

Accuracy of replication for non-destructive surface finish measurement

Y. C. Liu ¹, C.Y. Ling ², A.A. Malcolm ¹, Z.G.Dong ¹

¹ Singapore Institute of Manufacturing Technology, 71 Nanyang Drive, Singapore 638075
Phone: +65 67938529, Fax: +65 67922779; e-mail: yliu@SIMTech.a-star.edu.sg

² National University of Singapore, Singapore 119077

Abstract

Surface replication has been widely used in aerospace, automotive and other industries as a non-destructive method for examination and assessment of either surfaces difficult to be accessed by measurement tools or parts difficult to be dismantled for measurement. The fidelity and accuracy of the replication is one of the major concerns in actual applications. This paper presents a comprehensive study of accuracy of replica materials for replicating and measuring surface roughness of engineering surfaces. In this study, three different replica materials, namely, Repliset, Technovit and Press-O-Film, have been used to replicate four ground surfaces with average roughness values ranging from 0.2 μm to 1.6 μm . The original surfaces and their replicas were measured with tactile stylus profilometer and Alicona InfiniteFocus 3D optical microscope. Surface average roughness was calculated and compared between the original surfaces and their replicas. A discussion and suggestion on different replication techniques and materials used in surface roughness measurement are given.

Keywords: Replication, surface finish measurement, roughness

1. Introduction

Surface finish measurement is essential for components during manufacturing since the surface finish quality is known to affect the functionality of many components. Adequate characterization of surface texture is crucial in the optimization and control of functional surfaces [1]. In some cases, measurement instruments cannot access some surfaces to evaluate them directly. In other instances, the part to be measured is too heavy or too large or cannot be dismantled to be brought to a measurement instrument. Quantifying surface finish of such surfaces becomes a challenge.

Surface replication is one of the solutions for surface topography and finish measurement for difficult-to-access areas and unable-to-dismantle parts [2-4]. Replication is used to copy the surfaces and the replicas are brought to the measuring device for measurement. The accuracy of the replication, including replication materials and replication methods, is critical in actual applications. Different replication materials and methods have different replication performance. In-depth study on the accuracy of various replication materials and methods for replicating surfaces with different surface texture for surface finish measurement through laboratory investigation is required. In this paper, three replication materials, which come from three categories (silicone-based materials, epoxy resins and pressure sensitive films), have been selected to replicate four engineering ground surfaces with average roughness values ranging from 0.2 μm to 1.6 μm . Their replication processes have been investigated and their replication accuracy has been evaluated through experiment.

2. Experimental details



2.1 Machined surfaces to be replicated

Four typical engineering surfaces have been chosen for this study. All four surfaces are ground and the surfaces vary from smooth to rough. Their surface roughness values range from $0.2 \mu\text{m}$ to $1.6 \mu\text{m}$ in Ra, making them suitable for the fidelity evaluation of replication for different finished surfaces. Figure 1 shows the sample to be replicated and Figure 2 illustrates the micrographs of the four test surfaces. It can be noted that the four surfaces have different surface height variation and surface finish, the test surface 1 is the smoothest and the test surface 4 is the roughest.

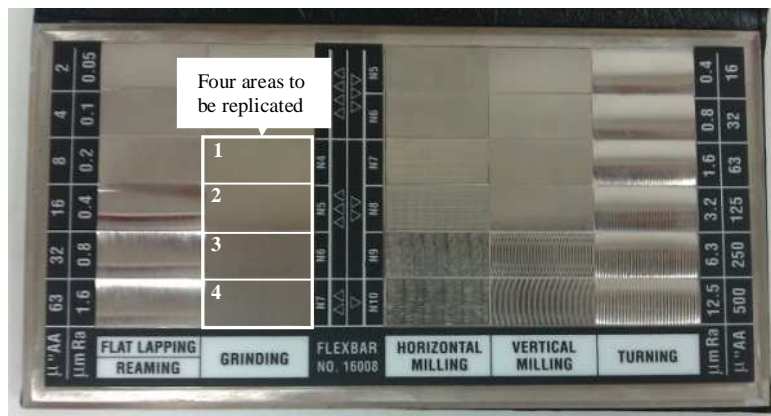
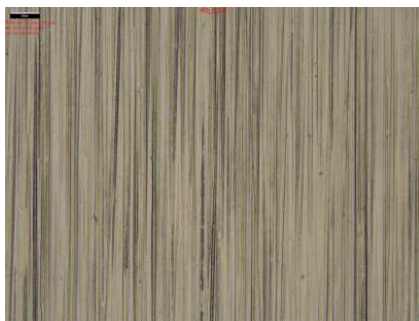


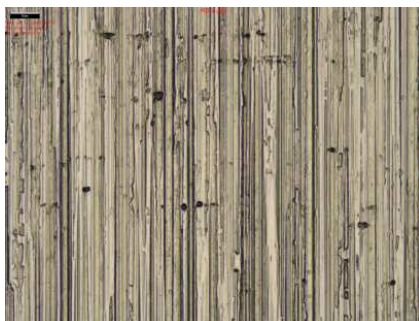
Figure 1: The sample to be replicated.



(a) Test surface 1



(b) Test surface 2



(c) Test surface 3



(d) Test surface 4

Figure 2: Micrographs of four test surfaces.

2.2 Replicating materials and their replication processes

The replication materials used in this study include RepliSet replica, Technovit replica and Press-O-Film replica. RepliSet replica is a two-part silicone rubber which is soft and flexible. Technovit replica is an epoxy resin which is hard. Press-O-Film replica is pressure sensitive film which is soft and thin like paper. Prior to replication, the sample was cleaned with alcohol and blown with N₂ gas to ensure that the surface was free of foreign particles and contaminant.

In the replication using RepliSet replica, the two-part materials (polymer and curing agent) in a cartridge were pushed out by a dispensing gun, mixed in a static-mixing nozzle and applied onto the surface to be replicated. The mixture of the replica was in cream form. A glass slide stuck with a backing paper was placed on top of the mixture and a small force was applied to make the replica flat. The mixture set for 5 minutes and then the replica was removed from the replicated surface by hand. The replica was taped flat on the glass slide and ready for microscopic measurement.

When using Technovit replica, a containment wall around the area to be replicated was created using blu-tack and ice-cream sticks. A thin layer of silicone release agent was applied onto the surface to aid in the removal of replica from sample after replication. The replica liquid and powder were mixed in a ratio of about 3:1 and poured onto the demarcated area. The mixture set for 15 minutes and then was carefully removed from the surface for measurement. The replication was conducted in a fume hood with proper equipment such as gloves and facemasks as some components, for instance, release agent and monomer liquid, are flammable, harmful if inhaled and mild irritant to skin and eyes.

Replication with Press-O-Film is simple and easy. Press-O-Film replica is made of a layer of compressible micro-foam that is coated onto an incompressible polyester substrate. In this study, the shiny compressible micro-foam was placed onto the replicated surface. An appropriate and uniform force was applied to rub on the polyester substrate using a burnishing tool for 30 seconds. The compressed foam collapsed and bore the impression of the rough surface. The replica was removed from the sample surface and stuck onto a glass slide for stability. The key aspect of replication using Press-O-Film is the proper application of force. Improper application of force would cause incomplete replication, destroying replica or double replication of the texture on the surface.

Figure 3 illustrates a set of RepliSet replicas, a set of Technovit Replicas, and a Press-O-Film replica. Small amount of pores was observed in Technovit Replicas. The pores were caused by the gas bubbles formed during the replication process. They can be reduced by lowering the mixing speed and letting the replica mixture set in a vacuum chamber to suck out the bubbles during replication. These solutions can reduce the number of pores in the desired area but do not completely eliminate the presence of pores.

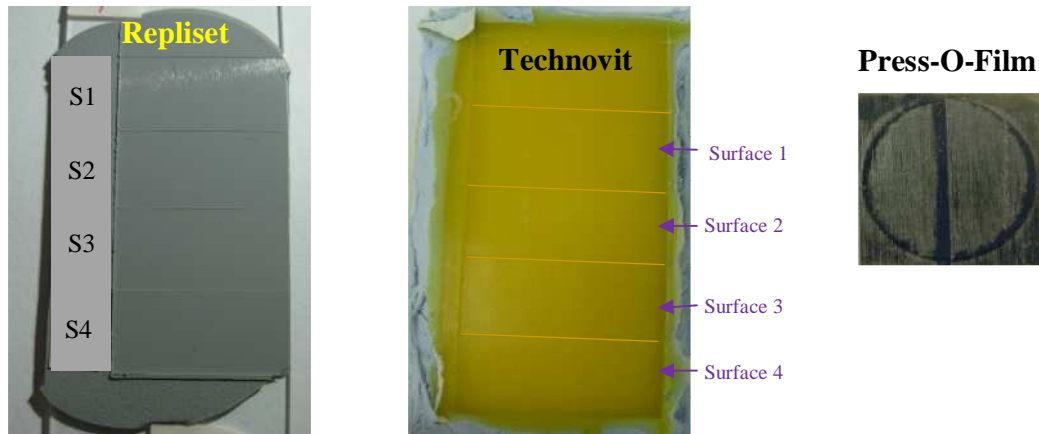


Figure 3: Illustration of sets of RepliSet replicas, Technovit Replicas and Press-O-Film replica.

2.3 Measurement of surface topography and determination of roughness

Since silicone-based replicas and pressure sensitive film replicas are soft, optical non-contact method is preferred for measuring the surface topography of these replicas. Alicona InfiniteFocus 3D optical microscope, which employs the technique of focus-variation combined with small depth of focus to measure surface [5], was used to measure surface topography of all replicas and original surfaces in three dimensions in this study. An objective of 50x was selected and area stitching was used. The total scanned area was 5 mm x 218 μm . The vertical resolution was 20 nm and the lateral resolution was 2 μm . Coaxial light and ring light were used to illuminate the test surfaces to measure the textures on flat and sloped surfaces.

For evaluation of replication fidelity of the selected materials, the four ground surfaces were prepared with two Vickers diamond-shaped indentation marks located as shown in Figure 4. The four samples were cleaned with alcohol and scanned in the region including the two diamond-shaped indentation marks before replication process. The ground surfaces were named as original surfaces or parent surfaces. After scanning, a line was drawn directly under the two diamond-shaped indentation marks to extract the surface profile along the line, the length of the line was about 4.2 mm. The surface roughness is then calculated by choosing cut-off length of 0.8 mm. Subsequently, the four ground surfaces were replicated by using three different replication materials, respectively. In between each replication, the parent surfaces were cleaned with alcohol, blown with N_2 gas and scanned with Alicona InfiniteFocus system to investigate if the parent surfaces have been changed due to replication. The experiments showed that the parent surfaces had no visible change and their roughness values were very similar before and after replication. After replication, the replicas were scanned and their roughness was evaluated at the same location as that on the original surfaces. Figure 5 illustrates 2D images of the test area on an original surface and its replica obtained by Alicona InfiniteFocus system. It was observed that the two diamond-shaped indentation marks

have been replicated well and they can be used as reference for drawing line to evaluate the same location on original surface and its replica for fidelity study.

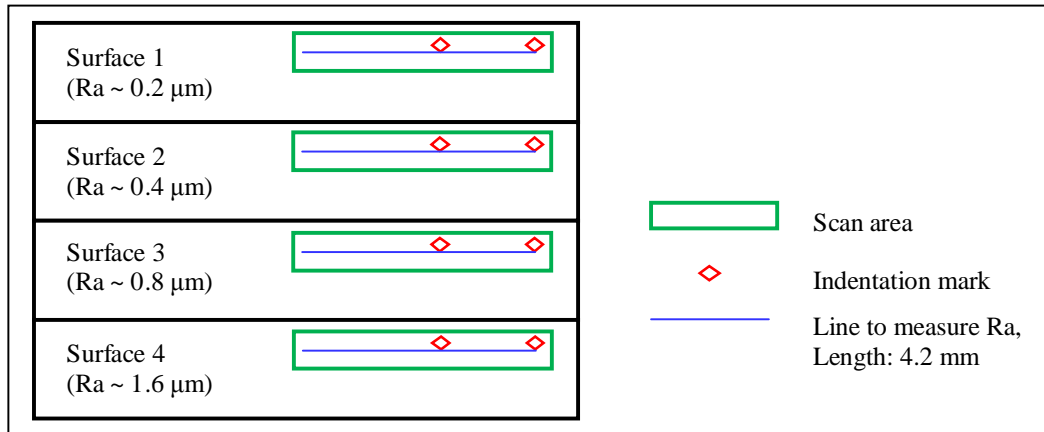


Figure 4: Schematic diagram of four test surfaces, scanned areas, indentation marks and evaluated lines.

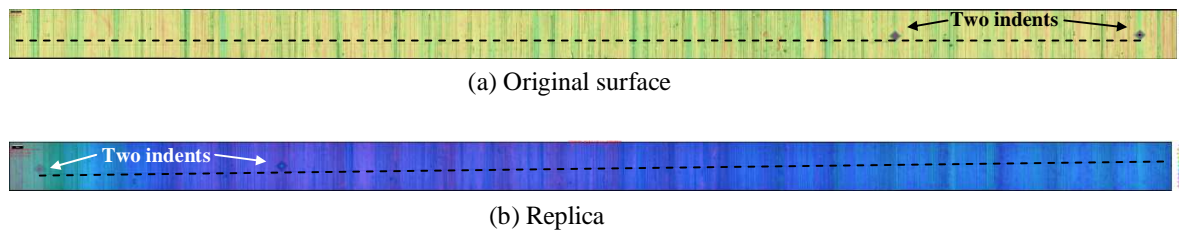


Figure 5: 2D images of the test area on an original surface and its replica.

Original surfaces and Technovit replicas are hard. Taylor Hobson stylus profilometer was also used to measure the surface roughness of the original surfaces and the hard replicas for comparison. A microscope was used to locate the two diamond-shaped indentation marks on the test surfaces and ensure that the evaluation by Alicona InfiniteFocus system and Taylor Hobson stylus profilometer was done on a very similar location. 2D line scan was conducted and the scan length was 5 mm. The stylus used for scanning was a diamond stylus with radius of 2 μm. The cut-off length of 0.8 mm was chosen for calculating surface roughness from the measured profile.

3. Results and discussions

3.1 Replication fidelity of surface profile and texture

The surface topography of the original surfaces and their replicas were imaged by Alicona InfiniteFocus 3D optical microscope. Figure 6 illustrates 3D surface topography of the original surface with Ra of 0.2 μm and its replicas produced by RepliSet, Technovit and Press-O-Film replication materials. Figure 7 shows 2D surface roughness profiles of the original surface and its replicas. It is noted that all three replicas can copy

the topography and texture of the surface with Ra at the level of $0.2\ \mu\text{m}$ reasonably well. It is also observed that there are small amounts of pores in Technovit replica, which cause spikes on its image as shown in Figure 6 (c). The form of Press-O-Film replica has been deformed slightly, which is due to the fact that the thickness of the Press-O-Film is as thin as a paper and its shape can be easily deformed in the transportation of replica from original surface to glass slide for stability after replication. Experimental result shows that Press-O-Film replica can copy the fine surface texture satisfactorily.

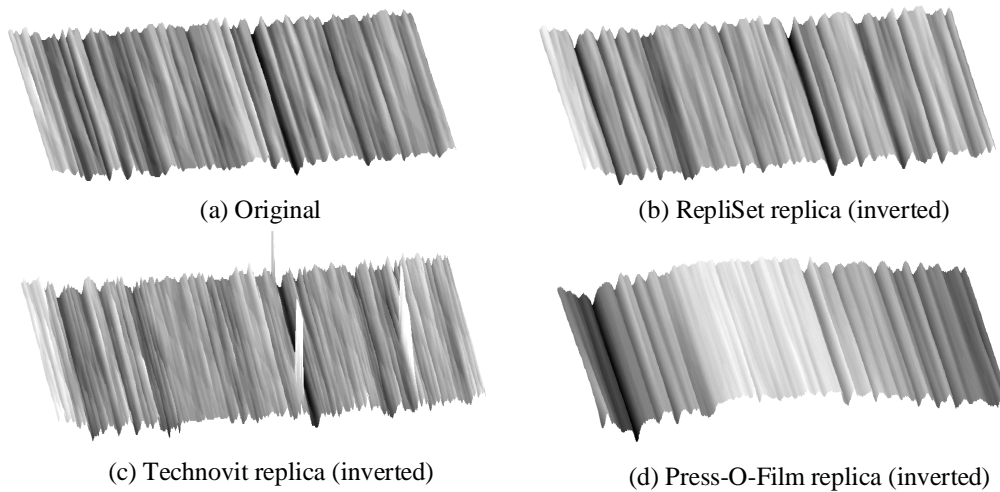


Figure 6: 3D images of original surface and their inverted replicas with Ra of $0.2\ \mu\text{m}$ (Selected area: $1100 \times 28\ \mu\text{m}$).

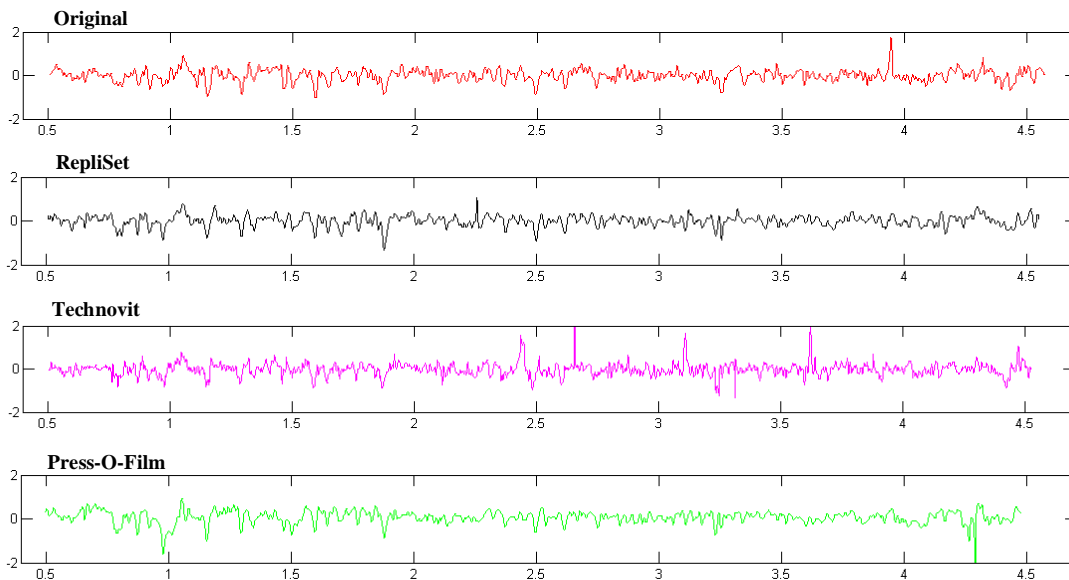


Figure 7: 2D roughness profiles of original surface and their replicas with Ra of $0.2\ \mu\text{m}$. Replica data have been inverted for easy comparison.

Figures 8, 10 and 12 illustrate 3D surface topography of the original surface with Ra at the level of 0.4 , 0.8 and $1.6\ \mu\text{m}$ and their replicas produced by RepliSet, Technovit and

Press-O-Film replication materials, respectively. Figures 9, 11 and 13 show their 2D surface roughness profiles. It is observed that all three replication materials can copy the topography and texture of the surface with Ra at the level of $0.4\ \mu\text{m}$ satisfactorily, and can copy the topography and texture of the surfaces with Ra ranging from 0.8 to $1.6\ \mu\text{m}$ very well, suggesting that RepliSet, Technovit and Press-O-Film replicas have high fidelity in the replication of the surface with Ra at the level of $0.4 - 1.6\ \mu\text{m}$. Small amounts of pores are seen in Technovit replicas.

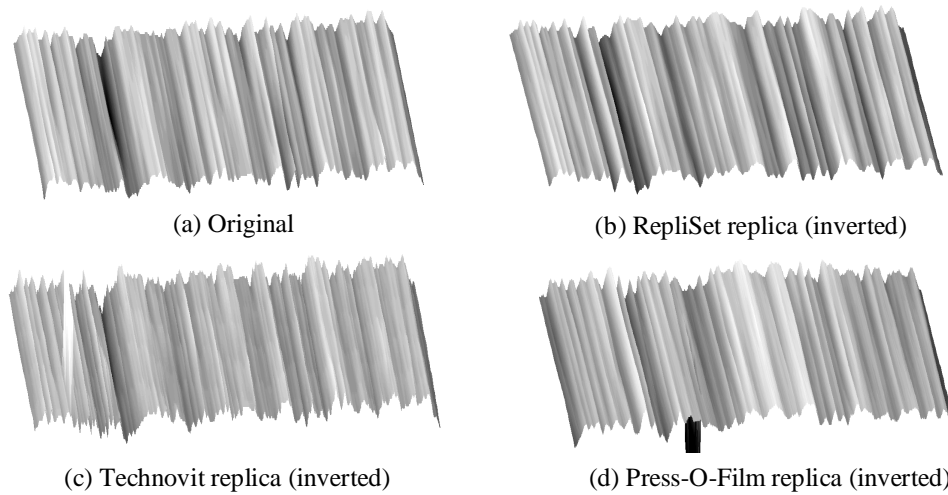


Figure 8: 3D images of original surface and their inverted replicas with Ra of $0.4\ \mu\text{m}$ (Selected area: $1100 \times 23\ \mu\text{m}$).

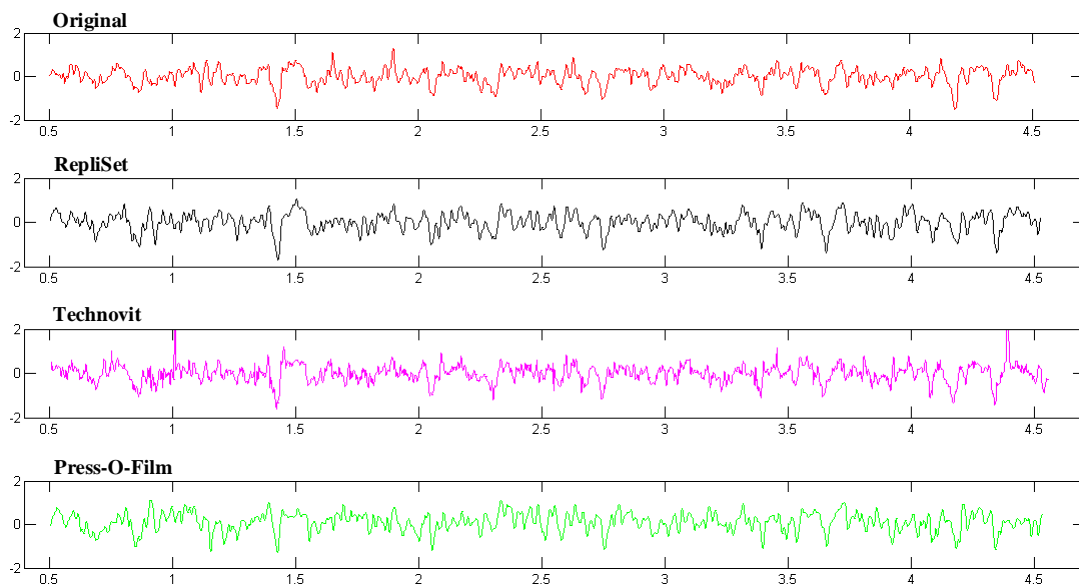


Figure 9: 2D roughness profiles of original surface and their replicas with Ra of $0.4\ \mu\text{m}$. Replica data have been inverted for easy comparison.

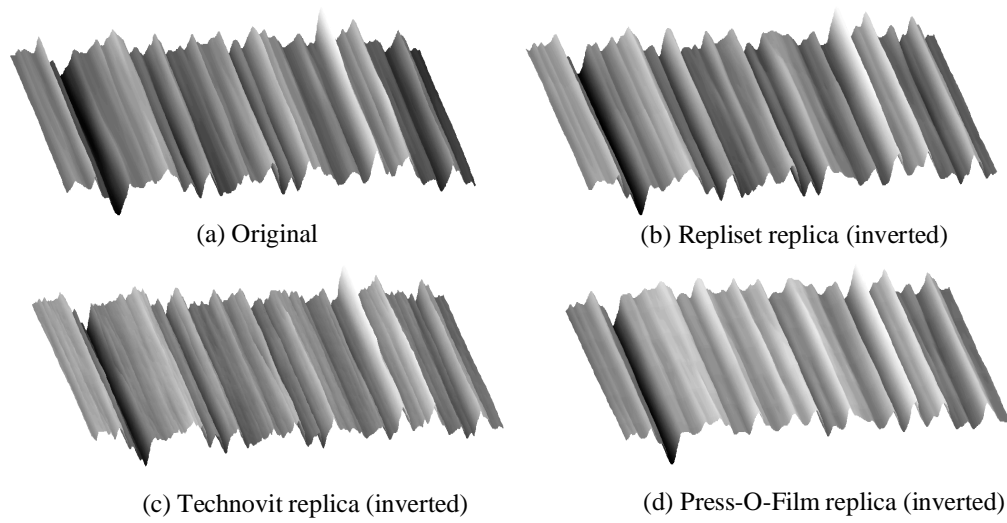


Figure 10: 3D images of original surface and their inverted replicas with Ra of $0.8 \mu\text{m}$ (Selected area: $850 \times 37 \mu\text{m}$).

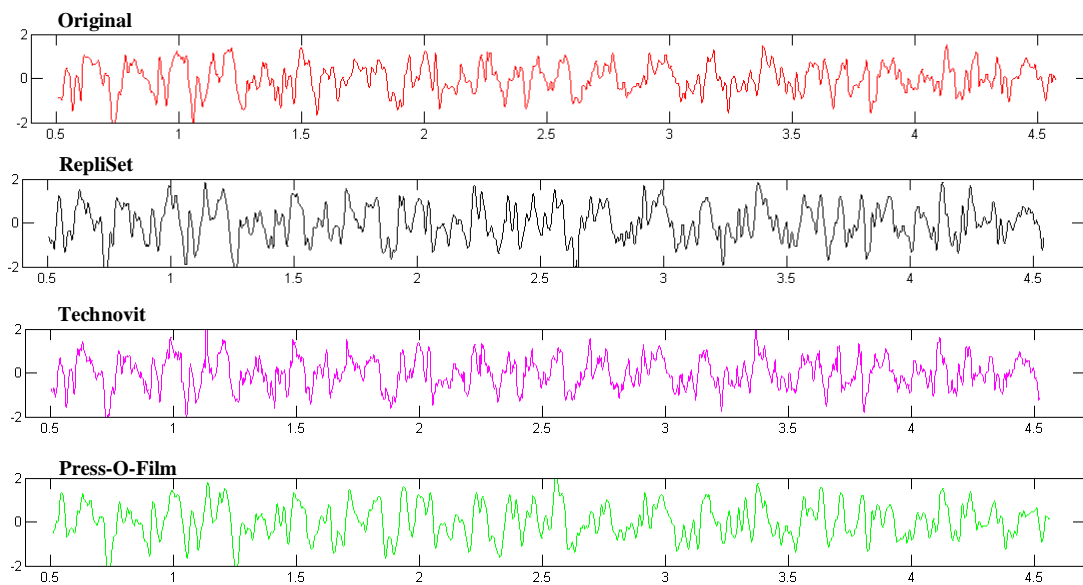


Figure 11: 2D roughness profiles of original surface and their replicas with Ra of $0.8 \mu\text{m}$. Replica data have been inverted for easy comparison.

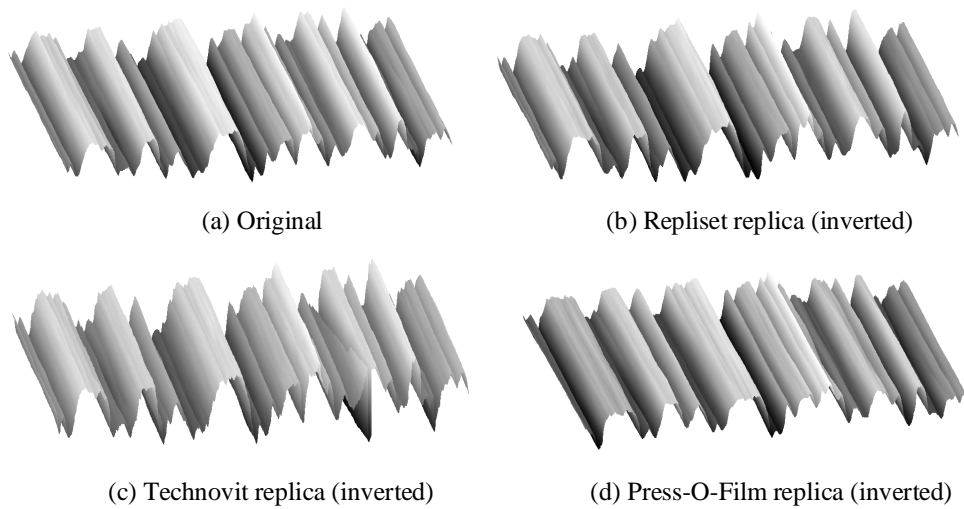


Figure 12: 3D images of original surface and their inverted replicas with Ra of 1.6 μm (Selected area: 1300 x 45 μm).

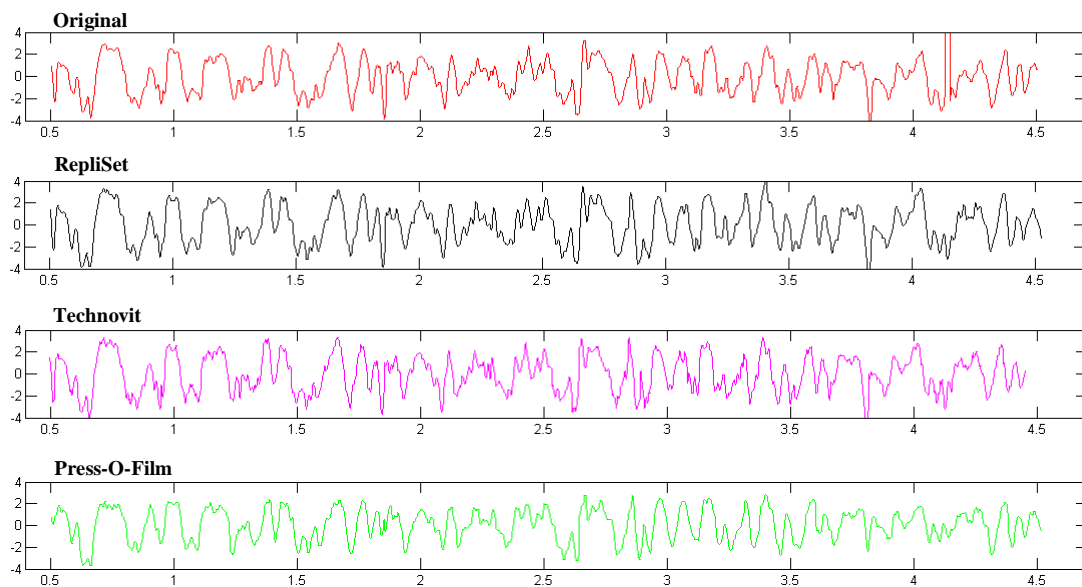


Figure 13: 2D roughness profiles of original surface and their replicas with Ra of 1.6 μm . Replica data have been inverted for easy comparison.

3.2 Replication accuracy in surface roughness measurement

Different replicas have different surface characteristics including color, shininess/reflectivity, transparency, hardness, etc. Optical non-contact methods are sensitive to the color, shininess/reflectivity and transparency of the test sample. Stylus profilometer is not sensitive to surface reflectance or color, but is only good for hard

samples. RepliSet and Press-O-Film replicas are soft, not shiny, opaque and in grey color. Experiments show that Alicona InfiniteFocus 3D optical microscope is particularly suited to measuring surface topography of RepliSet and Press-O-Film replicas for determination of roughness. Hence surface roughness measurements of RepliSet and Press-O-Film replicas were performed by Alicona InfiniteFocus system. Technovit replicas are hard, translucent and in yellow color. There are small amounts of pores in Technovit replicas. The pores in replicas cause spikes in the imaging using Alicona InfiniteFocus system, resulting in inaccurate roughness calculation. However stylus profilometry is a contact method, no artificial spikes are introduced in the scanned profile. Hence stylus profilometer was used to measure surface roughness of Technovit replicas in this study. Original surfaces are hard, shiny and in silver color; Alicona InfiniteFocus system gave lower Ra values for the original surfaces compared to stylus profilometer. To be traceable to ISO standard [6, 7], the average roughness (Ra) values of the original ground surfaces obtained by Taylor Hobson stylus profilometer are used as reference. A comparison of Ra values along the line just under two diamond-shaped indentation marks on replicas and their original surfaces is indicated in Table 1. The Ra values of replicas in the table are the average of at least two measurements from two replications, while the Ra values of original surfaces are the average of two measurements done on the two very close lines directly under the two diamond-shaped indentation marks. Experiments show that the deviation of the two measurements is insignificant. To quantify the repeatability of roughness measurement using Alicona InfiniteFocus 3D optical microscope, six repeated tests were done on a test surface. The standard deviation for the six measurements was 2.6%, showing that Alicona InfiniteFocus system can perform repeatable measurements in roughness determination for certain surfaces.

Table 1: Comparison of Ra values of replicas and their original surfaces

	Actual value of original surface (μm)	Repliset (μm)	Technovit (μm)	Press-O-Film (μm)
Surface 1 (Ra_0.2 μm)	0.21	0.24 (+14.3%)	0.21 (0%)	0.25 (+19.0%)
Surface 2 (Ra_0.4 μm)	0.37	0.37 (0%)	0.38 (+2.7%)	0.39 (+5.4%)
Surface 3 (Ra_0.8 μm)	0.68	0.70 (+2.9%)	0.68 (0%)	0.65 (-4.4%)
Surface 4 (Ra_1.6 μm)	1.51	1.56 (+3.3%)	1.49 (-1.3%)	1.37 (-9.3%)

- The data in the bracket are the deviation of the value of replicas from actual value of the original surfaces.

For the smooth surface with Ra at the level of 0.2 μm , RepliSet replica overestimates the surface average roughness (Ra) by more than 14%, while Press-O-Film replica overestimates Ra value by about 19%, indicating that these two replicas are not suitable for replicating fine surface with Ra of 0.2 μm for roughness measurement. Technovit replica has almost negligible difference in Ra compared to original surface, suggesting

that Technovit is suitable for replicating smooth surface and stylus profilometry can be used to measure surface roughness of this replica.

For the surface with Ra at the level of 0.4 μm , RepliSet and Technovit replicas perform well in replicating surface for roughness measurement. RepliSet replica has negligible difference in Ra compared to original surface, while Technovit replica overestimates Ra about 3%, which might be caused by the small gas pores introduced during replication process. The overestimation of 3% can be considered as insignificant. Press-O-Film replica overestimates Ra by 5.4%, showing that Press-O-Film replica can copy the surface roughness at the level of 0.4 μm in Ra reasonably well.

For replicating the surface with Ra at the level of 0.8 μm , RepliSet, Technovit and Press-O-Film replicas perform well. Technovit replica has negligible difference in Ra compared to original surface. RepliSet replica overestimates Ra about 3%, while Press-O-Film replica underestimates Ra by 4.4%. The experimental results reveal that all three replicas can be used to copy medium rough surfaces for surface finish measurement.

For replicating rough surface with Ra at the level of 1.6 μm , RepliSet and Technovit replicas perform well, their absolute replication deviation are less than 5%. Press-O-Film replica underestimates Ra about 10%; this could be caused by not enough force applied onto the compressible micro-foam during replication process. The experimental results demonstrate that Press-O-Film replica can copy rough surface reasonably well.

4. Conclusions and recommendations

Surface replication can be used for surface finish measurement for difficult-to-access areas, as well as the part difficult to be brought to measuring devices. It is a non-destructive method. Different replication materials achieve different accuracy. Technovit replica has shown high fidelity in replicating surfaces with Ra ranging from 0.2 μm to 1.6 μm , where the Ra deviation is within 5%. There are small amounts of gas pores formed in Technovit replica. Technovit replica is hard and its surface roughness can be measured by tactile stylus profilometer well. RepliSet replica has high accuracy in replicating surfaces with Ra ranging from 0.4 μm to 1.6 μm for roughness measurement, but is not suitable for smooth surface with Ra at the level of 0.2 μm . Press-O-Film replica can copy surfaces with Ra from 0.4 to 1.6 μm reasonably well, but is not good for replicating smooth surface. Both RepliSet and Press-O-Film replicas can be measured by Alicona InfiniteFocus 3D optical microscope easily, while the surface roughness of Technovit replica and original surfaces can be characterized by tactile stylus profilometer well. Replication using RepliSet replica is simple, easy and safe. Replication using Technovit replica requires building a containment wall around the area to be replicated and the replication should be done in fume hood with proper equipment. Replication with Press-O-Film requires appropriate force applied onto the film, which affects the replication accuracy significantly.

For replicating easy-access and big areas, Technovit and RepliSet replicas are recommended for use. For replicating difficult-to-access as well as confined areas,

RepliSet is a good candidate. Further study on accuracy degradation of the produced replicas and investigation of corrosion effect on the replicated surfaces are recommended to carry out in the future.

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