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Results from an interlaboratory comparison of areal surface texture parameter extraction from X-ray computed tomography of additively manufactured parts

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Abstract
This paper presents the results of the CT-STARR (CT-Surface Texture for Additive Round Robin) interlaboratory comparison. The study compares the results obtained for the extraction of areal surface texture data per ISO 25178-2 from five X-ray computed tomography (XCT) volume measurements from each of four laboratories. To reduce the number of process variables, all participants utilise a Nikon XCT machine, either an XT H 225 industrial CT or an MCT225 metrology CT. Measurement process parameters, such as physical X-ray filtering, acceleration voltage and filament current, are set at similar values for all machines. All data processing and computation to extract, align, crop, filter and generate surface texture parameter information and deviation analysis results from the measurement volumes is performed by one participant. Two Ti6Al4V ELI (extra low interstitial) components are included in each of the XCT acquisitions. The first component is an additively manufactured cube built on an Arcam Q10 electron beam melting machine. Surface texture data is extracted from XCT scans of this part. The second component is a machined artefact designed for XCT scaling and surface determination analysis and verification. The data extracted from XCT measurements of these components is compared with measurements from coordinate measuring machine, focus variation and stylus instruments. The effect of scaling correction and XCT surface determination on extracted surface texture data, as well as measurement repeatability and reproducibility, are discussed.

Additive manufacturing, areal surface texture data, interlaboratory comparison, X-ray computed tomography, metrology, ISO 25178.

1. Introduction

Additive manufacturing (AM) methods enable the manufacture of components with features that are not possible to manufacture using conventional subtractive techniques. However, the freedom to manufacture components with complex internal features presents measurement challenges. Currently the principal method available for imaging the internal features of metal AM components is X-ray computed tomography (XCT). The importance of areal surface extraction from XCT is discussed elsewhere [1, 2] but, until recently, the only reported research detailing the extraction of surface information from XCT was the extraction of profile data from lattice structures [3]. A novel methodology for the extraction of areal surface texture data per ISO 25178-2 [4] from metal AM components has been reported [5]. The results showed a 2.5 % difference between the mean measurements obtained using XCT when compared to a focus variation (FV) instrument in measurement of an AlSi10Mg AM component. The potential industrial and research applications of this technique have prompted development of a round robin to assess the variation of results between XCT laboratories. The current work reports on Stage 1 of the CT-Surface Texture for Additive Round Robin (CT-STARR).

Stage 1 is designed to be a tightly controlled, expeditious round robin with a limited number of participant laboratories (four) using similar XCT machines with defined measurement settings. The results of measurements and analysis of Stage 1 data will then be used to guide a second, expanded round robin (Stage 2).

2. Methodology

Two artefacts were manufactured from Ti6Al4V ELI (extra low interstitial) titanium alloy. One artefact was a cube with 10 mm sides additively manufactured using an Arcam Q10 electron beam melting (EBM) system. One side (vertical) surface of this artefact was used for the surface texture analysis. The size of this artefact was dictated by the measurement surface area requirements derived from ISO 4288 (profile) [6] and ISO 25178 (areal) specification standards; with the size and filtering based on the initial surface texture measurements. The second artefact, used for scaling and surface determination analysis, was machined to a similar overall size to enable optimum X-ray attenuation for both artefacts simultaneously. This dimensional artefact includes three measured dimensions: an outside diameter (OD) and an inside diameter (ID) of approximately 3 mm, and a length between two parallel surfaces of approximately 4 mm. Surface determination is the calculation of the surface position during XCT reconstruction; the calculated position of the surface is based on the grey scale values of the XCT images. Inaccuracies in this surface determination would affect these three dimensions differently: if the surface determination were to calculate the surface inside the actual surface the OD would be undersized, the ID would be oversized and the length would be minimally effected by errors, as the surfaces are parallel and facing the same direction. The AM surface and dimensional artefacts were measured using an Alicona G4 focus variation instrument and a Zeiss Prismo CMM respectively prior to the round robin. The two artefacts were mounted within an AM fixture designed to maintain an air gap between all measured surfaces and the fixture (see figure 1).

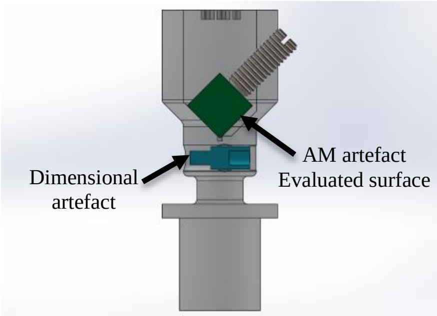

Figure 1. Artefacts within the fixture

The fixture development process is reported elsewhere [7]. The artefacts were not removed from the fixture during five XCT measurements performed by each round robin laboratory. Post round robin measurements included further measurements of surface and dimensions using FV and stylus, together with a repetition of the CMM measurements. The participants and the XCT machines used are shown in table 1.

Table 1. Round robin participant laboratories

Laboratory	Responsible	XCT machine
University of Huddersfield, UK	Andrew Townsend	Nikon XT H 225
University of Nottingham, UK	Richard Leach	Nikon MCT225
National Physical Laboratory, UK	Peter Woolliams	Nikon MCT225
Nikon Metrology, UK	David Bate	Nikon MCT225

All extracted surface data was aligned to one of the FV measurements. The FV and XCT data was processed per the methodology introduced in [5]. The surfaces were levelled and filtered with an L-filter nesting index of 8 mm and an S-filter nesting index of 0.025 mm per ISO 25178-3 [8]. Data was extracted and values for parameters per ISO 25178-2 were generated.

3. Results

Results reported here are for one set of measurements from the University of Huddersfield (XCTHUD) and one set of measurements from the University of Nottingham (XCTNOT). Table 2 shows the mean and standard deviation (SD) values of ISO 25178-2 parameters computed for the FV and XCT measurements.

Table 2. ISO25178-2 parameter values

Parameter	Mean FV	SD FV	Mean XCTHUD	SD XCTHUD	Mean XCTNOT	SD XCTNOT
Sq/µm	32.40	0.001	30.77	0.036	32.03	0.252
Sa/µm	25.33	0.001	24.05	0.031	25.07	0.241
Sz/µm	330.59	0.306	322.27	2.889	327.80	1.644
Ssk	0.246	<0.001	0.08	0.016	0.202	0.008
Sku	3.70	<0.001	3.67	0.009	3.66	0.040
Sdr/%	39.90	0.013	28.26	0.123	41.92	1.080

Figure 2 shows the results of the FV, XCTHUD and XCTNOT for *Sq* and *Sz,* showing the 95 % confidence interval for the mean. The XTHUD *Sq* and *Sz* are approximately 5 % and 2.5 % less than the FV values. The XCTNOT *Sq* and *Sz* are approximately 1.1 % and 0.9 % less than the FV values. Figure 3 shows the charts for the dimensional artefact OD, ID and length measurements taken on the CMM and both XCT machines. The OD, ID and length dimensional measurement errors for the XCTHUD were -0.27 %, -0.83 % and -0.54 % respectively. If a surface determination correction of 4.1 µm is applied, moving the calculated surface *into* the part, the errors become -0.55 %, 0.55 % and -0.54 %.

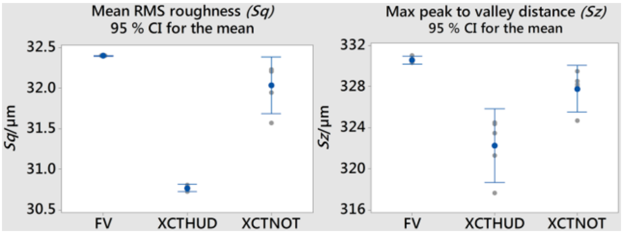

Figure 2. ISO 25178-2 parameter values

A global (*x*,*y*,*z*) dimensional scaling compensation of +0.55 % can then be applied. The effect of these compensations on the AM surface parameters will be investigated as part of future work.

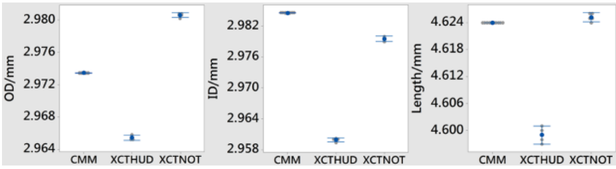

Figure 3. Scaling artefact dimensions

4. Conclusion

The round robin results of ISO 25178-2 areal surface data extraction from XCT scans of a Ti6Al4V ELI component have been reported for two of the round robin participants. The results for *Sq* for the XCTHUD and XCTNOT measurements are mean 30.77 µm (SD 0.036 µm) and mean 32.03 µm (SD 0.252 µm) respectively; these mean values are within 5 % and 1.1 % of the FV results (FV mean 32.40 µm [SD 0.001 µm]). Analysis of the differences in standard deviation values for the initial XCTHUD and XCTNOT surface parameters, together with the final results for all four participants will be presented at conference and in a later journal. This round robin, an extension of a novel technique to extract quantitative areal surface texture data reported in [5], validates the parameter extraction process, provides useful repeatability and reproducibility data and provides baseline information for an expanded, Stage 2, round robin.

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