Investigation of the speckle pattern effect for displacement assessments by DIC

Salim Caliskan and Hakan Akyuz
Turkish Aerospace Industries Inc, Ankara, Turkey

Received 12 January 2024
Revised 23 February 2024
Accepted 15 April 2024

Abstract

Purpose – This study aims to investigate the effect of speckle pattern on displacement measurements using different speckle diameters and coverage ratios.

Design/methodology/approach – In order to compare the coverage ratio and speckle diameter during the evaluation of the correlation of digital images (DIC) study, template speckle plates were produced on a computer numerical control (CNC) punch press with 600 punches per minute. After the speckle plates were manufactured, the speckled pattern was randomly painted on a plain white side through the manufactured template plates, and then tensile tests were performed under the same loading conditions for each sample to observe displacement variation via correlation parameters.

Findings – During the manufacturing of templates with thin plates, a punch diameter of less than 1.7 mm will cause tool failure; therefore, uniform speckle size can be assessed before operation. A higher coverage ratio resulted in more accurate and reliable results in displacement data. With smaller coverage, the facet size should be increased to achieve favorable results.

Research limitations/implications – If thick template plates are selected, speckle painting cannot be done properly; therefore, template thickness shall also be assessed before operation.

Practical implications – For randomly distributed DIC templates, increasing coverage beyond 50% does not make sense due to difficulties in the production process in the punch press.

Originality/value – Evaluating DIC results via templates manufactured in a punch press with different speckle diameters and coverage ratios is a new topic in literature.

Keywords Aluminum alloy, Tensile test, Digital image correlation, Experimental mechanics, Speckle pattern

Paper type Research paper

1. Introduction

Digital image correlation method has been known as a versatile and effective optical metrology implementation for displacement assessment in the field of experimental mechanics. In the experiments, the measurement accuracy of correlation of digital images (DIC) can be influenced by various factors, such as subpixel optimization algorithm, subset function, subset size, pixel intensity interpolation side effects, noise level along with camera lens distortion. Since the size of the subset explicitly decides the area of the subset via following the displacements between the reference and target subsets. The accuracy of displacements must be critically measured in the context of digital image correlation. The size of a subset must be substantial that there is adequately distinguishing intensity pattern involved within the subset to discriminate itself from others (Pan *et al.*, 2008a).

To investigate displacement feedback, the speckle pattern or more precisely the random contrast distribution, which can appear naturally or artificially on the surface of the test

Authors acknowledge Turkish Aerospace Inc.

Journal of Intelligent Manufacturing and Special Equipment
Emerald Publishing Limited
e-ISSN: 2633-660X
p-ISSN: 2633-6596
DOI 10.1108/JIMSE-01-2024-0002

pieces, plays a significant role by the DIC. The accuracy and precision of DIC measurements relies not only on the correlation algorithms but also heavily on the distribution of the speckle pattern. DIC, was first studied by a team of researchers at the University of South Carolina in the 1980s (Schreier *et al.*, 2009).

Because of its outstanding advantages such as simple test setup, easy application, high durability against ambient vibrations and light changes, as well as wide applicability with adjustable spatial and temporal resolution, the DIC technique has been extensively adopted as a powerful and versatile tool to measure displacement and strain data for different materials and structures, at different spatial and temporal scales and in variant test environments.

In general, the application of DIC techniques for measuring shape, motion and strain involves of three steps. First step is production of speckled patterns. It ensures that the surface of the test piece carries strain information. But, in case of having variable intensity distribution on the specimen surface with adequate contrast, then speckle pattern not needed. Second step is image acquisition. This step captures surface images of the specimen in different load levels using a single or two camera configurations for the measurements. Third step is image analysis. It collates the distorted images with the reference image using a specified cross-correlation algorithm for displacement and strain fields.

Therefore, it can be presumed that it is not possible to perform DIC measurements without the speckle pattern. Contrarily, the sample surface must be coated by a speckled pattern (i.e. random intensity distributed pattern), which enables to evaluate strain data, in order to obtain an accurate and reliable match in next correlation calculation. In addition to their prerequisite in DIC measurements, speckle patterns also have a significant effect on the accuracy and precision in measuring DIC displacements. Many studies have showed (Bomarito *et al.*, 2017) that a speckled pattern with intense gradients usually results in smaller bias errors and decreased random errors.

Speckle patterns can be easily manufactured for most routine investigations where the region of interest ranges from a few millimeters to several meters. As a carrier of strain information, the speckle pattern must have definite, distinctive, non-periodic and well-constructed grayscale characteristics to achieve reliable and accurate DIC measurements. It should be realized that speckle patterns generated by various methods or by different operators may result in markedly different outcomes via distributions, image contrasts, or other characteristics. To achieve accurate DIC measurements, a good speckled sample must meet various requirements. The pattern of speckle on the surface of the test piece must have: high contrast that is different grayscale intensity and relatively large intensity gradient; randomness that is non-periodic, non-repeating models to facilitate field-wide displacement mapping and isotropic characteristic that is there is no orientation in the model. Speckle particles having 3 to 5 pixels in size or slightly larger (Reu, 2015) are strongly suggested to prevent confronting the aliasing effect. Finally, last influencing factor is stability that is a good speckle pattern should stick firmly to the specimen surface and distort to the specimen surface even with severe displacement and deformation without obvious change in the geometry and grayscale characteristics. In DIC measurement, the implementation of subpixel registration algorithm is considered as the basic method to enhance the accuracy and precision of displacement measurement.

Newton–Raphson algorithm (Pan and Li, 2011) and the lately established elaborate inverse compositional Gauss–Newton algorithm for image correlation solution (Pan, 2013) have proven to be the two most extensively preferred due to their higher accuracy, broad applicability and better noise reduced performance. If the specimen has an inherently adequate natural texture distribution on its surface, that texture can be used to carry out the correlation calculation (Sánchez-Arévalo and Pulos, 2008). The method to exhibit the microstructure with sufficient contrast of the image is often evaluated as difficult. Hence, most of the speckle patterns are artificially generated. A commonly used artificial technique is to spray white or black paint with a spray bottle or airbrush to create white or black dots on the surface of the specimen (Pan *et al.*, 2009). Nevertheless, a severe de-correlation influence can take place in laser speckle samples when the test article is exposed to rigid body motion, extreme stress as well as out-of-plane displacement is observed (Brillaud and Lagattu, 2002).

As a beneficial method, spray and air injection are commonly used in the macroscopic scale from millimeter to meter (Lyons *et al.*, 1996) and spinning coatings, pneumatic engineering, nanofilm reshaping, nanoparticle patterning, focused ion beam, lithography applied at microscopic scales from micrometers to nanometer (Winiarski *et al.*, 2011). The diameter of the nozzle, the distance between the article and the nozzle, the air pressure and the viscidity of the solution are important because they can affect the distribution of speckle sizes and standard deviations of the sample (Rayan, 2008). Although speckle patterns created with spaying by help of airbrush are low-cost and easy to operate, the selection of appropriate parameters like powder size of raw material, fluid viscosity, injection distance and pressure must be evaluated in advance (Dong and Pan, 2017).

2. Experimental procedure

3D digital image correlation is a measurement method that utilizes two cameras in a stereo configuration to find out the three surface displacement elements of a test specimen. Each camera takes separately two images of the specimen at distinct load condition of testing (Helfrick *et al.*, 2011). The difference between consecutive pairs of images is accustomed to evaluate the surface displacement. This method produces clearly contrasted surface features in the captured image. It is barely invasive to the surface properties of the sample. The equipment used during this study are high-resolution cameras, each of which captures a 4,096 (H) x 3000 (V) pixel image with Bayer 8-bit resolution. Camera tilt permits the focal planes of two cameras in the same region of interest to rotate and overlap. An LED white light source was used for illumination.

Camera calibration was performed with a 3D calibration plate (Dantec Dynamics GmbH) containing a revealed rectangular dot pattern with known dot size and dot spacing at two distinct surface heights. Each camera captures an image of the calibration plate from their relevant established locations. DIC software used these two images to position the cameras spatially, enabling the image data to be converted to physical area. The stereo cameras are placed in a coordinate system linked to the position and orientation of the calibration target. The calibration target is usually oriented with the coordinate system of the test specimen. The image captured after correction is collected in the camera's coordinate system, then straightened and superimposed in the same coordinate system as the calibration target.

After the data are recorded, image correlation processing is performed to evaluate the physical displacements from the captured image data. For this, a subregion or window of the image is examined, and an image cross-correlation algorithm is carried out between consecutive taken images: one measured displacement image under loading and one reference image that is generally chosen as the initial capture. The window of the moved image is then distorted and compared with the reference image to try to present a finer correlation between the windows of the corresponding images. Since the purpose of this study was to investigate the influence of the speckle model on the derivative shift, all other influencing parameters were assumed to be constant. These cover the camera components and placement, the optical-mechanical components used and the light source.

In this study, it was aimed to investigate effect of speckle pattern on displacement measurements by different speckle diameter and coverage ratios. 7050 aluminum alloy specimens were manufactured with L grain direction and plate form. The chemical composition of the material is presented in.

Table 1. The specimen geometry is **5 × 100 × 200 mm in thickness, width and length respectively**.

A total of 9 specimens were studied to determine speckle pattern influence on DIC results. Static tests were performed at room temperature (23 ± 2 °C) and normal humidity conditions. Test specimens were assembled on Instron 8801 servo-hydraulic test bench and loaded at a constant load ensuring 500 μstrain for each specimen as shown below Figure 1.

3. Manufacturing process

Template plates were manufactured on a computer numerical control (CNC) punch press with a 600 punches per minute. Manufacturing parameters for each template can be seen in Table 2. Here, three different coverage ratios and speckle diameters were studied for template plates within the scope of this study.

Randomly distributed equal size speckles were machined on 0.2 mm thick template plates so that they could be easily painted on the specimen surface. Since the templates and specimens have the same width and length dimension, only speckle patterns are visible on the specimen surface after black color painting as seen Figure 2. After manufacturing template

Table 1. Chemical composition of the material (wt%)

Alloy	Al	Cu	Mg	Zn	Fe	Si	Zr	Mn	Other
7050	87.4	2.6	2.6	6.7	0.15	0.12	0.12	0.10	0.2

Source(s): Authors' own work

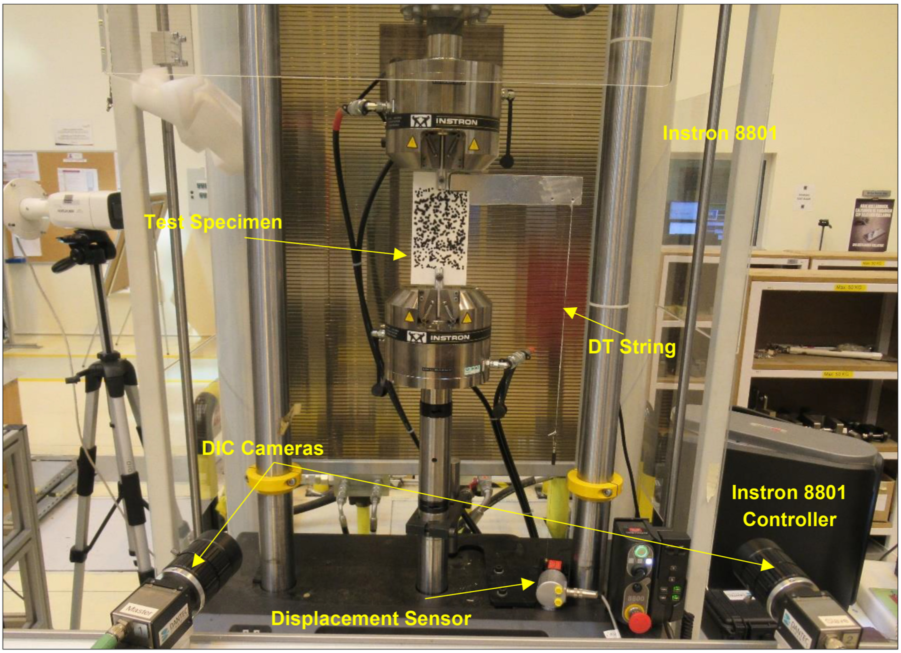


Figure 1. Test set up and DIC configuration

Source(s): Authors' own work

plates, speckled pattern is arbitrarily painted onto a flat white side via manufactured template plates.

4. Tensile test

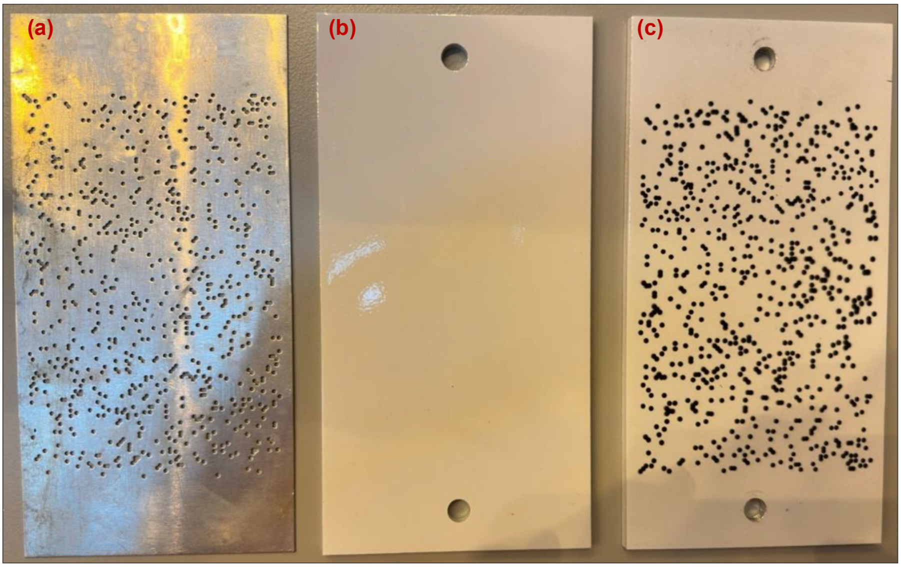
Tensile tests were carried out on Instron 8801 servo-hydraulic uniaxial test system. Before DIC measurements, linear gage was instrumented on the back surface of the specimen and corresponding strain was measured under constant tensile loading after Proportional Integral Derivative (PID) settings to ensure that all specimens have the same strain value of approximately 500 µstrain. Tensile tests were **carried out in one-fifth** increments for all specimens to eliminate effect of loading on DIC measurements. In total, 11 measurements were captured during loadings.

Before starting testing, camera brightness settings were performed to optimize illumination and calibration process was done to reach minimum global residuum values.

ID	Punch number	Punch diameter (mm)	Coverage (%)	Pixel
SP1	617	1.70	10	6
SP2	285	2.60	10	9
SP3	168	3.26	10	12
SP4	1850	1.70	30	6
SP5	856	2.60	30	9
SP6	503	3.26	30	12
SP7	3084	1.70	50	6
SP8	1426	2.60	50	9
SP9	839	3.26	50	12

Source(s): Authors' own work

Table 2. Manufacturing parameters for speckle pattern templates



Source(s): Authors' own work

Figure 2. Template plate after manufacturing (a), white painted test specimen (b) and speckle pattern (c)

After the adjustments, camera positions were fixed and all the measurements were done with same configuration to only see the effect of speckle pattern on DIC measurements.

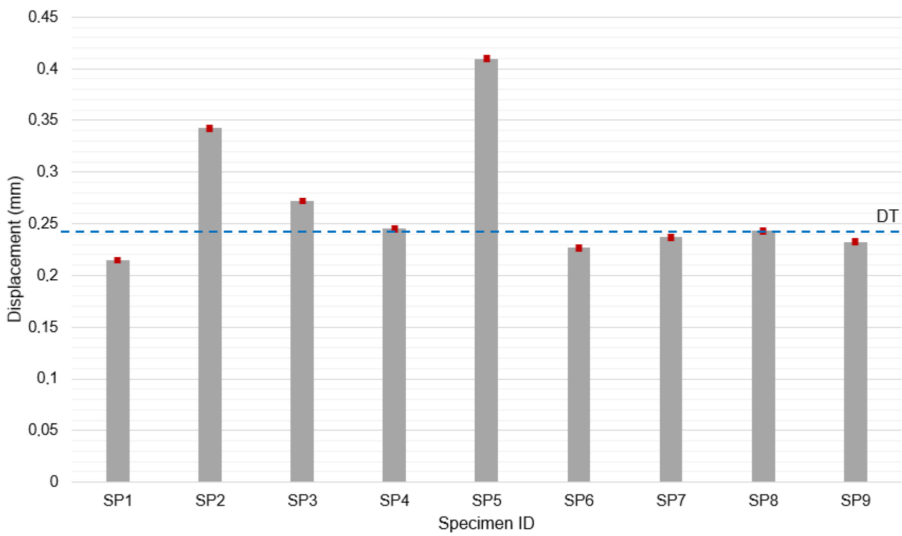
Although the servo-hydraulic uniaxial test system has the linear variable differential transformer (LVDT) sensor, an external displacement transducer was mounted on specimen surface to measure directly *x*-direction displacement under uniaxial loading. Displacement data were recorded with external data logger and DIC measurements were compared with displacement sensor data. Comparison was performed at highest loading case and performance of the speckle parameters was evaluated via displacement data.

Displacement transducer measured 0.243 mm in *x*-axis direction under maximum loading condition. On the other hand, displacement measurements can be seen in Table 3 via DIC method by given corresponding correlation parameters. Accordingly, coverage ratio is more dominant than speckle diameter. By increasing coverage ratio results in more accurate estimation of data as shown Figure 3.

ID	Facet size	Grid spacing	DIC displacement	St. Deviation
SP1	49	19	0.2147	0.0006
SP2	49	19	0.3424	0.0007
SP3	49	19	0.2720	0.0007
SP4	29	19	0.2453	0.0009
SP5	29	19	0.4095	0.0011
SP6	29	19	0.2266	0.0013
SP7	29	19	0.2370	0.0010
SP8	29	19	0.2431	0.0013
SP9	29	19	0.2326	0.0013

Source(s): Authors' own work

Table 3.
Test results for each speckle pattern



Source(s): Authors' own work

Figure 3.
Variation of displacement by speckle pattern and coverage ratio (DT: Displacement transducer)

5. Discussion

The displacement results via DIC system are affected by the equipment used, lighting environment and speckle pattern. For the image acquisition equipment, three principle factors can be discriminated: optical lenses, camera and image correlation package. The lenses manage for transmitting the light beam reflected by the object surface to the photoreceptors of the camera. First, a speckled pattern is arbitrarily painted onto a flat white side. Various trials have been made to achieve a uniformly distributed black speckle pattern. Thus, the number of black pixels in the subset is split by the total number of pixels. This enables to coverage percent of the speckle pattern. An important evaluation after performing tests is that the larger the subset, the more accurately measured displacements. If the displacement field is uniform, the data can be smoothed inside the subset, which certainly results in more reliable displacement values. Another evaluation is that in the case where a small subset is used as a correlation parameter, the most accurate results obtained with the smallest speckle points. Hereby, the size of the speckle should be suitable with the size of the subset. In addition, the size of the subset must be adjusted for the strain type. For instance, the large subset size associated with large speckles yields the best results for uniform strain. The accuracy of the DIC method was investigated based on the character of the speckle pattern, i.e. the average speckle size and the size of the subset used. In the present study, the test specimens exhibit that the larger the subsets, the better the results under tensile loading. This just proves that the size of the subset, for a given speckle sample, affects the precision measurement with envisaged displacement values (Lecompte *et al.*, 2006a).

The subset size relies on the expected strain distribution type. Upon handling with uniform strain, the size of the subset shall be as large as possible to allow noise reduction and thus flattening of the displacement values. Still, in the case of non-uniform strain, the size of the subset should be a compromise between avoiding blurring of the displacement input, correlation problems and noise reduction. The first parameter is the size of the speckles that appear, which varies for each specimen set. It has been demonstrated that the speckle pattern can be sufficiently random using only one speckle size. The second one is the coverage or ratio of grayscale pixels to total pixels. In fact, the image captured by an object with a charged-coupled device (CCD) camera is only a representative image of the object itself affected by the lighting conditions, the used lens and the noise level of the light-sensitive cells. In other words, the actual grayscale distribution does not reach from 0 to 255. Indeed, it is to some degree lower, which means that the black and white pixels are truly depicted by a value greater than 0 and less than 255. Finally, the existence of noise in the image is inevitable. Opacity can be simulated using a Gaussian filter with a size of 4x4 pixels and a standard deviation of 0.8. It is distinct that in the case of a subset size of 15x15 pixels, the optimum speckle size is 5 pixels and the optimal spot coverage is between 40 and 70%. It has been shown that using a subset of 15x15 pixels, the optimum selection for speckle diameter is 5 pixels, and the image overlap is between 40 and 70% (Lecompte *et al.*, 2006b).

The main purpose of this study is to examine the influence of speckle pattern on the uncertainty of the DIC measurement system. To diminish the speckle pattern uncertainty, it was resolved that a steady speckle size of spots with a diameter of 5 pixels with a density of one spot per 20 square pixels gave best result (Jee *et al.*, 2018).

Data recorded before and after surface displacement via speckle patterns are required to perform the analysis. The recorded images are converted to a matrix containing pixel intensity values. It should also be recognized that when the model size is less than 30x30 pixels, the accuracy of the displacement measurement is unstable. For reliable results, model size should be larger than 30x30 pixels. In the case of low-contrast speckle patterns, a larger sample size results in the best accuracy. When the model size is less than 30x30 pixels, the accuracy of displacement measurement is said to be unstable. Eventually, model size should be larger than 30x30 pixels for reliable results (Gubarev *et al.*, 2016).

It is noted (Sutton *et al.*, 1983) that the size of the subset is consistently an important parameter in the correlation algorithm. Two sorts of strain can be established, a uniform strain and a non-uniform strain; both are elicited from the results of a finite element analysis (FEM) analysis. Each pixel stores a certain grayscale value that ranges from 0 to 255, depending on the intensity of light reflected from the surface of the sample being tested. Two images of the article in different distortion states are compared using the pixel and its signature in the undistorted image and looking for pixels in the distorted image to maximize the similarity function.

While larger subset sizes often lead to larger errors in evaluation of the displacement values. DIC evaluation can yield significantly different results taken by different operator although the specimen, corresponding displacement and assembly size are all the same (Pan *et al.*, 2008b). As a whole, DIC utilizes random distributions speckles on the article surface to get full-field surface displacements by comparing the region of interest before and after deformation. Since the image captured from the data acquisition system certainly contains various types of noise like thermal noise, read noise and capture noise, the displacement of the subpixels can be calculated. It is clear that, for three pairs of test images, the standard deviation error decreases as the size of the subset increases. The accuracy of the DIC displacement measurement can be functionally enhanced in two schemes: First one is that using larger subsets if possible, the subset can also be increased by using a high-resolution CCD camera or making prominent the contrast of the speckle pattern. The other one is to reduce image noise level. Image noise can be eliminated through the use of supercharged equipment like exclusive cameras.

6. Conclusions

The following conclusions can be reached from this study:

(1) Higher coverage ratio resulted in more accurate and reliable results in displacement data.

(2) For random distributed DIC templates, increasing coverage beyond 50% does not make sense due to difficulties in the production process in the punch press.

(3) During processing of templates with thin plates, a punch diameter of less than 1.7 mm will cause failure on tool therefore; uniform speckle size can be assessed before operation.

(4) If thick template plates selected, speckle painting cannot be done properly; therefore, template thickness shall also be assessed before operation.

(5) The coverage parameter results as a more dominant influence compared to the punch diameter in terms of displacement results.

(6) With smaller coverage, the facet size should be increased to achieve favorable results.

(7) Standard deviation increased with larger coverage ratio based on displacement results.

References

Bomarito, G.F., Hochhalter, J., Ruggles, T. and Cannon, A. (2017), "Increasing accuracy and precision of digital image correlation through pattern optimization", *Optics and Lasers in Engineering*, Vol. 91, pp. 73-85, doi: 10.1016/j.optlaseng.2016.11.005.

Brillaud, J. and Lagattu, F. (2002), "Limits and possibilities of laser speckle and white-light image-correlation methods: theory and experiments", *Applied Optics*, Vol. 41 No. 31, p. 6603, doi: 10.1364/ao.41.006603.

Dong, Y.L. and Pan, B. (2017), "A review of speckle pattern fabrication and assessment for digital image correlation", *Experimental Mechanics*, Vol. 57 No. 8, pp. 1161-1181, doi: 10.1007/s11340-017-0283-1.

Gubarev, F., Li, L., Klenovskii, M. and Glotov, A. (2016), "Speckle pattern processing by digital image correlation", *MATEC Web of Conferences*, Vol. 48, 04003, doi: 10.1051/matecconf/20164804003.

Helfrick, M.N., Niezrecki, C., Avitabile, P. and Schmidt, T. (2011), "3D digital image correlation methods for full-field vibration measurement", *Mechanical Systems and Signal Processing*, Vol. 25 No. 3, pp. 917-927, doi: 10.1016/j.ymssp.2010.08.013.

Jee, C., Salata, G., Nobes, D. and Duke, K. (2018), "Investigating the effect of a speckle pattern on measurement uncertainty in a three-dimensional digital image correlation (3D-DIC) system", *Progress in Canadian Mechanical Engineering*. doi: 10.25071/10315/35392.

Lecompte, D., Smits, A., Bossuyt, S., Sol, H., Vantomme, J., Van Hemelrijck, D. and Habraken, A. (2006a), "Quality Assessment of Speckle patterns for digital image correlation", *Optics and Lasers in Engineering*, Vol. 44 No. 11, pp. 1132-1145, doi: 10.1016/j.optlaseng.2005.10.004.

Lecompte, D., Sol, H., Vantomme, J. and Habraken, A. (2006b), "Analysis of speckle patterns for deformation measurements by digital image correlation", *SPIE Proceedings*, Vol. 6341, pp. 80-85, doi: 10.1117/12.695276.

Lyons, J.S., Liu, J. and Sutton, M.A. (1996), "High-temperature deformation measurements using digital-image correlation", *Experimental Mechanics*, Vol. 36 No. 1, pp. 64-70, doi: 10.1007/bf02328699.

Pan, B. (2013), "An evaluation of convergence criteria for digital image correlation using inverse compositional Gauss–Newton algorithm", *Strain*, Vol. 50 No. 1, pp. 48-56, doi: 10.1111/str.12066.

Pan, B. and Li, K. (2011), "A fast digital image correlation method for deformation measurement", *Optics and Lasers in Engineering*, Vol. 49 No. 7, pp. 841-847, doi: 10.1016/j.optlaseng.2011.02.023.

Pan, B., Xie, H., Wang, Z., Qian, K. and Wang, Z. (2008a), "Study on subset size selection in digital image correlation for Speckle Patterns", *Optics Express*, Vol. 16 No. 10, p. 7037, doi: 10.1364/oe.16.007037.

Pan, B., Xie, H., Wang, Z., Qian, K. and Wang, Z. (2008b), "Study on subset size selection in digital image correlation for Speckle Patterns", *Optics Express*, Vol. 16 No. 10, p. 7037, doi: 10.1364/oe.16.007037.

Pan, B., Qian, K., Xie, H. and Asundi, A. (2009), "Two-dimensional digital image correlation for in-plane displacement and strain measurement: a Review", *Measurement Science and Technology*, Vol. 20 No. 6, 062001, doi: 10.1088/0957-0233/20/6/062001.

Rayan, M.K. (2008), *Spray Deposition of Biomolecular Thin Films*, Dissertation, University of South Florida.

Reu, P. (2015), "All about speckles: contrast", *Experimental Techniques*, Vol. 39 No. 1, pp. 1-2, doi: 10.1111/ext.12126.

Sánchez-Arévalo, F.M. and Pulos, G. (2008), "Use of digital image correlation to determine the mechanical behavior of materials", *Materials Characterization*, Vol. 59 No. 11, pp. 1572-1579, doi: 10.1016/j.matchar.2008.02.002.

Schreier, H., Orteu, J.-J. and Sutton, M.A. (2009), "Image correlation for shape, motion and deformation measurements", doi: 10.1007/978-0-387-78747-3.

Sutton, M., Wolters, W., Peters, W., Ranson, W. and McNeill, S. (1983), "Determination of displacements using an improved digital correlation method", *Image and Vision Computing*, Vol. 1 No. 3, pp. 133-139, doi: 10.1016/0262-8856(83)90064-1.

Winiarski, B., Schajer, G.S. and Withers, P.J. (2011), "Surface Decoration for improving the accuracy of displacement measurements by digital image correlation in Sem", *Experimental Mechanics*, Vol. 52 No. 7, pp. 793-804, doi: 10.1007/s11340-011-9568-y.

Corresponding author
Salim Caliskan can be contacted at: salim.caliskan@tai.com.tr