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Research on Optical Measurement for Additive Manufacturing Surfaces

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ABSTRACT

Surfaces made by Additive Manufacturing (AM) processes normally show higher roughness and more complicated microstructures than conventional machined surfaces. In this study, AM surface roughness measurements using both tactile and optical techniques are analyzed, theoretically and experimentally. Analytical results showed both techniques have comparable performance when measuring AM samples with good surface integrity. For surfaces with steep features, coherence scanning interferometry showed more reliable performance especially when peak-to-valley value was required. In addition of the benchmarking study, development of a low-cost measurement system, using laser confocal technology, is also presented in this paper. By comparing the measurement results with those from a coherent scanning interferometer, accuracy levels of the proposed system can be evaluated. It was concluded that with comparable accuracy, the proposed low-cost optical system was able to achieve much faster measurements, which would make it possible for in-situ surface quality checking.

Keywords: Additive manufacturing, surface topography, coherent scanning interferometry, tactile measurement, laser confocal system.

1. INTRODUCTION

Additive manufacturing (AM), also known as 3D printing, is a new technology to fabricate 3D objects with complex geometry. In the AM process, successive layers of material are formed based on given CAD model to generate a 3D object. However, due to limitations in control of surface finishing, AM samples always show much higher roughness than conventional machined samples [1][2]. Irregularity in surface microstructure of AM samples also poses new challenges for surface topographic measurement [3][4]. Tactile stylus profilometry [5], coherence scanning interferometry [6] and confocal microscopy [7] are commonly used to acquire surface topographic information for conventional machined surfaces. Efforts have been made on feasibility studies and limitation analysis for different techniques [8]. Tactile profilometers, interferometric or inductance-based method, has a common concern of flanking errors [9]. Optical approaches, normally have better lateral resolution than tactile techniques, but reflectivity variation and light scattering may introduce image noises or data dropout [10]. Comparison of these techniques are also available from literature, but most of the work was based on conventional machined samples or roughness masters, which have very regular surface patterns [11]. In this paper, feasibility analysis for these commonly used surface measurement techniques will be provided based on their performance at measuring AM surfaces.

2. TACTILE STYLUS PROFILOMETRY

Tactile stylus profilometry is a traditional method for surface metrology. As shown in Figure 1, during lateral scanning, movement of the stylus reflects the surface fluctuation and is tracked by a high-resolution displacement sensor. Typical resolution of a traditional structure with a stylus tracked by an inductive transducer is around 10 nm [12], while some newly developed systems using phase interferometric technology are able to achieve sub-nanometer resolution [13]. In this study, Taylor Hobson PGI 800 is used as a representative model of latest stylus profilometry. This stylus profilometer consists of a phase grating interferometer to trace the position of stylus to achieve sub-nanometer vertical resolution.

Figure 1 Structure of an inductive transducer stylus profilometer [14]

However, the tip angle is a common concern for lateral resolution of styli. To ensure enough robustness and smooth movement, the tip of a scanning stylus has a certain angle, which is between 45° - 90° [14]. Figure 2 (a) shows that the stylus used in this research has a tip angle of 53° . Figure 2 (b) shows a profile scanned on an AM sample using this stylus. This sample, with visible surface integrity issue, was intentionally selected to study the correlation between stylus tip angle and surface grooves. By zooming into some local valleys, it was found all these steep angle didn't exceed 53° . Therefore it can be concluded that local features with angles steeper than 53° would be falsely reflected in stylus scanned data. Considering the low probability of narrow grooves being built, it won't introduce notable error for R_a quantification. But for R_z , which is sensitive to peak-to-valley values, its influence could be significant.

(a) PGI 800 stylus tip (b) AM sample profile scanned by PGI 800 stylus profilometer
Figure 2. Influence of tip angle from a stylus scanning system

3. COHERENCE SCANNING INTERFEROMETRY

Coherence scanning interferometry, also known as white light interferometry, is a nano-resolution technique for surface topographic measurement. It utilizes white light or other light sources with very limited coherent length. As shown in Figure 3, interferogram can be detected, only when the optical path length of the imaging light is equal to that of reference light. The interference range is limited to a few nanometers. Using proper interpolation algorithm the vertical resolution can achieve sub-nanometer level. A main concern of using coherence scanning interferometry is the fringe order error, which may cause height measurement errors of around 300 nm at slopes with a certain angle [15]. Considering its low occurrence and low impact, for AM surface measurement, it will not be a significant error factor. In this study, Taylor Hobson CCI HD was used as a representative model of coherence scanning interferometer.

Figure 3. Schematic of a white light interferometer [16]

4. COMPARISON OF TACTILE SCANNING PROFILOMETRY AND COHERENT SCANNING INTERFEROMETRY

In order to practically verify the accuracy of coherence scanning interferometry at surface measurement, correlation study was performed for the two techniques discussed in above sections. Starting from the same location using the same scanning length, two sets of profile data from the AM sample were acquired, as shown in Figure 4 (a). Generally, two sets of data match well and the surface measurement results are comparable.

Figure 4 Comparison between PGI 800 and CCI HD

If an AM sample has notable surface integrity issue, measurements could be different. As shown in Figure 4(b), the coherence scanning interferometer showed the capability to scan steep grooves. Table 1 shows the R_a and R_z values of the data sets shown in Figure 4(b). These two technologies had consistent R_a measurements, while R_z measurements showed more significant difference.

Table 1. Roughness parameter comparison

Parameters	Tactile stylus profilometry (PGI 800)	Coherence scanning interferometry (CCI HD)
R_a	37.579	38.315
R_z	238.040	323.038

5. WHITE LIGHT CONFOCAL MICROSCOPY

Figure 5 shows the principle of white light confocal microscopy. Illumination and imaging lights share the same optical path and have the same focal length. When the target point is focused on the image sensor with highest contrast, it also receives highest illumination. During vertical scanning, a focus-dependent intensity curve, namely Depth Response Curve (DRC) is plotted and the peak intensity indicates the height of the current measurement point.

Figure 5. Schematic of a white light confocal microscopy [16]

Full-field confocal measurement normally has lower resolution than single point measurement because reflection from neighboring points will affect the current target point. In order to avoid this cross-talk phenomenon, most commercial confocal microscopes employ structures of pinholes or slits to sharpen the DRC. This structure is able to effectively improve the vertical resolution to a few nanometers. However, it also brings two inherent limitations:

1. Measurement efficiency will be affected. Additional vertical scanning at each vertical scanning position is needed to cover the whole field of view.
2. Noise and data dropout may occur due to low reflectivity. It's a common challenge for most optical systems. With pinholes or slits, to achieve minimum imaging intensity becomes more challenging. Therefore confocal microscopy shows higher noise level compared with other optical systems, such as coherence scanning interferometry [8][11].

Therefore white light confocal systems are usually used for smooth surface measurement. However, for AM surfaces, whose R_a values would typically be tens of microns or greater, white confocal microscopy is not suitable.

Laser confocal microscopy is able to partially overcome the second limitation. With more concentrated energy and higher monochromaticity, imaging light capturing and recognition become easier and more reliable. In the following section, a low-cost surface measurement system using laser confocal principle will be introduced.

6. DEVELOPMENT OF A FAST ROUGHNESS MEASUREMENT SYSTEM

With reference to Figure 4, coherence scanning interferometry is able to provide accurate surface topographic measurements for AM samples, and thus can be used as a benchmark for development of surface measurement techniques for AM samples. In this research, a low-cost AM surface measurement system was developed using a laser confocal sensor Keyence LT9000. Figure 6 shows the system configuration. The AM sample was carried and moved by a linear stage. The laser confocal sensor was used for single-point height measurement. By synchronizing the movement of the stage and data sampling from the laser confocal sensor, a line profile of the AM surface could be plotted.

Figure 6. System configuration of laser confocal sensor

In order to assess the performance of the developed system, a profile was sampled using this laser confocal system and superimposed with that from the coherence scanning interferometer at the same location, with results shown in Figure 7. Measurement of the developed system showed acceptable consistency with the benchmark set by the coherence scanning interferometer. In spite of missing local details, this system can still be considered capable of fast roughness quantification for AM surfaces.

Figure 7. Comparison between laser confocal sensor and CCI HD

7. CONCLUSIONS

In this research, optical approaches for AM surface measurement were studied. As an ultra-resolution technique, coherence scanning interferometry is able to overcome the flanking issue of stylus profilometry and provide more accuracy measurement results. Main conclusion of this research can be summarized as below:

1. Tactile stylus profilometry, coherence scanning interferometry and laser confocal microscopy show comparable performance for AM surface profiling. Coherence scanning interferometry is more capable of capture surface details and can be used as a benchmark for development of AM surface measurement techniques. Tip angle of stylus profilometers may cause surface measurement error for R_z , especially when the surface integrity is low.
2. Although white light interferometry is not recommended for AM measurement due to unacceptable noise level, laser confocal principle showed its potential in this area, because laser light sources have better energy concentration and monochromaticity.
3. Using laser confocal sensor, integrated with motion stage, a low-cost surface measurement system was proven to be capable of quick AM surface measurement. In future, efforts will be made to meet the requirement of free-form surface measurement by increasing its measurement range, and to improve the accuracy of R_z measurement by adaptively reducing noises.

REFERENCES

- [1] C. J. L. Pérez, "Analysis of the surface roughness and dimensional accuracy capability of fused deposition modelling processes," *Int. J. Prod. Res.*, vol. 40, no. 12, pp. 2865–2881, 2002.
- [2] T. Grimm, G. Wiora, and G. Witt, "Characterization of typical surface effects in additive manufacturing with confocal microscopy," *Surf. Topogr. Metrol. Prop.*, vol. 3, no. 1, p. 014001, 2015.
- [3] M. F. Fay, V. G. Badami, and X. C. De Lega, "Characterizing additive manufacturing parts using coherence scanning interferometry," in *Proceedings - ASPE 2014 Spring Topical Meeting: Dimensional Accuracy and Surface Finish in Additive Manufacturing*, 2014, pp. 135–138.
- [4] A. Triantaphyllou, C. L. Giusca, G. D. Macaulay, F. Roerig, M. Hoebel, R. K. Leach, B. Tomita, K. A. Milne, G. D. MacAulay, R. K. Leach, and K. A. Milne, "Surface texture measurement for additive manufacture," *Surf. Topogr. Metrol. Prop.*, vol. 3, no. 2, p. 024002, May 2015.
- [5] D. J. Whitehouse, "Surface metrology," *Meas. Sci. Technol.*, vol. 8, no. 9, pp. 955–972, 1999.
- [6] R. J. Hocken, N. Chakraborty, and C. Brown, "Optical Metrology of Surfaces," *CIRP Ann. Manuf. Technol.*, vol. 54, no. 2, pp. 169–183, 2005.
- [7] P. Sandoz, G. Tribillon, T. Gharbi, and R. Devillers, "Roughness measurement by confocal microscopy for brightness characterization and surface waviness visibility evaluation," *Wear*, vol. 201, no. 1–2, pp. 186–192, 1996.
- [8] T. V. Vorburger, H. G. Rhee, T. B. Renegar, J. F. Song, and A. Zheng, "Comparison of optical and stylus methods for measurement of surface texture," *Int. J. Adv. Manuf. Technol.*, vol. 33, no. 1–2, pp. 110–118, 2007.
- [9] D. Whitehouse, "A new look at surface metrology," *Wear*, vol. 266, no. 5, pp. 560–565, 2009.
- [10] P. Lehmann, S. Tereschenko, and W. Xie, "Fundamental aspects of resolution and precision in vertical scanning white-light interferometry," *Surf. Topogr. Metrol. Prop.*, vol. 4, no. 2, p. 024004, 2016.
- [11] M. Conroy and J. Armstrong, "A comparison of surface metrology techniques," *J. Phys. Conf. Ser.*, vol. 13, pp. 458–465, 2005.
- [12] W. Gao, *Precision Nanometrology: Sensors and Measuring Systems for Nanomanufacturing*. Springer, 2010.
- [13] R. K. Leach, *Fundamental Principles of Engineering Nanometrology*. Elsevier, 2010.
- [14] D. Whitehouse, "Surfaces and Their Measurement," in *Surfaces and Their Measurement*, vol. 1, Elsevier, 2002, pp. 1–15.
- [15] R. Leach, X. J. Leigh Brown, R. Blunt, and D. M. Mike Conroy, "Guide for the Measurement of Smooth Surface Topography using Coherence Scanning Interferometry," National Physical Laboratory, London, 2008.
- [16] T. G. Mathia, P. Pawlus, and M. Wiczorowski, "Recent trends in surface metrology," *Wear*, vol. 271, no. 3–4, pp. 494–508, 2011.