euspen's 25th International Conference & Exhibition, Zaragoza, ES, June 2025
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Accurate comparison of optical and X-ray computed tomography surface texture measurements on additively manufactured test specimens to improve the accuracy of fatigue life predictions

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Abstract
This paper introduces a novel approach to compare surface texture measurements obtained from computed tomography (CT) and optical profilometry (OP) on Ti6Al4V additively manufactured fatigue specimens, aimed at enhancing fatigue life predictions. Traditional alignment methods, often requiring fiducials or markers on the part, can alter the specimen's geometry or surface properties. To address this issue, we developed a measuring setup that allows precise data alignment without any alterations to the surface. Surface texture was analysed over the entire cylindrical gauge length using standardised roughness parameters, comparing CT and optical profilometry data to identify areas of agreement and discrepancy while identifying potential sites of crack initiation. This multi-instrument measurement approach will provide a deeper understanding and characterisation of surface pits that may undermine fatigue life and it lays the foundation for improving life prediction accuracy in as-built additive manufacturing surfaces.

Surface metrology, optical profilometry, computed tomography, multi-instrument surface characterisation, additive manufacturing

1. Introduction

Additive manufacturing (AM) of metals allows the fabrication of complex geometries and intricate surfaces that are challenging to achieve with conventional processes. As-built AM surfaces often exhibit significant roughness and micro-scale re-entrant features [1] complicating accurate characterization while critically influencing mechanical performance, especially under fatigue loading [2]. Predicting fatigue life based on local surface texture parameters like *Sv* (maximum pit depth) shows promise [2], despite difficulties in achieving comprehensive and reliable measurements. Various measurement techniques have been employed to characterize AM surface textures, each with its advantages and limitations. Optical measuring methods, such as optical profilometry (OP), offer high resolutions but are inherently limited by their inability to access overhang/shaded surfaces. In contrast, X-ray computed tomography (CT) is a non-destructive technique capable of assessing re-entrant surfaces [3], thus addressing many limitations of optical methods. However, CT data have lower spatial resolution than optical methods. Combining the complementary strengths and limitations of optical profilometry and X-ray CT offers a promising approach for comprehensive surface texture characterization. To achieve this integration, literature shows a reliable framework is needed for accurately aligning measurement data from different techniques [4].

Building on previous work that established the precise physical alignment of optical and X-ray CT measurements [5], this study systematically analyses the impact of OP and CT measurements on surface texture parameters relevant to fatigue life. This work serves as a step toward developing comprehensive, data-fusion-based surface texture measurements, ultimately advancing the accuracy of fatigue life predictions for AM components.

2. Materials and methods

2.1. Measuring procedure

The case study exploits the measurement setup described in [5], illustrated in *Fig. 1*. The central gauge section of the Ti6Al4V fatigue specimen was entirely measured using both measuring systems. The OP acquisition is performed using the focus variation principle and a 20x magnification lens. The full surface is captured in 16 overlapping scans with a size of 6.0x1.6 mm^2. The lateral resolution of the OP-scanned surfaces is 0.65 µm. Light intensity and other minor parameters are tuned to guarantee a minimum of 85% measured points and avoid excessive outliers due to high reflection. The consistent rotation of the specimen is ensured by a manual mandrel while a coupling notch in the specimen support provides the zero reference [5].

CT scans were performed using a metrological micro-CT system (MCT225, Nikon Metrology, UK), with 170 kV X-ray tube voltage, 41 µA filament current and exposure time of 1.4 s. A 0.1 mm thickness Cu filter was used to reduce beam hardening. A voxel resolution of 4 µm was achieved, allowing the gathering of the entire gauge length surface at a suitable resolution for measuring AM surfaces. A point cloud was then obtained after CT volume reconstruction and local-adaptive surface determination. The cylindrical CT point cloud was then unfolded into a planar surface by a direct transformation from cartesian

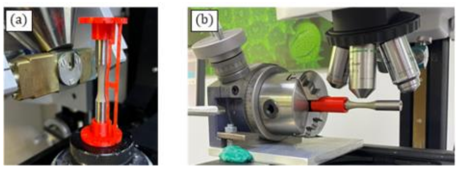

Figure 1. Measuring configuration for the computed tomography system (a) and optical profilometer (b)

into a planar surface by a direct transformation from cartesian to cylindrical coordinates, as schematised in Fig. 2. This isometric transformation preserves angles and distances.

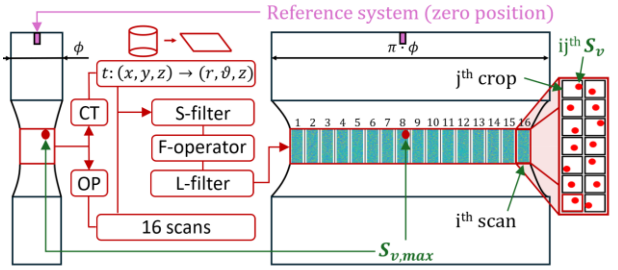

Figure 2. Schematic representation of surface data workflow

2.2. Elaboration of surface data

To ensure consistency in the evaluation of surface texture parameters, the same procedure was employed for both measuring instruments (see Fig. 2). Specifically, the set of operations performed follows the indication of the ISO 25178-2 standard [6]. Firstly, a 2.5 µm S-filter was applied to the primitive surface to remove small-scale lateral components. An F-operation was then performed for removing form, before applying a 0.8 mm L-filter to separate roughness and waviness. Filters were chosen based on the indication specified by ISO 25178-3 [6].

Once all the surfaces have been filtered, the alignment between the OP and CT scans is performed. The specimen support, featuring a dedicated reference system, allows to reliably relate OP scans with corresponding regions on CT scans.

2.3. Surface parameters extraction

The alignment operation results in two corresponding sets of 16 overlapping surfaces, each pair defined by an OP and a CT surface. Each OP and CT surface was divided into 14 adjacent crops, each measuring 0.8×0.8 mm^2, as shown in Fig. 2. The crop size was selected to match the L-filter nesting index, equal to 0.8 mm. The chosen dimensions ensure that all wavelengths of interest are retained, as 0.8 mm represents the largest wavelength component of the S-L surface. Moreover, applying such filtration to individual crops requires a minimum size equal to or greater than the nesting index value [6].

To investigate differences between the two measuring instruments in characterising the additively manufactured specimen, the *Sa, Sv, Sp* surface texture parameters were computed according to ISO 25178-2 [6] using the commercial software MountainsMap (DigitalSurf, FR).

3. Results & Conclusions

Fig. 3a shows the average and standard deviation (1σ) values of *Sa*, *Sv* and *Sp* computed over the 14 crops of all 16 scans for data from OP and CT measurements. Greater values were observed in OP measurements for all three parameters, particularly for *Sa* and *Sv*, where CT measurements yielded averages 16% and 28% lower, respectively. Minor differences were noted for *Sp*, with comparable averages and standard deviations between the two measurement techniques. *Fig. 3b* shows the average values of *Sa* calculated over the 14 crops of each scan, highlighting a systematic difference between OP and CT for this global surface texture parameter. In contrast, *Fig. 3c-d* shows the maximum values of *Sv* and *Sp* detected across the 14 crops of each of the 16 scans. As a further confirmation of the agreement shown in Fig. 3a, comparable values of *Sp* were found between the two measuring systems, except for scan No. 13, where a sintered particle was found to exceed the OP investigation range. Regarding *Sv*, a significant discrepancy was found for each scan, with non-systematic deviations across all the scans and occasional peak values affecting both CT and OP measurements. In the context of fatigue life predictions, further detailed investigation is required on regions of discrepancy to provide robust and accurate *evaluation* of *Sv*.

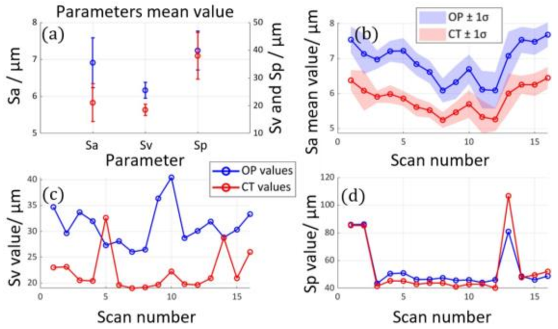

Figure 3. Mean value and standard deviation of *Sa, Sv* and *Sp* across all the 14 crops of each scan (a); average value of *Sa* on the 14 crops of each scan (b); maximum values of *Sv* (c) and *Sp* (d) on the 14 crops of each scan, respectively.

In conclusion, this paper presented an ongoing work in which a fatigue specimen was specifically designed alongside a tailored measurement setup [5] to enable the alignment and comparison of surface measurements without altering the functional surface. This approach allowed for investigating variations in surface texture parameters based on the measurement method. The results revealed discrepancies between OP and CT parameters, particularly *Sa* and *Sv*. Notably, *Sv*, critical for fatigue life prediction, showed inconsistent discrepancies across measurements. These findings underscore the need for localized investigations into such variations. As a next step, a detailed visual analysis of the morphology of the deepest pits will be conducted to characterize defects that undermine fatigue resistance. This will provide more accurate and comprehensive *Sv* evaluation, while enhancing its relevance for fatigue life predictions.

Acknowledgements

This study was carried out within the MICS (Made in Italy – Circular and Sustainable) Extended Partnership and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.3 – D.D. 1551.11-10-2022, PE00000004). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

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