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The use of in-situ surface metrology for advanced electrochemical polishing applications

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Abstract

Additively manufactured (AM) metallic parts have issues of inherently rough surface texture, which negatively impacts the precision potential functionality and ultimately limits applications. To make the workpieces functionally suitable and - improve the part aesthetic qualities, post-processing the additively printed parts is very much required. There are various methods of post-processing AM surfaces, of which the electrochemical polishing (ECP) methods have garnered significant attention recently due to their non-contact nature. ECP processes are subtractive and are in theory an easily controllable processing technique. While the electrochemical post-processing improves the part surface by reducing the roughness via a polishing process, it is essential to assess whether the part has achieved the desired surface quality to be deemed fit for the purpose. Current assessment methods involve offline measurement of parts, making the whole process less efficient and requiring removal and replacement of parts. Integration of metrology directly into the manufacturing platform would enable rapid inspection, making manufacturing more efficient and controllable. In this research work, we investigate the focus variation (FV) measurement principle for the implementation of in situ surface metrology within the electrochemical polishing system. A performance study of focus variation optical metrology compared against the stylus measurement was carried out to assess the FV potential. The test surface was a standard Rubert &Co Microsurf 334 comparator plate and a range of actual workpieces produced by AM and electrochemical polishing. Additionally, the - focus variation setup was developed, and the measurement output was compared with state-of-the-art optical surface metrology for performance verification, the system's robustness in the manufacturing environment.

Keywords: Additive Manufacturing (AM), Electrochemical Polishing (EP), Additive Manufacturing (AM), Focus Variation (FV)

1. Introduction

Recent progress in additive manufacturing (AM) technology has led to the manufacture of complex parts and geometries that are difficult or impossible to achieve using conventional manufacturing processes [1]. Combining its greater efficiency throughput, high degree of design flexibility, and shorter development cycles, and AM allows savings in small batch production time and raw materials [2]. While parts or components of desired functionality can easily be achieved using AM technology, the process has issues related to manufacturing defects and inherently producing rough surfaces, thus limiting part applications [3]. Addressing this issue mandates post-processing of the part or the component. Post-processing opens the application window for AM printed parts whilst enhancing their aesthetics. Several post-processing methods are in place, but the electrochemical polishing (ECP) method is increasingly becoming a popular option because of its non-contact nature, easily controllable process, ability to perform local and global processing with easy access to normally inaccessible geometries compared to contact post-processing techniques [4]. The EP technique is subtractive in nature and proceeds by immersing the part in a suitable electrolyte. Process uses a suitable electrode (anode), and the part is the anode. On application of direct current, the materials from "highest" features on the part surface are selectively removed by the process of anodic dissolution. Material removal from the AM part produces a smoothed part surface roughness. Extending the process time increases the smoothing process to a level where no more smoothing can occur. This process requires well-controlled process parameters such as electrolyte composition, current, time and temperature [5]. While the ECP process improves the surface, assessing whether the part has achieved the desired surface quality is very important to avoid excessive processing time. The current practice to assess such parts is to perform offline measurements in a laboratory setting. This makes the whole process -consuming and less efficient as it may involve multiple iterations of setting/resetting the part and its metrology in any manufacturing system. Integrating the metrology system directly onto the workpiece/part processing platform will enhance the ECP efficiency by providing metrology-informed process control. Currently, several metrology options are available; however, optical methods have advantages for online metrology applications, primarily due to their non-contact nature and fast measurement rates [6]. Across the range of optical metrology methods, focus variation (FV) seems to provide robust measurement, especially in situations where surfaces are relatively rough [7], and metrology is installed on the manufacturing/processing platforms where environmental vibrations are very likely to be produced during the process [8]. Other optical methods, such as interferometer-based metrology solutions, would require some form of additional stabilisation techniques to compensate for the environmental disturbances or vibrations [9]. In this work, we present the performance comparison of FV against other stylus and optical metrology tools using a standard Rubert &Co Microsurf 334 comparator plate (figure 1) for benchmarking in addition to actual workpieces produced by AM and electrochemical polishing. The Rubert "casting" sample was chosen as it resembled the surface texture produced by AM most closely (scale and isotropic nature of topography). The lower roughness values were also utilised to resemble progressively smoothed" AM surfaces.

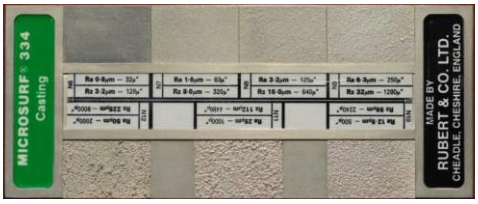


Figure 1. Rubert& Co Microsurf Casting 334 Roughness sample

2. ISO measurement using available in-lab instruments

ISO standards were mainly specified for conventional machined surfaces. So, ISO standards may not necessarily apply to the AM surfaces [10]. However, the main aim here is to benchmark and compare measured roughness values obtained using different instruments at settings defined by ISO specifications (ISO 4228 1996 and ISO 25178) [11, 12]. Table 1 shows the ISO evaluation length for a given roughness and its corresponding filter values to be used while evaluating surface roughness's.

Table 1. Ra/Sa value and the corresponding evaluation length and filter values as per ISO specifications.

Settings for ISO Measurement (ISO 4228, ISO 25178)				
Sample	Rubert Nominal Ra Value (µm)	Evaluation length/Area (mm)	S (µm)	L (mm)
N6	0.8	4	3	0.8
N7	1.6	4	3	0.8
N8	3.2	12.5	8	2.5
N9	6.3	12.5	8	2.5
N10	12.5	12.5	8	2.5
N11	25	12.5	8	2.5
N12	50	12.5	8	2.5

For benchmarking, four different instruments (stylus-based and optical non-contact metrology) were used: 1) Mitutoyo SURFTEST SJ-210 profilometer, 2) Somicronic Surfscan Profilometer, 3) Keyence VHX-7100 Optical Microscope and 4) Alicona G5 Optical Focus Variation Microscope (Objective 5x, 10x & 20x lenses). For tactile measurements Ra value is taken and directly compared with the Rubert Ra values, while for the areal measurements, using the Keyence and Alicona, the Sa parameter is considered. (Note that all instruments were verified using the manufacturer recommended calibration artefacts).

Table 2. Calculated roughness Ra (mean profile roughness) and Sa (areal surface roughness) values were obtained using the six different instruments: Somicronic, Mitutoyo, Keyence, Alicona 5x, Alicona 10x & Alicona 20x

SFOV Measurement using Alicona G5 (um)						
Sample	Somicronic Ra (µm)	Mitutoyo Ra (µm)	Keyence Sa (µm)	Alicona G5 Focus Variation		
				5x Sa (µm)	10x Sa(µm)	20 x Sa(µm)
N6 (0.8 µm)	0.4942	0.4818	1.315	1.875	0.957	0.557
N7 (1.6 µm)	1.6324	2.5122	1.975	4.053	2.672	2.500
N8 (3.2 µm)	3.347	4.11	4.825	4.352	4.238	4.144
N9 (6.3 µm)	5.1072	6.2496	8.73	6.043	6.248	6.314
N10 (12.5 µm)	9.8712	9.0208	13.41	10.833	11.476	11.473
N11 (25 µm)	20.5244	18.9122	23.73	23.643	23.453	24.653
N12 (50 µm)	43.3258	0	45.095	42.440	38.4	41.733

Table 2 shows the measured Ra/Sa values using four different instruments. The Somicronic Surfascan profilometer, having a 10nm resolution, a 2um tip radius and calibrated using a precision certified sphere, is taken to provide the "truest" measurement of the Rubert surface roughness (Rubert specimens assume tactile measurement) compared to the stated values. For smoother samples (N6, N7, N8, & N9), the measured roughness Ra value matches closely with the nominal Ra value of the Rubert sample. The Ra values obtained are lower than the Rubert specified value for higher roughness samples (N10, N11 & N12). For the Mitutoyo stylus, utilising the skid approach) the roughness values were higher for smaller roughness values and lower for higher roughness values. The highest roughness sample, N12 (50 µm), could not be measured using the Mitutoyo stylus instrument because the measurement went out of range for the instrument. Keyence areal surface measurement showed higher Sa measurement values for samples with a Ra value of <25 um and smaller roughness for a higher Ra >12.5 um surface roughness value.

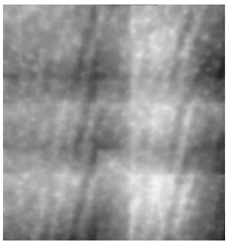


Figure 2. Keyence data stitching issue

Measurement with Keyence required data stitching to be ISO compliant and showed data stitching issues; clear-lined boundaries appeared at every FOV (field-of-view) boundary while scanning and stitching (figure 2). This can impact the overall reconstructed surface and the roughness values. The Alicona G5 measurement had higher Sa measurement values for samples having Ra value <25 um and smaller roughness for higher Ra >12.5 um surface roughness value. Objectives 5x, 10x and 20x were used for measurement of the samples. The roughness values obtained using the 10x objective were found to be much closer to the nominal Rubert Ra values except for the sample (N12, Ra - 50 um) having the highest roughness.

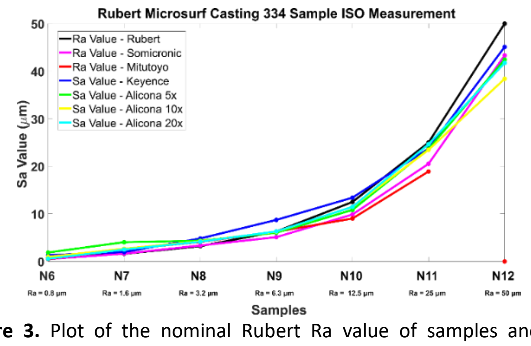


Figure 3. Plot of the nominal Rubert Ra value of samples and the calculated Ra and Sa values obtained using six different instruments: Somicronic, Mitutoyo, Keyence, Alicona 5x, Alicona 10x and Alicona 20x

Figure 3 shows the plot of the measured roughness values using four different instruments. Figure 4 shows the percentage error plot. The Somicronic stylus instrument exhibited the best performance with the least percentage deviation compared to the Mitutoyo. The percentage error plot for samples N6 and N7 noted that Ra and Sa are not necessarily assessing the same surface properties surface; calculated Sa values are often higher than the Ra value, as they inherently collect more surface data and are hence measuring more " outlier high spots" [13]. Across the optical metrology instruments, the Alicona G5 20x showed the lowest percentage roughness's error in the range (0.5 µm - 25 µm) of those that will be measured during the ECP process. The above study gave confidence to adopting and implementing the FV method as an onboard surface metrology solution for the chosen Holson ECP system [14].

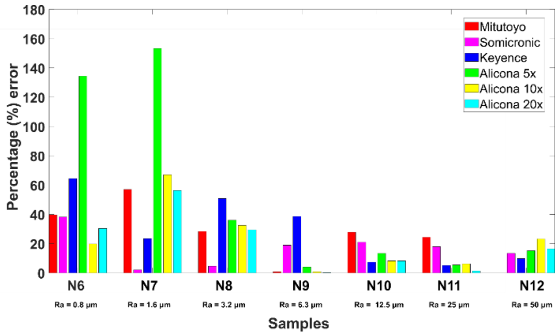


Figure 4. Plot of the percentage roughness error/deviation of measurements obtained using six different instruments: Somicronic, Mitutoyo, Keyence, Alicona 5x, Alicona 10x and Alicona 20x

3. Single Field of View Measurement (SFOV) using Alicona G5

In practice, capturing a single field of view (SFOV) measurement to quantify surface quality is optimal. This section will present the SFOV measurements using the Alicona G5 focus variation 5x, 10x & 20x objectives. SFOV measurements will provide evidence of how reduced FOV will affect the measured roughness values in contrast to the ISO measurements.

Table 3. Calculated SFOV roughness values obtained using the Alicona 5G 5x, 10x and 20x objective lens

SFOV Measurement using Alicona G5				
Sample	Nominal Ra Value (µm)	5x Sa (µm)	10x Sa (µm)	20x Sa (µm)
N6	0.8	2.299	1.105	0.677
N7	1.6	4.463	2.77	2.479
N8	3.2	5.052	4.143	3.39
N9	6.3	7.219	5.567	5.576
N10	12.5	12.65	13.31	9.914
N11	25	26.15	20.17	18.43
N12	50	30.55	26.89	28.2

SFOV measurements using 5x, 10x and 20x Alicona G5 objectives were performed on the Rubert samples (N6-N12). Three measurements per sample were taken, and the average roughness Sa values were calculated (table 3). Figure 5 shows the plot of the SFOV measurements as close to ISO conditions as possible using the Alicona G5 FV instrument using three objectives.

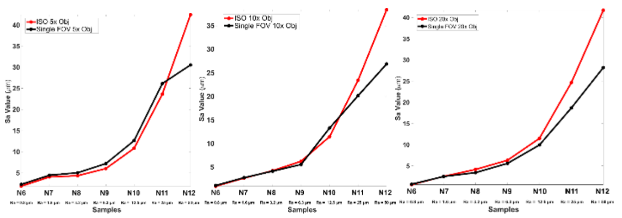


Figure 5. Single FOV and the ISO Sa roughness measurement values obtained using Alicona (a) 5x, (b) 10x and (c) 20x objectives

5x objective measurement, with a slightly higher Sa roughness value, the SFOV followed a similar trend to the ISO measurement except for the maximum roughness value of 50 µm where the single FOV value drops significantly as this measurement is the most non-ISO compliant. Figure 5(b) shows the plot of SFOV, and the ISO Sa roughness measurement values obtained using Alicona 10x objective. With the 10x objective, the roughness values closely matched for samples N6-N8 (0.8-3.2 µm), while the values deviated for higher roughness N9-N15 samples. In the case of measurements with the 20x objective, the single FOV measurement values followed the ISO trend, but the roughness values obtained were found to be lower than the corresponding ISO measurement values (figure 5, c).

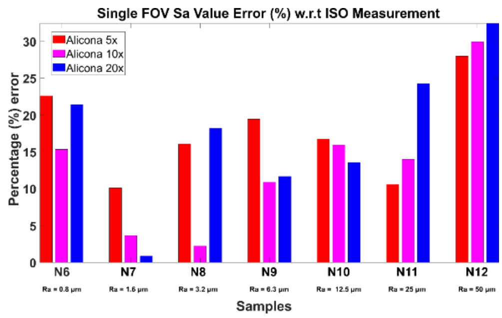


Figure 6. Percentage (%) error with the measurements performed using 5x, 10x, and 20x objective lenses

Figure 6 shows the plot of percentage error obtained from measurements performed using 5x, 10x and 20x Alicona G5 objective lenses. The target range of surface roughness after the ECP processing is 0.5-25 µm range, so excluding the highest roughness value sample N12 (50 µm) is valid for all other samples (N6-N11, 0.8-25 µm), the single FOV roughness measurement value shows an average percentage error of ranging from 10-17 % for all objective types.

The percentage errors are slightly higher than expected due to the Sa roughness calculations referenced to Rubert Ra roughness values. Since Ra and Sa do not inherently measure the same property, these results can be expected. Considering this, the actual percentage error/deviation will fall below 10%. Out of all the three Alicona objective types, the 10x objective showed the least percentage error in the calculated Sa roughness values with respect to the SFOV measurements. The -process FV system will be implemented on the Holdson Electroform 300 and incorporate a single FOV measurement approach for on-machine surface measurements. So, over the range of measurements and objective types, 10x objective lens will be recommended. The 10x objective lens will provide good size surface evaluation area as well as an acceptable spatial resolution.

4. In-Lab developed focus variation system

The authors have developed a focus variation system to measure the additively manufactured and electrochemically polished metal samples within the Holdson's ECP machine. The developed FV system will be integrated onto the Holdson's ECP system to be used as an onboard metrology tool. The experimental FV setup is shown in Figure 7. A white light source (LS-WL1, Laser Components Ltd) is collimated using a fibre collimator. It is fed into the beam splitter, which is then focussed onto the sample by a 10× Mitutoyo objective lens attached to a piezoelectric actuator (PIFOC-P-721). The piezoelectric actuator holding the objective lens is scanned, and the reflected light from the sample surface is focused back into the CCD camera (Imperx, ICLB0620M-KC000) using a 200 mm tube lens. A total of 128 images are obtained at different focus positions. The image stack is then used to extract a focus measure profile to generate the surface topography.

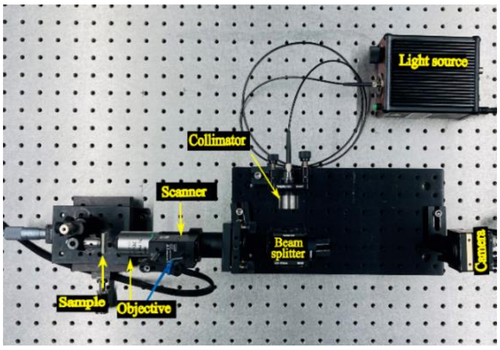


Figure 7. Rubert& Co Microsurf Casting 334 Roughness sample

Exemplar stainless steel samples were additively manufactured using a Renishaw AM 500 metal 3D printer and are shown in figure 8 (a). Figure 8 (b) shows the polished surface after the EC post-processing using the Holdson ECP system (figure 8 (c)).

(a) (b) (c)

Figure 8. 3D printed stainless steel sample (a) Unpolished, (b) Sample after Holdson ECP post processing (c) Holdson ECP machine [14]

The top surface of the sample (figure 8(a)) was measured using the Alicona G5 and an in-lab developed FV system using the 10x objective, with measurement spots not located in the exact same position. Figure 9 (a), (b) shows the areal topography of the unpolished surface measured using Alicona while 9(c), (d) is the surface topography obtained using the in-lab developed FV system. The calculated roughness Sa of the unpolished surface obtained using the Alicona and in-lab developed FV system was found to be 11.30 µm and 11.26 µm, respectively.

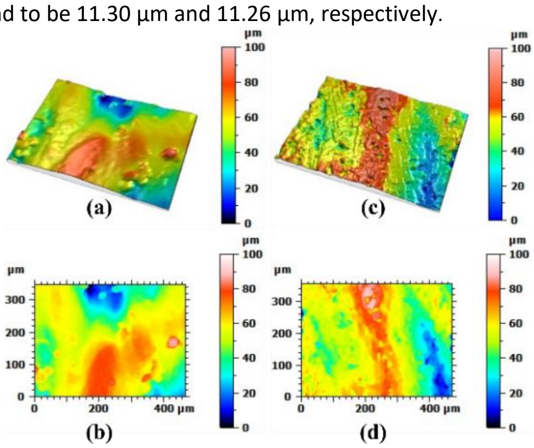
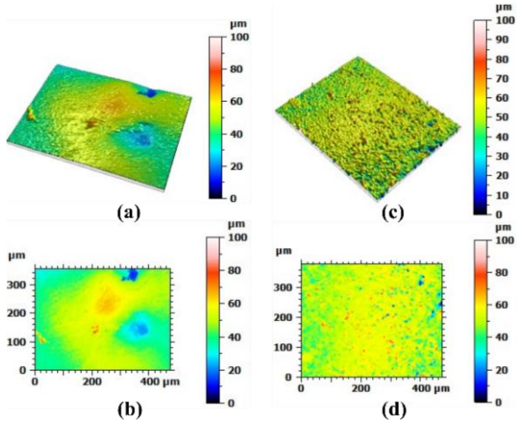


Figure 9. (a) Pre-polish sample measurement, Alicona: (a, b) areal surface Topography, In Lab FV system: (c, d) areal surface Topography

Further, the polished sample (figure 8(b)) was measured using the same two optical metrology systems. Figures 10 (a) and (b) show the areal surface topography image of the polished surface using Alicona. The surface roughness values obtained using the Alicona were found to be 6.660 µm. Similarly figure 10 (c, d) shows an aerial topography image of the polished sample measured using the in-lab developed FV system. The measurement data obtained using the FV system showed some outliners which were removed using a suitable filter. The calculated roughness value (Sa) obtained were found to be 6.756 µm. The roughness values obtained using the in-lab developed FV system are in close agreement with the ones obtained using the commercial Alicona G5 system, as the overall measurement difference is less than 0.1 µm. Further work will involve the measurement of different EC polished samples (0.5-25 µm roughness range) using an in-lab developed FV system for its performance verification and establish its robustness to be used as an onboard metrology within the Holdson's ECP system.

Figure 10. Polished sample measurement, Alicona: (a, b) areal surface topography, In Lab FV system: (c, d) areal surface topography,



5. Conclusion

An extensive surface measurement benchmarking exercise was undertaken to determine the best metrology method to be adopted for in-situ measurement in an electrochemical polishing system. Out of the available options, the FV system was the best possible option. Further, an in-lab FV system was developed, and its performance verification against the commercial Alicona G5 system was verified to be within 0.1 µm accuracy and shows its suitability as an onboard metrology for the Holdson's ECP system.

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