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Surface roughness evaluation of additive manufactured metallic components from white light images captured using a flexible fiberscope

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ABSTRACT

The added capabilities of Additive Manufacturing (AM) while processing metallic components have revolutionized the design and manufacturing flexibility of multitudes of aerospace components. However, AM being a stochastic process results in a degraded control of the surface topography of the printed structure and thus requires adequate finishing processes before implementation. Particularly, in the case of components having complex cross-sections and internal channels, none of the currently available technologies offer a solution for the measurement and certification of surface roughness parameters. In this context, this paper investigates a binary image processing technique applied to multiple white light images captured by a 0.3 mm diameter micro fiber endoscope. Further, AM sample surfaces generated by different build angles are investigated to demonstrate the advantages of the proposed technique. A surface roughness evaluation parameter is presented along with measurement results obtained using the Mitutoyo SJ400 (conventional profiler) and the Talyscan 150 (optical profiler).

1. Introduction

The role of AM has tremendously increased the overall process efficiency of large-scale manufacturing owing to its flexibility towards part design and a structured approach that translates onto a highly cost-effective manufacturing technique [1,2]. Contrary to conventional manufacturing systems, AM offers a higher degree of freedom which allows for the production of a new generation of complex and efficient internal channels for multiple applications such as internal coolant systems [3].

These rising requirements in the design and manufacturing of working components have imposed stringent requirements on the metrology forefront. Essentially, it can be predicted that the futuristic measurement systems must go hand in hand with the manufacturing process, thereby improving their standards in real-time [2]. One such parameter that is of great concern in determining the credibility of the manufacturing process is the surface quality of the manufactured component [4,5]. Surface measurements play an important role in achieving the desired quality for a metallic component thereby determining its average life-cycle [5]. As per the ISO 25178 part 6 (2010), conventional surface topography evaluation techniques can be broadly categorised into line techniques, areal techniques and area integrating techniques [6]. The line profiling instruments such as contact based stylus and line-scanning mode phase shifting interferometer produces a 2D plot of the surface height distribution [7,8].

Further, the measurement data can be mathematically represented as a height function $h\ (y)$. Areal topography methods, on the other hand, produce a 3D topographical image of the surface which can then be mathematically represented as $h\ (x,\ y)$. Techniques such as White Light Interferometry (WLI) [9], Confocal microscopy [10,11] and focus variation [12] are grouped under this category. In contrast, the areal-integrating methods, such as optical scattering [13] and speckle based techniques including, contrast [14–16], correlation [17–22] and image [23,24] analysis only provide a statistical representation of the surface under study.

These traditional surface topography evaluation techniques serve well in bench top applications for various AM components. However, one of the most significant point to be considered in the context of the design and development of advanced manufacturing techniques is the suitability of the mentioned techniques for evaluating the surface topography of areas hard-to-access and internal channels. Current available techniques for internal channel inspections either require the sample to be cut [25], necessitates expensive hardware [26] or utilize non-flexible probes [27]. Hence to address these issues, a flexible, easily maneuverable, miniature probe based surface topography evaluation system is envisaged.

In this context, this paper proposes and illustrates a new binary image analysis technique to quantify the surface roughness variations on

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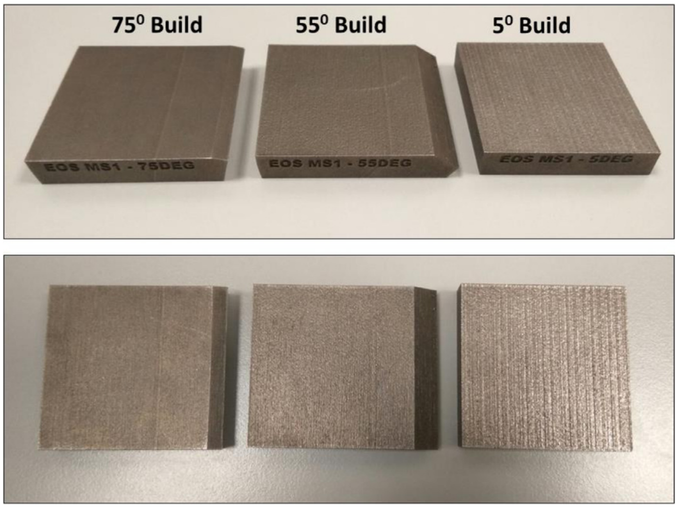

Fig. 1. AM Samples used for the tests with build angles of 5°, 55° and 75° shown to have distinct differences in surface quality.

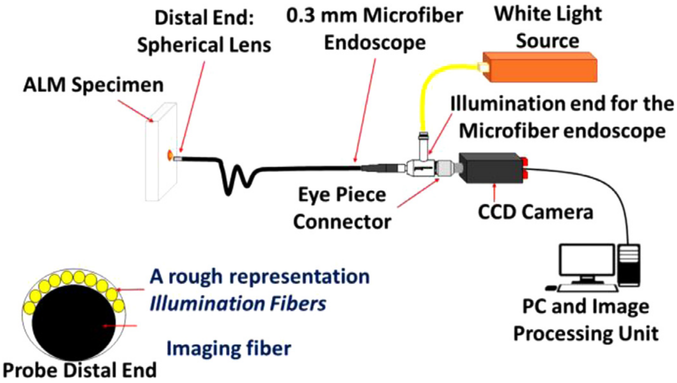

Fig. 2. Experimental arrangement of the optical fiber probe based surface roughness evaluation system.

AM components based on images captured using a 0.3 mm diameter flexible borescope. The use of optical fibers for imaging hard-to-access areas have been studied by various researchers [28–31]. Surface images captured from 3 AM samples generated using different build angles are compared for validating the process algorithm. Furthermore, the outcome of the technique is validated using conventional and optical stylus measurement systems, namely, Mitutoyo SJ-400 and Talyscan 150.

2. Materials and method

This section details the AM samples used for the trials along with the optical test arrangements adopted for this investigation.

2.1. AM sample details

The AM sampled used for the tests are manufactured using the Laser Beam Powder Bed Fusion technique, namely, Direct Metal Laser Sintering (DMLS). The materials used for process is Maraging steel (EOS MS 1) printed with a layer thickness of 40 µm. Fig. 1, shows the three samples that are built at 5°, 55° and 75°.

2.2. Experimental arrangement

The schematic diagram of the experimental setup used for the study of AM samples is presented in Fig. 2. A white light source (Thorlabs-OSL2-High-Intensity Fiber-Coupled Illuminator) coupled with a 0.37 mm diameter optical fiberscope (Myriad Fiber Imaging) illuminates the surface of the sample surface. A spherical imaging lens collects the image of the surface under study and passes it through the imaging fiber (FUJIKURA, FIGH-016-160S) within the fiberscope that contain 1,600 picture elements with a center-to -center pixel spacing of 3.3 µm.

The eyepiece of the fiberscope is further coupled with a sCMOS camera (ANDOR, XYLA-5.5-sCMOS) using a camera adaptor (Fujikura 30 mm- 60 mm). Figs. 3(a) and (b) show the distal end and the imaging end of the fiberscope, respectively.

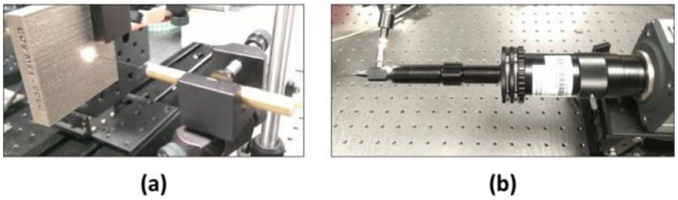

Fig. 3. (a) The distal end illuminating the AM sample and (b) the imaging end coupled with the sCMOS camera using the Fujikura camera adaptor.

2.3. Comb structure removal/ fiber de-pixelation algorithm

The use of a flexible optical fiberscope leads to the inevitable presence of comb structures that require additional processing for effective pattern recognition and quantitative image analysis [32–34]. In this context, we have investigated multiple static comb structure removal techniques prior to binary image analysis for surface roughness extraction. Three static techniques, namely, frequency filtering, Gaussian filtering and interpolation filtering are investigated to determine the most suitable algorithm for surface roughness extraction using binary image analysis [34].

Spatial averaging technique employs averaging filters to increase the intensity values at darker pixels with respect to the brighter pixels, thereby, reducing the comb structures. An averaging kernel, a spatial filter matrix, is traversed over individual pixels modifying and smoothening the overall image. Gaussian filtering utilizes a kernel that represents a Gaussian filter to remove the comb structures [35]. One drawback in employing spatial averaging techniques for comb removal arises from the choice of kernel itself. The use of spatial averaging filters results in the loss of high frequency information from the image due to its inability to localize the frequencies of the comb structure itself.

Frequency filtering technique removes high frequency components corresponding to comb structures in the image captured by the fiberscope [36]. A two-dimensional Fourier transform converts the captured image from the spatial domain to the frequency domain. Further, filter masks are employed to remove the high frequency components from the transformed image which is then converted back to the spatial domain using a two-dimensional inverse Fourier transform [35]. Compared to Gaussian filtering, the image quality is higher but with the expense of having a higher processing time and lower possibilities of automation [34].

Interpolation technique for comb structure removal utilizes a two-part algorithm designed to exploit the intensity variations between two neighbouring fibers [37]. The first part of the interpolation algorithm localizes the fiber centres based on a calibration image captured by illuminating the distal end using a white light illumination. The second part interpolates the intensity values between two adjacent fibers to form a uniform image [37]. Compared to the other two techniques, the interpolation method requires time-to-time recalibrations. Additionally, the overall processing time is much higher than the two techniques, a disadvantage in the context of an in-process measurement.

Fig. 4(a), shows an example of a resolution chart (1951 USAF resolution test chart) imaged using a flexible fiberscope (100 K fibers with GRIN lens at the distal end) processed using the three-different comb