with a developable form surface. CT sets of data will be finally analysed to investigate the effect of an unequally points spacing on the computation of the parameters with a discrete method.

Rubert sample: FV reconstruction

A Rubert sample with nominal *Ra* of 25 µm was measured with the Alicona Infinite focus microscope [10]. Figure 1 shows a portion of the measured points of the Rubert plate. The form surface was approximated with the total least square plane, that corresponds to the first two scores of the principal component analysis (PCA) of the point cloud covariance matrix. To describe both

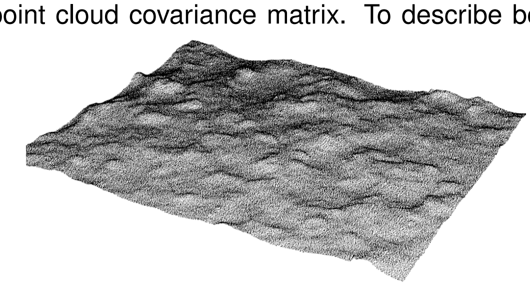

FIGURE 1. Point cloud of the nominal Ra *25* µm *plate*

the form surface and the residuals (distance between the acquired point and its projection on the form surface) the LR B-spline algorithm was applied. A maximum value of 10 iterations and a threshold value of 0.01 were set in the approximation algorithm. During the approximation stage all the values were coded between 0 and 1 to

	Sa (μm)	Error Sa (μm)	Sq (μm)	Error Sq (μm)	Ssk	Error SSk	Sku	Error Sku
ISO discrete	27.04	-	34.21	-	-0.33	-	2.93	-
ISO	27.04	0.01	34.21	0.02	-0.33	0.01	2.93	0.01
Surface	26.91	0.00	34.03	0.00	-0.31	0.01	2.93	0.01

TABLE 1. Height parameters FV data subset

	Sa (μm)	Error Sa (μm)	Sq (μm)	Error Sq (μm)	Ssk	Error SSk	Sku	Error Sku
ISO discrete	31.67	-	40.66	-	-0.45	-	3.52	-
ISO	31.65	0.00	40.65	0.02	-0.45	0.01	3.52	0.01
Surface	31.61	0.00	40.54	0.02	-0.42	0.01	3.50	0.01

TABLE 2. Height parameters FV data

avoid the scale effect. The abstract parameterisation domain was $[0, 1]^2$. Since no undercuts were present in the FV mesh, it is possible to approximate also the scores of the PCA with LR spline method. In Table 1 are reported the parameters computed according to the ISO 25178-2 norm and with the proposed method. Error represents the estimated error of the numerical integration. The ISO parameters are computed both with the discrete method and the surface that approximate the scores of the PCA (ISO discrete and ISO). Surface represents the parameters computed with the proposed method. There is no difference between the discrete and the integral method. Due to the surfaces approximations the error between the proposed and the ISO method is larger, the differences are 0.13 μm, 0.18 μm and 0.02, respectively, for Sa, Sq and Ssk; there is no differences on the estimation of Sku. The above procedure was applied to the whole set of data of the measured Rubert sample. The evaluation of the parameters was applied to a bigger point cloud to check the robustness of the approximation. Table 2 shows the parameters computed on the primary surface. There is a small difference between the discrete and the splines based computation of Sa and Sq. The absolute values are 0.01 and 0.02 μm. This errors are negligible compared to the values of the parameters. The differences between the surface and the ISO parameters get closer, they are 0.04 μm, 0.11 μm, 0.03 and 0.02, respectively, for Sa, Sq, Ssk and Sku. In this section it has been shown that, although there is an error due to the surface approximation, the proposed method can be used to compute the areal height parameters (the maximum percentage differences are 0.4% for Sa and 0.5% for Sq).

Rubert sample: primary surface on cylinder

To check the stability of the proposed method a data set with a cylindrical form is analysed. The scores of the PCA of the previous test case were approximated with the MBA algorithm [11] to predict the points in a regular grid. The LR algorithm was not applied to investigate the robustness of the reconstruction method. The approximate points on a regular grid of 985 $\times$ 799 were then added, along the normal direction, to a portion of a cylinder. The angle of the cylinder ranges from $-\pi$ to 0, while the radius is computed as

$$\rho = \frac{\Delta y}{\Delta \vartheta}$$

where Δy is the resolution of the coordinate in radial direction and $\Delta\vartheta$ is the angle resolution. With this radius the distances on the cylinder coincide with the distances on the plane. Figure 2 shows the simulated point cloud. The surfaces were reconstructed with the method described in the previous section. The computed parameters are reported in Table 3. The values of Sa and Sq slightly change, while Ssk and Sku have the same values. The differences between the parameters computed with the ISO compliant methods are negligible. The discrepancies between the methods based on the numerical integration are 0.10 μm for Sa, 0.13 μm for Sq and 0.02 for Ssk, illustrative that the proposed method can achieve good performance.

In order to evaluate the robustness of the procedure if the nominal form is not a plane, the whole

	Sa (µm)	Error Sa (µm)	Sq (µm)	Error Sq (µm)	Ssk	Error SSk	Sku	Error Sku
ISO discrete	27.02	-	34.19	-	-0.33	-	2.93	-
ISO	27.01	0.00	34.17	0.02	-0.33	0.01	2.93	0.01
Surface	26.91	0.00	34.04	0.00	-0.31	0.01	2.93	0.01

TABLE 3. Height parameters FV data subset on cylindrical shape

	Sa (µm)	Error Sa (µm)	Sq (µm)	Error Sq (µm)	Ssk	Error SSk	Sku	Error Sku
ISO discrete	31.31	-	40.26	-	-0.48	-	3.57	-
ISO	31.28	0.00	40.23	0.01	-0.49	0.01	3.58	0.01
Surface	31.18	0.00	40.06	0.00	-0.45	0.01	3.55	0.01

TABLE 4. Height parameters FV data on cylindrical shape

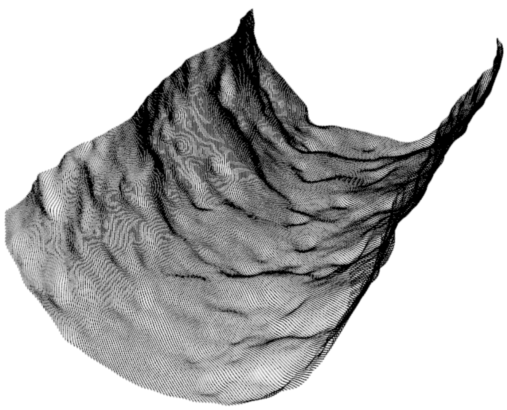

FIGURE 2. Point cloud on a cylindrical shape

Alicona point cloud was added to the half cylinder shape. Table 4 shows the computed height parameters. It is possible to observe that the differences are similar to the values of Table 3. In this section it has been shown that with the proposed method is possible to compute the height parameters approximating the form and the surface of residuals with the LR B-spline algorithm.

Rubert sample: CT reconstruction

Rubert sample with a nominal *Ra* of 25 µm was acquired also using a Nikon XT H 225 microfocus CT. Nikon CT-Pro software [12] was used to perform the volume reconstruction. CT voxel size for all coordinates was 12.9 µm (x, y, z). Mesh reconstruction was performed by an adaptive algorithm implemented in CGAL [1, 13]. This algorithm allows to reconstruct an implicit surface with a desired approximation; the maximum allowable error was set to 5 µm, almost $\frac{1}{3}$ of the voxel size. The output mesh is a manifold mesh, so no post processing is needed in order to compute the parameterisation. It should be noted that the mesh reconstructed with the marching cube algorithm [14] may have some non manifold vertices or edges. Figure 3 shows a subset of the reconstructed point cloud. Two datasets will be analysed, a subset and the whole point cloud. These sets of data correspond to the meshes analysed in the previous section.

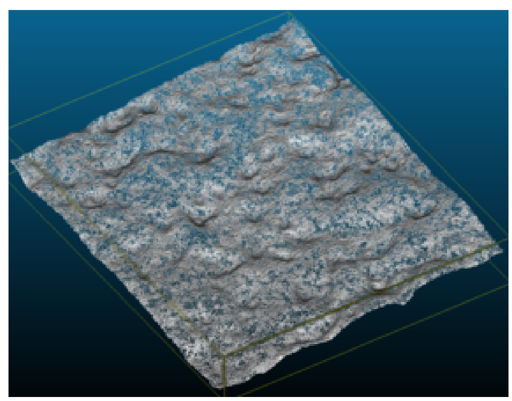

FIGURE 3. Subset of the whole point cloud

Considering the applied adaptive meshing the spacing of the points is not constant, this can lead to a biased estimation of the height parameters with the ISO discrete method. Since the surface may presents some undercuts, it is not possible to approximate the surface of the scores of the PCA. It should also be noted that the method called ISO discrete is not compliant with the ISO 25178-2 because it is not an approximation of integrals described in the standard. The values will be computed to evaluate the bias. After applying the parameterisation and the reconstruction

	Sa (µm)	Error Sa (µm)	Sq (µm)	Error Sq (µm)	Ssk	Error SSk	Sku	Error Sku
ISO discrete	30.26	-	38.58	-	-0.02	-	3.01	-
Surface	31.62	0.00	39.94	0.01	-0.51	0.01	2.33	0.01

TABLE 5. Height parameters CT data subset

	Sa (µm)	Error Sa (µm)	Sq (µm)	Error Sq (µm)	Ssk	Error SSk	Sku	Error Sku
ISO discrete	35.22	-	44.59	-	-0.20	-	3.19	-
Surface	36.35	0.00	46.03	0.05	-0.61	0.01	3.24	0.01

TABLE 6. Height parameters CT data

	Sa (µm)	Error Sa (µm)	Sq (µm)	Error Sq (µm)	Ssk	Error SSk	Sku	Error Sku
ISO discrete	16.37	-	20.61	-	-0.41	-	3.43	-
Surface	15.07	0.01	19.09	0.08	-0.31	0.01	3.65	0.01

TABLE 7. Height parameters AM part

the areal parameters were computed. Tables 5 and 6 show height parameters of the small and the big dataset. The difference between the ISO (discrete) and the surface method increase compared to the previous test case. This is the effect of the unevenly spaced points and the reentering features. The discrepancies are 1.36 and 1.13 µm for Sa, 1.36 and 1.44 µm for Sq, 0.49 and 0.41 for Ssk and 0.68 and 0.05 for Sku.

AM part: CT reconstruction

An additive manufactured part was measured and the surface was reconstructed with the algorithm mentioned above. CT voxel resolution was 17.5 µm in x, y and z directions. The threshold was selected according to the ISO 50 method implemented in VGStudio Max software [15]. A magnification, where it is possible to observe a reconstructed undercut, is shown in Figure 4. Reconstructed surface was again parameterised and reconstructed with the LR B-spline approximation. The computed parameters are reported in Table 7. Sa and Sq parameters computed with the discrete approximation are biased, while the differences between Ssk and Sku are negligible. The absolute value of the difference is comparable to the previous test case. But, since the estimation are smaller, the percentage differences correspond to 8.62% and 7.96% for Sa and Sq. These discrepancies should be taken into account because the values are computed on the same set of data.

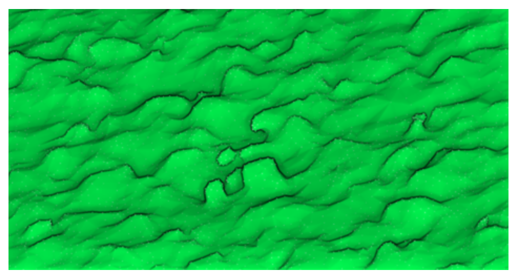

FIGURE 4. Undercuts on the reconstructed surface

CONCLUSION

A method to reconstruct and compute the areal height parameters has been proposed. Parameters values have been compared with the ISO 25178-2 definition on a point cloud measured with a focus variation device. It as been show that the parameters computation with the proposed method is robust respect to the form surfaces analysed: plane and cylinder. The robustness of the ISO parameters based on the reconstruction of two CT measurements has been verified. The computation of the Sa and Sq parameters with the discrete approximation is biased, while the differences of the estimation of Ssk and Sku are negligible. Although the standard method implemented in common software packages is slightly biased, when the surface has some undercuts it is not possible to compute other parameters or apply a filter (smoothing) on the point cloud. The proximity information is lost, neighbours points in the geometric space (x, y and z) can be far along the surface. The present work has presented a method to compute height parameters on a general free-form surface. Future developments involve the definition of other areal parameters if the analysed surface has a free-form shape or present undercuts. The concept of scale limited surface has also to be defined and investigated; all the computed values in this paper refers to the primary surface because the S and L operators are defined only if the measured point are on a regular grid.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the UKs Engineering and Physical Sciences Research Council (EPSRC) founding of the EPSRC Fellowship in Manufacturing: Controlling Variability of Products for Manufacturing (Ref:EP/K037374/1).

REFERENCES

[1] Boissonnat JD, Oudot S. Provably good sampling and meshing of surfaces. Graphical Models. 2005;(67):405–451.

[2] Dokken T, Lyche T, Pettersen KF. Polynomial splines over locally refined box-partitions. Computer Aided Geometric Design. 2013;30(3):331–356.

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

[4] The Centre for Precision Technologies, U o H . SurfStand; 2006.

[5] Edwards CH. Advanced Calculus of Several Variables. Dover, editor. Mineola, NY; 1994.

[6] do Carmo MP. Differential Geometry of Curves and Surfaces. Prentice-Hall; 1976.

[7] Yoshizawa S, Belyaev A, Seidel HP. A fast and simple stretch-minimizing mesh parameterization; 2004.

[8] Yoshizawa S. http://www.riken.jp/brict/Yoshizawa/Research/Param.html; 2016.

[9] Johnson SG. Cubature (Multi-dimensional integration); 2016.

[10] Danzl R, Helmli F, Scherer S. Focus variation - A new new thechnology for high resolution optical 3D surface metrology; 2009.

[11] Lee S, Wolberg G, Shin SY. Scattered Data Interpolation with Multilevel B-Splines. IEEE Transactions on Visualization and Computer Graphics. 1997;3(3):228–244.

[12] NV NM. Nikon CT-Pro; 2016.

[13] Rineau L, Yvinec M. A generic software design for Delaunay refinement meshing. Comput Geom Theory Appl. 2007;(38):100–110.

[14] Lorensen WE, Cline HE. Marching Cubes: A high resolution 3D surface construction algorithm. ACM Computer Graphics. 1987;21(4):163–169.

[15] GMbH VG. VGStudio MAX; 2016.