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Advancements in the accuracy investigation of X-ray computed tomography characterization of additively manufactured metal surfaces

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Abstract
X-ray computed tomography (CT) has recently started to be used for evaluating the surface topography of metal parts produced by additive manufacturing (AM). Differently from conventional contact and optical measuring techniques, CT enables non-destructive measurements of both internal and difficult-to-access AM surfaces, including typical complex micro-scale re-entrant features. This work aims at improving the understanding of the accuracy of CT-based surface topography characterization using a newly proposed reference sample design. The sample geometry allows evaluating the CT measurement accuracy on external and internal, planar and curved surfaces oriented along two orthogonal directions within the CT volume. An actual sample was produced by laser-powder bed fusion of Ti6Al4V and cut by micro electrical discharge machining to enable optical calibration of reference surface profiles.

Surface topography, metal additive manufacturing, X-ray computed tomography, accuracy

1. Introduction

Additive manufacturing (AM) technologies have the ability to produce highly customizable metal parts, containing complex external and/or internal geometries (e.g. freeform surfaces) that were previously impossible or difficult to be produced via conventional manufacturing processes [1], such as components featuring intricate internal channels and lattice structures [2]. However, adequate and accurate measurement techniques and procedures are required for achieving a deeper understanding of the causes leading to the still-present quality issues [3]. In particular, this work addresses the measurement of surface topography of AM metal parts. In fact, the high complexity of surface topographies is one of the main quality issues of AM metal products.

Industrial X-ray computed tomography (CT) is an advanced non-destructive inspection technique that has recently started to be considered for topographical measurements at micro-scale of AM surfaces thanks to the high structural resolution and good dimensional accuracy achievable with modern CT devices [4,5]. The greatest advantage for this specific application is the possibility of measuring also difficult-to-access surfaces (e.g. internal) and re-entrant surface features (both are typical characteristics of AM products [6]), overcoming the limitations of optical and contact instruments.

CT-based measurements of AM surface topographies have already been studied through comparison with optical areal measurements [7] and through investigation of some possible influence factors [8]. Moreover, their accuracy has been investigated using a reference sample, featuring external and linear calibrated surface profiles [6].

The aim of this work is to improve the accuracy investigation of CT surface topography measurements performed on AM metal parts by proposing a new reference object design to obtain both external and internal, linear and non-linear reference surface profiles representing the actual surface morphology (i.e. including re-entrant features), to be compared with the same profiles extracted from CT data.

2. Enhanced approach for accuracy investigation

The experimental approach used for evaluating the accuracy of CT surface topography measurements of metal additively manufactured parts is based on the research already presented in [6], in which reference measurements performed on an AM sample enabled the evaluation of systematic errors and the determination of measurement uncertainty. In that research the sample geometry was conceived to be suited for comparing CT surface topography measurements with measurements performed using optical techniques, hence it was limited to planar and accessible external surfaces.

In this work, in order to conduct a more complete accuracy evaluation specific for CT surface topography measurements, a new reference object was designed including surfaces/profiles having different characteristics (i.e. external and internal, planar and curved) and oriented along different directions within the CT scanning volume (i.e. parallel and perpendicular to the line joining the X-ray source focal point and the X-ray detector center). The latter aspect is important as significantly different errors may arise when measuring on different directions, for example due to diverse impact of beam hardening effect and cone beam artefact [9].

An initial sample was fabricated via laser-powder bed fusion (L-PBF) of Ti6Al4V, using an L-PBF system (Sisma, MYSINT100). Externally, it is a cylinder surmounted by a half sphere; internally, it features a cavity with the same offset geometry, with a central cylindrical pillar that has the function to sustain the dome structure. A micro electrical discharge machining (µ-EDM) system (Sarix, SX-200) was then employed to (i) generate micro-scale markers (i.e. planar slots with height 0.4 mm and different depths) useful for registration of the obtained CT volumes and (ii) cut the sample along two orthogonal directions (for the reason explained above). The final sample design is shown in Figure 1-a.

The µ-EDM process allows achieving a good polishing of the cut-surfaces, necessary for obtaining the reference measurements of surface profiles that were performed using the imaging probing sensor of a multisensor CMM (Werth Video Check IP 400; maximum permissible error (MPE) equal to 1.8+L/250 µm, with L expressed in mm).

The sample was firstly CT scanned after the L-PBF process to reconstruct its entire geometry before the cutting operation. The cut sample was then CT scanned again to align the CT volumes obtained before and after the cutting operation. The µ-EDM micro-markers were used as reference geometries for the alignment. The aim was to identify exactly the same profiles measured by the imaging probing system. Finally, the profiles acquired with CT were compared with the reference profiles in terms of generalized surface texture parameters, which were defined in [10] to be suited to be computed on CT data without removing re-entrant surface features (hence without discarding any potentially relevant surface information measurable by CT).

Finally, the accuracy of CT surface topography measurements was experimentally investigated using the approach defined in the guideline VDI/VDE 2630-2.1 [11], which is based on the availability of samples calibrated with low uncertainty and with similar characteristics in terms of material, size and geometry with respect to actual workpieces.

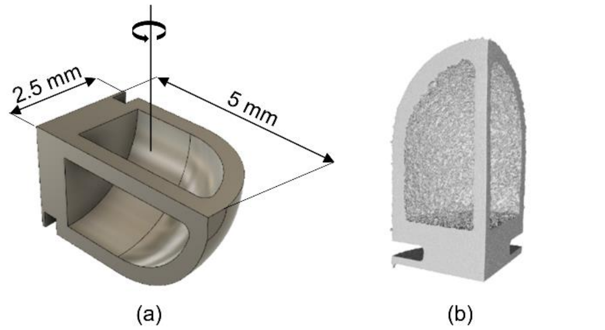

Figure 1. (a) Final sample geometry (CAD); (b) CT reconstructed volume.

4. Preliminary results

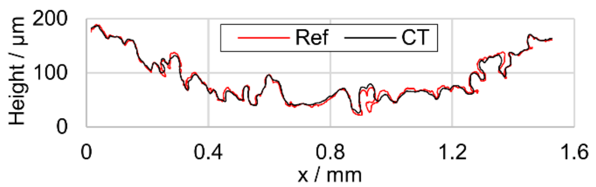

Figure 2. Example of internal curved surface profile acquired by CT and compared with the corresponding reference profile.

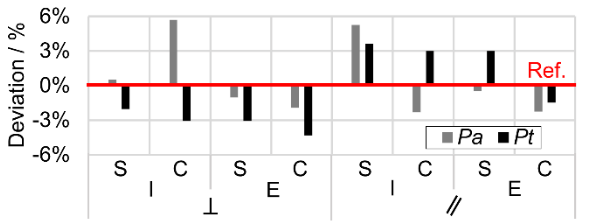

Figure 3. Percentage deviations of P-parameters computed from CT data with respect to reference values, grouped by profile type: straight (S), curved (C), internal (I), external (E), perpendicular (⊥) and parallel (∥).

The CT measurement of the reference sample described in Section 2 were conducted using a metrological CT system (Nikon Metrology MCT225) characterized by: micro-focus X-ray tube with 3 µm minimum focal spot size, 16 bit detector with 2000×2000 pixels, 20 °C temperature-controlled cabinet, and maximum permissible error (MPE) for length measurements equal to 9±(L/50) µm (with measured length L expressed in mm). For this preliminary analysis, three repeated CT scans were conducted with a voxel size of 4 µm. Figure 1-b shows a CT reconstructed volume of the cut sample. Figure 2 shows an example of internal curved profile. It can be noticed that the CT measured profile approximates well the reference profile and is capable of measuring also re-entrant features. Figure 3 reports the deviations computed as measured values minus reference values for all the available profiles, considering two generalized P-parameters [10]: *Pa* and *Pt*. In general, the determined percentage deviations are below 6 %, which is consistent with results obtained in [10]. Further work is ongoing for determining the influence of CT on measurement of additional parameters.

5. Conclusions

The proposed reference object enables the accuracy investigation of CT surface topography measurements considering different surface characteristics (internal and external, straight and curved) and two orthogonal directions within the CT volume. Preliminary results obtained in this work show that it is possible to perform CT surface topography measurements with limited influence from the surface type (i.e. internal and external), the surface form and the measuring direction. Such investigations increase the understanding of accuracy of measurement on actual workpieces produced using the same additive manufacturing technology, the same material and similar dimensions of reference samples (according to the approach defined in the guideline VDI/VDE 2630-2.1 [11]). Furthermore, the proposed approach can be easily adapted to other processes, materials and sample sizes.

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