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Accurate Roughness Measurement Using a Method for Evaluation and Interpolation of the Validity of Height Data from a Scanning White-light Interferometer

Namyoon Kim, Seung Woo Lee, Yongjun I, and Heui-Jae Pahk*

School of Mechanical and Aerospace Engineering, Seoul National University, Seoul, 08826, Korea

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An effective and precise method using a scanning white-light interferometer (SWLI) for three-dimensional surface measurements, in particular for roughness measurements, has been proposed. The measurement of a microscopically sloped area using an interferometer has limitations, due to the numerical aperture of the lens. In particular, for roughness measurements, it is challenging to obtain accurate height data for a sloped area using the interferometer, due to diffraction of the light. Owing to these optical limitations of the interferometer for roughness measurements, the Ra measurements performed using an interferometer contain errors. To overcome the limitations, we propose a method consisting of the following two steps. First, we evaluate the height data and set the invalid height area to be blank, using the characteristics of the modulus peak, which has a low peak value for signals that have low reliability in the interferogram. Next, we interpolate the blank area using the adjacent reliable area. Rubert roughness standards are used to verify the proposed method. The results obtained by the proposed method are compared to those obtained with a stylus profilometer. For the considered sinusoidal samples, Ra ranges from 0.053 μm to 6.303 μm, and we show that the interpolation method is effective. In addition, the method can be applied to a random surface where Ra ranges from 0.011 μm to 0.164 μm. We show that the roughness results obtained using the proposed method agree well with profilometer results. The R^2 values for both sinusoidal and random samples are greater than 0.995.

Keywords : Interferometry, Roughness measurement, Signal analysis, Surface interpolation, Roughness comparison

OCIS codes : (120.3180) Interferometry; (120.2830) Height measurements; (120.6660) Surface measurement, roughness

I. INTRODUCTION

Microstructural roughness measurements are of importance in manufacturing. Roughness measurements are performed by obtaining surface information. Nowadays, manufacturing technologies make structures that are more precise and smaller. Thus, surface topography measurement should be capable of being performed within a few minutes, and should be accurate to submicrometer levels.

There are several types of equipment for roughness measurements, such as the stylus-type profilometer, atomic force microscope, etc. In the early days of roughness measurements, stylus profilometers were widely used, but stylus measurements may damage the sample, and can be relatively time-consuming. Therefore, optical systems such as interferometers have been proposed as alternatives to stylus profilometers. While both profilometers and interferometers can measure a three dimensional surface, interferometers are advantageous compared to the profilometers due to their noncontact methods, as well as time efficiency.

There are two subcategories of interferometer: the phase-shifting interferometer (PSI), which uses a monochromatic laser, and the scanning white-light interferometer (SWLI), utilizing a white light source. Bristow *et al.* [1] used phase-shifting interferometry to measure roughness up to 6.25 μm. Brian Bowe [2] used white-light interferometry

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*Corresponding author: hjpahk@snu.ac.kr, ORCID 0000-0002-3838-6928

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for roughness measurements. The SWLI does not show ambiguity in its measurements, which is a strength over the PSI [3]. Therefore, the SWLI is now a standard device for roughness measurements.

Since the 1990s there have been many studies on surface roughness measurements using a SWLI. These studies have focused on evaluating the SWLI for roughness measurements, by comparing it to other types of devices, or studying the origin of errors [4-7].

The SWLI is an optical system that employs an interferometric lens; as it uses a lens, the numerical aperture (NA) limits the light received by the system. When the slope angle increases, the reflected light cannot enter the light-receiving part of the lens, and it becomes challenging to obtain proper information [8]. The objective lens collects not only the reflected and diffracted beam from the ideal imaging point, but also the neighboring light from the vicinity within a diameter of 1.22 λ / NA [8]. This leads to calculations with erroneous height data, and hence decreases the accuracy of the roughness measurement. This limitation influences the measurement of the light reflected from the slope. Studies have focused on the analysis of this limitation [9]. To overcome this limitation of the optical system, studies have considered using a post-processor, such as a Gaussian filter [10]. However, as the post-processing uses error-influenced data, the previous research has its own limitations in increasing the accuracy of the Ra measurement.

In this study, we propose a two-step method to overcome the above limitations of optical systems. The first step of the method is using the modulus peak value to set a certain sloped area not to be analyzed, as it is considered an erroneously measured region, due to the limitations of the optical system. Then the method interpolates to fill the unanalyzed area, using reliable height data from the vicinity. The validity of the proposed method was examined using the Sine and Random roughness standard samples. The accuracy of the height data (surface) and the measured value (Ra) are verified by profilometer measurements. The presented method is simple and very promising for increasing the reliability of roughness measurements.

II. METHODS

Figure 1 shows the flowchart of the proposed method. The interferograms are analyzed using the SWLI method [11]. As discussed above, the light that is reflected from a slope is not sufficiently gathered into the lens, and therefore leads to weak interferogram signal and shows modulation as low as the noise level. Note that steeper slopes lead to weaker interferogram signals. Thus, we propose a method to discriminate these sloped areas and interpolate the sloped or noisy area using the neighboring analyzed height data.

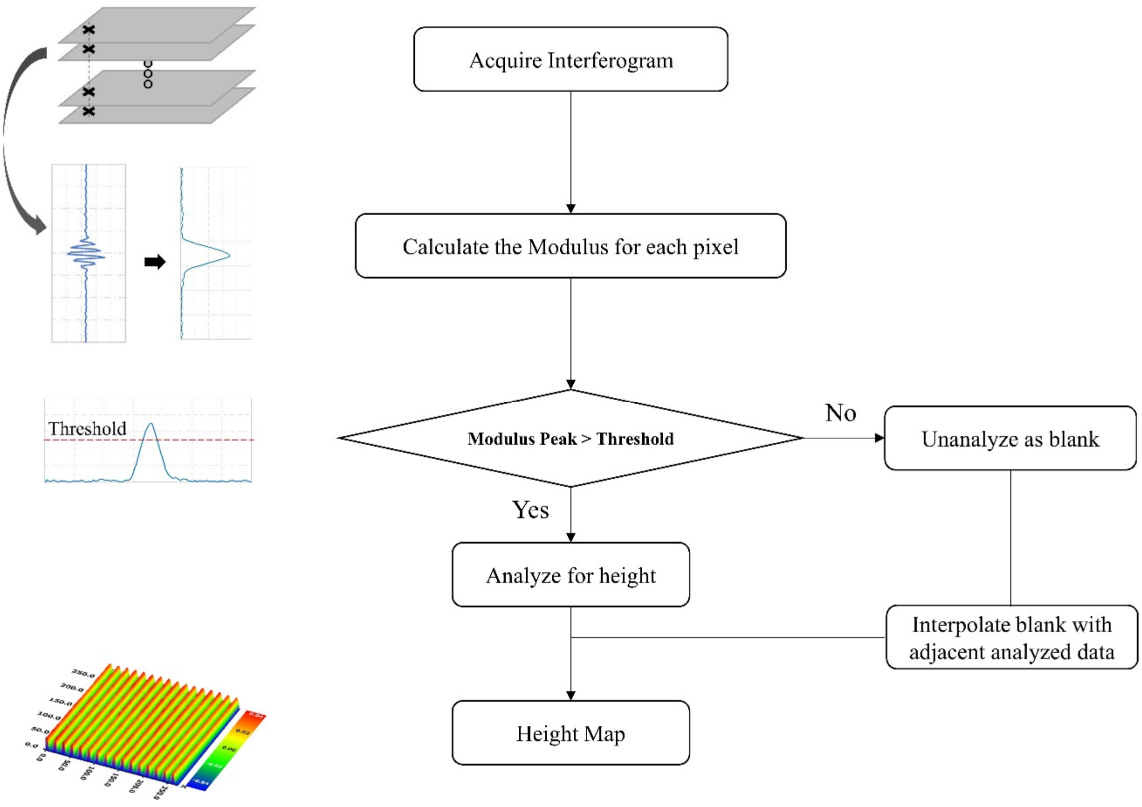


FIG. 1. Flow chart of the proposed method.

2.1. Evaluation of Reliable Height Data

The interference signal from the white-light interferogram is shown in Fig. 2. As shown in Fig. 3, the light reflected from the slope is not fully gathered into the lens. Therefore, the interference signal of these areas is modulated and has a weak background light intensity. For a complex structure, the light's behavior becomes unpredictable. Since the interference signal may be unreliable for this area, it is necessary to separate such a signal from the reliable signal [9].

In SWLI, peak modulation is used to evaluate signal validity. The main algorithm uses the modulus of the interferogram to find its peak position, to extract the zero optical-path difference (OPD) for the height analysis. The modulus calculations employ the sequential intensities of the interferogram, as shown in Eq. (1) [12], where M_i represents the modulus value at the i^{th} scanning step (phase step) and I_i represents the intensity value at each step. After the corresponding calculations for the whole range of the scanned interferogram, the white light interferogram (Fig. 2) can be converted to a modulation graph, as shown in Fig. 4.

$$M_i = \sqrt{(I_{i-1} - I_{i+1})^2 - (I_{i-2} - I_i)(I_i - I_{i+2})} \tag{1}$$

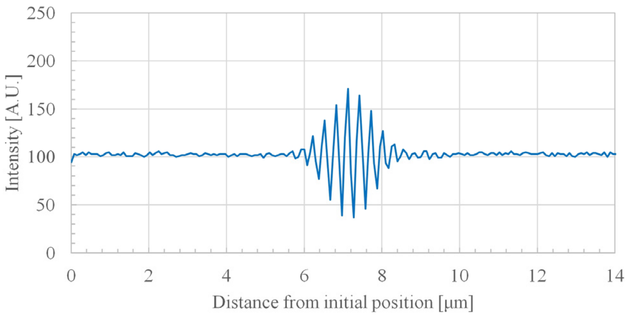


FIG. 2. Interferogram.

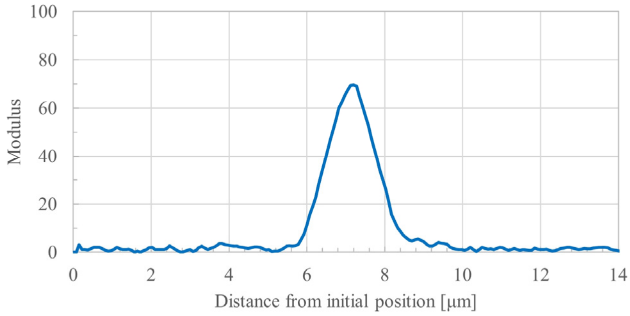


FIG. 4. Modulation of interferogram.

In the previous study, a modulation signal analysis is applied to the interferograms for each pixel. [12] Using the conventional method, the surface results contain erroneous data after the analysis. Due to the slope as well as the low signal-to-noise ratio (SNR), the modulation of these signals has a low peak intensity and poor measurement reliability [11]. The surface errors lead to errors in the roughness measurements.

Therefore, to check the signal's validity we propose a threshold method for the peak intensity of the modulation of the interferogram. Using the modulation peak value, we can check whether a pixel's height data is reliable. By applying this criterion, all of the interference signals within the field of view (FOV) are analyzed, as follows. For the pre-analysis step, we use the threshold of the modulation peak values for the interference images, including all of the pixels in the FOV. The reliable region is valid for the measurement analysis, while the unreliable region is designated "invalid". In this study, the threshold value of the modulus peak is 10. A threshold value of 10 can effectively filter erroneous height data due to the slope in a sample.

2.2. Interpolation Method

To fully analyze the surface, each invalid area should be interpolated using the reliable height data from its vicinity.

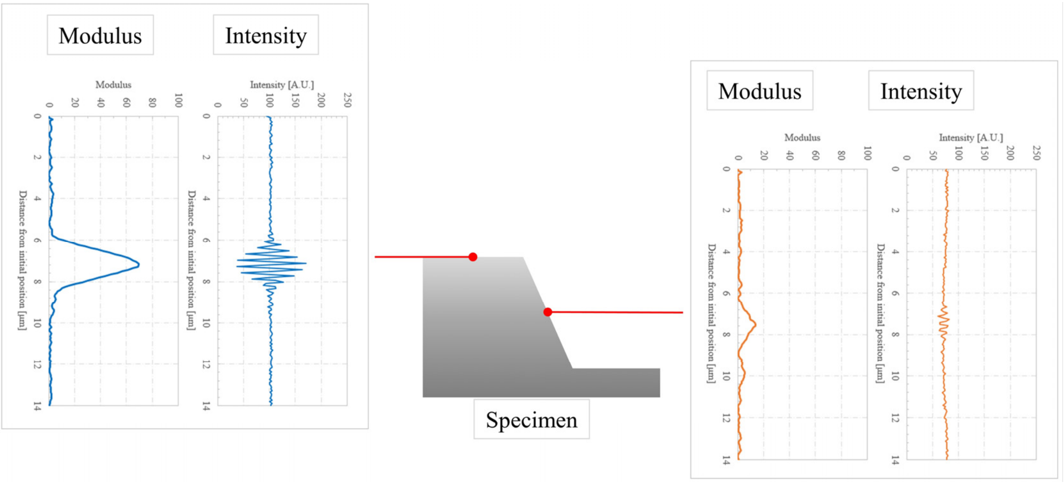


FIG. 3. Interferograms of a flat area (left) and a sloped area (right).

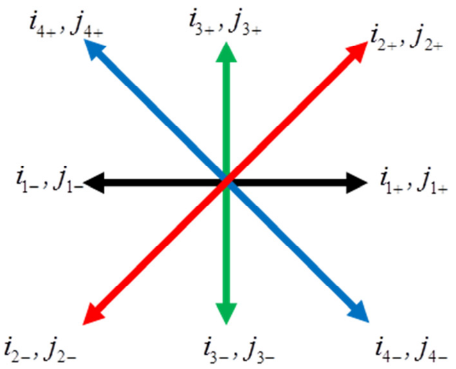


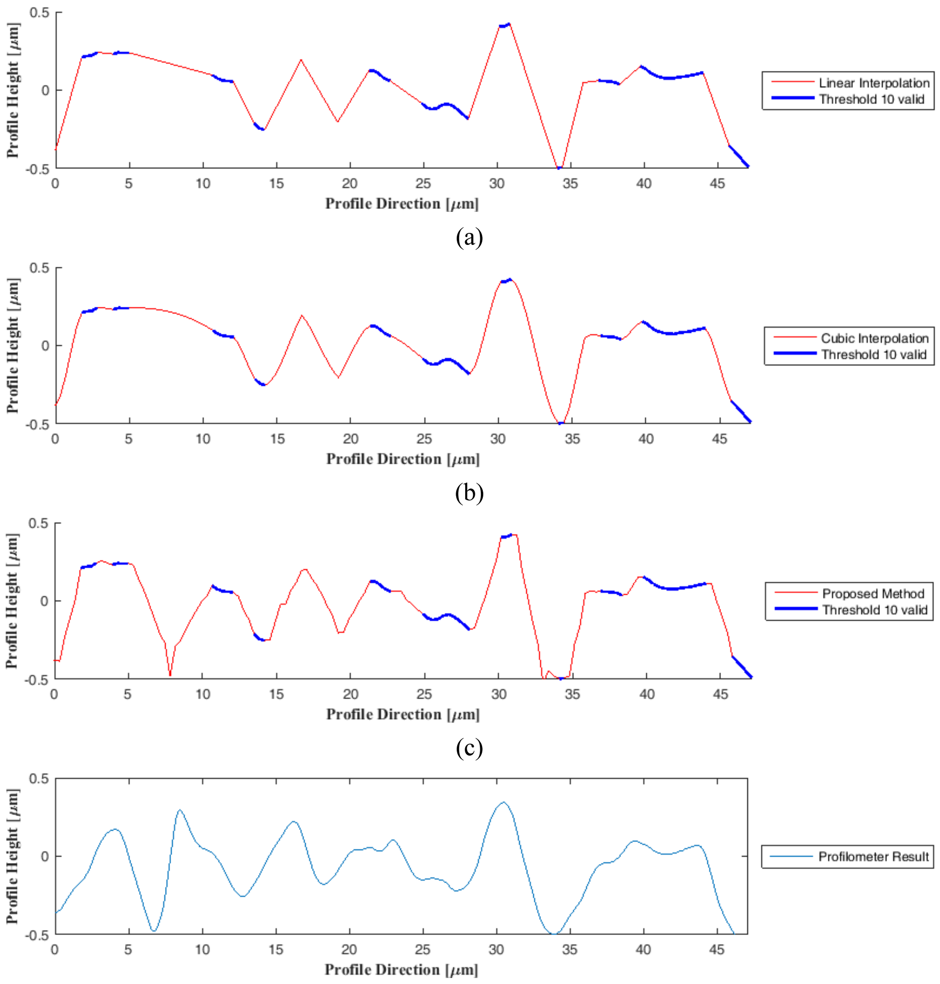
FIG. 5. Searching along four directions.

To interpolate the blank area, we need to take into account that invalid areas appear randomly over the field of view. Without such consideration, both bilinear and bicubic interpolation are limited only to data fitting; they cannot be applied for reliable data reconstruction, as only the vertical and horizontal directions are considered. Note that information for more than two directions is required for the interpolation. Interpolation using the radially adjacent regions to adequately fill the data would be ideal; therefore, the interpolation method should be applied using the eight adjacent directions.

Thus we propose a simple average linear interpolation method for the invalid area. The interpolation starts at the unreliable pixel and searches bidirectionally in four directions, until it reaches the nearest reliable pixel.

Then, the distance and height information of the closest reliable data pixel in each direction are used for the interpolation. The interpolated height value *H*(*i, j*) at pixel (*i, j*) is expressed in Eq. (2) as the average of linearly interpolated heights of each searching direction.

$$H(i,j)=\frac{\sum_{k=1}^{4}h(i_k,j_k)}{N} \tag{2}$$



(a)

(b)

(c)

(d)

FIG. 6. Interpolation results for the Rubert 503 random sample at 20× magnification: (a) linear interpolation, (b) cubic interpolation, (c) the proposed method, and (d) profilometer measurement. In (a)-(c), the bold blue sections represent the valid data, while the thin red sections represent the interpolation.

Note that (i_{k+}, j_{k+}) and (i_{k-}, j_{k-}) are the closest reliable pixels in the positive and negative directions of the k^{th} scan, respectively, while $h(i_k, j_k)$ is defined as

$$h(i_k,j_k)=\begin{cases}\dfrac{H(i_{k+},j_{k+})d(i_{k-},j_{k-})+H(i_{k-},j_{k-})d(i_{k+},j_{k+})}{d(i_{k+},j_{k+})+d(i_{k-},j_{k-})}, D(i_k,j_k)<2D_{\min}\\[2ex] 0, D(i_k,j_k)\geq 2D_{\min}\end{cases} \tag{3}$$

If the distance to a reliable pixel is very large, the interpolation results may be inaccurate. Therefore, as shown in Eq. (3), if the distance is greater than twice the minimum distance of the four scan directions, the interpolated height data is not included in the average calculations. In Eq. (3), $D_{\min}$ is the minimum distance of the four search directions, while the distance $D(i_k, j_k)$ is the Euclidian distance, defined as

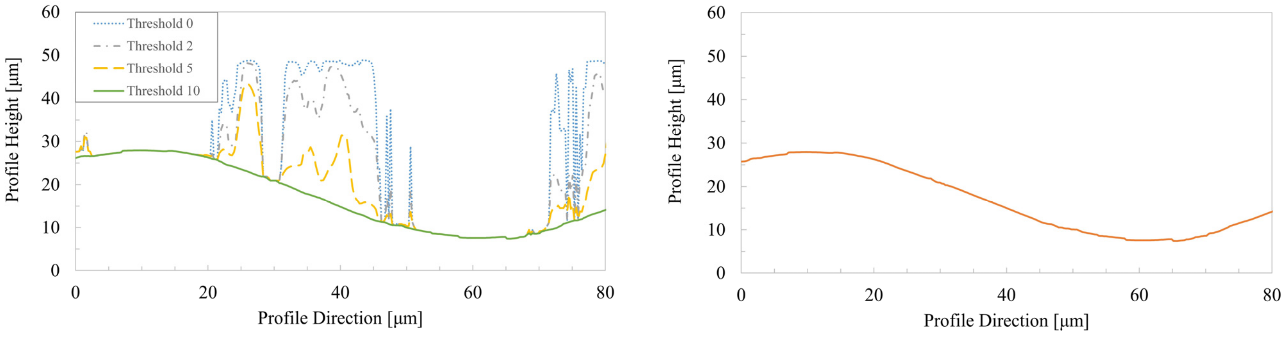
$$D(i_k,j_k)=\sqrt{(i_{k+}-i_{k-})^2+(j_{k+}-j_{k-})^2} \tag{4}$$

Figure 6 shows several types of interpolation results for the Rubert random sample 503, at 20× magnification. Neither the normal linear interpolation nor cubic interpolation contain the leftmost valley shape in the interpolated result. However, the proposed method can reconstruct the leftmost valley in the profilometer measurements. This demonstrates that the considered four-direction method can fully reconstruct the actual shape, using the reliable height data. Therefore, the proposed method is suitable for roughness measurements.

2.3. Method Verification

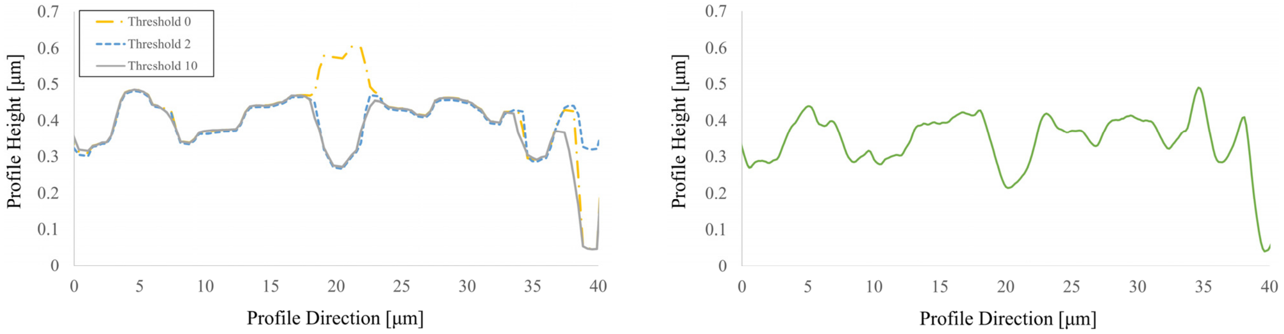
The objective of this study is to reduce the error in roughness measurement for the sloped areas. Regional slope is the main factor that causes inaccurate roughness measurements. With the proposed method, we can reduce the error of the roughness measurement.

Figure 7 shows the sinusoidal sample profile for the proposed method; several values for the modulus threshold are considered. When the modulus threshold is zero, the erroneous region is not filtered and the sloped area's result does not coincide with the measurement by a profilometer. In contrast, as the modulus threshold increases the profile becomes similar to that obtained by profilometry. This suggests that the proposed method is effective for a sloped area, which is assumed to provide a weakly reliable signal as well as erroneous height data.



(a) (b)

FIG. 7. Measurement of the sloped area for the Rubert 525 sinusoidal sample: (a) results obtained by the proposed method for several threshold values (20× magnification lens); (b) profilometer results.



(a) (b)

FIG. 8. Profile measurements for the Rubert 503 random sample: (a) results obtained using the proposed method with several threshold values (20× magnification lens); (b) profilometer results.

Similar phenomena are observed for the random sample, as shown in Fig. 8. The random sample can be regarded as a combination of various slopes. Note that the sloped region could be inappropriately analyzed due to noise. However, the threshold method can achieve accurate measurements by interpolation, using more reliable data.

Due to the correction of the height data included in the proposed method, the accuracy of the measurement for various Ra values is high, as shown in Fig. 10. Therefore, the proposed two-step method represents a powerful approach for roughness measurements.

III. EXPERIMENTAL SETUP

3.1. Scanning White-light Interferometer

A typical SWLI is used in our experiment, as shown in Fig. 9. A commercial white light-emitting diode plus a filter for producing a Gaussian-shaped spectral intensity are used; its mean wavelength is 613 nm, range 500-700 nm, and its spectral full width at half maximum (FWHM) is 116 nm. The magnifications of the Mirau type objective lenses are 20× and 50×. The images are captured at each phase-shift step, produced by the vertical movement of a piezoelectric transducer (PZT). The phase step is 76.625 nm, 1/8 of the mean light wavelength. The resolution of the 8-bit monochrome charge-coupled device (CCD) camera used for the image acquisition is 1280 (horizontal) × 1024 (vertical) pixels. The stack of captured images is called an interferogram.

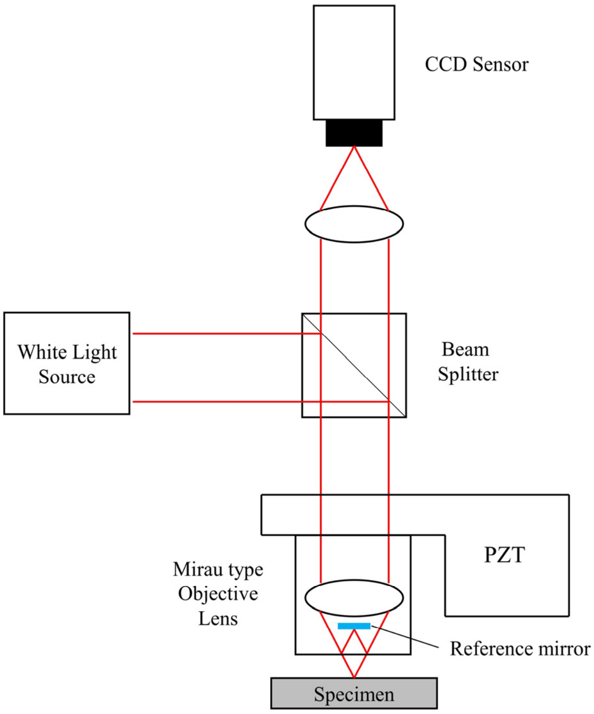


FIG. 9. Schematic of the optical system.

3.2. Profilometer

A commercial profilometer is used for comparison to the proposed method. The specifications of the employed profilometer are shown in Table 2.

3.3. Roughness Standard Sample

In our experiment, a Rubert sample with a vertically extended shape of its horizontal profile is used. The roughness values measured using the profilometer are shown in Tables 3 and 4. The roughness of the same area is measured using the SWLI, and the results are discussed in section 4.

TABLE 2. Profilometer specifications

Equipment	Profilometer (Dektak8)	
Environment	Vibration class: VC-E	
Measurement condition	Field of view	417 μm × 152.4 μm
	Sampling	3000(H) × 48(V)
	Sampling interval	0.139 μm × 3.175 μm

TABLE 3. Ra values measured by the profilometer, for the sinusoidal sample

Sinusoidal Sample No.	Ra [μm]
525	6.303
527	2.874
528	0.504
529	0.102
530	0.954
531	0.308
542	0.053

TABLE 1. Specifications of the interferometer

Equipment	SWLI measurement system		
Environment	Vibration class: VC-E		
Measurement condition	Objective lens	20× (3D)	50× (3D)
	Sampling	1280(H) × 1024(V)	1280(H) × 1024(V)
	Spatial sampling	0.367 μm	0.147 μm
	Field of view	469.76 μm × 375.81 μm	188.16 μm × 150.53 μm

TABLE 4. Ra values measured by the profilometer, for the random sample

Random Sample No.	Ra [μm]
501	0.011
502	0.032
503	0.059
504	0.164

IV. RESULTS

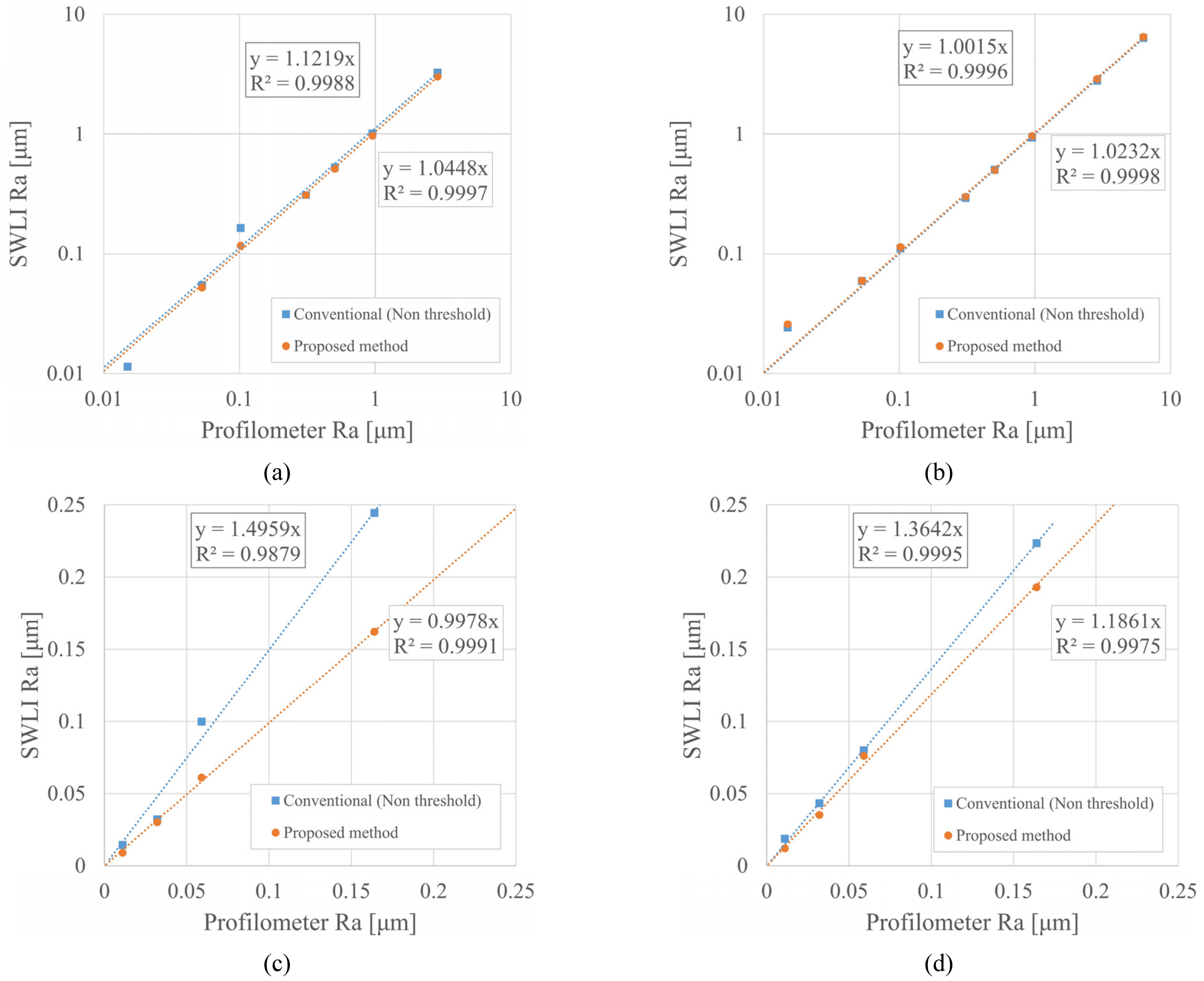
To verify the applicability of the proposed method for general roughness measurements, sinusoidal and random roughness samples are considered. We set Ra as the representative value of the roughness and validate it using the profilometer value, which is regarded as the true value. To check the improvement of the roughness measurement by discriminating the invalid regions and using the interpolation method, we conduct the experiments on an identical area.

We measure the Ra of various random samples using the method proposed in this paper. The comparison to the results obtained by profilometer shows that the proposed method is effective for accurate measurement of Ra.

V. DISCUSSION

The aim of this study was to increase the reliability of roughness measurement using a SWLI. Figure 10 shows plots of the Ra results. The slope of the curve represents the agreement between the reference profilometer results for each conventional method (zero threshold without interpolation) and the proposed method. If the slope of the curve is close to 1, it fits well with the true value. The proposed method shows better results than the conventional method for sinusoidal and random samples, because the slope is closer to 1.

However, outlier points can be observed at 50× magnification, as shown in Fig. 10, even if the proposed method is employed. This limitation of the proposed method



(a) (b)

(c) (d)

FIG. 10. Ra values obtained using a profilometer: (a) sine sample (20× magnification lens), (b) sine sample (50× magnification lens), (c) random sample (20× magnification lens), and (d) random sample (50× magnification lens).

originates from our assumptions: We have assumed that the measurement of the sloped region is less valid, and that these sloped regions can be interpolated as long as there are adjacent valid data. For a small field of view (at 50× magnification), fewer valid data exist, hence it is unlikely to achieve accurate interpolation in the sloped region. This can explain the presence of the outlier points.

We discuss the proposed interpolation method. We propose a four-direction interpolation method, as the unreliable height data occurs mainly in sloped regions; the areas of invalid regions can vary with position. Considering previously reported interpolation methods [13], we conclude that the bilinear method is not suitable, as it only provides a linear profile. In addition, for polynomial interpolations such as the bicubic interpolation, wrapping may occur; hence it is challenging to obtain reliable height data. Using the sinusoidal sample profile measurements, we could confirm that the proposed method properly interpolates the invalid area.

Next, the selection of the threshold is discussed. The profilometer value is set as the true value for the Ra roughness. Figure 11 shows the threshold as a function of the error of the Ra. As shown in Fig. 10, a threshold value of 10 can minimize the error. This threshold is used when the sample is homogeneous in exactly the same optical system. The sample used in this study can be assumed to be as homogenous as a metal; we have not modified the optical system during the experiment, except for changing the magnification. However, for inhomogeneous samples there is a reflectance difference in the field of view. In such a case, the global threshold cannot be used for a specific region that has a different reflectance compared to the others. In typical roughness measurements the sample is usually homogenous; hence the proposed method can be effective, if we know the threshold value for the sample. If the sample is inhomogeneous, however, an appropriate threshold value has to be chosen.

VI. CONCLUSION

In this paper, we proposed a two-step method to overcome the limitations of the optical system in measuring roughness using a SWLI.

In terms of hardware, the proposed method can be applied for a typical SWLI hardware system consisting of a white LED light source, an interferometric lens, a piezoelectric transducer used to make the phase shift, and a CCD camera.

To improve the accuracy of the roughness measurements, the proposed method consists of two steps. In the first step, taking into account that the magnitude of the modulus peak is not large in the sloped or noisy regions, we set the height data with small modulus peak values to a blank area. In the second step, we calculate the height data for the blank area by interpolation, using the reliable peripheral data.

The proposed approach is promising, as it can overcome the optical limitations that are related to the numerical aperture of the lens. Therefore, we can reduce the error in the sloped area, where the modulation is as small as the noise level.

To verify the proposed method, we use sinusoidal and random roughness samples. We measure the same point of the sample using both SWLI and profilometer. The one-dimensional profile as well as the Ra value of the measured area are used to verify the accuracy of the proposed method.

The measurements show that the Ra of the sinusoidal sample ranges from 0.053 μm to 6.303 μm. The results for the sinusoidal sample show that our hypothesis about the small modulation peak value in the sloped area is valid, and the proposed interpolation method can complement the height data of the blank area. The Ra of the random sample ranges from 0.011 μm to 0.164 μm. The proposed method can increase the accuracy of the Ra measurement for the random sample.

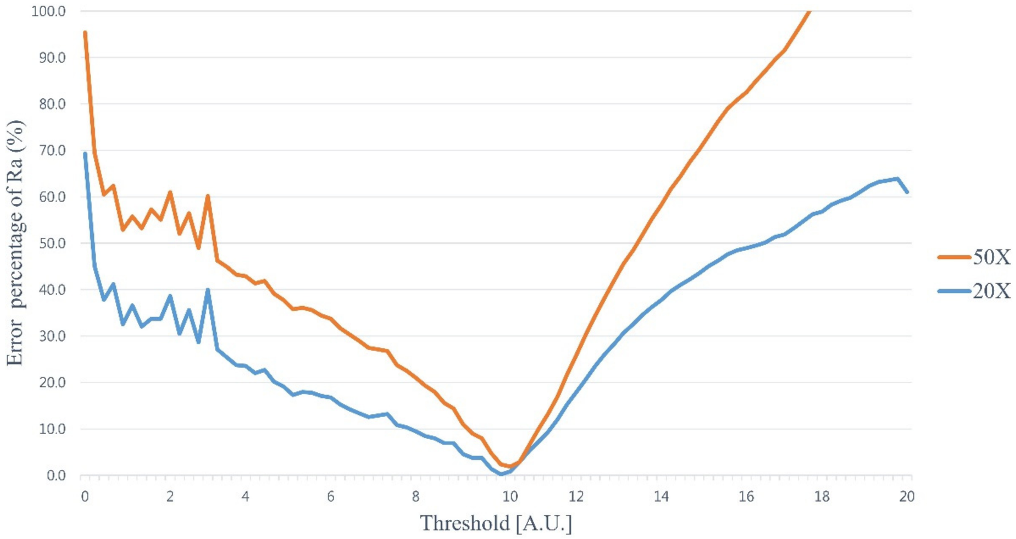


FIG. 11. Error percentage of Ra as a function of the threshold for the Rubert 503 random sample.

The comparison of the proposed method to the profilometer method shows that the proposed method is better than the conventional method of interpolation. The R^2 value for the sinusoidal sample is larger than 0.9996, while that for the random sample is larger than 0.996. In conclusion, when measuring roughness using an SWLI, we can increase the accuracy of Ra measurement by selecting only reliable height data and interpolating the unreliable height area.

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