**Proceedings of the ASME 2021 17th International
Manufacturing Science and Engineering Conference
MSEC2022
June 27-July 1, 2022, West Lafayette, Indiana, USA**

MSEC2022-85660

REVIEW OF KEI METHOD-BASED DIMENSIONAL MEASUREMENT, POSITIONING CONTROL AND PART INSPECTION

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ABSTRACT

This paper reviews knife-edge interferometry (KEI) capable of inspection and metrology for various engineering applications, including displacement measuring sensors for dynamic system controls and edge quality of the parts, such as cutting tools, corrosive blades, and photomask patterns. This paper includes the modeling, design, and data analysis of KEI. With the expanding market of manufacturing industries, edge topography and instrumentation technology become more and more vital to industrial manufacturing-related applications such as cutting tool wear inspection, photomask edge roughness determination, and edge corrosion propagation monitoring. Due to the limitation of measurement requirements like non-contact (photomask inspection), in-situ (cutting tool inspection), and real-time (corrosion propagation monitoring), there are only a few methods available in the market above, and those methods are based on post-processing. The KEI is capable of on-machine measurements, especially for the nanopositioning systems, providing a large working range and positioning accuracy compared with the conventional displacement sensor. This review addresses the current and future KEI technology. Here, including the theoretical approaches to KEI, this review details the data analysis method to feature the edge topographical information.

Keywords: Knife-edge interferometry, Edge diffraction, Pattern inspection, Control, Defect inspection

1. INTRODUCTION

The development of knife-edge interferometry-based metrology systems was driven by the industry's demand for monitoring the workpiece quality and the machine lifecycle at a low cost without any contact during the whole manufacturing process. KEI offers solutions for precision measurement in a low cost, in-situ, and real-time feature.

Knife edge interferometry was firstly discovered by Foucault in 1856 [1]. In 1961, Keller summarized the explanation of knife-edge interferometry by geometrical optics [2]. Formally, the knife-edge diffraction was utilized for diffraction-related analysis and did not get much attention on its potential of being an optical sensor.

The first KEI-based metrology sensor was proposed in 2006 [3] and has been utilized for dimensional measurement applications. Typically, there are two types of sensors for conventional dimension measurement: contact sensor, such as linear variable differential transformer (LVDT) [4], and non-contact sensors, such as laser interferometers [5] and capacitive sensors [6-9]. Industries choose different types of displacement sensors depending on the measurement requirement. For instance, the contact displacement sensors will be utilized in applications with high resolution (submicron), while the non-contact sensors are always accompanied by the requirement of high working range and fast displacement changes. There are no conventional methods for displacement measurement that can satisfy high-performance, compact, large range, and low-cost features simultaneously. However, a KEI-based displacement sensor can solve this problem and fill the blank in displacement metrology.

Meanwhile, the edge quality can also be determined by a KEI-based system. The traditional precision surface measurement studies are more likely to focus on the characterization of the surface such as surface roughness of a mirror by using SEM (Scanning Electron Microscope), AFM (atomic force microscope), confocal microscope, etc. [10-13] These methods show precision results of the measured surface. However, these methods above may be trapped by the high-aspect-ratio (HAR) problem since it's hard to scan a big structure with its tiny feature being inspected simultaneously. In 2017, Jeon [15] proposed the method that utilizes the KEI for cutting tool wear monitoring. Based on the difference in data recorded by the KEI system, the edge profile can be specified in real-time.

Based on the above KEI-based method, in 2021, we proposed the preliminary study for a KEI-based photomask inspection system. It's the first time the KEI be utilized for dimension measurement and edge characterization simultaneously by KEI-based line-scanning.

2. Measurement Principles

2.1 Conventional KEI

The measurement principle of the conventional KEI system is schematically illustrated in Fig. 1 based on the knife edge diffraction theory. When light is partially blocked by a sharp edge (e.g., razor blade or photomask pattern edges), based on the Huygens-Fresnel principle [16], the shined area of the edge itself can also be viewed as a Huygens wavelet, which can be represented as a point source in the optical system. Thus, the incoming light will interfere with the scattered point light source on the edge. With the edge moving along the perpendicular direction of the optical axis, the energy fluctuation from the interference can be recorded. Assuming the incoming light is a laser beam with the diameter equal to a, a sharp edge placed perpendicular to the optical axis and the photodiode located along the optical axis. Now the light intensity recorded on the sensor can be calculated by Fresnel equation [17] as.

$$U_0(r_0) = \frac{-je^{jkz_0}}{\lambda z_0} \int_{-\frac{a}{2}}^{\frac{a}{2}} e^{\frac{jk}{2z_0}(x_0-x_s)^2} dx_s \int_{-\frac{a}{2}}^{\frac{a}{2}} e^{\frac{jk}{2z_0}(y_0-y_s)^2} dy_s \tag{1}$$

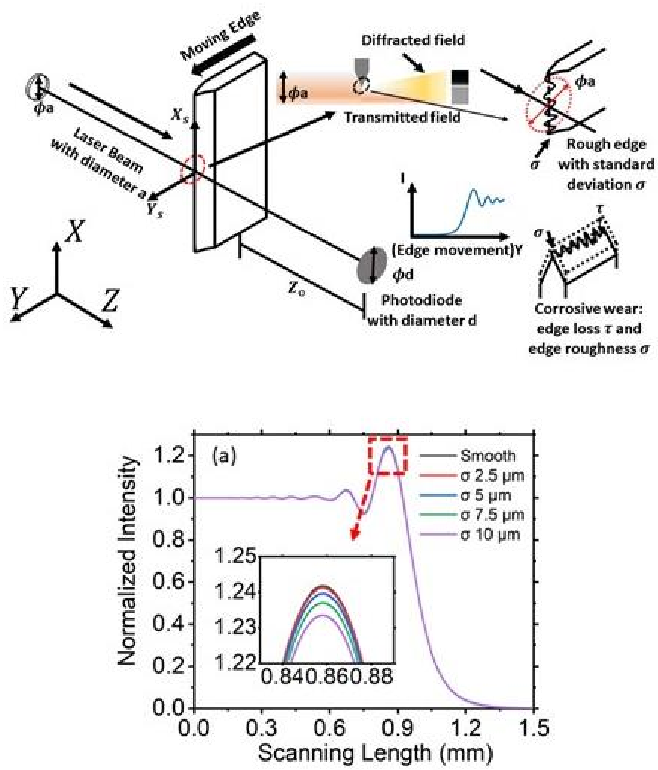

FIGURE 1. KEI system (top) and simulation results (bottom) [29].

In the above equation, j is the expression of the imaginary part. k is the wave number, which equals $2\pi/\lambda$. λ is the wavelength of the laser beam. z_0 is the distance between the razor blade and the sensor. The x_o and y_o are x and y positions of the sensor while x_s and y_s show the points on the cross-section of the sharp edge plane for integration. In 2014, Lee [5] added a new parameter into the conventional Fresnel diffraction equation for edge roughness characterization. In his article, the edge roughness profile is satisfied with the Gaussian probability density function (PDF). In that case, the roughness will add additional scatter parameters and change the diffraction intensity distribution. The deviated fringe pattern can be calculated by adding a PDF term with standard deviation σ into the Fresnel diffraction equation, that is,

$$PDF(\Delta h) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{\Delta h^2}{2\sigma^2}} \tag{2}$$

Thus, the edge diffraction effect on the edge roughness can be expressed as [5]:

$$U_0(r_0) = \frac{-je^{jkz_0}}{\lambda z_0} \int_{-\frac{a}{2}}^{\frac{a}{2}} e^{\frac{jk}{2z_0}(x_0-x_s)^2} dx_s \int_{-\frac{a}{2}}^{\frac{a}{2}} e^{\frac{jk}{2z_0}(y_0-y_s)^2} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{\Delta h^2}{2\sigma^2}} dy_s \tag{3}$$

The simulation of equation 2 with different edge roughness parameter can be found in Fig. 1 as well.

2.2 Beam-shaped KEI

The principle of BSKEI can be seen in Fig.2. For the conventional KEI system, we use the laser beam with its diameter in the millimeter range, which means the scanning resolution is in units of millimeters for roughness determination. However, for the BSKEI, with an objective lens added between the laser and the sharp edge, the resolution of the edge roughness can down to 100 μm, 10 times greater than the conventional KEI system.

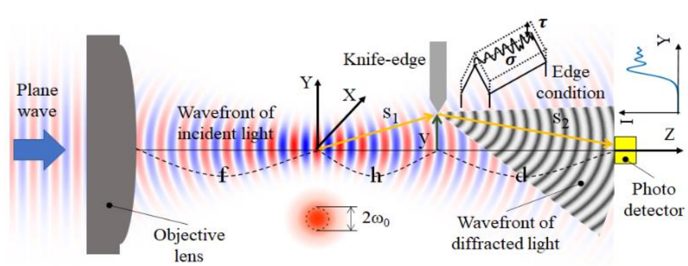

FIGURE 2. Principle of BSKEI system [30].

Compared with the conventional KEI system, the main advantage of the BSKEI system is its scanning resolution. For the KEI system, since we use the collimated laser beam without a lens for scanning, the scanning resolution is confined by the diameter of the aperture in the system. However, due to the diffraction effect of the aperture itself, if the aperture is in units of ~100 μm, then the output light from the aperture can be viewed as a point light source instead of the parallel light source. Thus, the resolution of the conventional KEI system was limited. Now if we have an objective lens in the system like Fig.2, the objective lens focuses the incident plane wave on the focal point and spread out the wave to the edge surface. In the BSKEI system, the resolution of the system is controlled by two parameters: the divergence angle for the objective lens and the distance between the focal point and the edge surface. Since these two parameters can be controlled by controlling the objective lens, theoretically we can increase the resolution from 1 mm to the level of diffraction limit (units of nanometers).

Another advantage for the BSKEI compared with conventional KEI systems is its spatial-filtering feature. For theoretical simulation of knife edge diffraction, we only calculate the light intensity at the on-axis point. However, in the real-world experiment, the sensor has its sensing area. Conventionally, the diameter for the sensing area is always more than 10 μm. In that case, not only the light intensity at the on-axis point will be recorded, the off-axis points on the sensing area will also record the light intensity and ruin the data [29]. But in the BSKEI system, just like the schematic in Fig.2, since the incoming light is not a plane wave but a spherical wave, only those light close to the optical axis will be recorded on the sensor, all rest of the light will not be recorded. That filtering effect can extremely increase the feature extraction in data analysis [30]. Compared with the conventional KEI system, the BSKEI system can improve the system resolution and sensitivity simultaneously by adding an objective lens into it. It costs more due to adding an additional element into the system, but the system performance also improves significantly [30].

3. Current Applications

3.1 Displacement Sensor for Nanopositioning Control

For The KEI-based system was applied to nanopositioning systems to gather the displacement signal of stage position. Lee [5,9,17-23] proposed a KEI-based optical knife edge sensor (OKES) system for XY nanopositioning measurement. The experiment setup can be found in Fig. 3. A double compound-type flexure mechanism with a displacement range of more than +/- 1.0 mm was designed and fabricated. In this setup, two knife-edges were placed in the stage to measure the XY displacement for feedback stage nanopositioning control. A laser beam with its wavelength equal to 650 nm and diameter equal to 5 mm will go through a beam splitter and pass through these two knife edges (razor blade). Voice coil motors give the motion control for the nanopositioning system. Four photodetectors were placed behind the knife edge for light intensity recording purposes. Figure 3 shows the result of the linear stage movement measurement versus the theoretical movement. The sensitivity for the OKES system is 8.99 and 9.02 mV/μm with a range of +/- 500 μm and non-linearity of 0.60% and 0.73% for the X and Y axis, respectively. The resolution for the OKES system is 21.5 and 19.3 nm along the X and Y axis, respectively. The OKES system shows its great potential to be a tool in nano-scale precision positioning system setup. This tool has been utilized for linear and angular motion measurement in a single axis nanopositioning system [24]. Wang [25, 26] use the KEI-based system for 2-D straightness error measurement of a linear stage provides local information or be performed offline, due to the complexity of metrology systems, the requirement for operational stability, and the inadequacy of metrology software, not to mention online measurement at high working speeds.

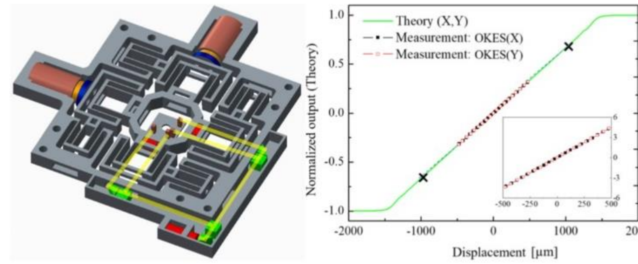

FIGURE 3. Experiment setup and results for KEI-based nano-positioning control system [21]

3.2 Displacement Sensor for Spindle Monitoring

In 2019, Lee [27] proposed the first KEI-based system for dynamic stiffness and damping measurement for a precision spindle. In this paper, he called the system 'OCES' (optical curved edge sensor) system. The experimental setup can be found in Fig. 4. This system split the HeNe laser by using two beam splitters, while the split beams transmit along the edge of the spindle shaft. Four photodiodes were placed around the spindle to record the light intensity for each split laser beam. When the spindle is working, the misalignment of the spindle will lead to changes in recorded light intensity from the photodiode. In that case, the stiffness and the damping ratio can be determined. The OCES system shows high linearity and the spindle condition during the experiment has been verified by using the capacitive sensor for validation. In 2021, Kim [28] proposed a KEI-based method for machine process monitoring.

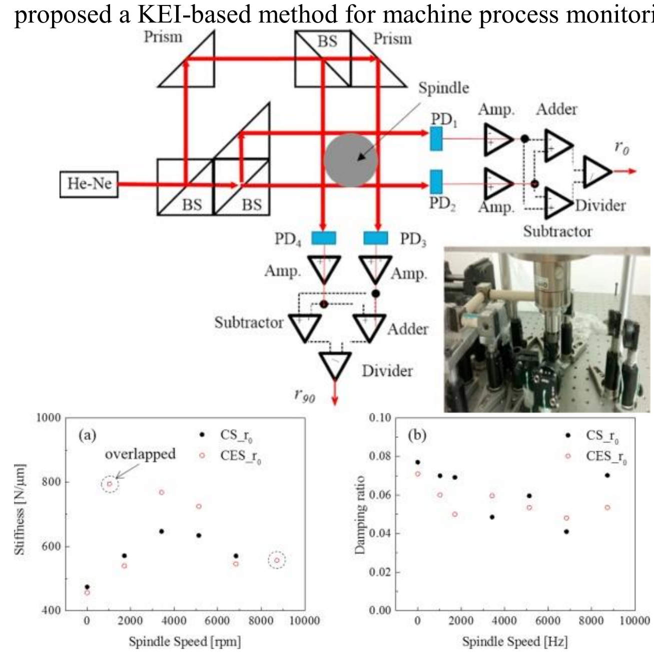

FIGURE 4. Experiment setup (top) and results for KEI-based spindle monitoring system (bottom) [27].

3.3 Edge Roughness Monitoring

As mentioned in the theoretical part, the KEI system can be utilized for edge roughness measurement. In 2017, Jeon [14] proposed a KEI-based system for cutting tool wear monitoring. The experiment setup can be seen in Fig. 5. To specify the difference between the worn-out cutting tool and the sharp cutting tool, the cross-correlation method was implemented for data analysis. Two groups of data, fringe pattern from worn-out tool and sharp tool, will be brought into cross-correlation calculation. The cross-correlation shows the similarity of two groups of data as a function of one relative to another. The output pf cross-correlation will be two parameters: pattern shift, τ, and the similarity value R of two groups of data. Based on the theory, compared with the sharp cutting tool, the worn-out cutting tool will generate the attenuated fringe pattern. If the cutting tool changes in roughness without any attrition wear, the cross-correlation result will return a similarity value changes with no pattern shift. In 2021, Wang [29] implemented this system for edge corrosion monitoring. Moreover, Wang [30] added an objective lens between the laser diode and the sharp edge to increase the sensitivity and the resolution of the conventional KEI system. The BSKEI (beam-shaped knife-edge interferometry) system is more than 10 times more sensitive compared with the conventional KEI method

3.4 Photomask Inspection System

Since the KEI system can measure the dimension and the roughness simultaneously, it is possible to use the KEI-based system for a photomask inspection. In 2022, Wang [31] proposed the method for a photomask inspection system. Due to the high-resolution requirement in the photomask inspection process, he used the BSKEI method for measurement to increase the resolution. The experimental setup can be seen in Fig. 6. In this research, we use the conventional cross-correlation method for pattern dimension determination, while the roughness was analyzed by a wavelet-based feature extraction method. The simulated result can be seen in Figure 7. Based on the simulation result, a higher magnification objective lens provides higher sensitivity of the roughness detection, which satisfies the experiment result in [29]. The whole experiment is validated by the picture of the pattern and the error rate is less than 0.5%. As a result, the pattern width, interval, LER (line edge roughness), and arbitrary defects on the photomask can be inspected and characterized. The experiment result can be seen in Figure 8. By using the BSKEI-based system, we successfully measured the 500 μm width linear pattern on the photomask. Compared with the results from the microscope validation, the difference in width measurement is only 0.47% (501.1 μm from microscope camera validation and 500.5 μm from the BSKEI method). When an additional film layer was added on the photomask to increase the width for the Cr coated area, the measured width changes from 501.1 μm to 1094.1 μm from microscope validation, while the measured result by BSKEI system changes from 500.5 μm to 1091.5 μm. The measurement result from the BSKEI system showed good agreement with the validation result. Also, with the additional layer with a rough edge added to the photomask, the roughness-relative value decreases from 0.991 to 0.925 while the control group with nothing added keeps its relative value close to 1.

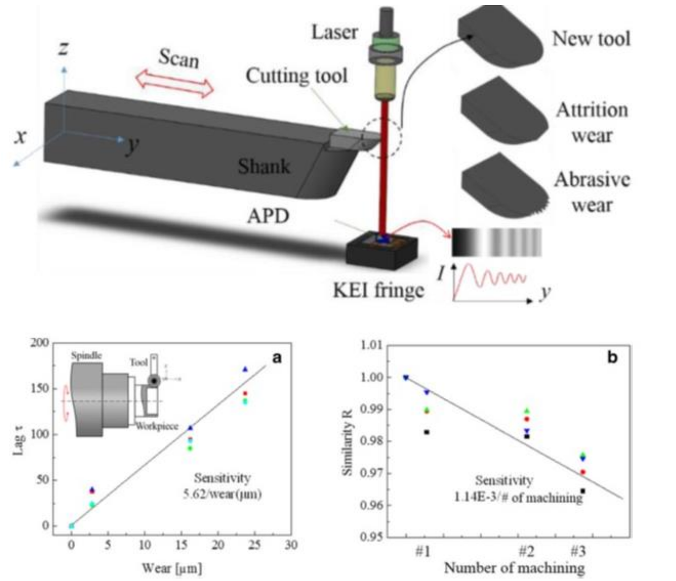

FIGURE 5. Experiment setup and results for KEI-based edge roughness monitoring system [14].

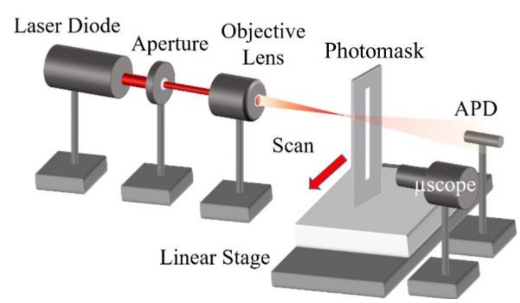

FIGURE 6. Experiment setup for KEI-based photomask inspection system [30]

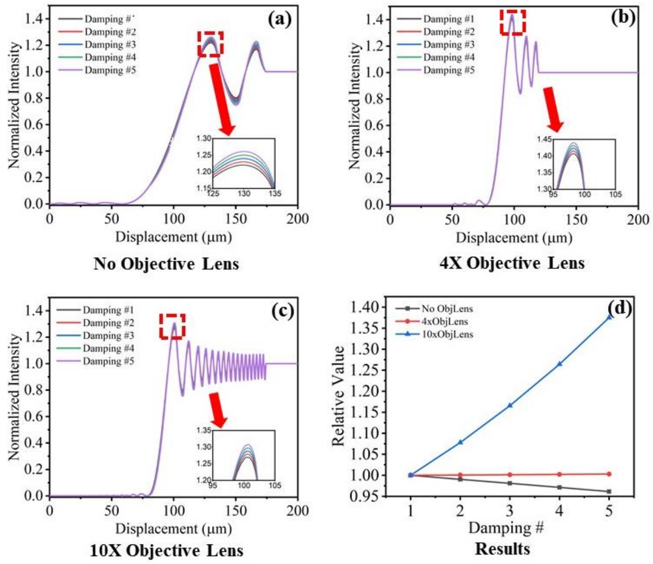

FIGURE 7. Simulation results for KEI-based photomask inspection system [31].

4. CONCLUSION

The KEI-based system for dimension measurement and inspection has been firstly reviewed in academic society. The theory of the KEI system was explained in this article. Moreover, several real applications of KEI-based systems were discussed, some of them focused on dimension measurement and positioning control, while others focused on edge roughness inspection and parts inspection. This review provides the great potential of using the KEI-based system for non-contact, in-situ, low-cost measurement with a high precision level. The reviewed technology can be implemented in real industry to increase the workpiece quality and the lifecycle of the machine itself. Moreover, this technology also has the potential to become a solution for precision semiconductor inspection systems. There are still a lot of aspects that can be optimized for the KEI-based system. In the future, for sure the resolution can be upgraded to nano-level by using UV light with a high NA objective lens. Second, the ANN (artificial neural network) or DL (deep learning) method may be implemented in a KEI-based system for roughness quantification. The KEI-based system also has the potential to be utilized for the photolithography process to simulate and remove the diffraction effect in that process to improve the product's quality.

ACKNOWLEDGEMENTS

This research has been supported by National Science Foundation (CMMI #1855473). The photomasks were provided from the Oak Ridge National Laboratory (ORNL).

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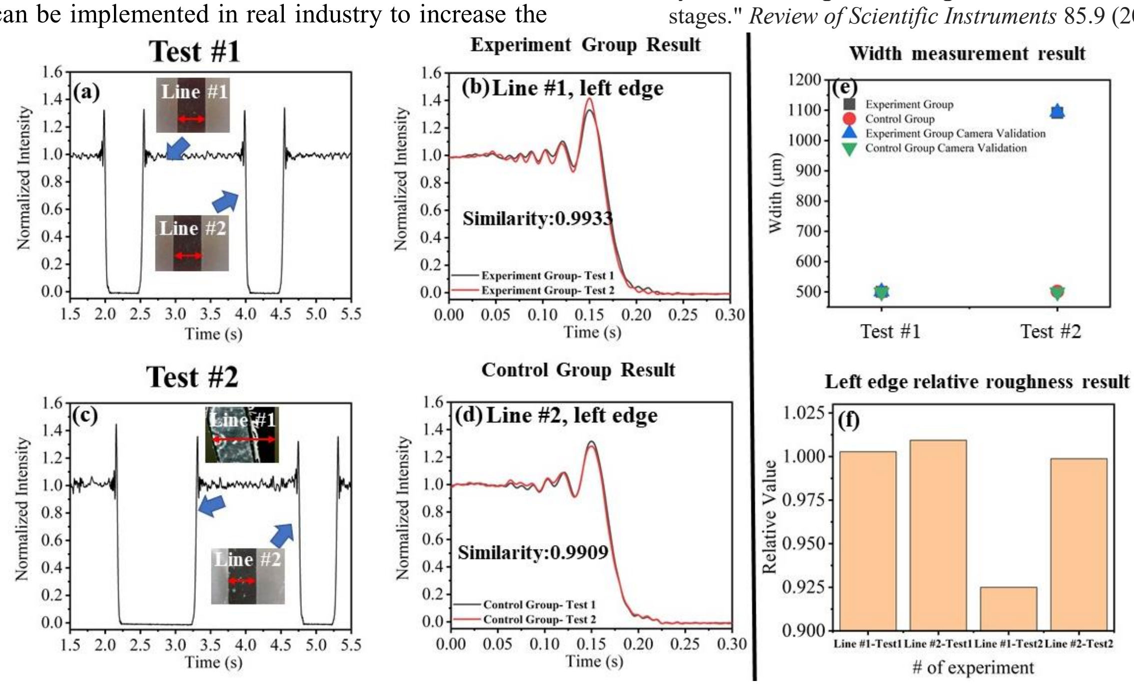

FIGURE 8. Experiment results for KEI-based photomask inspection system [31]

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