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2017

Dev, K., A. S., Guru Prasad, H, Aswin., P, Prabhathan., Chan, K. H. K., & Matham, M. V. (2017). Surface roughness measurement of additive manufactured samples using angular speckle correlation. Proceedings of SPIE - Fifth International Conference on Optical and Photonics Engineering, 10449, 104492W. doi:10.1117/12.2270900

<https://hdl.handle.net/10356/105708>

<https://doi.org/10.1117/12.2270900>

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Surface Roughness Measurement of Additive Manufactured Samples using Angular Speckle Correlation

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ABSTRACT

A speckle pattern is a direct fingerprint of surface height variation on the sample. In this paper, angular speckle correlation technique is applied to estimate surface roughness Ra of an additive manufactured sample with different surface roughness Ra values varying from 5 μ m to 20 μ m. Feasibility study is conducted to evaluate the correct incidence and the change in incidence angle for angular speckle correlation. Speckle correlation is computed from two speckle images that are recorded at two different incidence angles on the rough surface and surface roughness information is gleaned. Test results in terms of surface roughness measurement from standard calibration plate and additive layer manufactured samples are presented.

Keywords:Additive manufacturing, Angular speckle correlation, Non-destructive testing, Surface roughness,Laser speckle.

1. INTRODUCTION

Recently in November 2015, Rolls-Royce reported the successful flight of Airbus A380 flying testbed aircraft powered with Trent XWB-97 engine. It also marked the first flight of the world's largest 3D printed aero engine structure – the engine's front bearing housing has aerofoils made by the Additive manufacturing techniques[1]. In additive manufacturing, a part or component is constructed layer-by-layer from 3D computer model data. A high-power laser beam with sharp focus falls onto a bed of metal alloy powder and melt it layer-by-layer to create complex parts. This conserves material that can be scrapped to manufacture same complex part through casting, welding or other machining process. Thus, Additive manufacturing not only solves the manufacturing complexity and conserves material; it also helps in producing light-weight aerospace parts with great strength utilizing benefits of high grade materials such as Inconel 718 and Titanium Ti6Al4V.

To improve the performance of these additive manufactured components, optimum surface finish is required as a secondary process. The average surface roughness Ra of additive manufactured components generally varies between 5 μ m to 40 μ m due to laser melting of metal powder. Surface roughness of an aerospace component can influence its functionality in terms of friction, energy consumption, durability etc. and sometimes could cause irreversible damage or incur high repair costs. High pressure hydraulic systems and fuel injection systems in particular require high quality surfaces and precisely defined features. Thus, the roughness measurement of additive manufactured components is important to quantify their quality and performance.

In industry in general, the surface roughness of the machined component is measured accurately using contact based stylus profilometer. The stylus surface roughness profilometers due to their sharp diamond tip can produce micro-scratches on the machined surface and consume lot of time to scan small area. To subdue the problems associated with contact probe based measurements, non-contact surface profilometers based on optical methods such as laser scanning, confocal scanning, white light interferometry are employed. Although these non-contact optical methods can produce high resolution 3D surface profile of rough or shiny machined surface, they are not suitable for in-process measurement [2]. Thus, there is a need of non-contact and non-invasive in-process measurement method which can evaluate surface roughness of machined surfaces at faster speed to match industry requirements.

Recently, many papers have been reported on the significance of using optical interferometric techniques such as specular and speckle interferometry for applications in lithography, imaging, sensing and metrology [3-10]. Such use of optical measurement techniques for variety of applications has gained importance due to its inherent advantages [11-13]. For many years, researchers have studied the interaction of light with an optically rough surface in terms of diffraction, scattering and interferometry in detail[14-16]. It has been found out that the laser speckle pattern generated due to scattering of coherent light is the direct fingerprint of the surface height variation on the sample under investigation[17-19]. Therefore, laser speckle metrology is preferred non-contact method for surface roughness measurement. In laser speckle metrology, properties of a speckle pattern such as speckle size, contrast etc. can be correlated to the surface roughness under investigation. Several authors have reported the surface roughness measurement by computing speckle contrast of the speckle pattern[20-22]. A rougher surface produces speckle pattern with higher contrast in the far-field in comparison to the surface. The measurement range of the speckle contrast method limited to $\sim \lambda/4$ for normal coherent illumination on the surface[23]. Thus, speckle contrast measurement has many advantages; however, the measurement range is limited.

The measurement range of speckle metrology is extended using speckle correlation methods such as spectral speckle correlation (SSC) and angular speckle correlation (ASC). In both of these methods, the surface roughness of the sample is measured by finding the correlation (or linear relationship) between the two speckle patterns recorded at two different conditions illuminating the sample surface under investigation. In spectral speckle correlation, two speckle patterns are recorded with wavelengths λ_1 and λ_2 respectively. These two speckle patterns are then correlated to evaluate the surface roughness of sample under investigation. This measurement method is applicable to the polish surfaces with average surface roughness varying between $0.5\mu\text{m}$ to $5\mu\text{m}$ [23]. Early research related to angular speckle correlation was first reported by Léger et al. in 1975[24]. In ASC, two speckle patterns are recorded at two distinct coherent illumination angles on the rough surface and roughness parameters are evaluated by finding the correlation between these two speckle patterns. Léger and Perrin reported the surface roughness measurement between $1\mu\text{m}$ to $30\mu\text{m}$ using quasi-automatic setup in less than 30 seconds [25]. A detailed theory related to the speckle correlation methods was presented by Ruffing [26]. Spagnolo et al. verified the ASC technique by measuring the standard rough samples between $4\mu\text{m}$ to $31\mu\text{m}$ [27]. Toh et al. also studied standard rough surface with surface roughness varying from $1.6\mu\text{m}$ to $50\mu\text{m}$ using ASC technique with slightly modified experimental setup having sample is rotated rather than the illumination beam [28]. Persson in his research article presented the capability of ASC technique through simulations and measured the surface roughness between $1\mu\text{m}$ to $10\mu\text{m}$ [29]. Thus, the ASC technique is widely used to measure large surface roughness values and is capable to meet different requirements of the industry.

In this paper, angular speckle correlation technique has been employed for surface roughness measurement of additive manufactured samples having roughness variation ranging from $5\mu\text{m}$ to $20\mu\text{m}$ with interval of $5\mu\text{m}$. The speckle images are recorded in the far-field and maximum correlation calculated from two speckle images is used to calculate surface roughness parameters. The well-known theoretical aspect of the angle speckle correlation is adapted for conducting the speckle correlation studies presented in this manuscript. Further, a feasibility study is carried out to assess the optimum angles of beam incidences required for a range of surface roughness values. An experimental set-up to conduct ASC measurement is described and results from standard calibration surface as well as additive manufactured sample surface are presented.

2. THEORETICAL BACKGROUND

2.1 Speckle Statistics

When a rough surface is illuminated with coherent light with surface height variations of the same order as or a little greater than the wavelength of the light, light is scattered in all possible directions. These scattered waves interfere and form an interference pattern consisting of dark and bright spots, which are randomly distributed in space. This pattern is called a speckle pattern. Every speckle pattern formed either through free space propagation or through imaging lens on the active area of charge coupling device follows certain statistics. This speckle statics depends on the properties of coherent source and the scattering surface. Thus, the spatial properties of the speckle pattern can be related to the surface properties of sample under investigation. The two speckle images scattered from same randomly rough surface can be correlated if (a) its root mean square (RMS) surface roughness is greater than the wavelength of coherent illumination; (b) it produces fully developed speckle patterns and surface height probability distribution is Gaussian distribution and (c) it is formed by isotropic and homogeneous material whereby shadowing, multiple reflections and volume scattering is neglected [26-28].

The mathematical expression for arithmetic average height Ra and RMS roughness Rq is given by,

$$Ra = \frac{1}{l} \int_0^l |y(x)| dx \quad (1)$$

$$Rq = \sqrt{\frac{1}{l} \int_0^l \{y(x)\}^2 dx} \quad (2)$$

Here, $y(x)$ is the profile deviation from the mean line and l is the sample length. Also, assuming the Gaussian height distribution on the specimen surface, Ra and Rq are related as [30],

$$Ra = \sqrt{\frac{2}{\pi}} Rq \quad (3)$$

2.2 Angular Speckle Correlation

Considering that rough surface has properties as described in the section 2.1, the angular speckle correlation between two speckle patterns recorded at locations (ξ_1, η_1) and (ξ_2, η_2) in the far-field (or Fourier plane) of the rough surface due to coherent illumination from two different angles is given by[25],

$$\begin{aligned} \gamma_{12}(\xi_1, \xi_2) = & \exp(-R_q^2 k^2 \delta\alpha^2 \sin^2 \alpha) \times \exp[-(Lk / 2f \cos \alpha)^2 (\xi_1 - \xi_2 - f \cos \alpha \delta\alpha)^2] \\ & \times \exp[-(Lk / 2f)^2 (\eta_1 - \eta_2)^2] \end{aligned} \quad (4)$$

Here, α is the initial angle of incidence, $\delta\alpha$ is the change in angle of incidence, $k=2\pi/\lambda$ is the propagation constant of the coherent light source having wavelength λ , L is the diameter of laser spot on the rough surface, f is the focal length of the lens and γ_{12} is the angular speckle correlation factor between two speckle images [24]. The geometry of this far-field configuration is shown in fig. 1. The (x, z) plane is the object plane; whereas, (ξ, η) represents the far-field where speckle images are recorded using CCD.

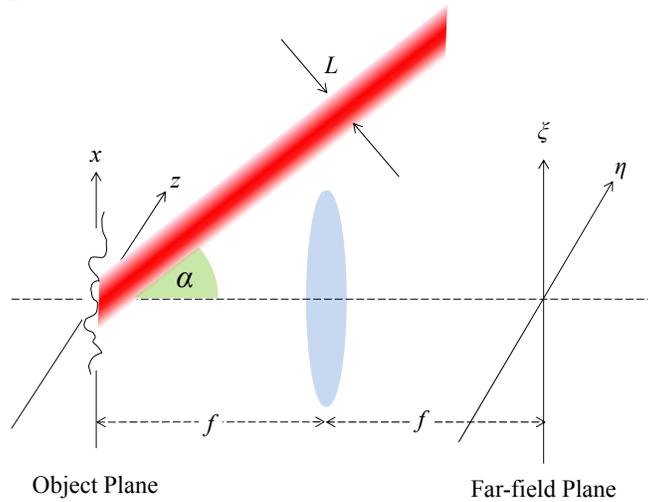


Fig. 1. Far-field plane geometry configuration

In eqn. (4), the speckle correlation between two speckle patterns can be reduced to only the roughness dependent correlation by following certain conditions as given below [25],

$$\xi_2 = \xi_1 - f \cos \alpha \delta \alpha \quad (5)$$

$$\eta_1 = \eta_2 \quad (6)$$

In order to record the two speckle patterns at two different angles of incidence, the incident beam angle is shifted slightly with amount $\delta \alpha$. This leads to the shift of whole speckle pattern initially in the direction of increase in angle by amount $f \cos \alpha \delta \alpha$ in far-field plane. Thus, the two speckle patterns are decorrelated in the far-field plane. To compensate this speckle decorrelation, eqns. (5) and (6) must be followed i.e. the observation plane must be shifted in ξ -direction by amount $f \cos \alpha \delta \alpha$ to achieve maximum speckle correlation.

Finally, the expression for the angular speckle correlation becomes,

$$\gamma_{12} = \exp(-(R_q k \delta \alpha \sin \alpha)^2) \quad (7)$$

$$R_q = \frac{\sqrt{-\ln \gamma_{12}}}{k \delta \alpha \sin \alpha} \quad (8)$$

The above expression shows the direct dependence of the angular speckle correlation factor on the RMS surface roughness variation. Thus, by carefully calculating the angular speckle correlation factor between two speckle patterns the surface roughness can be retrieved non-destructively. Practically, the angular speckle correlation factor between two speckle intensity patterns $I_1(\xi_1, \eta_1)$ and $I_2(\xi_2, \eta_2)$ recorded by CCD camera at the far-field plane is computed using the expression below,

$$\gamma_{12} = \frac{\sum_{\xi_1, \eta_1} \sum_{\xi_2, \eta_2} I_1(\xi_1, \eta_1) I_2(\xi_2, \eta_2)}{\sqrt{\sum_{\xi_1, \eta_1} I_1^2(\xi_1, \eta_1) \sum_{\xi_2, \eta_2} I_2^2(\xi_2, \eta_2)}} \quad (9)$$

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 ASC Feasibility Study

It is important to carefully study the relation between angular speckle correlation factor between two speckle patterns recorded from a rough surface and its surface roughness parameters as given in eqn. (7). Using this relation, a feasibility study is carried out to calculate an angle of incidence and its deviation. Eqn. (7) is scripted in MATLAB for ASC feasibility study to measure large surface roughness. Figure 2 shows the variation of angular speckle correlation factor between two speckle patterns with respect to arithmetic mean surface roughness R_a for different sets of the angle of incidence α and its deviation $\delta \alpha$.

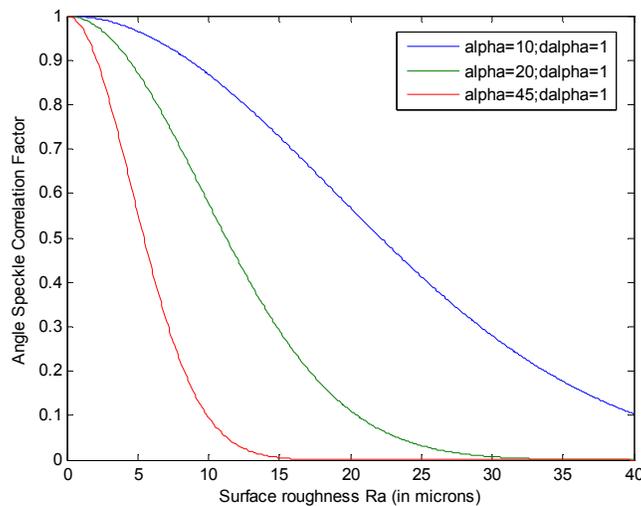


Fig 2. Angular speckle correlation factor as a function of arithmetic mean surface roughness Ra for different sets of an incidence angle and its deviation

From fig. 2, it is evident that the higher angle of incidence ($\alpha = 45^\circ$; $\delta\alpha = 1^\circ$) on the sample surface allows only measurement of smaller surface roughness values. The angle of incidence $\alpha = 20^\circ$ and its deviation $\delta\alpha = 1^\circ$ covers objective range of surface roughness measurement; however, it is always preferential to do measurement in the linear domain of plot. On the other hand, the incidence angle of 10° (which is close to normal incidence on the sample) and its change of 1° can cater the measurement objectives within the linear domain of the curve. The other advantage of considering the angle of incidence close to normal incidence is that an error in measurement due to shadowing can be easily neglected (section 2.1) for large surface roughness measurement. It should also be noted here that the angular speckle correlation factor between two speckle patterns is higher for smoother surface.

3.2 Experimental Setup

A schematic diagram of an experimental setup to measure surface roughness utilizing angle speckle correlation is shown in Fig. 3. A He-Ne laser with a wavelength of $\lambda = 0.633\mu\text{m}$ is used to illuminate the rough sample surface, and the speckle pattern is captured with a CCD camera placed in the far-field plane. As per the feasibility study done and the data of which is presented in the previous section, the angle of incidence on the sample is $\alpha = 10^\circ$ and change in this angle of incidence $\delta\alpha = 1^\circ$ is achieved by manually rotating the sample which is placed on the rotation stage. The rough sample surface is placed in the first focal plane of a biconvex lens with a focal length of $f = 10\text{cm}$. The aperture size of this lens is 2.54cm . Thus, the scattered light from the rough surface is collimated by this lens. At the second focal plane or the far-field plane of the lens, the CCD camera is mounted on a linear translation stage to record the multiple speckle patterns. The CCD is capable of recording images with maximum resolution of 2594×1944 having square pixel a size of $2.2\mu\text{m}$. The dynamic range of the CCD is 8 bit i.e. the image gray scale value varies from 0 to 255.

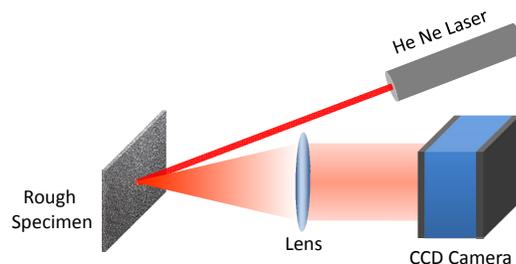


Fig. 3. Schematic diagram of surface roughness measurement experimental setup

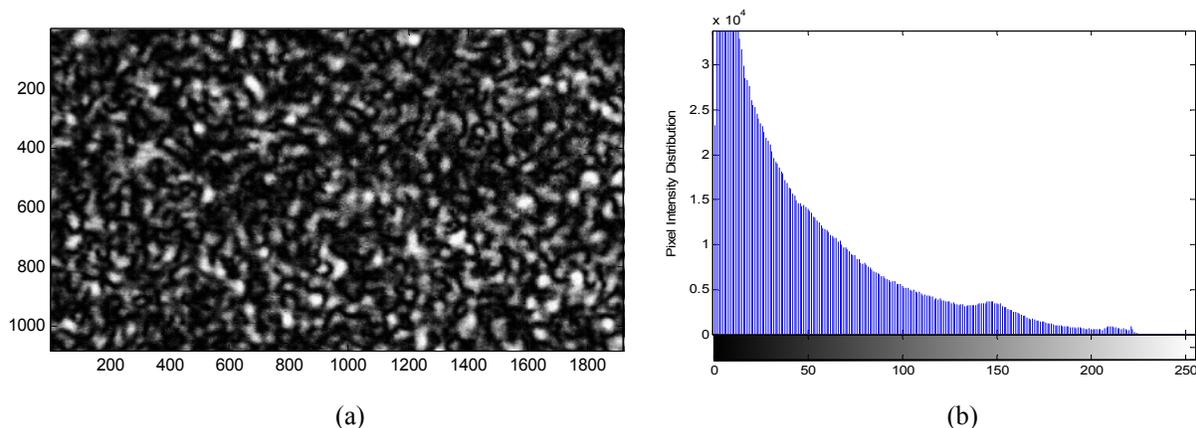


Fig. 4. (a) A typical speckle pattern recorded by CCD ($Ra = 6.3\mu\text{m}$ and $\alpha = 10^0$) and (b) Image histogram of the fully developed speckle pattern for image gray scale values 0 to 255 shown in (a).

At first, speckle pattern representing the initial state of the rough specimen is recorded by CCD with angle of incidence $\alpha = 10^0$. The histogram and speckle contrast of the speckle image are examined to confirm that speckles are fully developed. This is important to study second order speckle statistics as detailed in sec. 2.1. Figure 4 shows (a) a typical speckle pattern recorded with 1920×1080 image resolution and (b) its histogram which confirms the negative exponential decay of probability density. Subsequently, the rough sample is rotated by $\delta\alpha = 1^0$ and 20 speckle images are recorded one after another by moving CCD on translation stage from initial position in step of $100\mu\text{m}$. An image processing code is written in MATLAB to calculate the angular speckle correlation factor between two speckle patterns as depicted in eqn. (9). A small 200×200 -pixel area is selected at the centre of first speckle image and its angular speckle correlation factor is computed with other speckle images that are recorded in steps. The maximum speckle correlation factor calculated from speckle patterns is used further to calculate the RMS surface roughness Rq and arithmetic mean surface roughness Ra utilizing eqns. (8) and (3).

3.3 Results and Discussion

In our experiment, first RubertMicrosurf spark-erosion comparator R-331 is used as test specimen. The area of comparator plate with surface roughness Ra of $6.3\mu\text{m}$ and $12.5\mu\text{m}$ are mounted on the rotation stage one by one to record speckle images in order to confirm the repeatability and accuracy of the ASC experimental setup as shown in Fig. 3.

Eight (8) different sets of speckle images are recorded for each of these two surfaces with different roughness values on the comparator plate. The speckle images are further processed in MATLAB environment to evaluate the maximum speckle correlation factor. As a result of this measurement, the maximum correlation factor, mean and standard deviation of RMS surface roughness Rq and arithmetic mean surface roughness Ra are tabulated as given in Table I.

TABLE I: Comparison of mean surface roughness parameters and its standard deviation obtained from angle speckle correlation surface roughness measurement ($\alpha = 10^0$, $\delta\alpha = 1^0$) to standard RubertMicrosurf spark-erosion comparator R-331.

| Standard Ra (μm) | Max Correlation Factor | ASC- Rq (μm) | ASC- Ra (μm) |
|---------------------------------|------------------------|-----------------------------|-----------------------------|
| 6.3 | 0.9275 ± 0.0110 | 9.09 ± 0.75 | 7.27 ± 0.59 |
| 12.5 | 0.7987 ± 0.0241 | 16.14 ± 0.89 | 12.91 ± 0.66 |

From the results demonstrated in Table 1, it is evident that surface roughness parameters measured using angle speckle correlation is in good agreement with standard samples. Hence, the measurement process can be repeated with the additive manufactured sample with surface roughness varying from $Ra \sim 5\mu\text{m}$ to $20\mu\text{m}$ in steps of $5\mu\text{m}$. This flat rectangular specimen ($100\text{mm} \times 40\text{mm} \times 2\text{mm}$) is made up of Titanium alloy using additive manufacturing process. The surface roughness of this additive manufactured sample in the beginning after completion of additive manufacturing process is around $20\mu\text{m}$. Later, the test sample is divided into four equal sections and three such sections are vibratory

finished (Walther Trowal- MV 32) to achieve surface roughness $R_a \sim 5\mu\text{m}$, $10\mu\text{m}$ and $15\mu\text{m}$ respectively. The surface roughness of this additive manufactured sample is measured with scanning probe based surface tester Mitutoyo©, SJ-301 at 10 distinctive positions on test areas and is tabulated in Table II along with measurement results from angle speckle correlation experiment.

TABLE II: Comparison of mean surface roughness parameters and its standard deviation obtained from angle speckle correlation surface roughness measurement ($\alpha = 10^\circ$, $\delta\alpha = 1^\circ$) to scanning probe based surface tester, Mitutoyo©, SJ-301

| Scanning Probe R_a (μm) | Correlation Factor | ASC- R_q (μm) | ASC- R_a (μm) |
|--|---------------------|------------------------------|------------------------------|
| 5.456 ± 0.79 | 0.9607 ± 0.0271 | 6.31 ± 2.71 | 5.04 ± 2.19 |
| 9.97 ± 1.16 | 0.7255 ± 0.1148 | 18.52 ± 4.96 | 14.81 ± 3.97 |
| 15.02 ± 0.93 | 0.6681 ± 0.0163 | 21.10 ± 0.64 | 16.88 ± 0.51 |
| 18.77 ± 0.65 | 0.5899 ± 0.0091 | 24.12 ± 0.39 | 19.31 ± 0.28 |

The ASC surface roughness measurements with additive manufactured test sample show large variation in Table II. The reason behind this variation can be attributed to the vibratory finishing process as there is minimum variation in original surface roughness ($R_a \sim 20\mu\text{m}$) of additive manufactured test sample. However, it should be noted here that the measurements from the developed ASC experimental setup showed promising results with the standard spark-eroded random rough surface.

4. CONCLUSIONS

In this paper, the angle speckle correlation technique is used for measurement of surface roughness of additive manufactured sample with R_a varying from $5\mu\text{m}$ to $20\mu\text{m}$. The measurement technique requires minimum optical components but is sensitive to alignment. The angle of illumination and its deviation to measure the range of surface roughness is studied and it is found that if the angle of illumination on the specimen surface is large, the range of measured surface roughness is narrow. The surface roughness parameter is directly related to the correlation factor between two speckle images recorded in the far-field plane of the sample rough surface illuminated at two different angles. The roughness parameters measured with this method are consistent with standard rough specimen. However, the measurement results with additive manufactured test sample have large deviation which is attributed to the limitation of the surface finish due to vibratory surface finishing process. Further, angle speckle correlation technique has many advantages as it can be implemented as a non-destructive and non-contact surface roughness measurement method. Hence it is envisaged that this proposed methodology can be applied to in-process industry measurements.

ACKNOWLEDGEMENT

This work was conducted within the Rolls-Royce@NTU Corporate Lab MRT 4.1 project with support from the National Research Foundation (NRF) Singapore under the Corp Lab@University Scheme. The authors are also grateful for the support from COLE EDB funding.

REFERENCES

- [1] [Rolls-Royce Trent XWB-97 completes first test flight], (2015).
- [2] D. J. Whitehouse, "Surface metrology," *Measurement Science and Technology*, 8(9), 955 (1997).
- [3] P. Greguss, "Optical engineering and industrial sensing for advanced manufacturing technologies," *Optics & Laser Technology*, 21(1), 57-58 (1989).
- [4] V. M. Murukeshan, and K. V. Sreekanth, "Excitation of gap modes in a metal particle-surface system for sub-30 nm plasmonic lithography," *Optics letters*, 34(6), 845-847 (2009).
- [5] P. Prabhathan, Z. Jing, V. M. Murukeshan, Z. Huijuan, and C. Shiyi, "Discrete and Fine Wavelength Tunable Thermo-Optic WSS for Low Power Consumption C^+ Band Tunability," *IEEE Photonics Technology Letters*, 24(2), 152-154 (2012).

- [6] O. D. Soares, [Optical Metrology: Coherent and Incoherent Optics for Metrology, Sensing and Control in Science, Industry and Biomedicine] Springer Science & Business Media, (2012).
- [7] K. Sreekanth, and V. Murukeshan, "Large-area maskless surface plasmon interference for one-and two-dimensional periodic nanoscale feature patterning," *JOSA A*, 27(1), 95-99 (2010).
- [8] K. Sreekanth, and V. Murukeshan, "Four beams surface plasmon interference nanoscale lithography for patterning of two-dimensional periodic features," *Journal of Vacuum Science & Technology B, Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena*, 28(1), 128-130 (2010).
- [9] K. Sreekanth, V. Murukeshan, and J. Chua, "A planar layer configuration for surface plasmon interference nanoscale lithography," *Applied Physics Letters*, 93(9), 093103 (2008).
- [10] K. V. Sreekanth, J. K. Chua, and V. M. Murukeshan, "Interferometric lithography for nanoscale feature patterning: a comparative analysis between laser interference, evanescent wave interference, and surface plasmon interference," *Applied optics*, 49(35), 6710-6717 (2010).
- [11] A. Kishen, V. Murukeshan, V. Krishnakumar, and A. Asundi, "Analysis on the nature of thermally induced deformation in human dentine by electronic speckle pattern interferometry (ESPI)," *Journal of dentistry*, 29(8), 531-537 (2001).
- [12] N. K. K. Mohan, P. J. Masalkar, V. M. Murukeshan, and R. S. Sirohi, "Separation of the influence of in-plane displacement in multiaperture speckle shear interferometry," *Optical Engineering*, 33(6), 1973-1982 (1994).
- [13] V. Murukeshan, P. Chan, O. L. Seng, and A. Asundi, "On-line health monitoring of smart composite structures using fiber polarimetric sensor," *Smart materials and structures*, 8(5), 544 (1999).
- [14] R. Erf, [Speckle metrology] Elsevier, (2012).
- [15] E. Mendez, and K. O'donnell, "Observation of depolarization and backscattering enhancement in light scattering from Gaussian random surfaces," *Optics Communications*, 61(2), 91-95 (1987).
- [16] W. Welford, "Laser speckle and surface roughness," *Contemporary Physics*, 21(4), 401-412 (1980).
- [17] P. Guru, M. V. Matham, and K. H. Chan, "A flexible image fiber probe based speckle imaging for extraction of surface features with possible application in intra-cavity inspection." 95242Q-95242Q-7.
- [18] V. Murukeshan, N. Sujatha, L. Ong, A. Singh, and L. Seah, "Effect of image fiber on the speckle fringe pattern in image fiber-guided DSPI endoscopy," *Optics & Laser Technology*, 39(3), 527-531 (2007).
- [19] C. Song, G. Prasad AS, K. H. Chan, and V. M. Murukeshan, "Characterization and optimization of illumination vector for contouring surface form and feature using DSPI," *Review of Scientific Instruments*, 87(6), 063116 (2016).
- [20] H. Fuji, T. Asakura, and Y. Shindo, "Measurement of surface roughness properties by means of laser speckle techniques," *Optics Communications*, 16(1), 68-72 (1976).
- [21] H. Fujii, and T. Asakura, "Effect of surface roughness on the statistical distribution of image speckle intensity," *Optics communications*, 11(1), 35-38 (1974).
- [22] J. W. Goodman, "Dependence of image speckle contrast on surface roughness," *Optics Communications*, 14(3), 324-327 (1975).
- [23] U. Persson, "Measurement of surface roughness on rough machined surfaces using spectral speckle correlation and image analysis," *Wear*, 160(2), 221-225 (1993).
- [24] D. Léger, E. Mathieu, and J. Perrin, "Optical surface roughness determination using speckle correlation technique," *Applied optics*, 14(4), 872-877 (1975).
- [25] D. Léger, and J. Perrin, "Real-time measurement of surface roughness by correlation of speckle patterns," *JOSA*, 66(11), 1210-1217 (1976).
- [26] B. Ruffing, "Application of speckle-correlation methods to surface-roughness measurement: a theoretical study," *JOSA A*, 3(8), 1297-1304 (1986).
- [27] G. S. Spagnolo, D. Paoletti, A. Paoletti, and D. Ambrosini, "Roughness measurement by electronic speckle correlation and mechanical profilometry," *Measurement*, 20(4), 243-249 (1997).
- [28] S. Toh, C. Quan, K. Woo, C. Tay, and H. Shang, "Whole field surface roughness measurement by laser speckle correlation technique," *Optics & Laser Technology*, 33(6), 427-434 (2001).
- [29] U. Persson, "Surface roughness measurement on machined surfaces using angular speckle correlation," *Journal of Materials Processing Technology*, 180(1), 233-238 (2006).
- [30] E. Gadelmawla, M. Koura, T. Maksoud, I. Elewa, and H. Soliman, "Roughness parameters," *Journal of Materials Processing Technology*, 123(1), 133-145 (2002).