A novel method for creating speckle pattern in digital image correlation based on nanoparticles coating, appropriate for study intense gradient of displacement in small zones

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Abstract: - Digital image correlation (DIC) is a powerful full-field displacement measurement technique of surfaces, which has been employed for laboratory and industrial researches. Creating an appropriate randomly speckle pattern is the first step of the DIC that has a considerable role in the accuracy of results. In the current paper, a new speckle pattern, which is considerably effortless in creation and modification, is introduced that is applicable in the study of high displacement gradients in small fields of views by the DIC technique. The new speckle pattern is created by spreading a coating of graphene oxide nanoparticles on the specimen surface. In this study, after the introduction of the new method, the accuracy of DIC results through the new pattern is investigated under translation, rotation, and tensile tests. Obtained results showed that the technique is useful and can decline the trouble of the creation and modification of a speckle pattern on a small field of view, particularly in industrial applications.

Key-Words: - Digital Image Correlation, Speckle Pattern, Nanoparticle Spreading, Coatings

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1 Introduction

Over the last decades, Digital Image Correlation has been applied for displacement and strain measurement [1]. The DIC method has been introduced by Peters and Ranson in 1982 [2]. Due to the advantages of the DIC such as simple setup and accuracy, most recent studies have been done by this technique particularly in a study on the fracture properties of materials [3-8]. The DIC technique also has acceptable accuracy and precision, easy implementation, vibration, and noise robustness. This technique can be used in different scales from nanoscales to macroscale about hundreds of meters.

The DIC method includes three main steps. The first step is to create the speckle pattern on the surface of the target specimen, the second is imaging, and correlation of images is the final; In overall, the main concept of the DIC technique is the correlation between two images that have been taken from the specimen surface before and after deformation. For this correlation, each point in the target area of the taken images from the specimen surface must be recognized by an algorithm that is written to compare images and calculate displacements. If the surface does not be recognizable by the algorithm, the results will not be accurate. Thus, a random speckle pattern should be created on the target surface before imaging. The DIC speckle pattern is typically made up of black spots on a white background. The second step of the DIC is the imaging of the speckle pattern created on the surface of the specimen. In this step, two images are taken before and after deformation from the speckle pattern. Finally, the algorithm calculates the displacements of speckle patterns spots in two images.

The creation of an appropriate speckle pattern is the most important task in the DIC technique. In a proper speckle pattern, speckles must have some features to reach high accuracy. The ability to create a proper speckle pattern will be provided by the experiment, and it is clear that without experience it will take a long time to create a speckle pattern. Thus, one of the important categories of study on the DIC techniques refers to the development of creative methods of speckle patterns to facilitate the creation and improve patterns features, and many attempts have been made on speckle patterns.

1.1 Speckle pattern

1.1.1 Speckle pattern creation methods

There are various methods in patterning. In the first studies on the DIC by Peters and Ranson, reflected laser beams from specimen surfaces were considered as a speckle pattern. In their method, a beam radiated to the surface and is scattered in different directions and that scattering generated a speckle pattern [2]. Further, there are other methods in patterning which are divided into natural and artificial patterns.

Sometimes the natural texture of the sample can be used as a speckle pattern. This type of pattern usually is in microscopic order and an optical microscope or scanning electron microscopy (SEM) must be used to recognize them. In 2004, Rae [9] et al measured displacements at the surface of a composite material. Their specimen contained a large volume of crystalline explosives within a polymeric matrix. The sample was imaged by a high-resolution camera mounted on an optical microscope. In 2006, Sutton et al used SEM for displacement measuring on the specimen surface and after that combined it with DIC for the first time [10, 11]. There are many studies on this method, but the usage of natural texture as a speckle pattern is not utilizable in all cases. The surface of many materials is not recognizable for algorithms. Finding a region of interest also is very difficult and in some materials it is impossible.

Other than natural speckle patterns, moreover, there are many different techniques to create an artificial speckle pattern. Artificial speckle patterns are generally made by spraying and airbrushing. In 1986 Chu [12] et al for the first time sprayed black speckles on a white-colored background. In this method, black spots are sprayed on a white surface by an airbrush gun. This technique is very cheap but needs experience and also it takes a long time that the sprayed pattern to become dry and adhere to the specimen surface. Furthermore, it is possible that the pattern not be appropriate or needs to modify and improve. Therefore, the surface of the specimen must be cleaned and a new pattern must be sprayed. However, these methods are the most selected technique in the patterning on the macro-scale. Airbrushing and spraying are generally used at room temperature, but they are also used in high temperatures via spraying particular coatings. Lyons [13] et al used Al2O3 based ceramic coatings to make a speckle pattern resist up to 700 degrees of centigrade. Pan [14] et al could use high-temperature ceramics and made a pattern with a 1550 degree of centigrade resistance. Airbrushing also has been used in micro and nanoscales. Dong [15] made a pattern with 1 micrometer per pixel by using aluminum powder. They examined different patterns to find the best pattern at high temperatures. Berfield [16] et al used fluorescent nanoparticles by deposition of a solution with a resolution of 10 micrometers per pixel. Niendorf [17] used silicon particles for patterning and an optical microscope for imaging. His image resolution was about two micrometers per pixel. Patterning by airbrushing and spraying have many applications in biomechanics. Due to the fluorescent particles' biocompatibility, they have been used in many studies on biomaterials and human bodies such as brain tissue [18], liver [19], skin [20], vertebra [21], etc.

Airbrushing and spraying is the most used technique in patterning because of the easy-operating, cheapness, wide-ranging scale, and various field applications with qualification enabling. There are also other techniques to create a pattern, particularly in micro and nanoscales. Kammers [22] et al poured a suspension of citrate stabilized gold nanoparticles on a sample with chemical functions which is called self-assembly nanoparticle surface patterning. The method was first introduced in 1995 for chemical purposes and is useful for metallic and non-metallic substrates [23]. In this method, nanoparticles coating makes a spatial resolution that is recognizable under SEM, and SEM is used for imaging and calculating local strains by the DIC technique. Their results showed the method is fine and useful. There are also other techniques for patterning. Spin coating, compressed air technique, nano-film remodeling, lithography, focused ion beam, scratching and abrading, carbon printer towner usage, chemical etching, etc are other techniques to make speckle patterns in micro and nano-scales [8].

Most of these micro and nano-scale patterning techniques are only useful in laboratory researches, not in industrial. Besides, they also need time and advanced equipment with experience to use them. In this article, we introduced a comfortable patterning method with only spreading black nanoparticles on the specimen surface without any complex process and equipment. Pattern creating, in this method, is facile but it also must have some other features to achieve true results with good accuracy. In the next section, pattern features will be studied.

1.1.2 Speckle pattern features

In the DIC technique, a speckle pattern must have some features to achieve accurate results. There have been many types of researches to find out what features a good speckle pattern must-have. Firstly, a speckle pattern must be recognizable. For this reason, the speckle pattern must have randomness with high contrast. Contrast is the amount of difference of colors between the bright regions and dark speckles. Results showed with high contrast noise becomes less [24]. Stability also is important. The pattern must adhere to the specimen surface and replace it with its displacement. The density of Spots must be appropriate. Low and high density can make errors in results [25]. Speckles must be aliased. It means the size of speckles should be in a proportion range and one speckle must not be extremely smaller or bigger than the average of speckles [26]. The average size and edge sharpness of speckles are important parameters to reach a suitable pattern [27, 28]. The quality of the speckle pattern demonstrates various parameters introduced by researchers. Zhao [29] and Goodson studied speckle size with a developed algorithm. They resulted in that pattern with speckle size in rang 2 to 5 pixel have a lower error. Hung [30] studied the influence of the average size of speckles in strain measurement. Their results showed the best average speckle size is between two and eight pixels. Lecompte [31] studied the speckle pattern distribution using image morphology. They showed that the size of speckles and the size of the subset have an interrelated influence on results. They selected a small field from one pattern and zoomed in it with three steps, and with MATLAB software changed the speckle density by eliminating some speckles. They also resulted that a bigger subset size improves accuracy. Sun et al investigate pattern quality by proposing a new parameter named subset entropy which quantifies the subset [32]. Pan [33] et al investigated choosing subset size by proving a theoretical model that indicates the accuracy of DIC based on a new parameter. They defined the Sum of Square of Subset Intensity Gradients (SSSIG) as a new parameter and could quantify the subset with it. Pan also proposed the mean intensity gradient as another novel parameter and verified it [34]. They showed there is a directed relationship between this parameter and errors. There are also several works to study speckle pattern characteristics with different parameters. Mean subset fluctuation [35], Shanon entropy [36], autocorrelation peak [37], and autocorrelation peak sharpness radius [38] are other parameters that have been introduced. There are also several studies on speckle size by morphological method or other techniques [39, 40]. There are also different studies on error sources, equipment, algorithm, and other fields on the DIC technique. The results of these studies gathered and made the principle of DIC. These principles are necessary and must be applied to achieve accurate results from the DIC technique.

In the current study, a new method in the creation of a speckle pattern is proposed. The main concept of the method is the spreading of black nanoparticles to a white background. Nanoparticles, after the spreading process, aggregate on random zones of the specimen surface and make black speckles. Due to the small size of nanoparticles, small speckles will be generated, and it will be possible to zoom on the area of interest that nanoparticles were spread on and have a proper speckle pattern in a small field of view. This magnification also considerably decreases the size of pixels, and it means a pixel in the conventional DIC divides into several smaller pixels. As a result, the software will be able to calculate very small displacement in a remarkable lower order of one pixel in the conventional method, and it is appropriate to calculate high gradients of displacement in small fields of view until lower than one pixel in conventional DIC techniques. The process of spreading, moreover, does not need any devices and is done by a small comb or by hand. As a result, the creating and modifying process is more effortless and faster than spraying. In this article, first, the process of creating of pattern with various densities of nanoparticles will be investigated to find out the amount of nanoparticles that is necessary to create a proper pattern. Then, to assess the method, the pattern will be studied by translation, rotation, and tensile test.

2 Problem Formulation

2.1 Principle of the DIC technique

DIC is an optical non-contact displacement measurement technique that is widely used in research studies and industrial applications. In this technique, the surface of the specimen is coated with a speckle pattern. In general, the speckle pattern is randomly black spots sprayed on a white background on the specimen surface. In most cases randomly speckle pattern is made by spraying or airbrushing black speckles on a white background of the surface. The white background can also be made by spraying, however, it is created before spraying of black speckle. The randomness of the speckle pattern enables the algorithm to recognize the location of any point on the surface of the specimen.

After patterning, two images before and after deformation should be taken from the speckle pattern. A CCD or CMOS camera must be used for imaging. These types of cameras sense the intensity of lights which are reflected from the speckle pattern, then convert these intensities to a voltage with their sensors. The voltage is converted to a number between zero and 255 which represents the light intensity. In this type of imaging, images include the small grids named pixels, and there is a light intensity for each pixel with a number representing the light intensity of the pixel. These numbers in taken images are compared with the algorithm to calculate the displacement of each pixel. Fig.1 shows a schematic diagram of the DIC configuration. In general, LED light sources are used to reduce light noises.

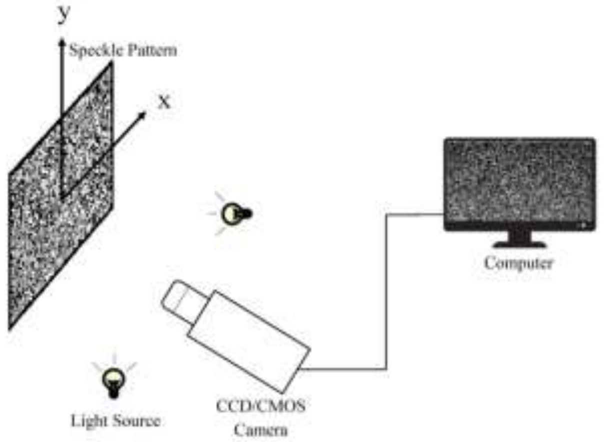

Fig. 1: Schematic of DIC setup

The third step in the DIC technique is the correlation of two images by the algorithm. To this comparison, an area in two taken images is selected by the operator which is an area of interest. The algorithm analyzes the area of interest in two images that are taken before and after deformation. Then, the result of displacements will be calculated and outputted for each pixel in the area of interest. Moreover, the results of displacement in the area of interest will be demonstrated by a colorful picture which is the field of results. The colors in the field of results are harmonized with the measure of the displacements, and thus, the field of results with a colorful picture helps the researchers to find out an overall view about the displacements of pixels in the area of interest. There are different algorithms to analyze the speckle displacement Algorithms investigate the location and movement of each pixel via comparison of pixels in those two captured images before and after deformation. To this purpose, the algorithm divides these images into square subsets with a selectable edge size number. The algorithm, compares subsets in two taken images and considers the displacement of the central pixel in subset as rigid displacement, and investigates other pixels' displacement in subset comparative to the center pixel to determine strains. A schematic of the process of this comparison is shown in Fig. 2.

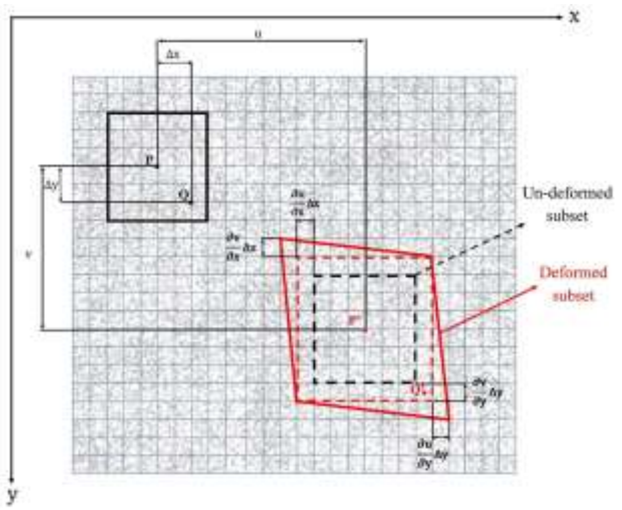

Fig. 2: Displacement determination schematic

Considering rigid displacement, displacement of each pixel is determined by first-order shape function or higher-order. In first-order shape function total displacements are equal to the summation of three terms as follow:

$$U = u + \frac{\partial u}{\partial x}\Delta u + \frac{\partial u}{\partial y}\Delta y \quad (1)$$

$$V = v + \frac{\partial v}{\partial x}\Delta x + \frac{\partial v}{\partial y}\Delta y \quad (2)$$

where U and V are total displacement in x and y directions respectively, u and v are translations, $\partial u/\partial x$ and $\partial v/\partial y$ are normal strains in x and y direction, $\partial u/\partial y$ and $\partial v/\partial x$ are shear strains in x and y direction, Δx and Δy are the distances from subset center pixel in x and y direction.

Finally, the algorithm determines the total displacement for each pixel from the selected region and output them in unite of pixel. In the recent study, Moire V0.958a was used as the software to correlation.

2.1 Research method

To investigate the new method in the creation of a speckle pattern, the pattern should be characterized. The DIC photos are captured and stored as 8-bit digital images. In 8-bit digital images, the intensity of light is shown by a number between 0 and 255. The number zero for the intensity of light refers to completely black speckles and the number 255 refers to complete white color speckles. The gray speckles proportionally have a number between zero to 255 which is related to reflected beam light intensity. In the current study, the mean of these numbers of pixels was used as a parameter to investigate the darkness of the pattern. A dark pattern has a lower mean compared to a white one. The darkness of the pattern is related to the number of black nanoparticles on the specimen surface. The number of mean is calculated by the equation (3).

$$M = \frac{\sum_{i=1}^{N} I_i}{N} \quad (3)$$

where M is the mean, N is the number of pixels, and I is the number of light intensity. There is another parameter to characterize a speckle pattern that is the standard deviation of light intensities' numbers. The standard deviation is related to the difference between each number of light intensities with the mean of them and expresses the contrast between the darkness of black points with the white background. High deference between numbers means high deference between black points with a low number and white points with a large number. Equation (4) shows the standard deviation formula.

$$Sd = \sqrt{\frac{1}{N-1}\left(\sum_{i=1}^{N}(I_i - M)^2\right)} \quad (4)$$

To investigate a speckle pattern, translation and rotation tests usually are used. In translation tests, noise error and bias error generally have been used to investigate a speckle pattern [41, 42]. In the translation test, all of the pixels in the area of interest should have equal numbers of displacement. Therefore, in this case, the measured translation by the DIC method should be equal for each pixel in an ideal situation, but usually, there are small fluctuations in the measured displacement for the pixels. This fluctuation from the average of the measured displacement is called noise error. The noise error refers to the band of uncertainty and represents the distribution of calculated translation. If the distribution of the results is far from the actual translation, the noise error will be considerable, and if the value of results is near the actual rigid displacement it will be small. To evaluate the noise error, the standard deviation is used as a parameter to study the band of fluctuation. There is another error in the translation test which is called bias error. Bias error indicates the difference between the average of measured displacement of pixels and the applied translation. In the tensile test also the average of the software strain results is compared to applied strain to evaluate the pattern under tensile test.

According to the output of the Moire, only displacements of each pixel are available. Software outputs are displacement in two perpendicular directions and it is not able to calculate the rotation directly. Thus, to find the rotation, it is necessary to calculate the slope of the displacement graph in the vertical direction for a horizontal line that passes through the center of rotation. When a horizontal line rotates each point on it moves along the vertical direction, and the rotation number is proportional to this movement. In Fig.11 a schematic of rotation for a line is demonstrated. The angle of rotation is equal to the slope of the rotated line and the not rotated, which is calculated by the equation (5).

$$angle\ of\ rotation = tg^{-1}\left(\frac{\delta}{x}\right) \quad (5)$$

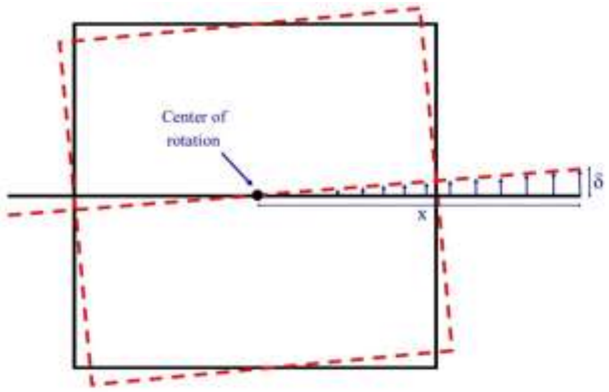

Fig. 3: Schematic of rotation calculation method and vertical displacements of a horizontal line which pass through the center of rotation

3. Experiment

3.1. Patterning

In this study, a new method was proposed based on nanoparticles spreading on the specimen surface to create a DIC speckle pattern. In the proposed method of creating the speckle pattern, nanoparticles were spread on the specimen surface and aggregate between. The process of the spreading is done by a small ordinary comb and it is not to use any particular devices such as air compressor or spraying gun. The process of modifying or removing nanoparticles, moreover, is done by the comb via the displacement of nanoparticles.

Actually, one advantage of this method is its simplicity in creating and modifying the speckle pattern. In this study, graphene oxide nanoparticles were used to create black spots on a polymeric specimen which is a white one. Due to the small size of nanoparticles, an optical microscope was used to magnify the speckle pattern. The new method in the creation of the speckle pattern can be used to measure the displacement of the areas with the concentrated strain field.

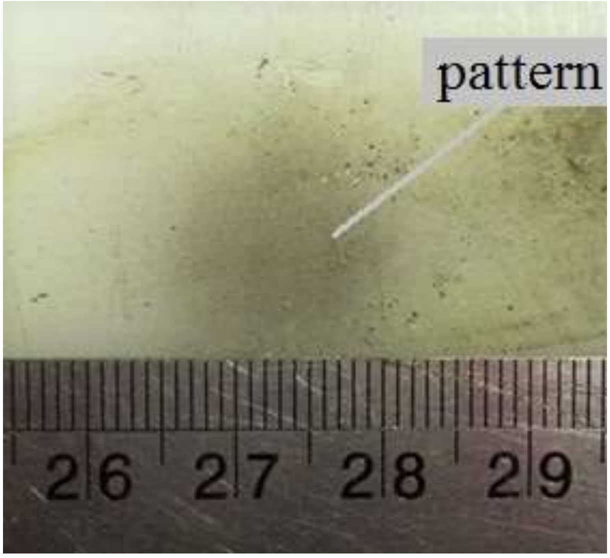

Fig. 4: A sample of the nanoparticle coating speckle pattern without magnification.

They used graphene oxide (GO) is the industrial-grade, produced by United Nanotech Innovation PVT, and manufactured by modified Hummer's method using a proprietary processing unit by increasing the distance between adjacent sheets from 3.35 A^ºin graphite powder to 7.0 A^º to GO. The thickness of each nanoparticle is about 3-6 nm, and the lateral dimension is about 5-10µm. White polyvinyl chloride (PVC), moreover, was used as the specimen to apply displacement, rotation, and tensile test on it.

3.2. Setup

To prove the effectiveness of the new patterning method for DIC measurements, the pattern was investigated under translation, rotation, and tensile tests. The experimental configuration of the translation and the rotation tests is shown in Fig.5. For imaging, a USB CCD camera from the company of ARTRAY with a resolution of 3.2MP was used to take images. A simple microscope, moreover, was used in front of the camera's lens for magnification. The setup was located on an optical table. Two light LED sources were used to illuminate the sample surface.

To apply translation and rotation two manual actuators were used. The least translation which can be applied by the translation actuator was 10 micrometers, and in the same way, the least rotation angle which can be applied by the rotation actuator was 0.05 degrees. The specimen with the pattern on it was located on translation and rotation actuators by two bolts, and rotation and translation were applied to it. The pattern was also investigated under the tensile test. Fig.6 shows the tensile setup to investigate the proposed speckle pattern under the strain test. The tensile test machine is GOTECH-Al7000 with a capacity of 50 kN and 0.5% load accuracy.

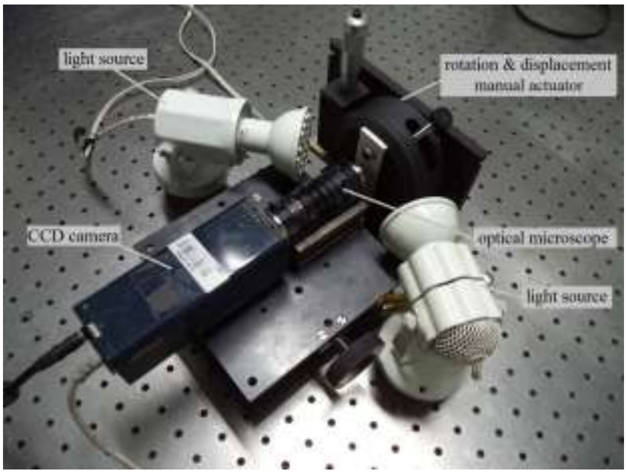

Fig. 5: Setup of the DIC with an optical microscope for translation and rotation tests.

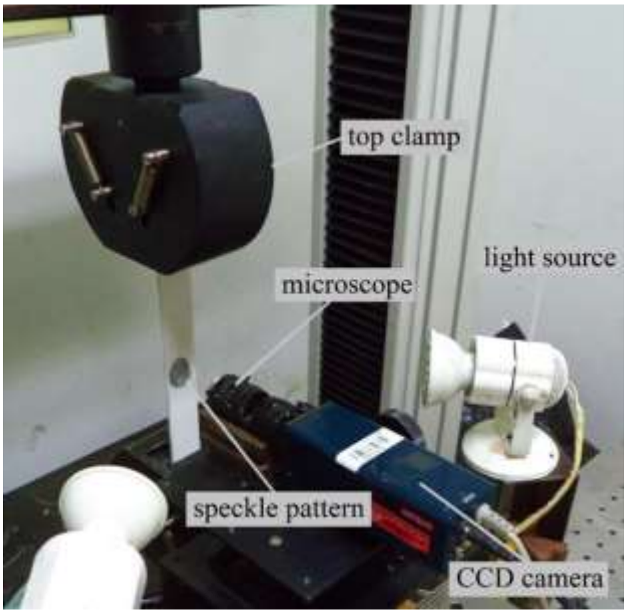

Fig. 6: setup of the DIC with an optical microscope for strain test.

4. Results and discussion

4.1. Pattern

To investigate the method of the creation speckle pattern, five patterns according to the new method with different densities were created on a specimen. The various density of coating was created to find out which one has the most accurate result. To avoid the influence of the roughness of specimen surface on the aggregation of particles in the pattern creation, and better comparison as well, all five patterns were created on a common place on the target surface. Due to the convenience of the creation and modifying of the method various densities of nanoparticles were applied and different patterns were simply created on the common zone. Indeed, only one pattern was created and modified by adding or removing particles several times. Small parts of each pattern and the corresponding histograms are shown in Fig.7.

The mean and standard deviation of light intensity for the image pixels were determined for each pattern (table1). The mean light intensity is the mean numbers of pixels, and the standard deviation is the amount of dispersion of the mean value. A low mean light intensity presents a dark pattern with a lot of black speckles and a high mean light intensity indicates a bright pattern with a lot of white speckles. While, a high standard deviation indicates that the numbers are spread out over a wide range, and as a result, high standard deviation refers to a high difference between speckles darkness, and high contrast.

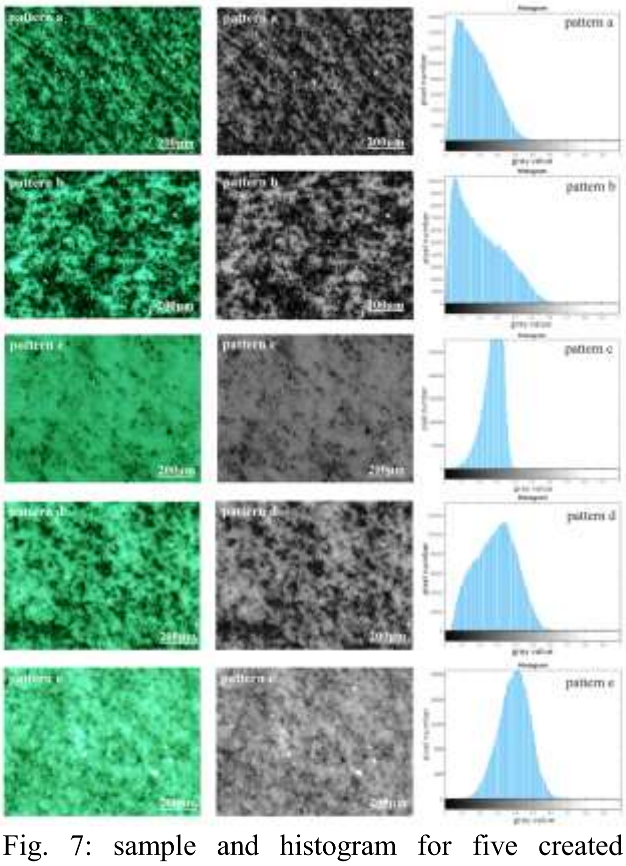

Fig. 7: sample and histogram for five created pattern; the left column shows five patterns with different density; the middle column shows images of left Column in 8-bit format; the right column is related to the histogram of each pattern.

Table.1. patterns characteristics

pattern	Mean	STD
a	44.1665	25.4796
b	52.4024	35.0064
c	70.5382	14.5066
d	73.7045	29.4856
e	100.4333	22.7768

4.2. Comparison of the DIC patterns under translation

To investigate and comparison of patterns, various translations from 10 micrometers to 200 micrometers were applied to each pattern by the translation actuator. After applying the translation, several images were taken from the patterns. In the next step, the images were given to the Moire software and were analyzed. Eventually, the displacement distribution was calculated by the algorithm, and the translation of each pixel in the area of interest was measured. Fig. 8 shows an example of the field of results for the translation test. According to the colors, there are e few differences between colors which represent the fluctuation.

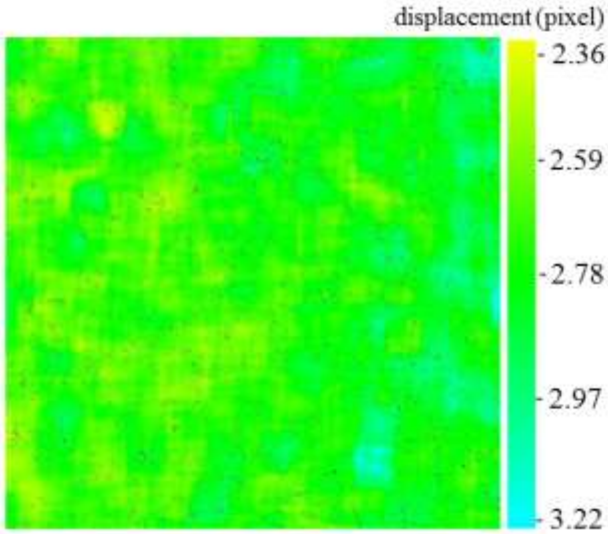

Fig. 8: A sample field of displacement results for translation test.

To investigate the created patterns, various translations with numbers about 10, 30, 50, 100, and 200 micrometers were applied to each pattern. The applied translation and the average of measured translation for each pattern are shown in Fig 9. To calculate the bias error, the average of the measured translation for the patterns was calculated and compared with the applied translation. The difference between the average of measured translations and the applied translation is the bias error. To compare results for each pattern, the average of the bias errors of the applied translation for each pattern were calculated and are shown in Fig.10. Furthermore, means the averages of the standard deviations for each pattern were calculated to compare noise error. A comparison of the average of standard deviations is shown in Fig.11.

Results showed that pattern b which had the highest standard deviation and a low density had the least noise error and the least bias error simultaneously, thus it can result that the pattern should be created by high contrast and the density not to be much low and or high.

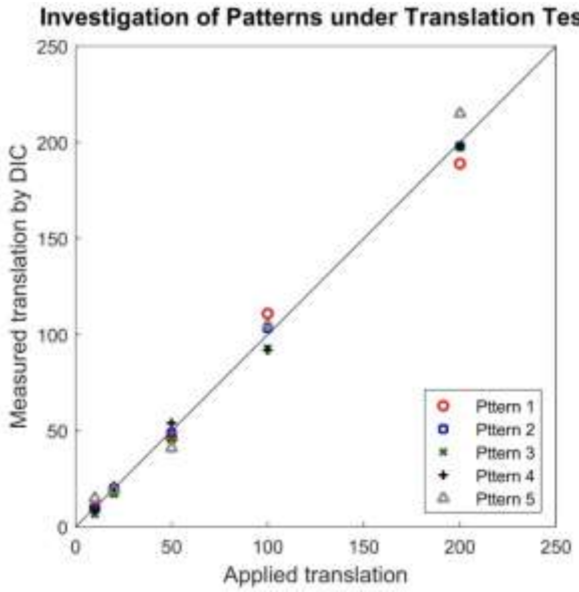

Fig. 9: DIC result for five created patterns under translation test from 10 micrometers to 200.

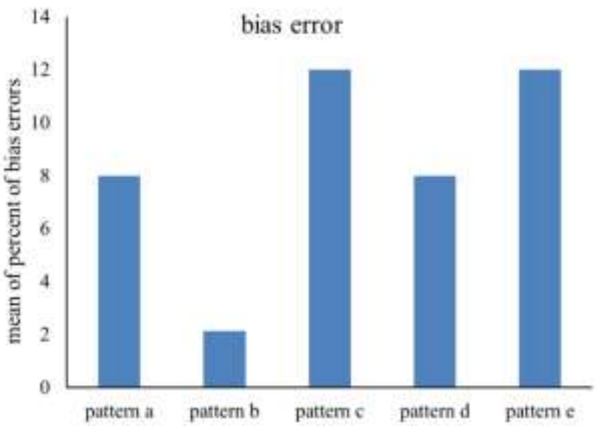

Fig. 10: comparison of means of bias errors for each pattern.

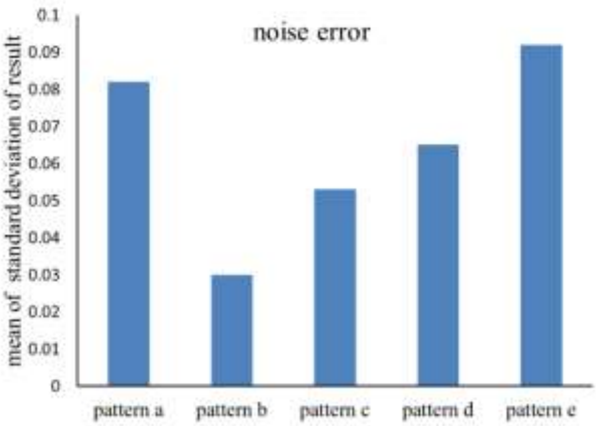

Fig. 11: comparison of means of noises for each pattern.

4.3. Investigation of Rotation

Rigid rotation is one of the different tests that has been selected by researchers to investigate new methods in creating speckle patterns [43]. In the recent study, the rotation was applied to only one of these previous patterns which were investigated under translation test. The selected pattern was the best one in the results of the translation test which had the highest standard deviation or high contrast. In the recent study, various rotations contained 0.05, 0.2, 0.5, and 1 degree were applied to the selected patterns. A selected example of output displacement fields in u and v direction are demonstrated in Fig.12. According to the calculation method of rotation, displacements in the vertical direction were calculated for a horizontal line that passed through the centre of rotation is shown in fig.13. The slop of each line, which is equal to the degree of rotation, was calculated and demonstrated in Fig.14.

Fig.13 shows that at the center of rotation there are several fluctuations due to very small displacements of pixels in comparison to neighbor pixels, and based on fig.14, in small rotations the accuracy is high, but in high rotation, a high error is seen. The experiment for high rotation was repeated several times, but the results were the same. Thus, it can result from the fluctuating in the center of rotation and the error in high rotations that the algorithm is capable to calculate the field of displacement in a particular range of displacement variation of pixels, comprising with other pixels. It means that if two pixels that are next to each other, have a dramatic difference in displacement, the algorithm cannot perform the field of displacements accurately.

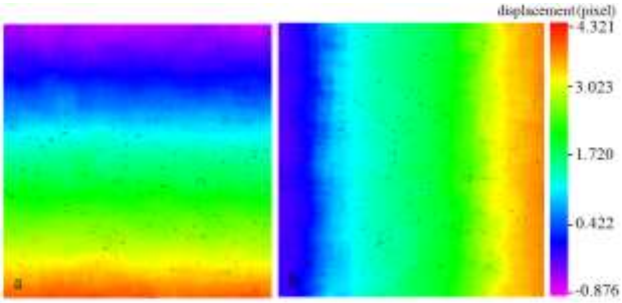

Fig. 12: A sample field of displacement result for rotation test; a) in horizontal direction. b) in vertical direction.

Fig. 13: displacement of each pixel along a line passes from rotation center.

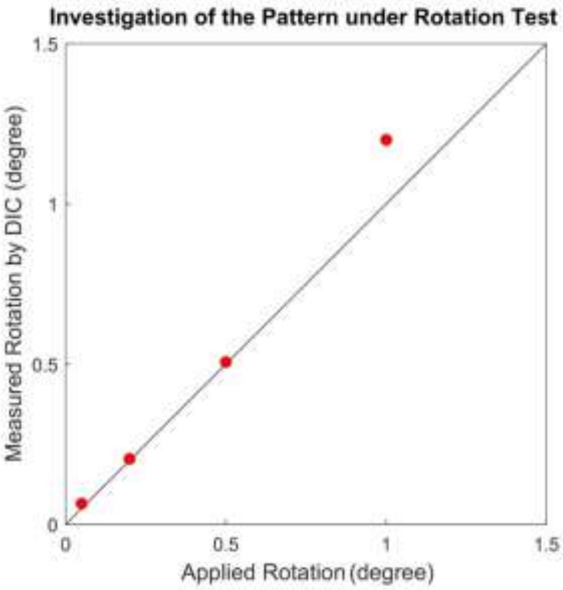

Fig. 14: DIC results for rotation test.

4.4. Investigation of pattern under tensile test

After translation and rotation, the pattern was investigated under the tensile test. The specimen was tended by the displacement control tensile test machine. Different displacements were applied to the top side of the specimen and it was tended by different strain values from half percent to 2.5 percent. The results are shown in fig.15.An example of the field of results is shown in Fig.16. The specimen was extended by a soft slant, and it was expected that the halos be parallel, but they are tangled. It is because of the tensile test machine error. There is a small horizontal displacement in vertical tension and it causes this soft slant. However, results are reasonable and acceptable and the maximum error was under 5 percent. If the strain is calculated along vertical lines in the field of study, equal results with small differences will be obtained. It can be said that the influence of the fine horizontal displacement in the grips of the tensile machine does not have any noticeable influence on the vertical strain.

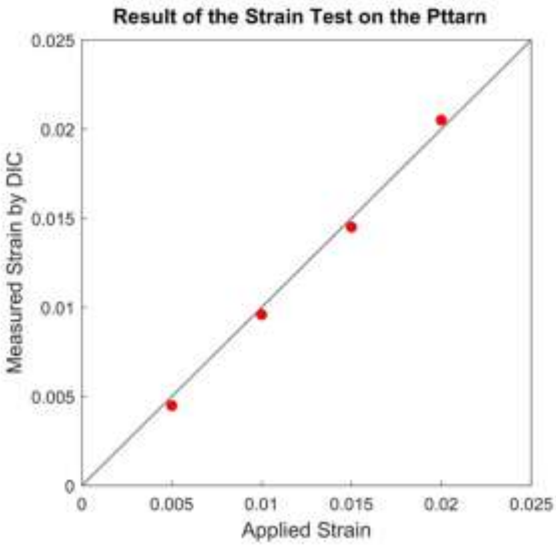

Fig. 15: DIC results for tensile test.

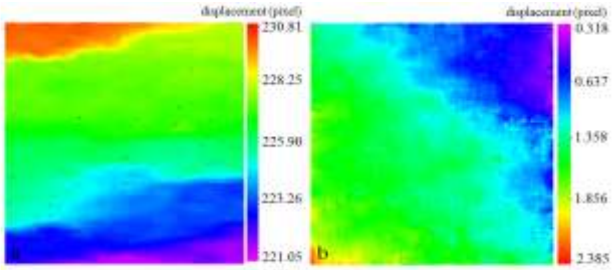

Fig. 16: A sample field of displacement result for strain test; a) in tension direction, b) perpendicular to tension direction.

According to the obtained results in translation, rotation, and tensile tests, it was proved that the pattern is practical and can be used in industrial and research studies. Errors in three types of tests are acceptable to prove the beneficiary of the new patterning method in the DIC technique. The objective of the recent study was to propose and investigate a new method in the creation of a speckle pattern, therefor only GO was used to create black speckles, however, it is possible to use other nanoparticles to the creation of speckles.

4 Conclusion

In this paper, graphene oxide nanoparticles were introduced to create a coating of black particles that can be used as a speckle pattern on the specimen surface for the DIC technique. The speckle pattern in the novel method was simply created by spreading without any special devices. This simplicity made this patterning method effortless and fast to modify the speckle pattern or remove it completely.

Due to the small size of particles and small speckles, the area of interest was magnified by an optical microscope, and as a result, the area of interest was decreased by around one millimeter. Furthermore, the pixel size decreased from about 50 micrometers to around one micrometer, and this reduction in the pixel size increases the accuracy of the DIC technique due to the process of measurement of displacements which is based on the calculation of displacements of pixels in the unit of one pixel.

According to the new patterning method, five patterns with different densities of particles were created on a common specimen. Histogram, average intensity, and standard deviation were measured for each pattern to compare the density of nanoparticles for spreading. Then, different displacements were applied to each pattern, calculating the distribution of the displacement using the DIC method. According to the displacement tests, the best results were related to the pattern with the highest contrast. The speckle pattern also was investigated by strain and rotation tests, and as a result, the capability of the new method in patterning was proved. In general, the result showed that the new method in creating the speckle pattern is efficient in the measurement of displacement, rotation, and strain.

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