FRACTAL SPECKLE IMAGE ANALYSIS FOR SURFACE CHARACTERIZATION OF AEROSPACE STRUCTURES

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ABSTRACT

Surface characterization of the working components has always been a subject of interest among researchers and industry specialists. Especially in the aerospace industry where the aerodynamic capabilities are largely altered by the surface quality of the component of interest, there remains an extensive need for developing systems for effectively characterizing the surface quality.

To realize an optical based non-contact and an in-line surface roughness measurement system, it is essential to understand the relationship between the quality of the surface and statistical parameter of the reflected speckles. The range of the measurement system being proportional to the wavelength of light used makes the analysis fundamentally important in order to understand the properties of speckles at a different wavelength. In this context, this paper examines the nature of the formed IR speckles from three different diffusers by analyzing their raw structure. Image processing algorithms that are developed study the different parameters of the 8-bit binary speckles, namely, the fractal property and number of connecting components. The paper also discusses the future work direction on relating the proposed analysis to derive the algorithm required for evaluating the surface finish parameters.

Keywords: Image processing, Fractal dimension, Infra-Red, Surface Roughness

1. INTRODUCTION

Surface roughness estimation is of great importance in the field of engineering as it determines the aerodynamic and structural performance of the component, especially relevant in the long run. Particularly, in the field of aerospace engineering, an accurate determination of surface roughness is of prime importance. Stylus based profilometers have been one of the most widely used for measuring the different roughness parameters in [1]. Applying a contact based surface roughness measurement system poses multiple disadvantages, mainly due to probe and component damage. Since the advent of lasers, several researchers have proposed multiple methodologies for surface roughness measurements. This, in turn, leads to the development of non-contact optical techniques based on the laser for the non-destructive evaluation of the component [2, 3]. Initial developments in laser technology focused at advancements in high precision machining and manufacturing [4-6]. Further developments in laser research span about to understand the properties of the reflected laser beam with respect to the surface morphology [8, 9]. Multiple probes based fiber optic systems were also developed for imaging and reflected laser beam analysis from hard to access areas [10-13].

When a coherent beam of light falls onto an optically rough surface, i.e. surfaces with roughness comparable to the wavelength of light, the reflected light scatters and interferes to produce random dark and light patterns. These random patterns are termed speckles and they have been proved to be a direct representative of the quality of such surfaces. Measurement methodologies based on laser light-scattering techniques especially focusing on speckle-based statistical approach had been proven to effectively characterize surface roughness [14-17]. Application of speckle metrology was not restricted to statistical surface measurements but also to multiple applications ranging from displacement measurements to non-destructive evaluation of cracks and defects [18-22].

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Several speckle based techniques have been proposed for the measurement of surface roughness parameters *Ra* and *Rq*. Few methods including speckle, light scattering, interferometry and specular reflection have been reported widely in the literature [23-28]. Speckle contrast based techniques and light scattering techniques rely strongly on specular components of the reflected while correlation techniques such as the Spectral Speckle Correlation and Angular Speckle Correlation have much higher ranges of roughness measurement. The former being an easy technique to implement shows high potentials in an on-line industrial environment while the latter being affected by vibrations need correction loops for implementation [30]. In addition to these techniques, speckle-based image analysis based on Digital Fourier Transform (DFT) [30], autocorrelation [32], the degree of agglomeration of the numerical speckle images [33] and fractal [34].

However, all these methods are limited in the range of roughness measurement due to the chosen wavelength of the laser [30]. In this context, this paper aims to develop the proof of concept of an optical measurement system based on IR speckle analysis based on speckle pattern processing for surface roughness characterization envisaging an on-line system implementation. For this purpose, we study the pattern variations in IR speckles generated by passing a 1064 nm laser beam through diffusers of multiple grit polishes. For a fundamental analysis, we observe the fractal dimension and the element connectivity of the speckle pattern through subsequent image processing analysis.

2. MATERIALS AND METHOD

To understand the fundamental variations in the property of the IR speckles due to the surface roughness, we use a linear setup. This is to ensure that no errors are induced due to the incident angle of illumination. Fig. 1, provides a schematic of the linear experimental diagram followed for our report. The laser beam portrayed in Fig. 1 is just a representative of the IR beam vector.

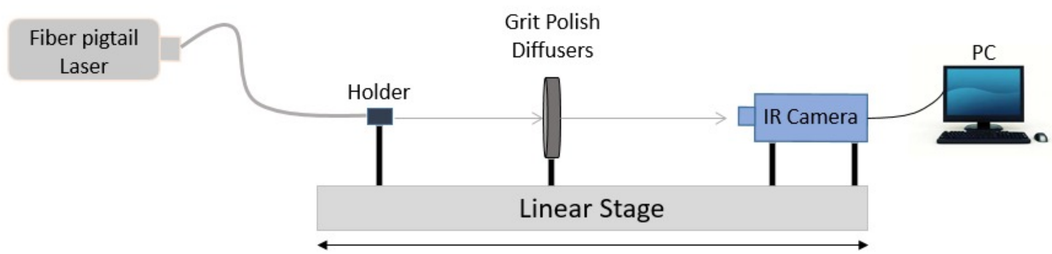


Fig.1 Linear experimental setup for understanding the speckle pattern variations caused by the diffuser grit polish

We use a tunable power fiber pigtailed IR laser (ML111-1064-100 mW) which illuminates at a wavelength of 1064 nm. For our application, we fix the power at 80mW. The laser illuminates a chosen diffuser (220 grits, 600 grits or 1500 grits) with a grit polish number from the diffuser kit (THORLAB DGK01). The diffused light is then collected by an IR sensitive InGaAs camera (ARTCAM-032TNIR) fixed with a zoom lens (NAVITAR F=25 mm/ f 1.4). The camera records the image for each of the diffusers used an image processing algorithm determines the speckle property variations due to the change in a diffuser.

3. EXPERIMENTAL RESULTS AND DISCUSSION

In order to understand the dependence of the formed speckle image on the surface quality, we analyze the binary IR speckle image for any variation in fractal property and number of connecting components. This section details and discusses the parametric studies of the formed speckles with respect to different grit polished diffuser used.

3.1 Observed speckle images and the algorithm used for parametric extraction

To determine an adequate algorithm to be used for parametric extraction, we first analyze the IR speckle images formed due to the diffusers. Firstly, we calculate the size of each speckle relative to the pixel pitch of the IR camera. For these experiments, we are constrained with the maximum f-stop (minimum speckle size) achievable due to the chosen IR camera lens.

For a chosen wavelength of 1064 nm and a maximum f-stop setting of 16, we obtain the minimum speckle size of 20.77 μm, which is comparable to the center to center distance between the pixels of the IR camera (20 μm). The speckle patterns from the three diffusers, namely, 220, 600 and 1500 grits, are shown in Fig. 2 (a), (b) and (c), respectively.

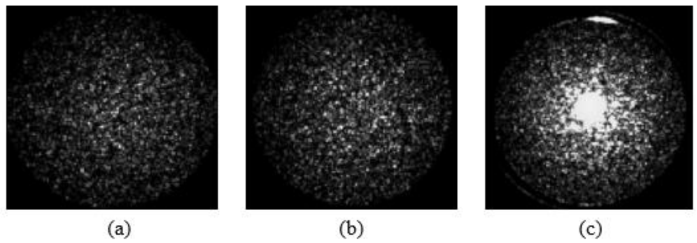


Fig.2 IR Speckle images captured from the different diffusers (a) 220 grit polishes, (b) 600 grit polishes and (c) 1500 grit polishes

It can be clearly observed that for a coarser grit (220 grits), the IR speckle contrast is low in comparison with the finer grit (1500 grits). Also, it must be noted that the exposure of the image observed at 2(c) is enhanced only for viewing purposes. For further analysis, the exposure of the camera is adjusted in order to collect maximum statistical properties of the speckle.

To characterize the fractal properties and number of connecting components of the speckle patterns in fig. 2, we convert these speckle images into an 8-bit binary image with varying chosen thresholds. Fig. 3 (a), (b) and (c) shows each set of 4 binary images for the three different diffusers.

Fig. 3, describes the variation of the binary speckle pattern caused due to the diffuser, for four different thresholds chosen. In this study, the chosen thresholds are determined by dividing the range of possible threshold values into four and choosing one threshold value from each section. For a coarser diffuser, there are small and discontinuous spots of dark areas while for the finer diffuser there is a large and continuous coverage of the dark spot. This implies that by studying the contrast of the IR speckles we can determine its statistical relation to the surface quality of the specimen of interest.

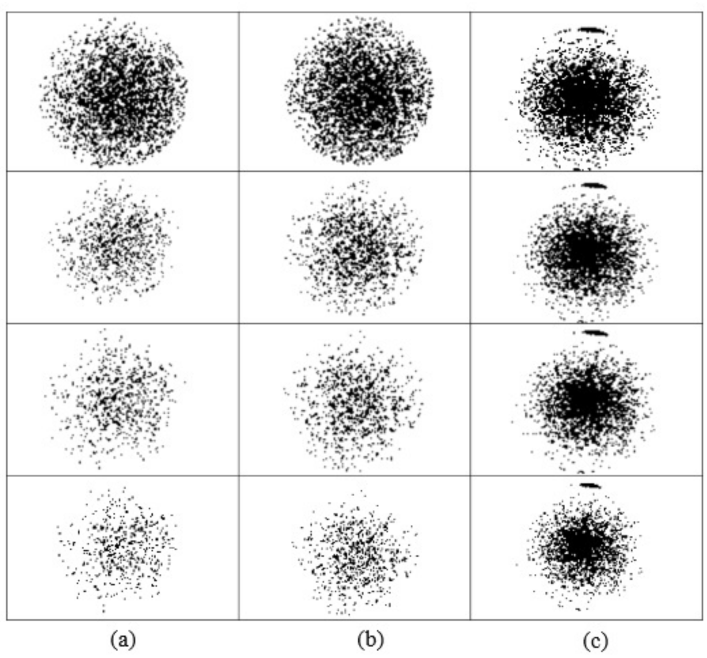


Fig.3 Binary speckle images of varying thresholds (1-4, a fixed threshold for every row) for (a) 220 grit polishes, (b) 600 grit polishes and (c) 1500 grit polishes

In this study, we develop an alternate methodology to determine the parametric variation of the formed IR speckles by processing the 8-bit binary images to understand the fractal properties and number of connectivity. For this purpose, we develop an algorithm with respect to the flowchart shown in fig. 4.

With respect to the flowchart shown in Fig. 4, we develop an automated algorithm using Matlab that determines the fractal dimension and element connectivity of the captured image. The algorithm being automated could thus be applied directly onto an in-line process providing a faster analysis for determining the variation in surface quality. It must also be noted that for our initial analysis, we do not iterate on the binary threshold limits. Thus, for proving the concept, we would consider fixed threshold values for all the speckle images under consideration.

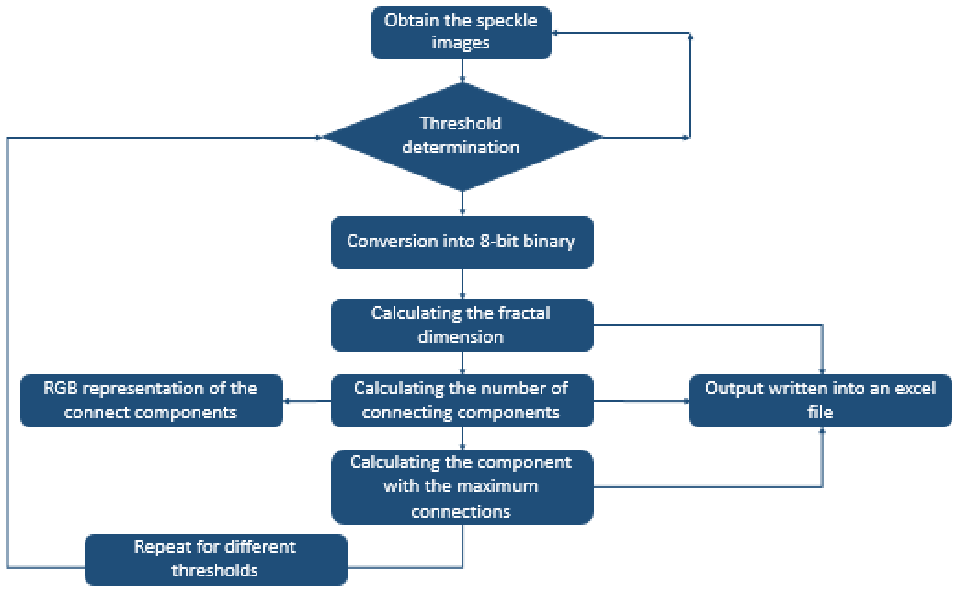


Fig.4 Flowchart describing the algorithm used for parametric extraction from the 8-bit binary speckle pattern.

3.2 Parametric extraction from IR speckle images

For characterizing the fractal properties of the formed IR speckle, we generate a suitable box-counting fractal algorithm in our process automation loop. The results from the fractal dimension analysis of the IR speckles for the different binary thresholds is plotted in Fig. 5.

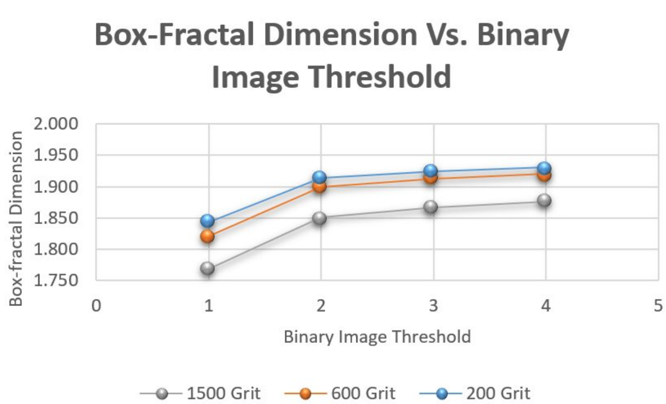


Fig.5 Box Fractal Dimension Vs. 8-Bit binary image threshold

Fig. 5, describes the relationship between the box fractal dimension and the grit polished diffuser used. It can be noted that for a finer grit the calculated box fractal dimension is lower than the coarser grit. This is in line with the theory of fractal dimension which defines a higher fractal dimension for structures having larger randomness. In our case, due to a larger diffusion from the coarser grit (220), we observe more random speckles compared to the finer grit (1500) and thus is associated with a larger fractal dimension. This analogy can thus be generalized for Gaussian rough surfaces, i.e. for a surface with a larger roughness, the fractal dimension would be higher [33]. Thus, by optimizing the chosen threshold for the 8-bit binary image and calculating the box fractal parameter, a good understanding of the surface quality can be obtained.

To extend our analysis in understanding the properties of the speckle pattern, we study the change in a number of connected components and the maximum connected component (in pixels) in all the binary speckle images shown in Fig. 3. Understanding the number of connected elements in a speckle pattern, one can generalize about the diffusive properties of the speckle pattern. This, in turn, can be extended to understand the surface quality.

In order to clearly distinguish the number of connected components and the maximum number of connected components, we apply a suitable color code. The maximum number of connections are always denoted by black, while rest of the connections are randomly colored. Fig. 6 (a), (b) and (c), describes the connected components for different thresholds for the three diffusers, 220 grit, 600 grit and 1500 grit, respectively.

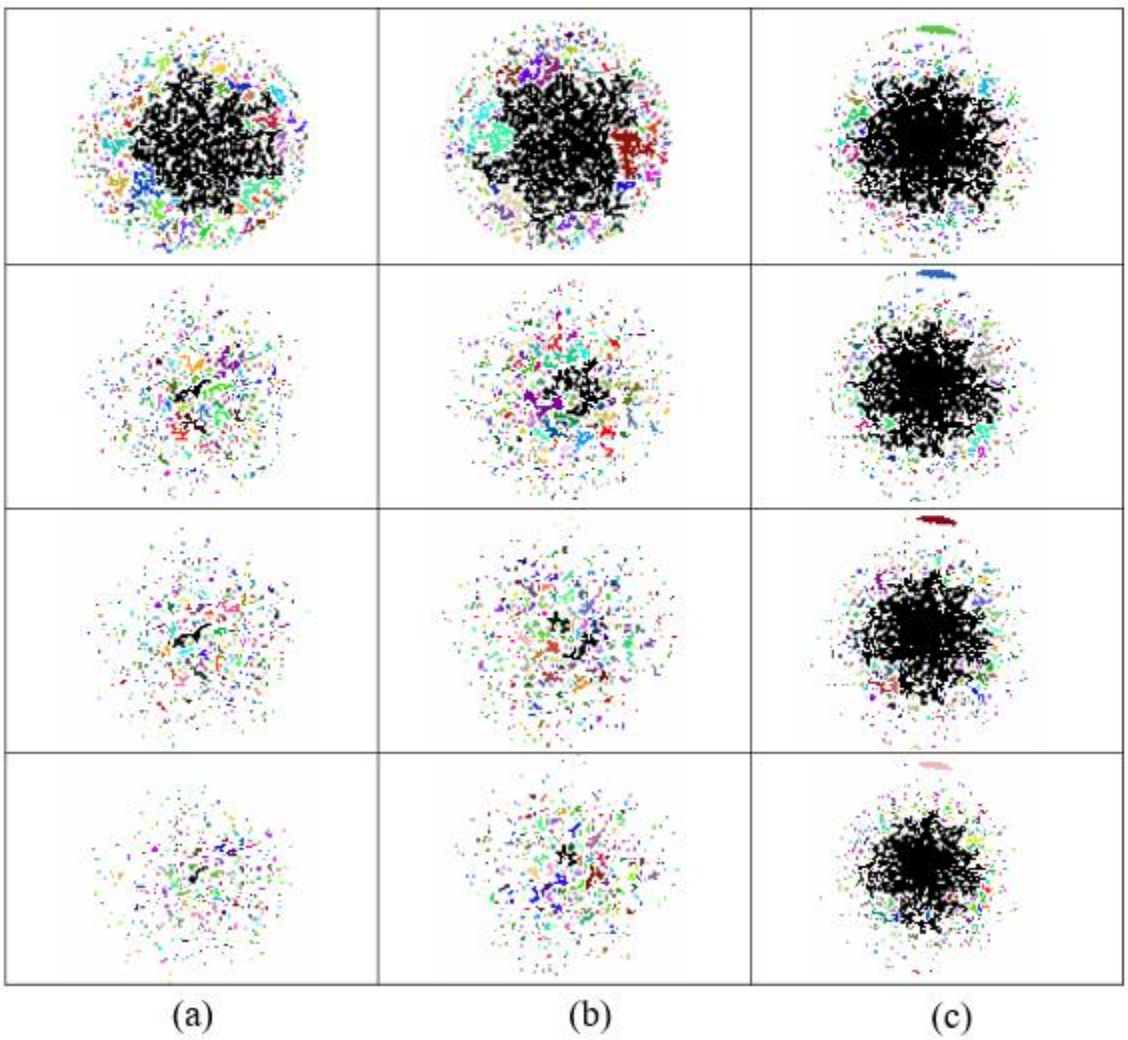
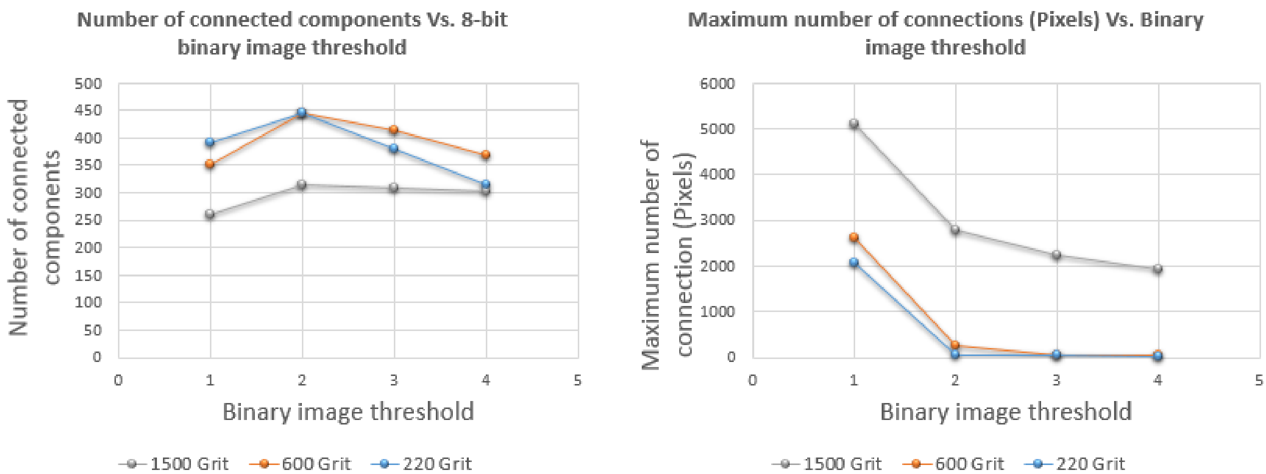


Fig.6 Element connectivity and maximum connections (in black) for the different thresholds ((1-4, a fixed threshold for every row)) for (a) 220 grit polishes, (b) 600 grit polishes and (c) 1500 grit polishes

From a quick observation, it can be noted that the connected component that covers the maximum number of pixels decreases as the surface roughness increases. Also, it can be observed that for a detailed analysis of the total number of connected components and the maximum connections, the chosen threshold plays an important role. Fig. 6 (a) clearly describes how the maximum number of connected components drops when the chosen threshold is changed.

In order to quantify the number of connected components and the maximum number of connected pixels, we plot them in Fig. 7.



(a) (b)

Fig.7 Total number of connected elements (a) and a maximum number of connected pixels (b) Vs. binary image threshold

It can be observed that in the case of a coarser grit, the total number of connected components are higher while the number of pixels defining the component with maximum connectivity is lower. This could be because of the diffusive nature of the IR light when passed through the grit. This would reduce the areas of bulk intensity that is captured in turn resulting in smaller and distributed black spots in its binary speckle image. Extending the analogy onto a finer grit we see that a smaller diffusion causes bulk intensity capture. This increases the number of pixels of the maximum connected element while having a smaller number of elements in total.

Fig. 7 (a) and (b), described the variation of the number of connected components and the total number of pixels in the maximum connected element, respectively. It can be observed that the analogy made in surface characterization using element connectivity is valid only for the threshold numbered 1. This emphasizes the need for developing a suitable algorithm to optimize the chosen threshold values. This algorithm must be developed such that images captured from surfaces with different roughness show the maximum deviation in fractal property, the number of connected elements and a maximum number of connected elements. This would thus imply that the range of roughness between the chosen known surfaces is also distinguishable by this method.

4. CONCLUSIONS

This paper presents a technique for surface characterization using a 100mW IR-laser, $\lambda = 1064$nm. The technique relies on using speckle pattern analysis for determining surface roughness dependent parameters. Three different parameters, namely, box-counting fractal dimension, the number of connected elements and the total number of pixels in the element with maximum connectivity are chosen as the three parameters of interest. For an initial study, IR speckle patterns generated using three different grit polished diffusers, graded 220 (coarse grit), 600 and 1500 (fine grit), are studied. From the analysis of the box fractal dimension of the IR speckle, it was observed that for a coarser grit diffuser, a higher diffusion of the laser increases the randomness of the speckle, resulting in larger fractal dimension compared to the finer grit diffuser.

Further analysis of the speckle pattern based on connected elements also shows good variation with the quality of surface under study. It was observed that for a coarse grit diffuser, due to greater diffusion, the total number of connecting components would be higher while the number of pixels of the maximum connected element would be lower. This algorithm was repeated for a set of binary threshold limits and was seen that an optimization algorithm for choosing the right threshold is mandatory for obtaining the highest accuracy and repeatability of the method. Future work direction will be on relating the proposed analysis to derive the necessary formulations required for evaluating the surface finish parameters. Also, an iterative algorithm for choosing the optimal threshold values would be generated to improve the speed and accuracy of the technique.

Including the optimization algorithm, the next step in the project would be to use IR speckle pattern for roughness analysis of machined components to determine the range of the measurement system. IR based interferometric system based on speckle pattern characterization could also be developed for a fast in-line inspection. Due to the above-mentioned advantages, it is thus envisaged that the proposed methodology can be applied to an in-process inspection system.

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