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Effect of speckle size on surface crack detection via digital image correlation

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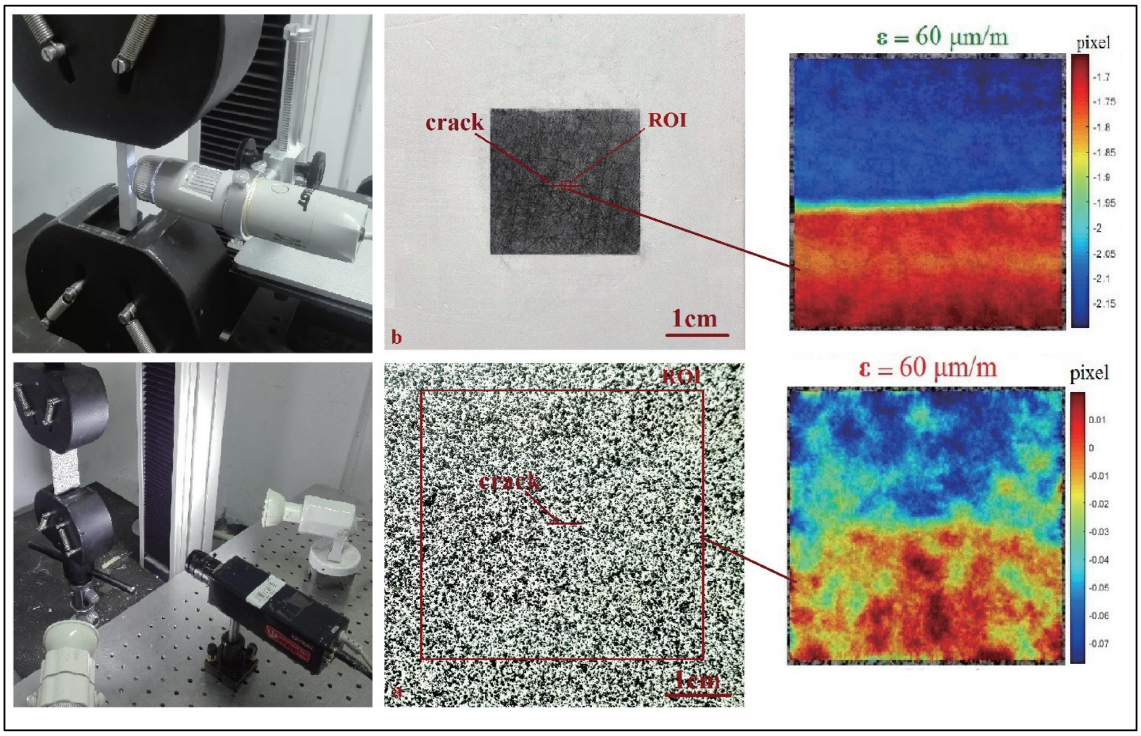
Graphical abstract



Comparison between two speckle patterns containing conventional spraying method and nanoparticle spreading in surface crack detection by DIC technique.

Public summary

- A novel simple method is introduced for speckle pattern creation in digital image correlation technique based on nanoparticle coating.
- The new method is validated for real crack detection using an optical microscope.
- A real crack is successfully detected by the method.
- The conventional DIC technique using the spraying method for pattern creation is compared with the new method.
- The advantage of the new method is verified.

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Abstract: Digital image correlation (DIC) is an experimental stress analysis technique used in nondestructive tests. The accuracy of DIC in crack detection depends on various factors such as the sizes of speckles and pixels. In the current study, a speckle pattern based on the spreading of nanoparticles with small speckles is compared with a conventional sprayed pattern to understand whether crack detection via DIC is improved by reducing the sizes of speckles and pixels. Owing to the small size of nanoparticles, an optical microscope is used for magnification. The spreading method for crack detection is first investigated experimentally. Results show that cracks can be detected easily when a 250 nm opening appears in the crack edges. Subsequently, the spreading method is compared with the conventional DIC, in which the spraying method is used for patterning, in terms of crack detection. Results show that by reducing the speckle size and closely analyzing the speckle pattern, the DIC technique is considerably better than the conventional technique in detecting small cracks. Moreover, the conventional method is more suitable for detecting large cracks.

Keywords: nondestructive testing; crack detection; digital image correlation

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1 Introduction

Crack detection is a significant issue in industrial applications. Nondestructive testing (NDT) techniques, including the use of dye penetrants, ultrasound, thermography, magnetic particle, radiography, shearography[1], and eddy current testing, are useful for this purpose. Each technique has its advantages and disadvantages. Penetrant testing is applicable to the detection of cracks, porosity, and other defects, in which the defects appear on the surface of a material and possess a sufficient volume to trap and hold the penetrant. Using this technique, only surface cracks on smooth surfaces can be detected. In addition, surface cleaning is required after the test. Another NDT method, known as magnetic particle testing, is appropriate only for testing ferromagnetic materials. However, it requires a large magnetic field to perform inspection over large areas, which is a disadvantage. Ultrasonic testing is suitable for defects on and near a surface; however, this method requires a certain amount of experience and the appropriate skill. Moreover, this method is not suitable for thin specimens and the detection of linear defects. Meanwhile, eddy current presents a limited penetration depth and cannot detect parallel defects in the winding direction of the inspection probe coil. Radiographic testing is expensive and requires extensive operator training. Moreover, it poses health risks to personnel, requires safety precautions, and is disadvantageous in terms of the radiation beam orientation. Shearography is applicable to only a particular specimen, and its results are difficult to interpret; furthermore, it requires perfect lightning[2].

Digital image correlation (DIC) is another technique used in NDT. DIC is an optical, noncontact experimental stress-analysis technique that is typically used in damage monitoring and fracture mechanics. DIC is based on a comparison of two images taken before and after the specimen surface is deformed. After imaging is performed, the images are correlated via an algorithm, and the displacements at each point on the specimen surface are calculated. DIC allows researchers to investigate the crack tip opening displacement, fatigue crack growth, and stress intensity near cracks and notches [3–7]. In addition, it is applicable to the health monitoring of large structures, such as walls and bridges[8]. Rajaram et al.[9] used DIC to monitor damage development in a reinforced masonry building during seismic excitation. In a separate study, Iliopoulos et al.[10] evaluated cracking in a cylindrical concrete structure that measured approximately 3.5 m in height, 2 m in diameter, and 0.7 m in thickness. Using this method, a surface crack measuring 0.5 m long was detected. In addition, the crack width (140 μm) was calculated using the DIC results. DIC is typically used as an NDT technique to investigate cracks and damages in large structures, particularly in cement structures[11, 12].

In the DIC technique for crack detection, the displacement between two edges of a crack is compared with that in a more distant zone. In a cracked specimen, by opening the two edges of the flaw, the field of view can be classified into two areas based on the two sides of the crack. The displacements of the pixels in each zone are approximately equal. The displacements of these two zones, however, are different because of the opening of the crack edges. The results yielded by DIC show various displacements represented by different colors for two area divided by the crack. Therefore, the contour of the displacement near the crack will be presented in two different colors owing to the opening of the crack edges. Thus, the crack is distinguishable by the contour colors. At small scales, particularly in metal cracking, conventional DIC is typically not applicable because of the small size of cracks and the small opening of crack edges. To apply this method for detecting defects in metals, a magnification is required. The surface displacement can be determined by imaging the specimen surface before and after deformation and comparing the images. Therefore, a randomly recognizable pattern, known as a speckle pattern, should be created on the surface. The speckle pattern is fabricated by attaching spots with different colors to the surface. The size of the selected speckle pattern is directly related to the area that will be investigated. The sample texture exhibits a desirable speckle pattern in some cases[13]. Magnification is mandatory for naturally occurring speckle patterns on small scales. This is typically performed by scanning electron microscopy (SEM) and optical microscopy (OM). Mehdikhani et al.[14] used SEM images to detect matrix cracks in a composites by correlating the images. However, it is noteworthy that SEM is a laboratory device, and its utilization in the industry is not desirable. Therefore, different techniques have been proposed for creating artificial speckle patterns on a small scale. In a study by Kammers et al.[15], a suspension of citrate-stabilized gold nanoparticles was spread on a sample via chemical reactions, which is known as self-assembly nanoparticle surface patterning. Spraying or airbrushing a suspension of nanoparticles on a specimen is another technique that requires additional equipment and experience[16]. To distribute a suspension, a solution is must be first synthesized, which requires knowledge in chemistry. Nevertheless, nanoparticles can be spread directly onto the specimen surface without any suspension or airbrushing equipment.

In this study, nanoparticles are spread to create a speckle pattern with small speckles. The small size of the nanoparticles allows a pattern with small speckles to be created. After patterning, the capability of DIC for crack detection using nanoparticles based on a real crack is investigated. A crack is detected by calculating the displacement between two edges of a crack. Finally, the small speckles and pixels afforded by the nanoparticle spreading method are compared with the typical speckle size afforded by conventional spraying.

2 Experiment

2.1 Fundamentals of DIC

DIC involves the comparison of two images captured from a speckle pattern created on a specimen surface before and after the surface is deformed. A speckle pattern is typically created by attaching black speckles on a white background, which results in the high contrast and high edge sharpness of the speckles, followed by increased accuracy[17, 18]. The relationship between the size and density of the speckles should be established[19, 20]. The speckles must be aliased to avoid speckles that are significantly smaller or larger than the average speckles[21]. Using the digital correlation algorithm which compares two images, the two images are compared, and the deformations and displacements are detected. The correlation process is illustrated in Fig. 1. To aid comparison, the pattern is classified into subsets of optional size. Subsequently, the central pixel is selected to calculate the rigid displacement of the subset, and the deformation is calculated based on the correlation of other pixels in the subset. Finally, the displacement of each pixel in the field investigated due to deforma-

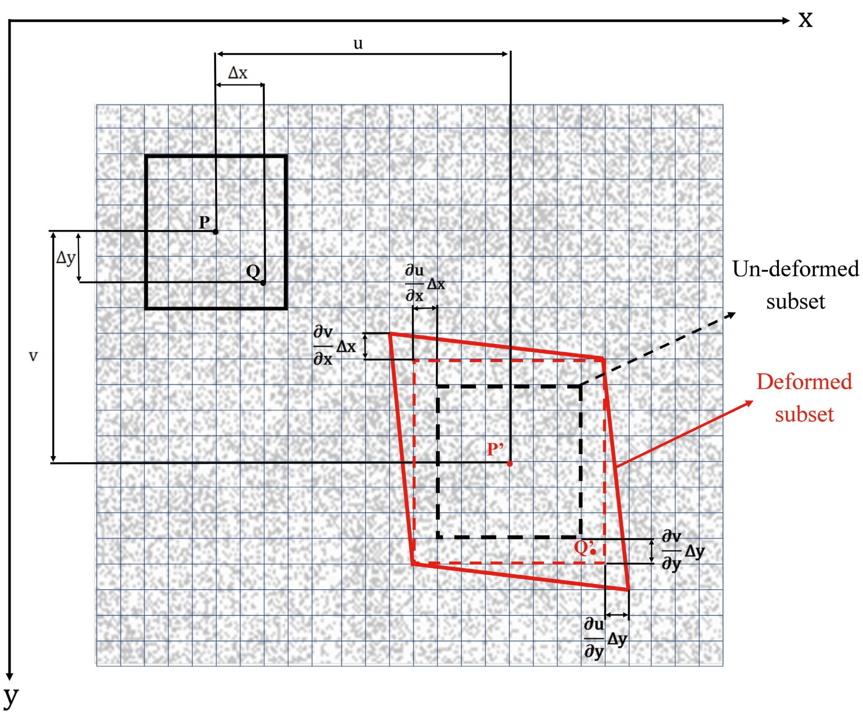

Fig. 1. Correlation process of algorithm.

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JUSTC, **2022**, 52(6): 6

tion and rigid displacements is calculated. Using this procedure, a surface crack can be detected by calculating the crack zone displacements when the crack edges are open.

2.2 Nanoparticle patterning method

In this study, nanoparticles are spread to create a speckle pattern. In this technique, nanoparticles without any specific solution, adhesive, or device are spread on the specimen surface and displace along with displacements. Owing to the small size of the nanoparticles, when any area of the surface displaces, the nanoparticles in that zone are displaced depending on the surface, thereby resulting in the displacement or deformation of the surface. Moreover, the small size of the nanoparticles allows a pattern with small speckles to be creased. A pattern created by spreading nanoparticles, as viewed under a digital microscope, is shown in Fig. 2.

2.3 Specimen preparation and test setup to investigate proposed method of metal crack detection in first part of study

To investigate the effect of the proposed patterning on crack detection in metals, a steel specimen with surface cracks was prepared, as shown in Fig. 3. First, a three-point specimen was selected based on the standard test method for measurement of fracture toughness (ASTM E1820), and a notch was created using the wire-cutting technique. The dimensions of

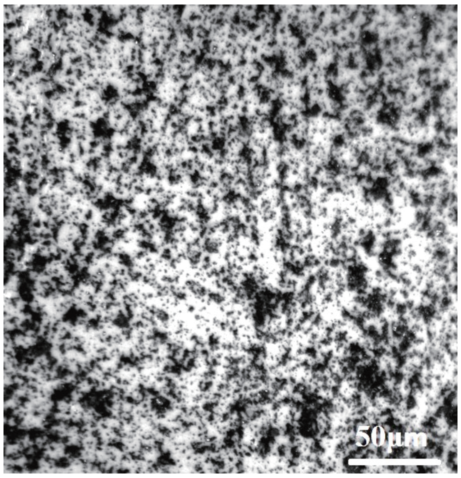

Fig. 2. Sample of pattern created by spreading nanoparticle viewed under digital microscope.

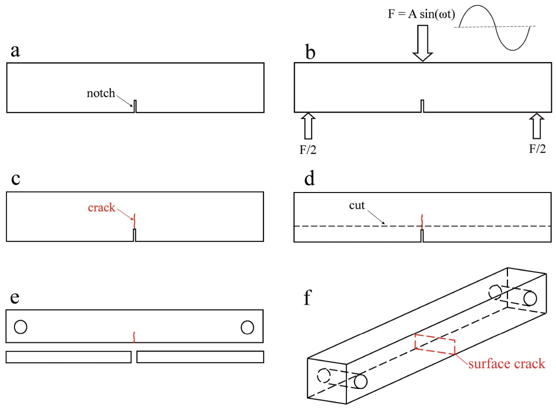

Fig. 3. Illustration showing preparation of surface-cracked specimens for first part of study.

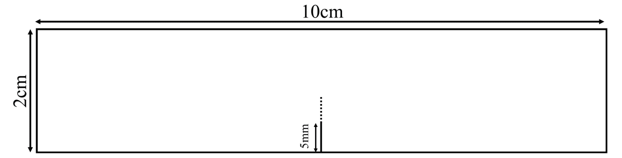

Fig. 4. Dimensions of specimen used in first part of study.

the specimens are shown in Fig. 4. After notching is performed, a fatigue crack was grown on the specimen by exposing it to fatigue loading to initiate and improve the crack. Then, the specimen was cut to remove the notch, and a crack remained on the surface. Fig. 5 shows the specimen before the fatigue load with a notch on it, as well as the specimen with a visible crack after the cutting process. Finally, the cracked specimen was cut over the crack to remove the notch, and a surface crack was created. Two holes were created to apply the tension. The specimens prepared for testing are shown in Fig. 6. Dust on the cracked surface was in fact graphene oxide spread onto the surface to create the pattern. The pattern must be magnified to create a speckle pattern with an appropriate speckle size.

After the specimen was prepared, DIC and spreading techniques were used to prepare a speckle pattern for crack detection. The test setup for applying tension and for imaging is shown in Fig. 7. The cracked specimen was stretched using a tensile machine, and a digital microscope was used to image the cracked surface.

2.4 Specimen preparation and test setup for comparison between proposed and conventional methods in second part of study

To compare the effect of the new spreading method involving small speckles and pixels for crack detection with that of the conventional method, both methods be applied to the same crack. Owing to the small size of the specimen, the conventional patterning method was not achievable previously, and a specimen with a larger field of view was requir-

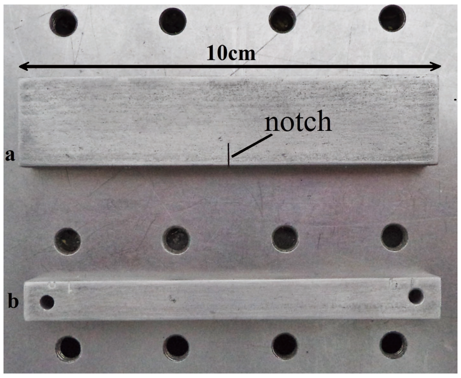

Fig. 5. Specimen for test: (a) Before loading process (with a notch on specimen); (b) final specimen with invisible crack.

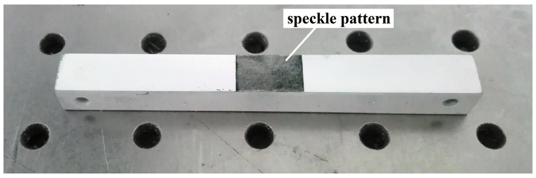

Fig. 6. First specimen with pattern.

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JUSTC, **2022**, 52(6): 6

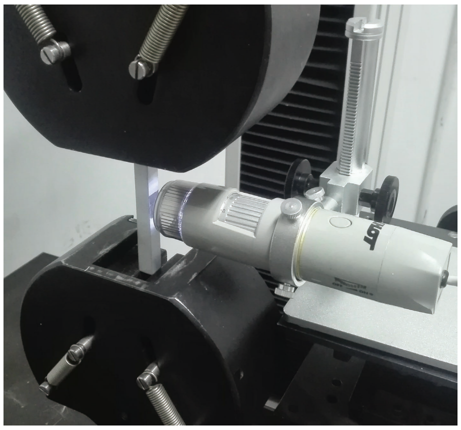

Fig. 7. Setup used for test in first part of study.

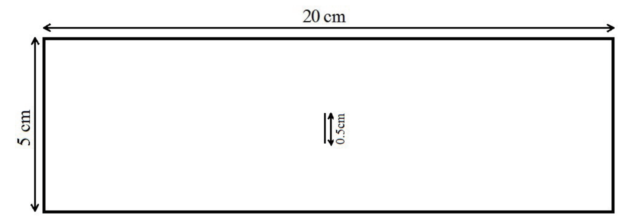

Fig. 8. Dimensions of specimen used for second part. of study.

ed. Therefore, a specimen suitable for tension testing was selected. The dimensions of the specimens are shown in Fig. 8. To compare the conventional method with the proposed method, a polymeric specimen fabricated using compressed white polyvinyl chloride was selected as it can be prepared effortlessly; Furthermore, it allows fatigue cracks to be introduced more easily as compared with a metallic specimen. The material was evaluated via a simple tensile test. The results indicate the brittleness of the material as well as its linear behavior at low forces. After preparing the specimen, a small notch was created on one side of it, as shown in Fig. 9. Sub-

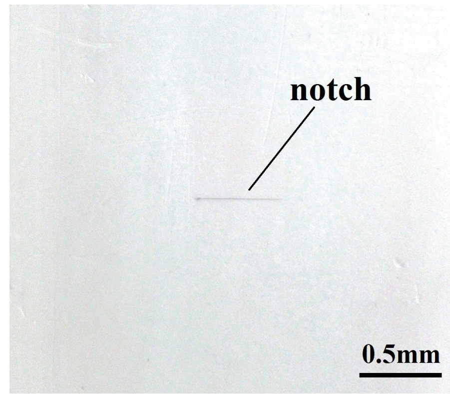

Fig. 9. Notch created on one side of second. specimen.

sequently, the specimen was loaded under a fatigue load to initiate a crack that would progress to the other side of the specimen, thereby resulting in a fatigue crack on the second side. The crack creation process is illustrated in Fig. 10. Using the first step, a small surface crack measuring approximately 5 mm long was created on the specimen to compare between the new and conventional methods in their ability to detect cracks when creating a speckle pattern. In the second step of the loading process, a small crack further developed into a large crack measuring approximately 10 mm long, which allowed the effect of crack size on the capability of the conventional method in detecting surface cracks to be investigated. First, a cracked specimen was coated with nanoparticles and evaluated under different strain levels. Subsequently, the coating was removed. Next, a conventional pattern was created via spraying and then tested—this test was repeated on a large crack. Fig. 11 shows a specimen with two patterns in the same zone, and Fig. 12 shows two speckle patterns for the tensile test in the same zone, which encompasses the crack region. Additionally, these images show the regions of interest (ROIs) for the two tests. The setup for the conven-

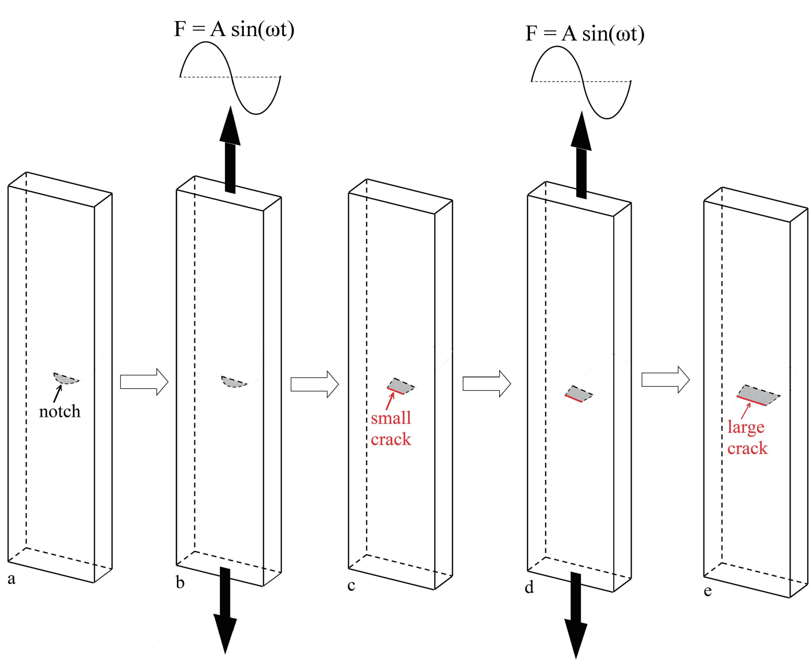

Fig. 10. Process of creating of a fatigue crack on the surface of the second specimen.

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JUSTC, 2022, 52(6): 6

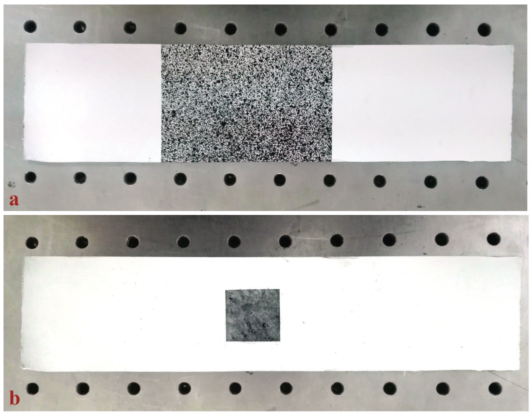

Fig. 11. Speckle pattern created on second specimen via (a) spraying and (b) nanoparticle coating.

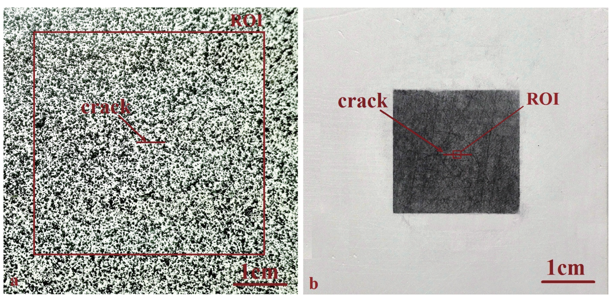

Fig. 12. Speckle pattern created on second specimen (with ROI shown) via (a) spraying and (b) nanoparticle coating.

tional test is illustrated in Fig. 13. The setup of the proposed method is the same as that shown in Fig. 7. To investigate the proposed method, HOT-80PS (Hotviewer Company), which was equipped with a 3.2 MP CMOS sensor to magnify and capture images, was used as a digital microscope. For the conventional method, an ARTRAY 3.6 MP CCD camera was used for imaging. Each pixel in the images captured by the digital microscope measured approximately 1 µm, which corresponds to approximately 50 µm on the images captured using the CCD camera.

3 Result and discussion

After preparing the two types of specimens using the two test setups, the specimens were subjected to various forces. The Ncorr software with a subset size of 51×51 pixels was used in all tests. First, a metal specimen was tested, where a crack was detected clearly. Fig. 14 shows one of the fields of the results. The crack line is evident, and the crack is detected ef-

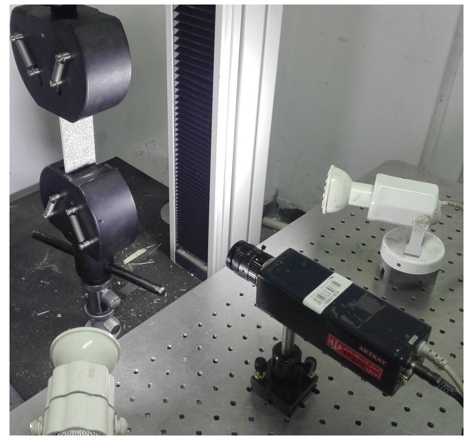

Fig. 13. Setup for conventional method used in second part of study.

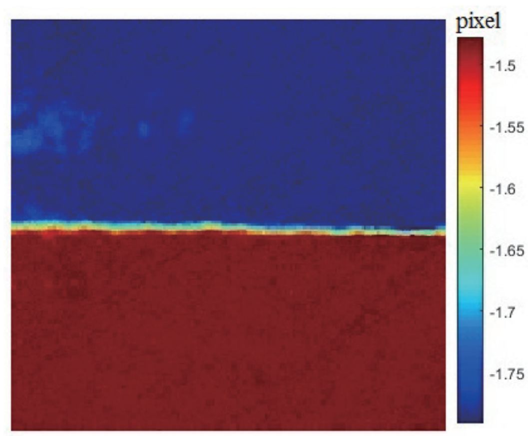

Fig. 14. Crack detected on metallic specimen when using proposed method to create speckle pattern.

fortlessly. Based on Fig.14, the two edges of the crack opened by approximately 0.25 pixels. Each pixel in the magnified images measures approximately 1 µm long; Hence, an opening of approximately 250 nm between two edges of a crack allows a crack to be detected in a metallic specimen. This dimension can be reduced using smaller nanoparticles and more powerful microscopes.

The polymeric specimens were investigated under different strain level in the second part of the study. First, the proposed method for crack detection was investigated. Various strain levels beginning from 20 µm/m were applied to the specimen, and the strain value was increased 20 µm/m at each step. Simultaneously, several images were captured from the pattern and correlated using the Ncorr software. The results

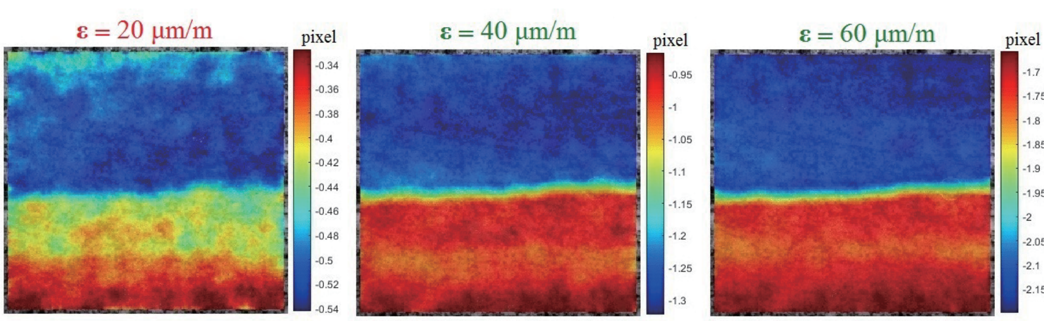

Fig. 15. Result of proposed method for crack detection at various strain levels.

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JUSTC, **2022**, 52(6): 6

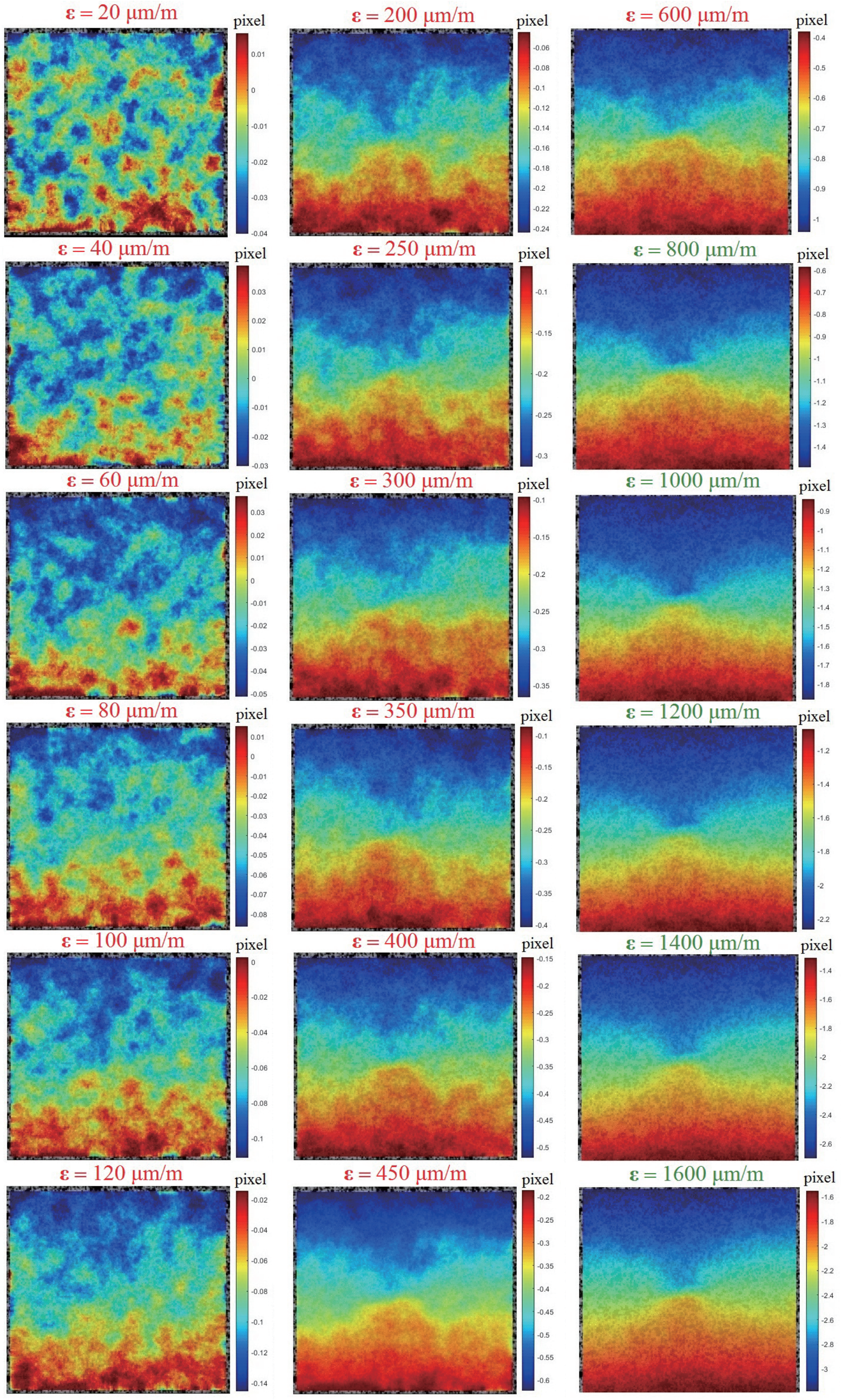

Fig. 16. Result of small crack detection by conventional method at various strain levels.

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JUSTC, **2022**, 52(6): 6

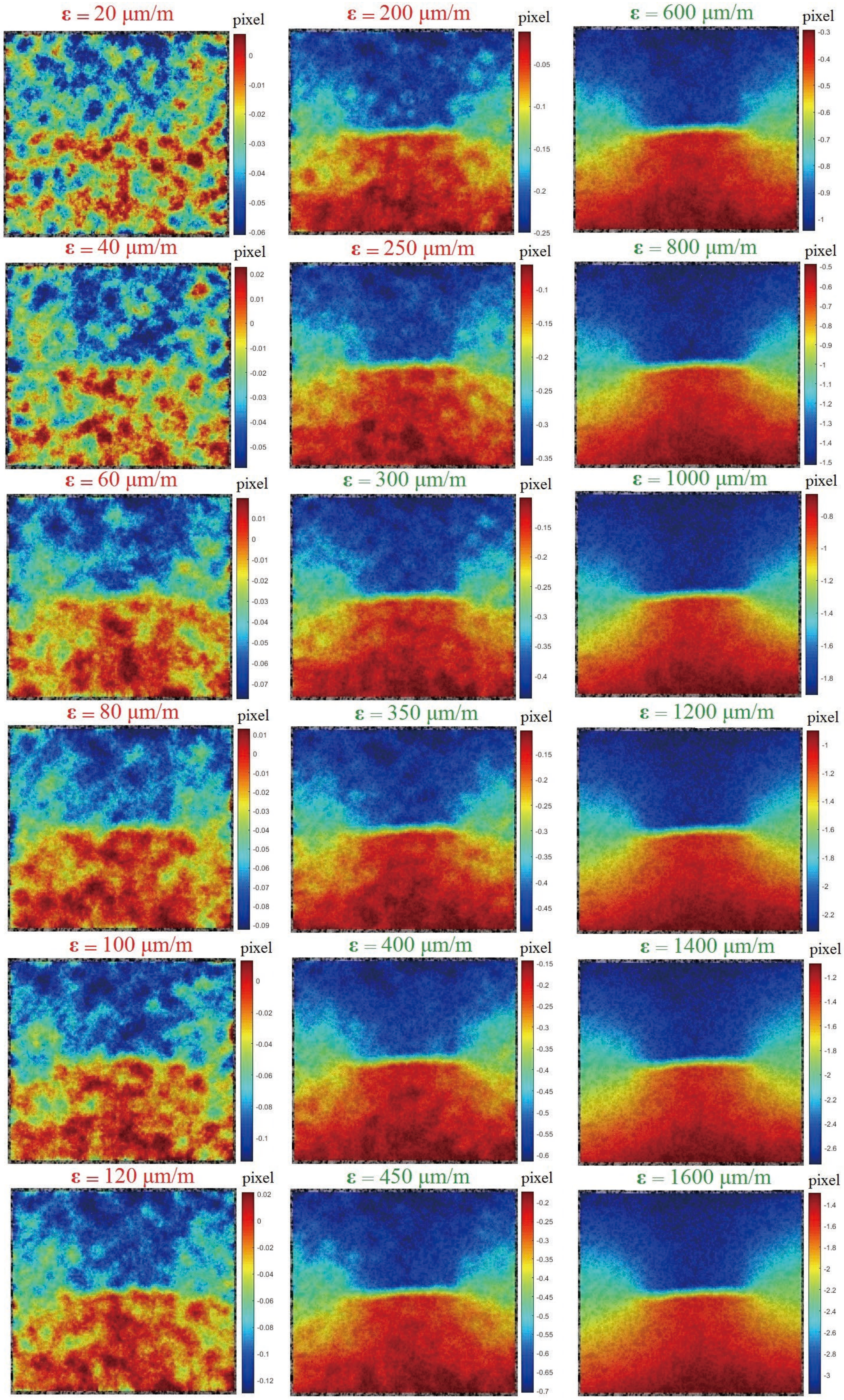

Fig. 17. Result of large crack detection by conventional method at various strain levels.

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JUSTC, **2022**, 52(6): 6

for the first three strain values are shown in Fig. 15. In this Figure, ε is the sign of strain. At a strain of 20 μm/m, the crack was blurry; however, at strains of 40 μm/m and 60 μm/m, cracks were detected.

Second, the nanoparticle pattern was removed and a speckle pattern was created on the specimen via spraying. In the first step, various strains were applied to the specimen, and images were captured and correlated. Fig. 16 illustrates the results. When the strain is increased from 20 μm/m to 120 μm/m, no strain is detected. Hence, the strain is increased by 50 μm/m at each step. At this point, only the displacement intensity is detectable. The tension of the specimen resulted in a few some horizontal halos, which rendered detection difficult. Third, the strain was increased by 200 μm/m at each step. At the strain of 800 μm/m, the crack is visible but is not completely clear because of the small size of the crack. Using the proposed method, the crack can be detected effortlessly, and the required value of crack edge opening for detection is considerably lower as compared with that of the conventional method. To investigate the effect of crack length on detection, in the third step, the tests for the conventional method were repeated using a larger crack. Fig. 17 shows the results of the third test using the conventional method for a large crack. As shown, the crack is detected at 300 μm/m; hence, the conventional method is appropriate for detecting large surface cracks, particularly on walls or large industrial structures[8, 10].

A comparison between the proposed method and the conventional spraying method in terms of crack detection shows that owing to the reduction in pixel size, i.e., from approximately 50 μm in the conventional DIC using the spraying method to create a pattern to approximately 1 μm in the proposed method to create a speckle pattern, the capability of DIC in detecting small surface cracks was better. Because the algorithm calculates the displacements of each pixel in the field of view, the algorithm can calculate higher gradients of displacement in the field of view when the pixel size is reduced. To reduce the pixel size, a pixel is partitioned into several pixels. This allows displacements in areas that are smaller than one pixel to be calculated, which improves the ability of the DIC in detecting small cracks. Moreover, the algorithm calculates the displacements in units of pixels. By reducing the pixel size, the algorithm can calculate the displacement in smaller pixel units, thereby allowing the DIC to calculate smaller displacements. Consequently, a small opening is detectable at the edges of the crack.

In the proposed technique, the images are magnified and the field of study decreases. Because the field size can be determined, the specimen surface must be scanned during the industrial test. For small target areas, such as the surface of a weld, scanning can be performed easily; however, in large areas, scanning is more difficult and would require a longer time. This problem can be solved using movable devices that can perform regular imaging before and after loading over the specimen surface, as well as by correlating the captured images.

4 Conclusions

The effect of reducing speckle and pixel sizes on crack detection using DIC techniques was successfully investigated. First, a speckle pattern was created by spreading nanoparticles to prepare small speckles near a crack; subsequently, the speckles were analyzed under a microscope. The prepared crack was detected effortlessly after a 250 nm opening at the two edges of the crack, which was created under low strain levels. Another crack was detected via the conventional spraying method and the proposed method by closely examining the small speckle pattern. Results showed that the proposed method based on reduced speckle size was more effective than the conventional method. Subsequently, the effect of crack length on the performance of the conventional method was investigated. Results indicated that the conventional method is more suitable for detecting larger cracks.

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Conflict of interest

The authors declare that they have no conflict of interest.

Biographies

Milad Z. Aghdam received his Bachelor's degree from the Iran University of Science and Technology and his Master's degree from the University of Tehran. His research interests include experimental stress analysis methods and NDT, both associated with fracture mechanics and life assessments.

Nasser Soltani pursued his Bachelor's and Master's degrees from the University of Oklahoma from 1981 to 1985. He received his Ph.D. degree in 1989 from Iowa State University. After that, he started his professional work at the University of Tehran until now. His research mainly focuses on experimental stress analysis methods and fracture mechanics.

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