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Accuracy of surface topography measurements performed by X-ray computed tomography on additively manufactured metal parts

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Abstract

Additively manufactured metal parts are inherently characterized by surface topographies that are challenging to be measured due to several complexities, including: presence of undercuts and non-totally melted powder particles. Micro X-ray computed tomography has recently started to be considered as an alternative technique for topographical measurements of additively manufactured surfaces, as it is capable of measuring also non-accessible surfaces and micro-scale surface features including undercuts. In this work, a new approach to determine the accuracy of surface topography measurements performed by computed tomography is proposed and applied on Ti6Al4V specimens produced by selective laser melting. Reference cross-sectional profiles including undercuts were obtained after cutting and polishing the specimens at specific locations, by measuring the resulting cut-sections using an imaging probing system. In addition, the results of computed tomography measurements were compared with the results obtained from focus variation and confocal microscopy.

Surface topography, metal additive manufacturing, X-ray computed tomography, confocal microscopy, focus variation

1. Introduction

Additively manufactured metal parts are inherently characterized by complex surface topographies with high roughness, presence of undercuts and non-totally melted powder particles, which limits the achievement of tight tolerances on parts produced for precision engineering purposes [1-3]. In addition, the high surface roughness is a major cause of deviation between dimensional measurements performed with different techniques, such as tactile coordinate measuring machines (CMMs) and X-ray computed tomography (CT) [4]. Optical areal measuring techniques – such as focus variation (FV) and confocal microscopy (CM) – can be used to measure the topography of AM complex surfaces; however, significant differences can result from different techniques [4]. Moreover, these techniques do not allow internal surfaces and re-entrant features (undercuts) to be accessed, providing only a limited description of the actual surface morphology [1, 6]. X-ray computed tomography 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 [6]. Although CT-based measurements of AM surface topographies have already been studied through comparison with optical areal measurements [5, 6], their accuracy has not yet been investigated thoroughly so far. In this work, a new methodology is proposed to evaluate the accuracy of CT as well as optical areal surface topography measurements of AM parts.

2. Experimental approach for accuracy evaluation

Ti6Al4V parallelepipeds produced by selective laser melting were investigated in this work. Specifically designed micro-scale markers (i.e. cylindrical holes and slots) were milled on the surfaces of interest in order to enable the accurate alignment of 3D topographies and 2D profiles acquired with different instruments. Such samples were scanned by means of a metrological CT system (Nikon Metrology MCT225), using low X-ray power in order to achieve good metrological structural resolution, which is necessary for the measurement of micro-scale surface features [7]. Surface topographies were extracted from the obtained CT data and the topographies were acquired on the same surfaces by focus variation (FV) and confocal microscopy (CM) by means of a Sensofar Plu Neox with 20× objective. Such topographies were aligned and compared in terms of areal texture parameters (S-parameters defined by the ISO 25178-2 [8]) after the subtraction of a least-squares mean plane. The next step consisted in cutting and polishing one face on the sample perpendicularly to the analysed surfaces, in order to allow imaging of actual cross-sectional roughness profiles including re-entrant features (see example in Fig. 1). Reference profiles were acquired using a multisensor CMM equipped with imaging probing sensor (Werth Video Check IP 400; MPE = $1.8+L/250$ µm, with L in mm). Another CT scan of the sample was performed after it was cut. By the alignment of topographies (CT, CM and FV) acquired before the cutting/polishing procedure with the CT volume obtained after cutting/polishing, it was possible to identify exactly the same profiles measured using the CMM. In this way, the profiles acquired with CT, CM and FV could be compared with the reference profiles in terms of ISO 4288 [9] parameters on the primary profile (P-parameters) after subtraction of the least-squares mean line, and – in case of presence of undercuts – in terms of area measured under each profile.

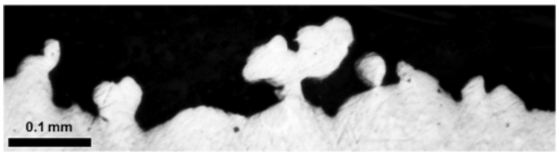

Figure 1. 2D profile imaged by CMM with imaging sensor on the cut-sections of a reference AM part, presenting several undercuts.

3. Results

Fig. 2 compares three regions extracted from the aligned three-dimensional surface topographies acquired with CT (Fig. 2-a), FV (Fig. 2-b) and CM (Fig. 2-c). Table 1 reports the chosen areal texture parameters, calculated for comparing the employed measuring technologies. Standard deviations were found to be below 2 % for CT and below 1 % for both FV and CM.

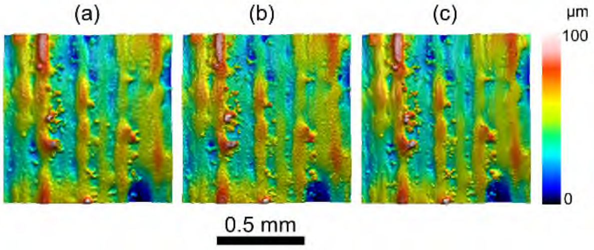

Figure 2. Portions of aligned surface topographies acquired by means of: CT scanning (a), focus variation (b) and confocal microscopy (c).

Table 1 S-parameters measured on CT, FV and CM topographies.

Parameter	CT	FV	CM
Sa	11.6 µm	11.8 µm	12 µm
Sq	14.3 µm	14.6 µm	14.9 µm
Sz	97.6 µm	102.0 µm	101.0 µm
Ssk	0.11	0.13	0.12
Sku	3.00	3.05	3.03
Sal	0.069 mm	0.068 mm	0.069 mm

Fig. 3 illustrates a cross-sectional 2D reference profile (obtained by the CMM with image probing sensor, after removal of re-entrant features), compared to the corresponding CT profile after removal of re-entrant features, and to the profiles measured using FV and CM (the reference profile was aligned to the other profiles by a marker-based registration followed by fine algorithmic cross-correlation registration).

Such profiles, being without undercuts, can be analysed as conventional roughness profiles: the calculated P-parameters are listed in Table 2. Standard deviations were found to be below 3 % for CT, below 2.5 % for FV and below 1.5 % for CM.

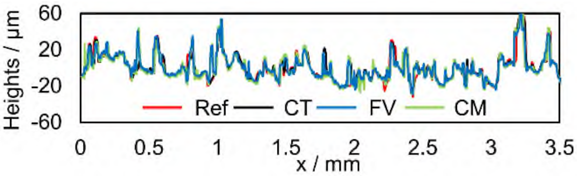

Figure 3. 2D profiles containing undercuts measured using: CT (a), FV (b) and CM (c). All profiles are compared with the reference profile (in red), measured using a CMM with imaging probing sensor.

Table 2 P-parameters measured on profiles acquired by means of: CMM with imaging probing sensor (reference), CT, FV and CM.

Parameter	Reference	CT	FV	CM
Pa	11.3 µm	10.6 µm	10.7 µm	11.2 µm
Pq	14.9 µm	14.2 µm	14.1 µm	14.7 µm
Pz	92.6 µm	87.0 µm	88.5 µm	89.4 µm
Psk	1.23	1.21	1.11	1.16
Pku	5.32	5.42	4.75	5.22

Profiles and surfaces containing undercuts (see Fig. 1) cannot be used to calculate conventional roughness parameters [10]. Instead of removing every undercut from the profile/surface, a redefinition of such parameters would allow to obtain a more representative and accurate description of the actual roughness/topography of additive manufacturing surfaces [10]. In this work, while a new definition of parameters is not yet available, profiles containing undercuts (see Fig. 4) were compared by measuring the areas under each investigated profile. In particular, a maximum difference of 8 % (negative) was obtained between CT and reference measurements, while the difference was of 55% (positive) between FV and reference measurements and 46 % (positive) between CM and reference measurements.

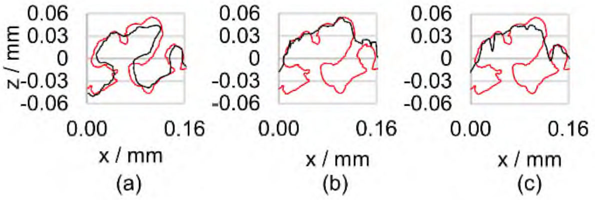

Figure 4. 2D profiles containing undercuts measured using: CT (a), FV (b) and CM (c). All profiles are compared with the reference profile (in red), measured using a CMM with imaging probing sensor.

4. Conclusions

Using the newly developed methodology, X-ray CT was determined to be capable of acquiring profiles containing also re-entrant features, with deviations within 8 % (in terms of area under the profile, for the investigated case) with respect to the reference profiles. Focus variation and confocal microscopy can measure profiles close to the reference profiles only if no inaccessible features occur. Conventional areal texture parameters and profile roughness parameters can be applied on AM parts only after removal of re-entrant features. In this work, topographies and profiles (with no undercuts) acquired by means of CT, FV and CM showed a good agreement in terms of areal texture parameters (deviations within 4 % for most S-parameters) and profile roughness parameters (maximum deviations to the reference profiles equal to 6 % for CT and CM, and 11 % for FV). A redefinition of such parameters should be pursued in order to achieve a more accurate and representative description of AM surfaces. The method presented in this work can be used for experimental validations of new proposed definitions. Further work is ongoing to use the method for determining the uncertainty of CT surface topography measurements by applying the substitution method [11].

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