Journal of Metallic Materials 2022, 74 (3-4), p. 30–41

Marcin KEMPNY

Łukasiewicz Research Network – Institute for Ferrous Metallurgy
Sieć Badawcza Łukasiewicz – Instytut Metalurgii Żelaza

DOI: 10.32730/imz.2657-747.22.3-4.4

DIGITAL IMAGE CORRELATION – METHOD DEVELOPMENT, SCOPE, PRINCIPLE OF FUNCTIONING, AND FUTURE GOALS

CYFROWA KORELACJA OBRAZU – OPRACOWANIE METODY, ZAKRES, ZASADA DZIAŁANIA I CELE NA PRZYSZŁOŚĆ

This paper presents the basics of the Digital Image Correlation System, its algorithm of operation, methods of data recording and implementation. In addition, the paper characterises in detail the standard bench instrumentation necessary for the implementation of this type of measurement. The paper also describes the procedure of sample preparation and classifies the main methods of applying a marker to the surface of the sample. The article highlights the main advantages of the system and the main difficulties associated with its operation, and indicates the important parameters affecting the quality of the measurement. The paper shows a wide range of applications of Digital Image Correlation (DIC) and the possibilities of cooperation with other measurement systems as well as extended versions of the system, such as Digital Volumetric Correlation. The article also outlines further directions for the development of the DIC research methodology including, among others, extending the temperature range in which the method can be applied, as well as increasing the speed of camera image recording. Such modifications will allow the image correlation method to be used for research where it has not yet been possible.

Keywords: *Digital Image Correlation, Digital Volume Correlation, non-destructive tests, research methodology, optical measuring systems*

W pracy przedstawiono podstawy systemu cyfrowej korelacji obrazów, algorytm działania, metody rejestracji danych oraz implementacji. Ponadto w pracy szczegółowo scharakteryzowano standardowe oprzyrządowanie stanowiskowe niezbędne do realizacji tego typu pomiarów. W pracy opisano również procedurę przygotowania próbki oraz sklasyfikowano główne metody nanoszenia znacznika na powierzchnię próbki. Artykuł podkreśla główne zalety systemu, główne trudności związane z jego działaniem oraz wskazuje istotne parametry wpływające na jakość pomiaru. Manuskrypt pokazuje szeroki zakres zastosowań cyfrowej korelacji obrazu (DIC) oraz możliwości współpracy z innymi systemami pomiarowymi, a także rozszerzone wersje systemu, takie jak cyfrowa korelacja wolumetryczna. W pracy nakreślono również dalsze kierunki rozwoju metodologii badań DIC, w tym m.in. rozszerzenie zakresu temperatur, w których metoda może być stosowana, jak również zwiększenie szybkości rejestracji obrazu z kamer. Takie modyfikacje pozwolą na wykorzystanie metody korelacji obrazów do badań, w których zastosowanie DIC nie było dotychczas możliwe.

Słowa kluczowe: *Cyfrowa Korelacja Obrazu, Cyfrowa Korelacja Objętościowa, testy nieniszczące, metodologia badawcza, optyczne systemy pomiarowe*

1. INTRODUCTION

The article is a short review of the digital image correlation technology. The Author prepared this article to introduce researchers, who are not familiar with image correlation techniques, to this measurement technique.

The first part of the publication exmplains the basic rules of the method's functioning. Further paragraphs describe a wide range of digital image correlation applications in research projects from different fields of science. In the last part, the Author predicts the directions of further development of the technology and indicates what attempts are currently being made at developing the system.

As a conclusion, the Author highlights the main advantages and disadvantages of the digital image correlation techlogy discovered in presented research projects.

2. HISTORICAL ORIGINS OF THE METHOD

Since the first photograph was taken in 1827, the technique of 'drawing with light' –photography, there have been attempts at using it to measure various

Corresponding Author: Marcin Kempny, email: marcin.kempny@imz.lukasiewicz.gov.pl
Sieć Badawcza Łukasiewicz – Instytut Metalurgii Żelaza, ul. K. Miarki 12-14, 44-100 Gliwice, Poland

quantities. These attempts gave birth to photogrammetry – a field that deals with the reconstruction of shapes, sizes, and mutual location of objects in the field based on photographs – photograms. Depending on the way the photographs are used, the following can be distinguished:

- Planar, single-image photogrammetry,
- Spatial, two-image photogrammetry, also called stereophotogrammetry, in which a spatial image of an object is obtained using a stereogram – a pair of images taken from two points in space.

The photogrammetric method is used in fields requiring measurement of very large areas. These fields include geodesy, geology, architecture, archaeology, meteorology, and cartography. The first photogrammetric images were taken in 1858 in Paris from a tethered balloon. Since then, along with the technology's development, photogrammetry progressed, which can be divided into 4 phases [1]. Motion and Deformation Measurements provides a comprehensive overview of data extraction through image analysis. Readers will find and in-depth look into various single- and multi-camera models (2D-DIC and 3D-DIC:

- Plane photogrammetry (1850–1900) – an early form of photogrammetry based on the analysis of single photographs of the planes of an examined area.
- Analogue photogrammetry (1900–1950) – at this stage of development, analogue instruments of mechanical and optical design began to be used to reproduce geometric relationships between photogrammetric images and photographed objects.
- Analytical photogrammetry (1950–1985) – developed with the emergence of computers, which made it possible to numerically process recorded coordinates of observed points. It reduced the use of expensive equipment and labour-intensive techniques of analogue photogrammetry.
- Digital photogrammetry (1985–present) emerged with the advent of digital cameras, making it possible to input photogrammetric images directly into a computer without prior scanning.

The digital image correlation method can be classified as one type of photogrammetry, as it is largely based on tracking coordinate changes of recorded points through cameras.

3. DIGITAL IMAGE CORRELATION METHOD AND SYSTEM

3.1. ALGORITHM DIC (DIGITAL IMAGE CORRELATION)

Digital image correlation has its basis in the principles of continuous medium mechanics. In simple terms, the method involves tracking, via a subset of pixel values, the movement of points from a reference image to deformed images. The subset of pixels is defined to contain a wide distribution of grayscale levels. With this definition, each pixel subset defined in this way is unique enough to be distinguished from other subsets in the deformed image. The square subset is centred at point $A(x_A y_A)$ (Fig. 1) relative to the centre of the reference subset, the centre of the deformed subset is shifted in the x and y directions resulting in point A' $(x_A' y_A')$. Point B in the reference subset has coordinates $(x_B y_B)$, assuming continuity of the solid object, neighbouring points in the reference subset, will be the neighbouring points in the deformed subset. Therefore, point B' in the deformed subset will have coordinates $(x_B' y_B')$, as illustrated in Fig. 1 [2]. The following equations presents the basic mathematical rules which describe image correlation.

$$A_1 = (x_1, y_1, z_1) = [x + u(A), y + v(A)] \tag{1}$$

$$\begin{gathered} B_1 = (x_1 + \mathrm{d}x_1, y_1 + \mathrm{d}y_1) \\ B_1 = [x + u(A) + u(B) - u(A) + \mathrm{d}x, \\ y + v(A) + v(B) - v(A) + \mathrm{d}y] \end{gathered} \tag{2}$$

$$|AB|^2 = (\mathrm{d}s)^2 = \mathrm{d}x^2 + \mathrm{d}y^2 \tag{3}$$

$$|A_1B_1|^2 = (\mathrm{d}s_1)^2 = \mathrm{d}x_1{}^2 + \mathrm{d}y_1{}^2 \tag{4}$$

where: u, v are the components of displacement in the x, y-axis direction.

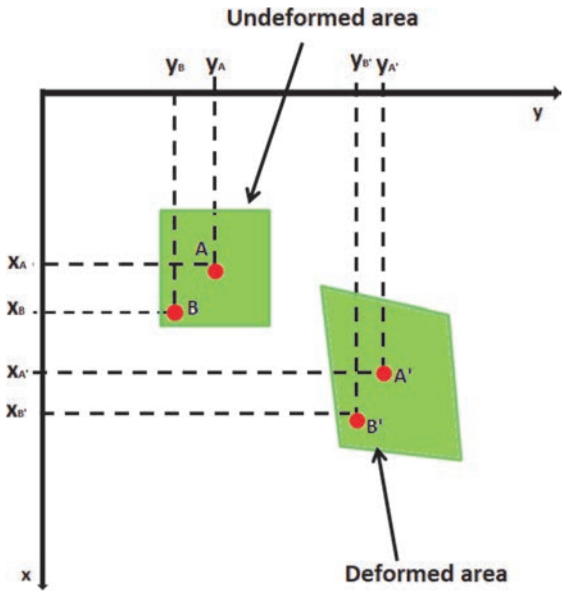


Fig. 1. Deformation diagram of a section of the scanned surface in a two-dimensional coordinate system [4]

Rys. 1. Schemat deformacji fragmentu skanowanej powierzchni w dwuwymiarowym układzie współrzędnych [4]

By performing transformations of formulas (1), (2), (3) and (4), equations defining the components of the deformation state in a two-dimensional coordinate system can be obtained [3]:

$$\varepsilon_{xx} \cong \frac{\partial u}{\partial x} + \frac{1}{2}\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial x}\right)^2\right] \tag{5}$$

$$\varepsilon_{yy} \cong \frac{\partial u}{\partial y} + \frac{1}{2}\left[\left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2\right] \tag{6}$$

$$\varepsilon_{xy} \cong \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) + \frac{1}{2}\left[\frac{\partial u}{\partial x}\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\frac{\partial v}{\partial y}\right] \tag{7}$$

To compare the reference subset with the deformed subset, it is necessary to introduce a correlation criterion. Let us assume that f(x, y) and g(x', y') describe the grey intensity distribution of the reference and deformed subsets. The three most commonly used correlation functions are based on the sum of squares of differences method, as follows:

1. Sum of squares of differences (SSD):

$$C_{\mathrm{SSD}}(\vec{p}) = \sum_{i=-M}^{M}\sum_{i=-M}^{M}\left[f(x_i, y_i) - g(x_{1i}, y_{1i})\right]^2 \tag{8}$$

2. Normalised sum of squares of differences (NSSD):

$$C_{\mathrm{NSSD}}(\vec{p}) = \sum_{i=-M}^{M}\sum_{i=-M}^{M}\left[\frac{f(x_i, y_i)}{\bar{f}} - \frac{g(x_{1i}, y_{1i})}{\bar{g}}\right]^2 \tag{9}$$

where:

$$\bar{f} = \sqrt{\sum_{i=-M}^{M}\sum_{i=-M}^{M}\left[f(x_i, y_i)\right]^2} \tag{10}$$

$$\bar{g} = \sqrt{\sum_{i=-M}^{M}\sum_{i=-M}^{M}\left[g(x_{1i}, y_{1i})\right]^2} \tag{11}$$

3. Zero-normalised sum of squared differences (ZNSSD):

$$C_{\mathrm{ZNSSD}}(\vec{p}) = \sum_{i=-M}^{M}\sum_{i=-M}^{M}\left[\frac{f(x_i, y_i) - f_m}{\Delta f} - \frac{g(x_{1i}, y_{1i}) - g_m}{\Delta g}\right]^2 \tag{12}$$

where:

$$f_m = \frac{1}{(2M+1)^2}\sum_{i=-M}^{M}\sum_{i=-M}^{M} f(x_i, y_i) \tag{13}$$

$$g_m = \frac{1}{(2M+1)^2}\sum_{i=-M}^{M}\sum_{i=-M}^{M} g(x_{1i}, y_{1i}) \tag{14}$$

$$\Delta f = \sqrt{\sum_{i=-M}^{M}\sum_{i=-M}^{M}\left[f(x_i, y_i) - f_m\right]^2} \tag{15}$$

$$\Delta g = \sqrt{\sum_{i=-M}^{M}\sum_{i=-M}^{M}\left[g(x_{1i}, y_{1i}) - g_m\right]^2} \tag{16}$$

The SSD function is sensitive to illumination fluctuations. For the NSSD function, the effect of linear illumination scaling (e.g. changes in camera sensitivity) has been eliminated, but it remains sensitive to shifts in illumination (e.g. additional light sources). Only the ZNSSD function is insensitive to both linear scaling and shifts in illumination. Given the change in the shape of the subsets during deformation, the correlation function becomes a nonlinear function concerning the mapping parameter vector:

$$\vec{p} = (u, u_x, u_y, v, v_x, v_y)^{\mathrm{T}} \tag{17}$$

To solve the six parameter vectors (17), a Newton-Raphson method called iterative cross-correlation algorithm in the spatial domain is used [4]. The solution is represented by equation (18):

$$\vec{p} = \vec{p}_0 - \frac{\Delta C(\vec{p}_0)}{\Delta\Delta C(\vec{p}_0)} \tag{18}$$

where:

$\vec{p}_0$ – initial assumption,
$\vec{p}$ – subsequent iteration solution,
$\Delta C(\vec{p}_0)$ – first-order gradient of the correlation function,
$\Delta\Delta C(\vec{p}_0)$ – second-order gradient of the correlation function.

3.2. PHYSICAL SYSTEM DESIGN

A system capable of performing strain measurements according to the equations presented above must consist of cameras (depending on the two- or the three-dimensional version with one or two cameras), a light source, and a computer with appropriate software, with an example of such system [5] presented in Fig. 2.

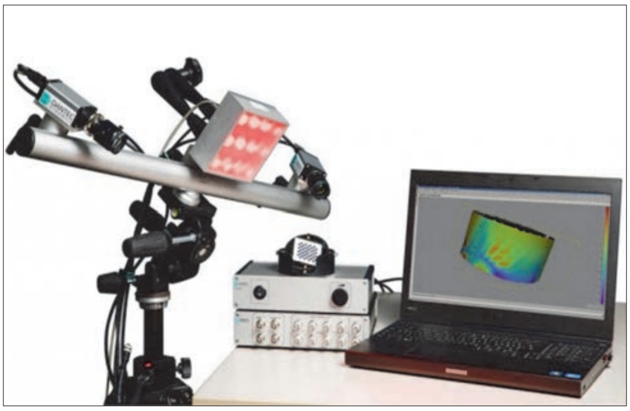


Fig. 2. A configuration of digital image correlation system [5]

Rys. 2. Przykładowa konfiguracja systemu cyfrowej korelacji obrazów [5]

The cameras take a series of digital images of the object. The first of them is used as a reference image, on which the implemented algorithm identifies characteristic points and then determines the deformation of the body by comparing the coordinates of the points from the reference image with the coordinates of the same points in the images taken during the deformation. To properly delineate the characteristic points, selected areas are assigned rectangular or square boxes of approximately 15×15 pixels, called ‘facets’ [6]. The size and number of facets determine the accuracy and speed of computation. Feature points are identified based on the grey gradients in each facet.

3.3. ADVANTAGES AND DISADVANTAGES OF MEASUREMENT TECHNOLOGY

The digital image correlation system determines coordinates based on the reorientation of the facet centre, as seen in Fig. 3. Therefore, covering the tested surface with a speckle structure becomes the key issue. Applying random 'markers' in the right way poses many difficulties for researchers. The most common problems include:

- 'peeling' of the applied paint from the surface of the test specimen,
- colour change of the painted surface under the influence of temperature during the experiment,
- creating a marker pattern that may be too dense, too sparse, or too regular.

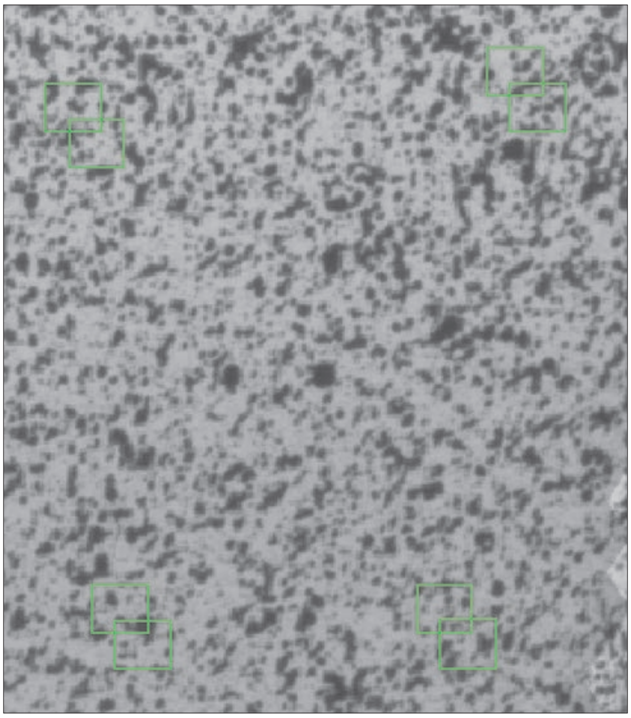


Fig. 3. Fragment of measurement field with an arrangement of facets

Rys. 3. Fragment pola pomiarowego z rozmieszczeniem fasetek

To overcome these difficulties, researchers use different types of dyes, depending on the material to be studied and the experimental conditions. Different methods of applying the markers have also been developed. In his work [4], Thai Thinn uses a common toothbrush as a tool to spray dye onto a test surface. In contrast, Blaber et al. [7] sandblasted the test specimens and then used a laser to engrave a pattern of more than 2,000 random dots on the test surface. Pan et al. [8] in their study used a proprietary mixture of tantalum carbide and alcohol to coat the samples with a speckled structure. A different approach was presented by Blug et al. [9]. They abandoned the use of tracer coating in the work. In their design, it was sufficient to polish the test surface and use a wide analysis field, above 10 mm^2.

The DIC system has other limitations in addition to its demanding sample preparation process:

- This type of equipment requires a complex calibration before the measurement, which requires at least 8 images and a specially prepared calibration table, placed in the field of view of the cameras in different positions [10]. The suggested positions of the calibration table are shown in Fig 4.

Fig. 4. Calibration process

Rys 4. Proces kalibracji

- Since the digital image correlation method is a non-contact method that works by the light reflected from the surface under test and recorded by the camera system, any obstacles, and contaminants in the light source – surface under test – camera system path will cause measurement errors. Therefore, it is important to maintain a clear, smoke-free atmosphere around the test object [11].
- The digital image correlation system uses reflected light to record measurements. This system limits the temperature range over which the DIC can operate. If the sample reaches a temperature at which it starts to emit the delivered energy in the form of visible radiation, the measurements carried out may be significantly disturbed [11].
- Maintaining proper focus on the recorded area is also an important factor. If the exposure time is too long during measurements in which the sample is subjected to high-frequency vibrations, the image will be blurred, making it impossible to obtain measurement data [12].

In addition to the above limitations, the digital image correlation method has numerous advantages. Among the most important are [11]:

- No physical contact with the test sample – the measurement does not apply additional pressure to the test surface and does not change the heat balance of the sample.
- Camera images can cover samples of any geometry and any size. Therefore, the system can be used to conduct micro and macro examination.

- Contact gauges are usually matched to a single surface shape. The DIC system has great flexibility in the shape and size of the object to be analysed.
- Measurement data received from the system can be presented in the form of graphs and tables, as well as a deformation map generated from the sample image, see Fig. 5.

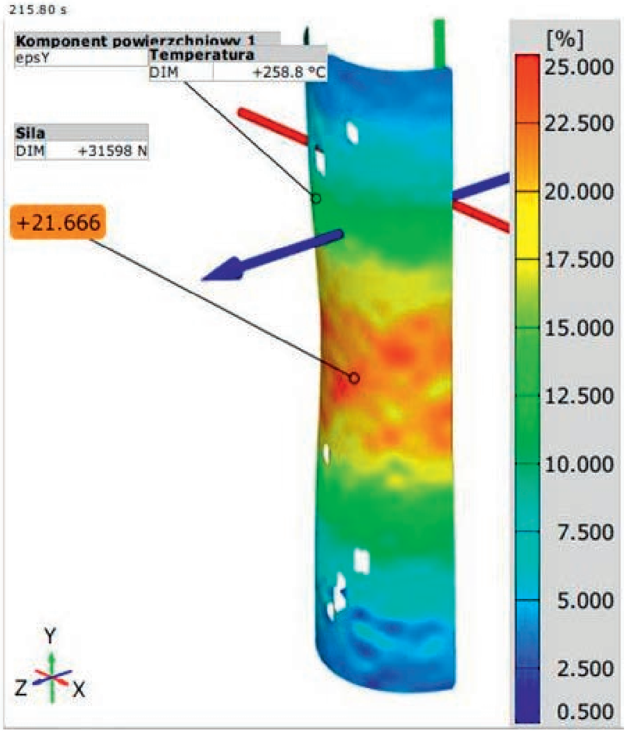


Fig. 5. Deformation map generated on a specimen [5]

Rys. 5. Mapa odkształceń wygenerowana na próbce [5]

- There is no need for a model material with special properties. This numerical-visual method can be applied to real structures, even during their operation [13].

4. CURRENT APPLICATIONS

Due to its high flexibility and adaptability, the DIC system has gained great popularity in many fields of experimental science. Some of the most important fields that use DIC include construction, biomechanics, and materials engineering.

4.1. BUILDING

The digital image correlation system is capable of recording the deformation of the test object on both macro and micro scales, so it is ideal for detecting cracks in concrete beams even before they become visible to the unaided eye, as seen in Fig. 6 [13–15]. Using the DIC system, in her work [15], Marcinczak-determined the effect of PBO-FRCM composite strips applied to the surface of a concrete beam on its flexural strength.

The image correlation method was also used by Seshu et al. [16] to develop a new method for shear strengthening of reinforced concrete members using a steel wire mesh placed along the beam in the core zone of the section.

A well-calibrated system allows measurements to be made with high accuracy. In their work [14], Li et al. described the damage development in the case of a concrete beam caused by acoustic wave action. In

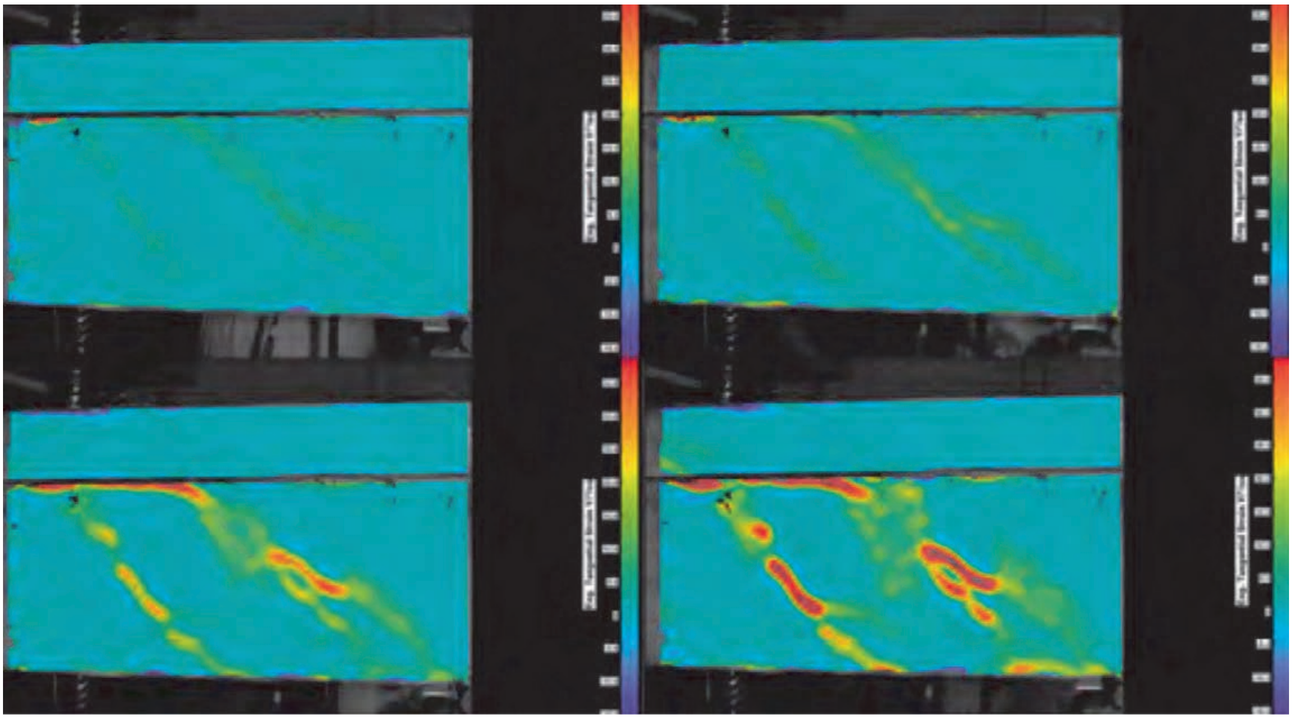


Fig. 6. DIC camera image showing diagonal crack development [15]

Rys. 6. Obraz z kamery DIC przedstawiający rozwój pęknięcia ukośnego [15]

this paper, the standard deviation of the elastic wave velocity AE was determined as a criterion to evaluate the concrete failure process, and the whole failure process was divided into three stages, such as steady failure process (standard deviation < 70), accelerated failure process (standard deviation in the range of 70–1700), and buckling failure process (standard deviation > 1700). By using the digital image correlation system, it was possible to see the exponential relationship between the elastic wave velocity and the relative stress ratio. The analysis of the obtained data also showed the negligibly small effect of specimen dimensions and coarse aggregate content on the acoustic wave velocity in the beam.

4.2. BIOMECHANICS

Using a digital image correlation system, the deformation of any object can be recorded. The material of the object does not have to exhibit any characteristic features. Therefore, this system has found applications in many fields. One of them is biomechanics. In work [17], Genovese et al. developed a material model of a highly heterogeneous tissue such as the gallbladder (Fig. 7). The validity of the model was verified using analytical methods.

The accuracy of the DIC system is determined mainly by the resolution of the lenses of the cameras used [18]. Using this tool, a team of French researchers [18] was able to perform three-point bending tests on a material sample taken from a human tooth. The mechanical property values thus determined achieved a better agreement with the numerical model than in similar experiments by other groups of researchers [19] using other measurement techniques.

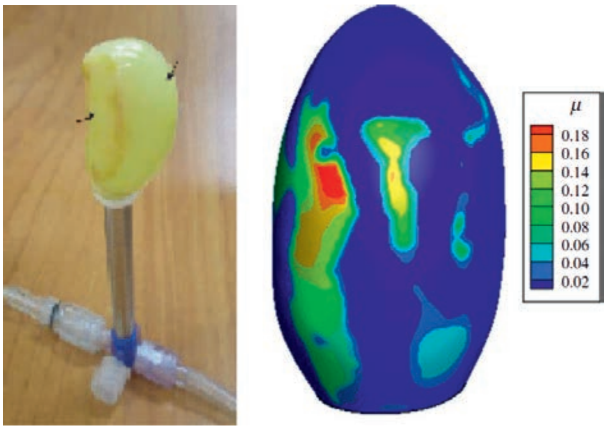


Fig. 7. Gallbladder on a test bench, along with a strain map of the surface of the test object [17]

Rys. 7. Pęcherzyk żółciowy na stanowisku badawczym wraz z mapą odkształceń powierzchni badanego obiektu [17]

The image correlation method is also an important tool for assessing the structure and testing the strength of bone tissue. However, since the DIC system is capable of recording the load and strain on the surface of the specimen, the application of the digital image correlation technique to record the load and strain of living tissues is greatly hindered. Therefore, for medical purposes, the DIC technique has been developed into DVC (Digital Volume Correlation). It is a powerful tool for calculating three-dimensional internal stresses and can be combined with imaging techniques, such as computed microtomography, as seen in Fig. 8 (microCT), synchrotron radiation microCT (SR-microCT), clinical CT, and micromagnetic resonance imaging (micro MRI) [20], or XCT X-rays [21]. This extension of the system allows observation of the deformation of the sample not only on its

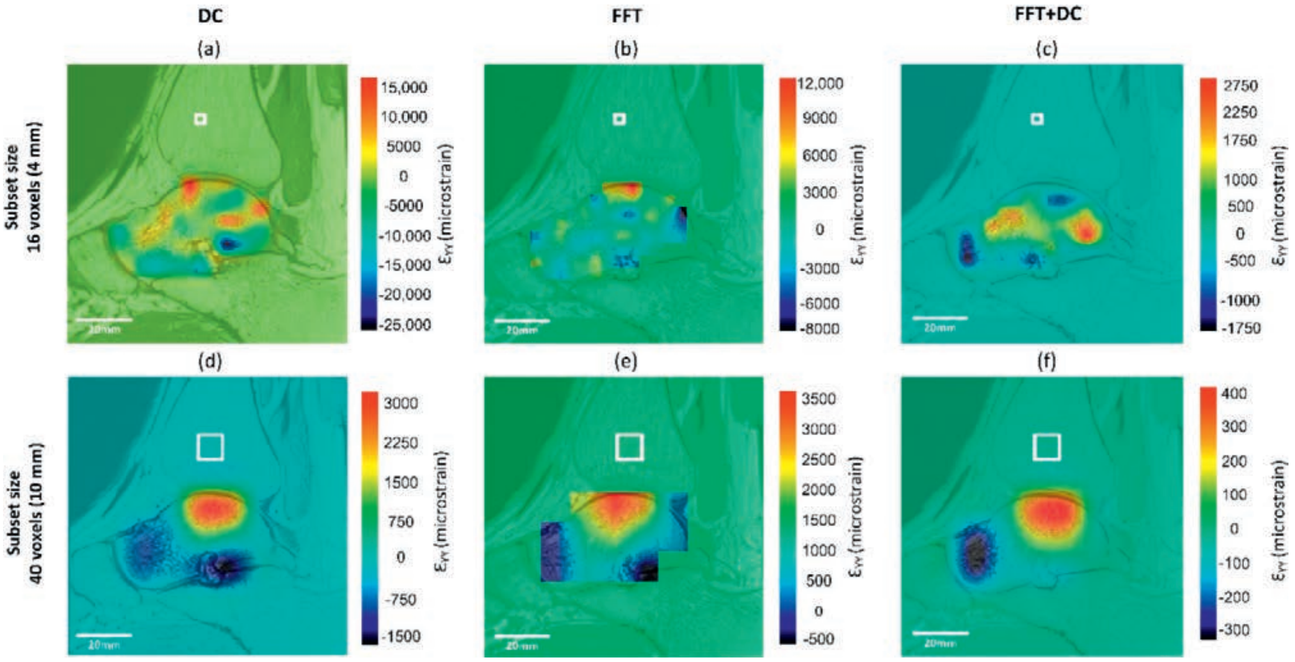


Fig. 8. Deformation of ankle joint under load photographed using DVC [20]

Rys. 8. Odkształcenie stawu skokowego pod wpływem obciążenia sfotografowane przez DVC [20]

surface but also in its depth, which is important for heterogeneous materials, such as tissue [21]. However, DVC examination of tissues in living organisms involves double exposure of the organism to radiation – a reference image (in the unloaded state) and a minimum of 1 in the loaded state are necessary for the data to be meaningful [20]. Therefore, the number of measurements made with this technique must be limited.

4.3. PLASTICS

The good results of the study of bone tissues using the DVC method led some researchers to implement this test method to determine the deformation fields of plastics. Borstnara et al. [22] were among the first to use DVC together with CT to create 3D strain maps of plastic samples (Fig. 9). Image correlation also works well for in-service deformation analysis of adhesive joints. It is one of the few methods that take into account the effect of adhesive buildup on the overall deformation picture [13].

4.4. METALLIC MATERIALS TESTING

Numerous successes in research conducted using digital image correlation systems in fields such as construction, biomechanics, and polymer chemistry have led the metallurgical research community to apply DIC in their research projects. However, data obtained from DIC measurements cannot be directly compared with those from traditional extensometer measurements. Karolewska et al. [23], on the example of the Ti6Al4V alloy, presented ways to determine the Poisson's ratio and Young's modulus, yield strength, and tensile strength based on the digital image correlation method. The study showed that the mentioned properties cannot be compared with each other directly. The data obtained using this method require preprocessing. This is because DIC is sensitive to local changes in material properties and is excellent for quantifying these properties [24], as opposed to an extensometer, which records results globally for the area defined as the measurement base of the instrument.

The way a digital image correlation system works can be compared to a situation where hundreds of miniature extensometers are mounted to the surface of a test specimen to locate the fastest deforming regions and predict where cracks will occur. This property was used in their work by Chakraborty et al. [25] to determine the mechanical properties of cast iron, as other measuring instruments prevented accurate results due to the heterogeneity of the material structure. The DIC measurements confirmed that the mechanical properties of cast iron change consistently and predictably during directional solidification, despite the variation in microstructure and system sensitivity.

Researchers from the University of Tomsk [26] avoided time-consuming analyses by using the virtual extensometer option available in the DIC system

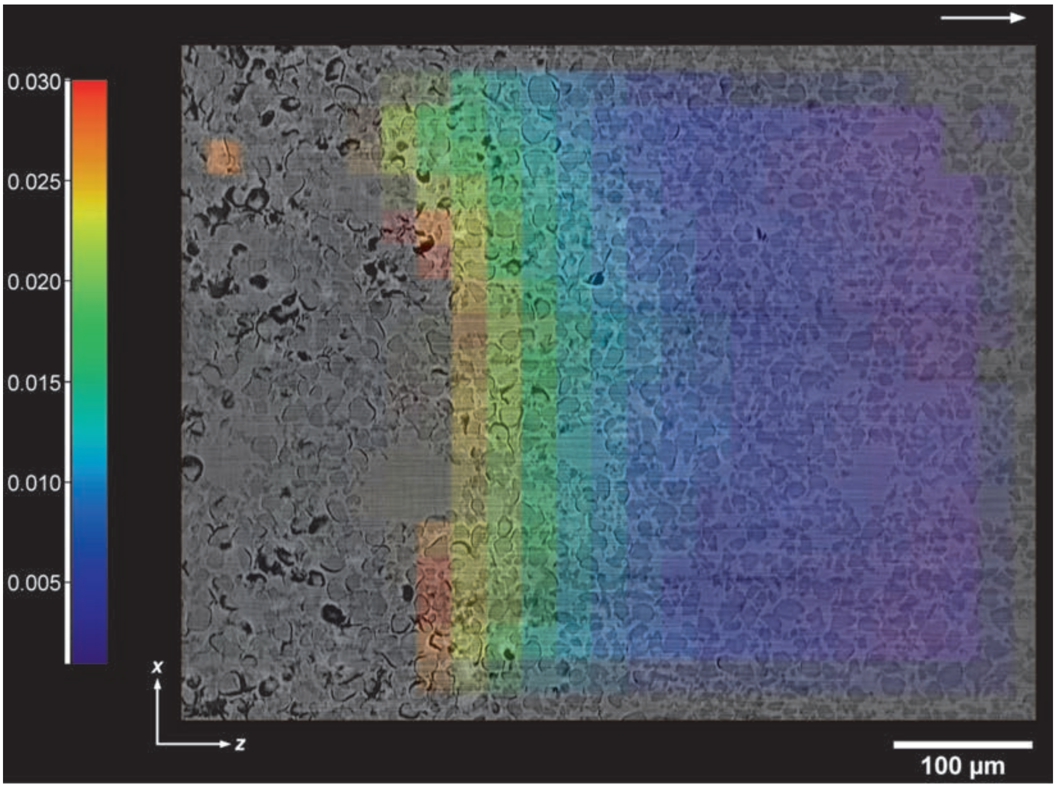


Fig. 9. Interlayer microstructure in plan view overlaid with ε_{xx}' strain [22]

Rys. 9. Widok mikrostruktury międzywarstwowej w widoku z planu nałożony na odkształcenie ε_{xx}' [22]

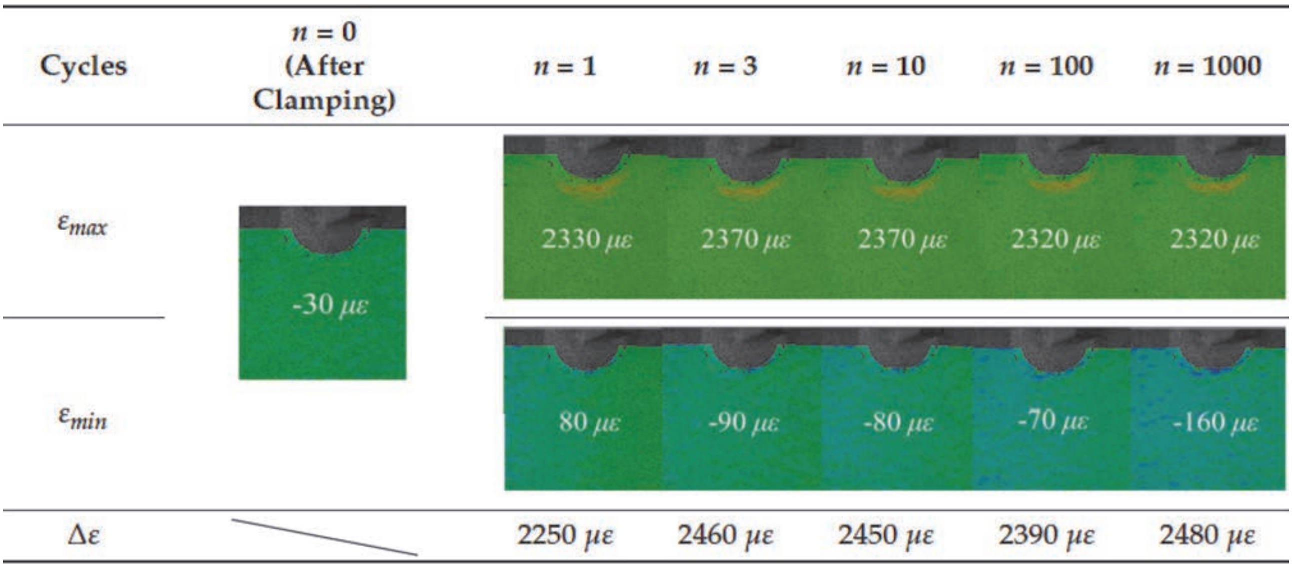
software to determine the mechanical properties of the Ti6Al4V alloy. The virtual extensometer outperforms the traditional instrument by eliminating the obstacles associated with the limited geometry and scope of the traditional instrument. Using the virtual extensometer option, the researcher can independently determine not only the size of the area analysed using the virtual extensometer, but also its range.

4.5. WELDED JOINT TESTING

Metallurgical researchers also value the digital image correlation method as an aid in the examination of welded joints. Due to the specificity of different manufacturing technologies, and different weld quality, the DIC method may be the only reliable analysis method that can also detect micro-cracks, as seen in Fig. 10, in the weld [27] and determine the area in which the structures of joined elements mix or the heat-affected zones. Because it is a non-contact method, depending on the parameters of the cameras used, it is possible to register the course of the wear process in welded joints [28].

4.6. STUDY OF MATERIAL DEGRADATION AND CRACK DEVELOPMENT

Another field in which digital image correlation technology is gaining supporters is machine and equipment diagnostics. In paper [29], Van Rooyen et al. used the DIC system for accelerated creep testing. Unlike traditional resistance extensometers and LVDTs, there is no need to use a single specimen for only one load and temperature condition. In this type of testing, the biggest disadvantage of the system is that it can only record data from the surface of the test object, which can lead to an incorrect assessment of material degradation. However, unlike standard LVDTs and extensometers, using DIC technology one



Cycles	$n = 0$ (After Clamping)	$n = 1$	$n = 3$	$n = 10$	$n = 100$	$n = 1000$
ε_{max}	-30 $\mu\varepsilon$	2330 $\mu\varepsilon$	2370 $\mu\varepsilon$	2370 $\mu\varepsilon$	2320 $\mu\varepsilon$	2320 $\mu\varepsilon$
ε_{min}		80 $\mu\varepsilon$	-90 $\mu\varepsilon$	-80 $\mu\varepsilon$	-70 $\mu\varepsilon$	-160 $\mu\varepsilon$
$\Delta\varepsilon$		2250 $\mu\varepsilon$	2460 $\mu\varepsilon$	2450 $\mu\varepsilon$	2390 $\mu\varepsilon$	2480 $\mu\varepsilon$

Fig 10. Strain distribution in a welded joint [27]

Rys. 10. Rozkład odkształceń w złączu spawanym [27]

Fig. 11. Small fatigue crack initiation (stress amplitude: 260 MPa; fatigue life: 1 × 106 cycles). a) Panoramic image [31]

Rys. 11. Mała inicjacja pęknięcia zmęczeniowego (amplituda naprężeń: 260 MPa; trwałość zmęczeniowa: 1 × 106 cykli). a) Obraz panoramiczny [31]

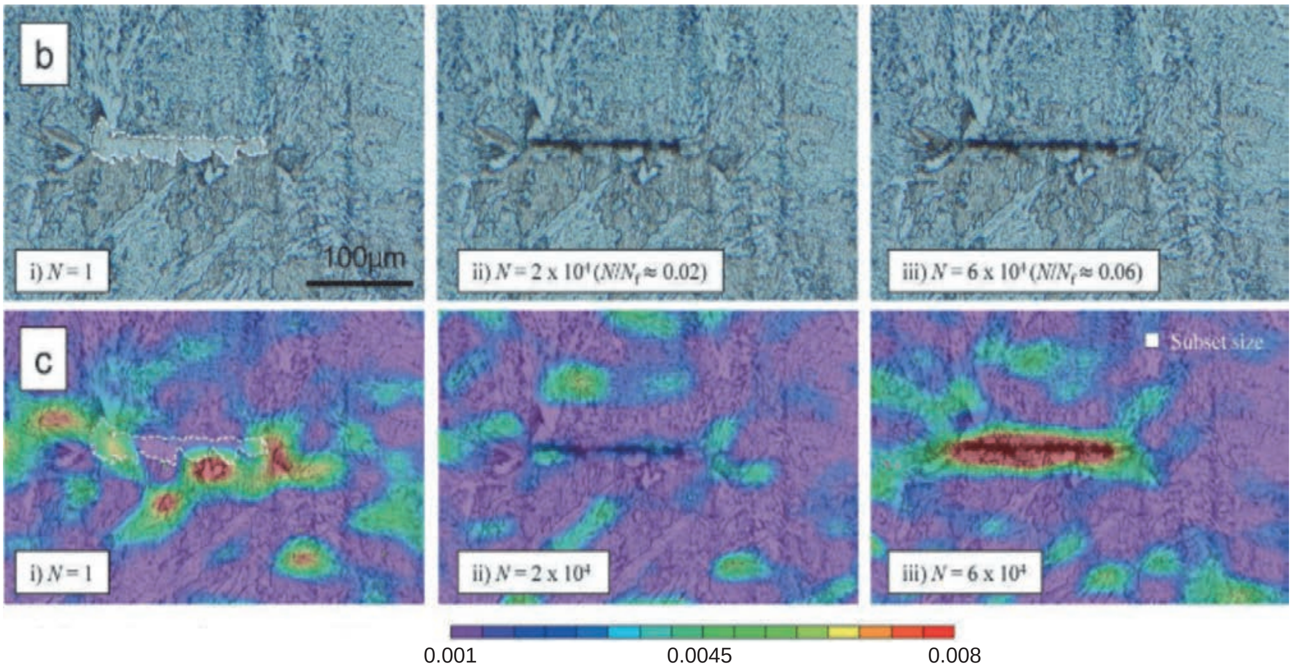


Fig. 11 cont. Small fatigue crack initiation (stress amplitude: 260 MPa; fatigue life: 1 × 106 cycles). b) Fatigue crack initiation, and c) DIC image of vertical strain distribution [31]

Rys. 11 cd. Mała inicjacja pęknięcia zmęczeniowego (amplituda naprężeń: 260 MPa; trwałość zmęczeniowa: 1 × 106 cykli). b) Inicjacja pęknięcia zmęczeniowego oraz c) Obraz DIC pionowego rozkładu odkształceń [31]

can observe crack growth from the micro-scale (see Fig. 11), to the macro-scale [30]. In addition, a digital image correlation system has been successfully implemented in a bench that enables live monitoring, tracking, and recording of microscopic deformations and cracks [31].

5. FUTURE GOALS

After many years of development and many implementations in various scientific fields, digital image correlation technology still shows potential for development. Its main directions are: increasing the temperature range in which DIC can operate and increasing the accuracy of measurements in high-cycle fatigue tests.

5.1. UV-DIC

The most serious limitation of the DIC system is its sensitivity to high temperatures. If the sample reaches a temperature at which it begins to emit light within the range of the cameras, the images analysed by the system will show significant measurement errors due to light pollution from the sample (Fig. 12). The solution to this problem appears to be to change the wavelength of light used in the DIC system. Ultraviolet radiation has a shorter wavelength than visible and infrared radiation. Thus, it can be assumed that if the cameras of the digital image correlation system only capture ultraviolet radiation, it will be possible to neutralise this image contamination.

Several research entities, guided by these considerations, have developed correlation systems operating in the UV-DIC ultraviolet range. Of particular

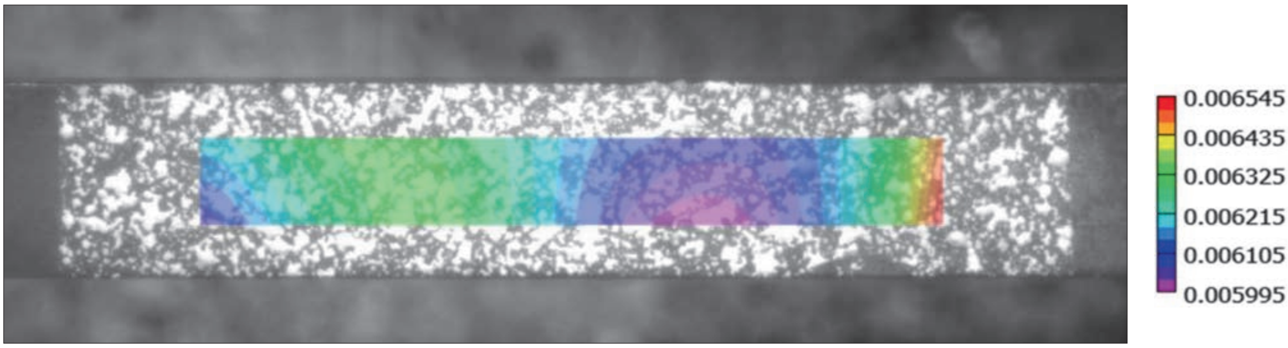


Fig. 12. Sample surface image in ultraviolet light [4]

Rys. 12. Obraz powierzchni próbki w świetle ultrafioletowym [4]

note are studies performed in Utah, USA, conducted at temperatures as high as 1600 °C [4, 30], as well as research done at the University of Illinois [33], where data was successfully collected at 1125 °C.

5.2. HIGH-CYCLE FATIGUE TESTING

Another future challenge of the system is to find the trade-off between obtaining good quality images and the amount of data delivered to the system. This challenge becomes more difficult at higher temperatures and/or high cycle fatigue tests (Fig 13). In his work [32], Q. Thai notes that camera optics set to record rapid strain changes significantly reduce their operating temperature range, so the system user is forced to choose the experimental input data, so that recording results is possible.

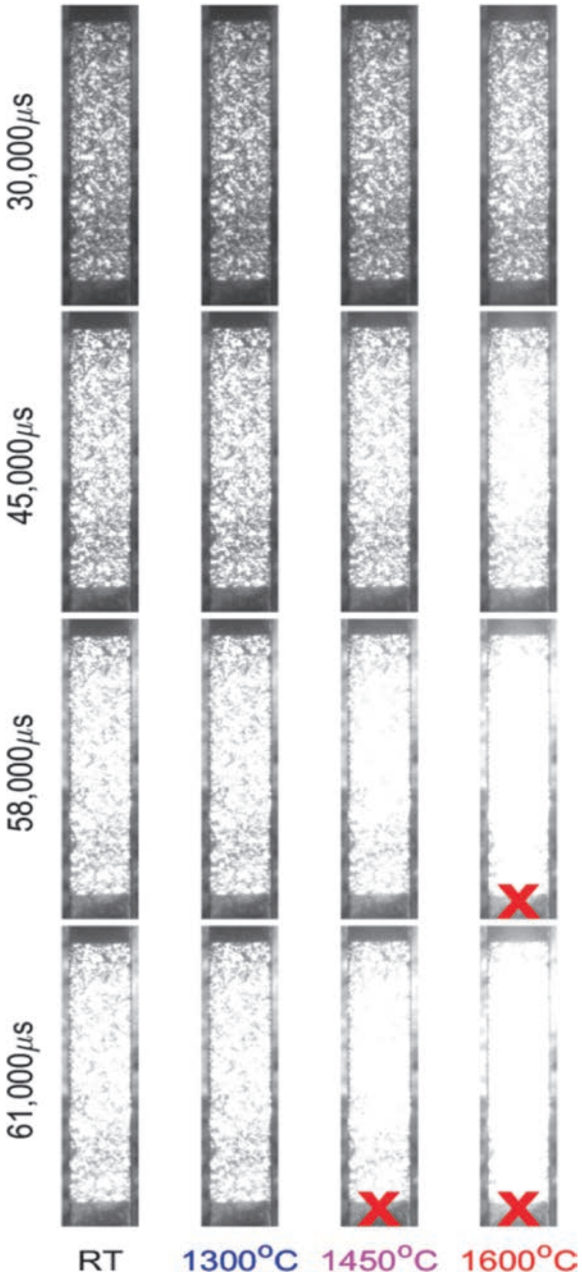


Fig. 13. Shaping of sample surface image as a function of sample temperature and exposure time [32]

Rys. 13. Kształtowanie się obrazu powierzchni próbki w funkcji temperatury próbki i czasu ekspozycji [32]

6. CONCLUSION

In conclusion, the development of measurement techniques associated with photography, which has lasted for almost 200 years, has contributed to progress in many fields of science. The digital image correlation method described in this paper has gained importance in many fields, as evidenced by the growing number of studies conducted using DIC systems year after year in fields such as biomechanics, construction, and broadly defined material science. Researchers value this measurement technique because of several advantages that other methods do not have:

- No physical contact with the test material – testing does not apply additional pressure to the test surface and does not change the heat balance of the specimen.
- Due to a large degree of freedom in the selection of cameras, the analysed image can cover objects of any geometry and any dimensions. Therefore, the system can be used to conduct examinations in micro and macro scale.
- Contact gauges are usually matched to a single surface shape. The DIC system has great flexibility in the shape and size of the object to be analysed.
- Measurement data received from the system can be presented in the form of graphs and tables, as well as a deformation map generated directly from the sample image.
- There is no need for a model material with special properties. This numerical-visual method can be applied to real structures, even during their operation [13].

On the other hand, the technique also has some limitations, among the most serious being:

- ‘peeling’ of the applied tracer from the surface of the test sample;
- colour change of the tracer-coated surface under the influence of temperature during the experiment;
- this type of instrument requires the surface to be properly prepared and a complex calibration to be performed before measurement;
- since the digital image correlation method is a non-contact method that works using the light reflected from the surface under test and recorded by the camera system, any obstacles or contaminants in the light source – surface under test – in the camera system path will cause measurement errors;
- the digital image correlation system uses reflected light to record measurements. This system limits the temperature range over which the DIC can

work. If the sample reaches a temperature at which it starts to emit the delivered energy in the form of visible radiation, the measurements carried out may be significantly disturbed [11];

– maintaining proper focus on the recorded area is also an important factor. If the exposure time is too long during measurements in which the sample is subjected to high-frequency vibrations, the image will be blurred, making it impossible to obtain measurement data [12].

Despite the mentioned limitations, the digital image correlation technology has great application potential and wide development prospects. Currently, research is being conducted [4, 8, 32] to increase the temperature range at which the system will be able to obtain reliable results. In turn, the development of photography allows the system to use more advanced cameras and lenses. As a result, the digital image correlation system will become a more precise measurement tool, capable of recording images even of high-cycle fatigue tests.

In times of high environmental concern, with the rapid increase in energy demand and space expansion, systems operating in extremely harsh environments are increasingly being considered. This approach requires the development of laboratory benches capable of simulating extreme conditions and recording data in such an environment. The DIC system, thanks to its wide application potential, may become one of the key measurement systems in such a bench.

In the future, along with the development of technology, one should expect further development of optoelectronic measuring methods and their expansion into other fields of science.

REFERENCES

[1] H. Schreier, J.J. Orteu, M.A. Sutton. *Image correlation for shape, motion and deformation measurements: Basic concepts, theory and applications*. New York: Springer Science+Buisness Media, 2009, pp. 1-10; 13.

[2] M.A. Sutton, J. Walters, W.H. Peters, W.F. Ranson, S.R. Mcneil1. Determination of displacements using an improved digital correlation method. *Image and vision computing,* 1983, 1, (3), pp. 133-139.

[3] T.C. Chu, W.F. Ranson, M.A. Sutton, W.H. Peters. Applications of Digital. Image-Correlation Techniques to Experimental Mechanics. *Experimental Mechanics,* 1985, 9, pp. 232-244.

[4] T.Q. Thai. *Improvement of Ultraviolet Digital Image Correlation (UV-DIC) at Extreme Temperatures Extreme Temperatures*. Utah State University: Graduate Studies, 2020.

[5] DantecDynamics. Photography of the DIC Standard 3D [no date] [Online] http://www.dantecdynamics.com [accessed on 10 August 2022].

[6] Z.L. Kowalewski, L. Dietrich, M. Kopeć, T. Szymczak, P. Grzywna. Nowoczesne Systemy Optyczne w Badaniach Mechanicznych – Budowa, Działanie, Zastosowania" In: *XXII Seminarium Nieniszczące Badania Materiałów.* Zakopane, 16-18 March 2016, pp. 5-36.

[7] J. Blaber, B.S. Adair, A. Antoniou. A methodology for high resolution digital image correlation in high temperature experiments. *Review of Scientific Instruments*, 2015, 86 (3), pp. 1-10.

[8] Z. Pan, S. Huang, Y. Su, M. Qiao, Q. Zhang. Strain field measurements over 3000 °C using 3D-Digital image correlation. *Optics and Lasers in Engineering*, 2020, 127, pp. 105-109.

[9] A. Blug, D.J. Regina, S. Eckmann, M. Senn, A. Bertz, D. Carl, C. Eberl. Real-time GPU-based digital image correlation sensor for marker-free strain-controlled fatigue testing. *Applied Science*, 2019, 9 (10), pp. 2-15.

[10] B. Turoń, D. Ziaja, B. Miller. Rejestracja i analiza pól przemieszczeń i odkształceń za pomocą systemu cyfrowej korelacji obrazu 3D. *Journal of civil engineering, environment and architecture*, 2017, 24 (64), pp. 7-28.

[11] M. Kempny. Analiza mozliwości zastosowania system DIC w symulatorach Gleeble 3800, In: *XXII Międzynarodowa Studencka Sesja Naukowa*. Katowice 28 May 2021, pp. 36-43.

[12] P.R. Gradl. Digital Image Correlation Techniques Applied to Large Scale Rocket Engine Testing. In: *53rd AIAA/SAE/ASEE Joint Propulsion Conference*, Atlanta 12 September 2017, pp. 1-17.

[13] W. Zielecki, A. Kubit, Ł. Święch. Analiza doświadczalna odkształcenia elementów klejonych w próbie statycznego oddzierania. *Pomiary Automatyka Robotyka,* 2013, 2, pp. 71-78.

[14] G. Li, J. Gu, Z. Ren, F. Zhao, Y. Zhang. Damage evaluation of concrete under uniaxial compression based on the stress dependence of ae elastic wave velocity combined with DIC technology. *Materials (Basel)*, 2021, 14 (20), pp. 2-19.

[15] D. Marcinczak. Wzmacnianie konstrukcji betonowych za pomocą materiałów kompozytowych. *Nauka i Budownictwo,* 2019, 66 (2), pp. 1-3.

[16] D. Rama Seshu, C. Manjula, T.D.G. Rao, C.B.K. Rao. A new way of using welded wire mesh [WWM] for enhancing the shear strength in reinforced concrete beams. *Cement Wapno, Beton*, 2020, 25 (3), pp. 188–197.

[17] K. Genovese, L. Casaletto, J. D. Humphrey, J. Lu. Digital image correlation-based point-wise inverse characterization of heterogeneous material properties of gallbladder in vitro. *Proceedings of the Royal Society*, 2014, 470 (2167), pp. 1-20.

[18] W. Wang, N. Roubier, G. Puel, J. Allain, I. C. Infante, J. Attal, E. Vennat. A new method combining finite element analysis and digital image correlation to assess macroscopic mechanical properties of dentin. *Materials (Basel)*, 2015, 8 (2), pp. 535–550.

[19] J.E.A. Palamara, P.R. Wilson, C.D.L. Thomas, H.H. Messer. A new imaging technique for measuring the surface strains applied to dentine. *Journal of Dentistry*, 2000, 28 (2), pp. 141–146.

[20] S. Tavana, J.N. Clark, N. Newell, J.D. Calder, U. Hansen. In vivo deformation and strain measurements in human bone using digital volume correlation (DVC) and 3T clinical MRI. *Materials (Basel)*, 2020, 13 (23), pp. 1–15.

[21] G. Tozzi, M.P. Fernández, S. Davis, A. Karali, A.P. Kao, G. Blunn. Full-field strain uncertainties and residuals at the cartilage-bone interface in unstained tissues using propagation-based phase-contrast XCT and digital volume correlation. *Materials (Basel)*, 2020, 13 (11), pp. 1–15.

[22] G. Borstnar, F. Gillard, M.N. Mavrogordato, I. Sinclair, S.M. Spearing. Three-dimensional deformation mapping of Mode I interlaminar crack extension in particle-toughened interlayers. *Acta Material*, 2016, 103, pp. 63–70.

[23] K. Karolewska, B. Ligaj, D. Boroński. Strain analysis of Ti6Al4V titanium alloy samples using digital image correlation. *Materials (Basel)*, 2020, 13 (15), pp. 1–19.

[24] W. Song, J.E. Houston. Local deformation and Mn-C short-range ordering in a high-Mn Fe-18Mn-0.6C steel. *Metals (Basel)*, 2018, 8 (292), pp. 1-11.

[25] S. Chakraborty, J. Indeck, P. Steinmetz, J. Friess, K. Hazeli, A.L. Genau. Localized strain analysis of Ce-and Mg-treated cast iron under uniaxial compression. *Metals (Basel)*, 2020, 10 (12), pp. 1–10.

[26] V.V. Skripnyak, V.A. Skripnyak. Localization of plastic deformation in Ti-6Al-4V alloy. *Metals (Basel)*, 2021, 11 (11), pp. 1-13.

[27] H. Gao, G. Agarwal, M. Amirthalingam, M.J.M. Hermans, I.M. Richardson. Investigation on hot cracking during laser welding by means of experimental and numerical methods. *Welding in the World*, 2018, 62 (1), pp. 71-78.

[28] Y. Wang, K. Ueda, R. Nagao, and S. Tsutsumi. Measurements Using DIC and XRD. *Materials (Basel)*, 2021, 14 (19), pp. 1–11.

[29] M. van Rooyen, T. Becker, J. Westraadt, G. Marx. Creep damage assessment of ex-service 12% Cr power plant steel using digital image correlation and quantitative microstructural evaluation. *Materials (Basel)*, 2019, 12 (19), pp. 1-31.

[30] K.A. Kasvayee, E. Ghassemali, K. Salomonsson, S. Sujakhu, S. Castagne, A.E.W. Jarfors. Strain localization and crack formation effects on stress-strain response of ductile iron. *Materials Science & Engineering*, 2017, 702, pp. 265-271.

[31] H.A. Nishikawa, Y. Furuya. Development of a method for evaluating microstructurally small fatigue crack initiation and growth by using an automatic system for in situ observation in conjunction with a digital-image correlation technique. *ISIJ International*, 2020, 60 (9), pp. 2090-2096.

[32] T.Q. Thai. *Importance of Exposure Time on Digital Image Correlation (DIC) Importance of Exposure Time on Digital Image Correlation (DIC) at Extreme Temperatures at Extreme Temperatures*. Utah State University: Graduate Studies, 2018.

[33] R.B. Berke, J. Lambros. Ultraviolet digital image correlation (UV-DIC) for high temperature applications. *Review of Scientific Instruments*, 2014, 85 (4), pp. 1-10.