FLEXIBLE OPTICAL FIBER PROBE FOR SURFACE ROUGHNESS EVALUATION OF INTERNAL CHANNELS IN ADDITIVELY MANUFACTURED COMPONENTS

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ABSTRACT: Recent developments in Additive Manufacturing (AM) has revolutionized the production capabilities of multitudes of aerospace components. However, being a stochastic process, there is minimal control over the surface quality and thus require adequate quality checks before implementation. In this context, this paper investigates a flexible optical fiber probe and speckle correlation measurements to quantitatively estimate the average surface roughness, Ra, of areas within internal channels. Details on probe design and preliminary measurement results on a comparator plate with Ra values varying between 6.3 µm and 25 µm are presented. The measurements are compared and validated using the Keyence optical tester (VR-3000).

KEYWORDS: Additive manufacturing, Laser speckle, Angle speckle correlation, Surface roughness, Non-destructive testing

INTRODUCTION

The added capabilities in the production of critical components using AM has resulted in flexible part designs and overall manufacturing cost reduction, Adrián et al. (2015). This has resulted in a new generation of component with complex internal channels that serve for multiple important functionalities such as, coolant systems, Pietropaoli et al. (2017). AM often results in degraded surface topographies that affect the functionality of the component, Andrew et al. (2015). Currently available techniques for surface topography measurements can be grouped into three categories, namely, line profiling, areal profiling and areal integrating techniques as per the ISO 25178 part 6

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(2010) standards, Leach (2011). However, for the surface topography measurements of internal channels all these techniques necessitates the sample to be cut, requires expensive hardware or use rigid probes, Kobayashi et al. (2003) and Xu et al. (2009). Therefore, to address these issues, a flexible miniature probe based surface topography measurement system for a fast, non-contact and non-invasive measurement is envisaged.

After the advent of lasers, optical techniques have been widely recommended for multiple engineering and biological applications, Sreekanth & Murukeshan (2010), Murukeshan et al. (2008) and Sujatha et al. (2003). For many years, speckle metrology for surface topography measurements have been studied in great detail. It has been proven to be a statistical representation of the surface topography. Out of all the speckle based techniques available, Angle Speckle Correlation (ASC) provides an extended surface roughness measurement range. First established by Léger et al, several researchers have demonstrated the capability for surface roughness assessment using ASC, Léger et al. (1975). Léger and Perrin reported surface roughness measurement for samples with average roughness between 1 µm to 30 µm using a quasi-automatic setup in less than 30 seconds. Spagnolo et al. verified the ASC technique by measuring standard rough samples having a roughness range of 4 µm to 31 µm, Spagnolo et al. (1997). Persson, in his research article, presented the capability for modelling the ASC technique through mathematical simulations and further measured samples with an average surface roughness between 1 µm to 10 µm, Persson (2006). In this paper, a flexible optical fiber probe is designed and developed for performing quantitative surface roughness measurements within internal channels using ASC. Probe design and simulation using Zemax© along with preliminary surface roughness measurements on a RubertMicrosurf spark-erosion comparator R-331 calibration plate is presented.

THEORITICAL BACKGROUND

When a rough surface is illuminated by a spatially coherent light, the reflected light scatters and interferes to produce dark and light patterns. These random patterns are termed as speckles. The properties of the speckle pattern are seen to be dependent on the properties of the coherent source and the surface topography of the sample. For demonstrating speckle correlation based on the orientation of the illumination source, two speckle patterns are simultaneously captured from the same sample area illuminated by two coherent plane waves at two different angles of incidence. By measuring the correlation factor (ASC) between the two recorded speckle patterns, it is possible to calculate the surface roughness by the theoretical formulation,

$$ASC = \exp\left(-\left(\left(\frac{2\pi}{\lambda}\right) R_q sin\theta_1 \delta\theta_1\right)^2\right) \tag{1}$$

Equation (1), gives the relationship between the RMS surface roughness (R_q) and the parameters of geometrical orientation, θ_1 and $\delta\theta_1$ in Figure 1 (a). Here, λ is the wavelength of the coherent illumination used. Generally, the correlation factor is less than 1 as the two speckle patterns recorded by the imaging camera are not fully correlated. Using this relation, a feasibility study is conducted in MATLAB© to determine $\theta_1$and $\delta\theta_1$to cater the surface roughness requirement for this study (< 25 µm). The result of the simulation is shown in Figure 1 (b).

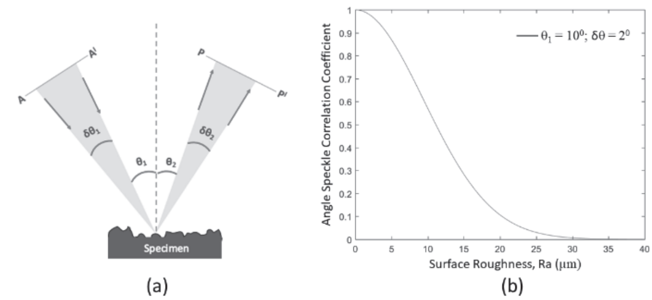

Figure 1. (a) The geometric arrangement for Angular Speckle Correlation (ASC) experiments and the theoretical plot depicting the relationship between ASC and average surface roughness, Ra, for $\theta_1 = 10^0$ and $\delta\theta\ [\theta_2 - \theta_1] = 2^0$ is shown in (b).

PROBE DESIGN

Image Probe

The design methodology for the ASC probe is based on conducting ray tracing simulations that considers both engineering design and optical design requirements of the imaging probe. The lens system and the imaging fiber is considered as a single entity at the distal end of the probe, as shown in Figure 2.

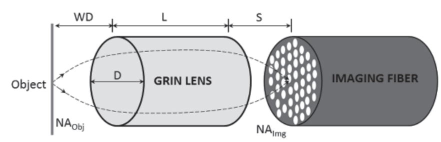

Figure 2. Schematic diagram of a GRIN lensed speckle imaging system.

Here, NA_{obj} and NA_{img} are the object space and image space Numerical Aperture [NA], respectively. D is the diameter of the lens, S is the image distance, WD is the working distance and L is the length of the lens. For a speckle imaging probe, $NA_{img} < 0.3$ is targeted. A minimum Field of View (FOV) of 0.3 mm is chosen. For Zemax© simulation, various lens objectives are simulated for WD varying between 0.3 mm to 5 mm. Two viewing configurations are simulated. A front view configuration and a side view configuration for 0^0 and 90^0 viewing with respect to the optic axis, respectively. For our application, a front view WD of ~ 5 mm and a side view WD of ~ 0.3 mm is anticipated. GT-FBIS-FIGH-10-350S-1.0-IFRL050-005-50-NC, a 1 m long imaging fiber with an outer diameter of ~ 0.9 mm, containing 10,000 picture elements having a WD of ~ 5 mm at 635 nm is selected for the front view probe. In case of the side view probe, a customized imaging fiber, GT-FBIS-FIGH-10-350S-1.0-IFRL050-003-50-P9 (CR 3963-3), having a 90^0 prism with a 2 mm edge is attached onto the probe tip is selected. The side view probe also has an outer diameter of ~ 0.9 mm, containing 10,000 picture elements, but a WD of ~ 0.3 mm at 635 nm.

Illumination Probe

The ASC probe requires precise angle of illumination onto the targeted surface. This can be achieved through angled fiber cleaving. Figures 3 (a) and (b) show the schematic diagram of proposed front view and side view ASC probe.

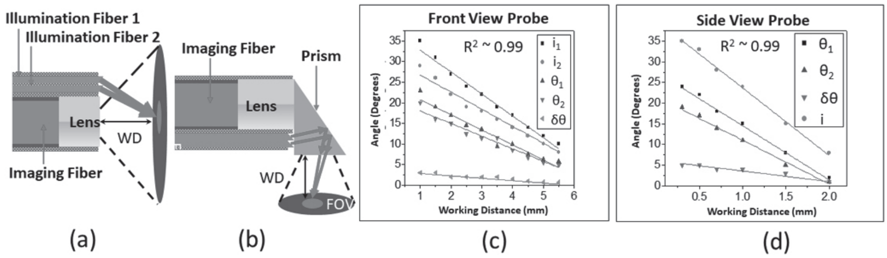

Figure 3. Shows the proposed design for the (a) front view and (b) side view ASC probe. Relationship between the fiber cleaving angle (i) and the illumination angle (θ) required for the (c) front view ASC and the (d) side view ASC experiments.

For a side-view ASC probe configuration a prism has been used for both imaging and illumination purpose as shown in Figure 3 (b). The angle of illumination at the specimen (θ_1 and θ_2) is obtained through Zemax© ray tracing simulation for different WD and varying angle of cleaving at the fiber (i_1 and i_2). Figures 3 (c) and (d) show the relationship between the fiber cleave angle and the specimen illumination angles with respect to varying WD for the front view and side view probes, respectively. From the stated requirements on the WD and the roughness range, θ_1 and $\delta\theta$ are chosen to be 10^0 and ~2^0, respectively for the front view probe. However, for the side view probe, the WD requirements are less than 1 mm and therefore the fiber cleaving angle from Figure 3 (d) is observed to be greater than 20^0.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Experimental Setup

Figure 4, shows the schematic diagram of the optical components to successfully perform speckle imaging and inspection of the test specimen. A self-contained, diode-pumped, solid-state fiber pigtailed Helium-Neon (He-Ne) laser (JDSU, Edmund Optics; Power ~20 mW) with a wavelength, λ = 635 nm is used as the illumination source.

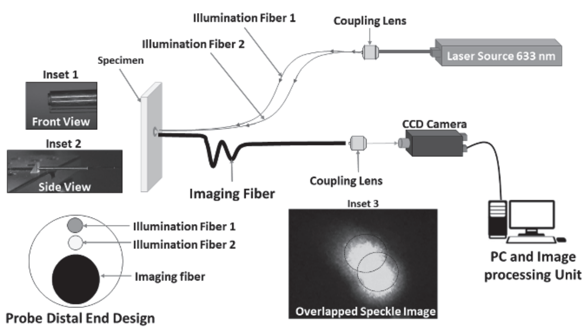

Figure 4. Proposed optical probe configuration for front view and side view ASC experiments.

The laser source is coupled into two single mode fibers of 9/125 µm diameter (9 µm core diameter and 125 µm cladding diameter) for illuminating the sample. For the front view probe, in order to adhere to the ASC principle, the illumination angle $\theta_1 = 10^0$ and the deviation angle was $\delta\theta \sim 2^0$ was chosen. However, in the case of the side view probe, i_1 and i_2 are selected such that $\theta_1 = 18^0$ and $\delta\theta \sim 4^0$. The imaging fiber is coupled to a sCMOS camera (ANDOR, XYLA-5.5-sCMOS) using a 60X objective lens (CFI Plan Fluor 60XC). For the preliminary study RubertMicrosurf spark-erosion comparator R-331 is used as a representative sample for AM surfaces. Two speckle patterns are recorded at two angles of illumination as per the ASC requirements. Further, the developed MATLAB© code compares the two images using a cross-correlation algorithm. Finally, the maximum angular speckle coefficient is displayed as a 2D plot which is compared with the roughness values calculated using the Keyence optical profiler (VR-3000).

Results and Discussion

Multiple trials are conducted to capture speckle patterns from a RubertMicrosurf spark-erosion comparator R-331. The areas on the comparator plate marked by Ra of 6.3 µm, 12.5 µm and 25 µm are mounted successively on a translational stage to record speckle patterns. Figure 5 below, compares the ASC coefficients calculated for different sets of 30 speckle patterns captured at each of the three locations on the comparator plate. The ASC coefficients are compared with the average surface roughness, Ra, measured at each of the three locations calculated from 20 images captured and processed using the Keyence optical profiler (VR-3000). From the comparison made in Figure 5, a relationship between the ASC values and measured Ra is evident.

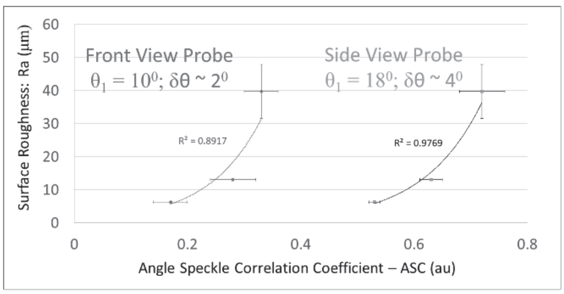

Figure 5. ASC measured using the front view and the side view probe compared with the average surface roughness, Ra, measured using the Keyence optical profiler (VR-3000).

However, for the section with Ra = 25 µm, the ASC values calculated and the Keyence measurements show a large deviation. This could be attributed to the local Ra variations across the sample due to the manufacturing process. The positive exponential trend observed could be associated with the influence of the optical imaging fiber on the transmitted speckle patterns. However, it should be noted that the measurements from the proposed ASC probe shows promising results with the samples considered.

CONCLUSION

In this paper, a flexible optical fiber probe is designed for performing quantitative surface roughness measurements within internal channels of additively manufactured components using Angle speckle correlation. The measurements are made on a RubertMicrosurf spark-erosion comparator R-331 calibration plate with Ra varying between 6.3 µm and 25 µm. A parametric study was conducted along with Zemax© simulations to determine the design for the illumination and imaging segments for the probe for the proposed front view and side view probes. Experiments conducted indicated a relationship between ASC and the surface topography. However, large measurement deviations in surface roughness measured on the 25 µm section of the sample is attributed to the local Ra variations. Finally, it was observed that the technique was sensitive to alignment and therefore correction algorithms are necessary for industrial applications. Combining all the advantages offered by ASC for surface roughness measurements with a flexible probe, the proposed methodology is envisaged for applications that require surface roughness characterization of complex internal channels, especially, for additive manufacturing applications.

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