Analysis of the Effect of Changing the Position of a Unique Drilling Device for Residual Stress Analysis using Digital Image Correlation

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Abstract: The quantification of residual stresses by the hole-drilling method is one of the most widely used techniques. Nowadays, there is an effort to replace strain gauge sensors with full-field optical systems, which requires intervention in the design of the drilling machine or the development of its own. The paper reports on a unique drilling/measuring device that is being developed at the authors' facility. In the case of the analysis of thick samples, it is necessary to mill a blind hole in the material in several steps. The principle of the digital image correlation (DIC) method, i.e. recording and correlating images at each measurement step, requires a mutual change of position between the milling cutter and the camera system. Therefore, this paper focuses on the analysis of the influence of the change of the position of the stereo camera correlation system on the quality of the strain/stress analysis results around the milled hole. The conclusion from the analyses performed is that there is no significant influence of the obtained fields and thus the results obtained by the DIC method can be accepted.

Keywords: residual stress; hole drilling; drilling device; positioning; digital image correlation.

1 Introduction

Residual stresses arise in the material as a result of various technological processes, sudden temperature changes, or surface structure changes such as oxidation or corrosion. As these stresses are easily overlooked, they can superimpose with operational stresses, and thus their determination is an important part of the experimental mechanics' work.

Methods for quantifying residual stresses can be classified into three groups:

- non-destructive,
- semi-destructive,
- destructive.

A frequently used semi-destructive method is the drilling method, where a blind or through-hole is made in the analyzed structure [1–3]. In the presence of residual stresses, the surroundings of the milled hole are deformed, which is recorded by special strain gauge rosettes, and based on the methodology described in ASTM E837-13a [4], the levels of residual stresses in thin and thick samples, respectively, are determined.

In order not only to speed up the measurement itself but also to be able to evaluate the deformations released at more than one point, the combination of the drilling method with non-contact full-field methods is now becoming more common. In particular, optical measuring systems based on electronic speckle interferometry or digital image correlation are used. Since commercially produced drilling devices are designed to work with strain gauge apparatus, their construction does not allow simple application of the above-mentioned optical systems, which leads to the design and implementation of custom portable drilling devices [5,6].

The authors of the paper proposed a unique drilling device allowing the application of a single or stereo camera correlation system. Unlike almost all custom drilling devices, this device is unique in such a way that it allows horizontal and vertical movement of not only the milling cutter (MC) but also the camera system

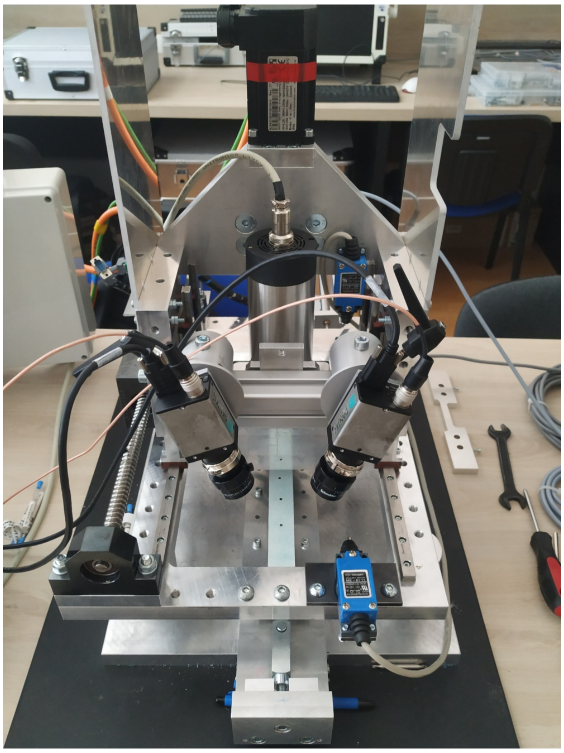


Fig. 1: Drilling/measuring device for quantification of residual stresses using 3D DIC.

(Fig. 1). As a consequence, images can be acquired with the required quality from a suitable distance for various specimen shapes and thicknesses [7].

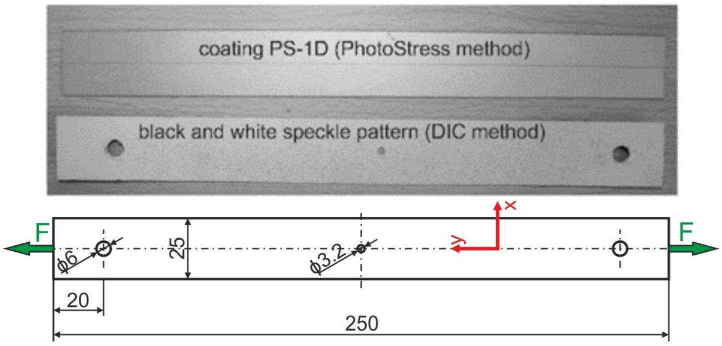
As in the process of measuring residual stresses by the hole-drilling method, it is mainly necessary to create a blind hole in a stepwise (sequential) manner, the accuracy of the results obtained by the correlation system is influenced by the accuracy with which the positioning device can return the camera system to its initial position. It has been proven that even a very small rotation of the camera system can cause a large correlation error, especially when a single camera system is used [8]. However, in the case of very small displacement deviations (level on the order of a few μm), it can be assumed that the influence of correlation errors will not be so serious that the values of the quantified residual stresses will be significantly affected.

2 Experimental analysis

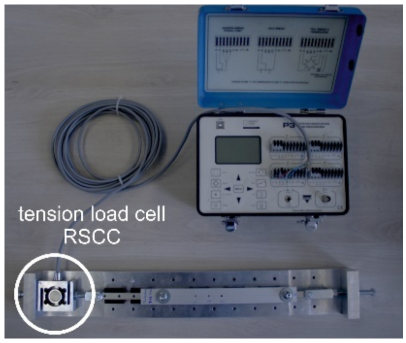
Full-field analysis of displacements and stresses was performed on a specimen made of Vishay PS-1D material with a thickness of $t = 0.5$ mm, which is used as a coating in the PhotoStress method. The mechanical properties of the analysed material are Young's modulus of elasticity $E = 2{,}500$ MPa and Poisson's ratio = 0.38. The specimen, whose shape and dimensions are shown in Fig. 2a, was subjected to uniaxial tensile loading. The magnitude of the tensile force was recorded by an HBM RSCC-50kg sensor and displayed on the display of Vishay P3 strain indicator and recorder (Fig. 2b).

The full-field non-contact measurement was performed using a Q-400 Dantec Dynamics stereo camera correlation system consisting of low-speed cameras with an image resolution of 5 Mpx. Digital image correlation is a modern optical method that allows the analysis of displacement or strain fields based on the comparison (correlation) of digital images captured during the loading process of the analysed object. The image correlation is carried out over small image elements, which have mostly squared shape, reach the size of several pixels and are called facets. It should be noted that the quality of the results of the analyses performed by Dantec Dynamics correlation systems depends on many aspects, described e.g. in [8–10]. Among the main factors influencing the results of an experimental analysis performed with correlation systems, the following can be included:

- obtaining images with the highest possible quality (resolution, uniform and sufficient illumination, etc.),
- the accuracy of the calibration of the camera system,
- correct adjustment of correlation parameters such as facet size or smoothing level.



(a)



(b)

Fig. 2: (a) Dimensions and shape of the specimen to be analysed, (b) measuring string recording the magnitude of the tensile force.

As the results of the analyses performed by the correlation devices also depend on the quality of the acquired images (which need to be acquired with the highest possible image resolution), the correlation system was attached to the proposed drilling device in a position allowing the recording of the surroundings of the milled hole, as shown in Fig. 3. According to the manufacturers of the Dantec Dynamics digital image correlation systems, the largest correlation error occurs at the edges of the analysed objects and therefore the evaluated area around the hole was reduced to an area of approximately 19×19 mm^2 shown in Fig. 3 in yellow. The above-mentioned images, recorded with an image resolution of 2452×2056 px (pixel density of approximately 83 px/mm), are reference images of the analysed specimen (i.e. the images of the specimen captured before its loading).

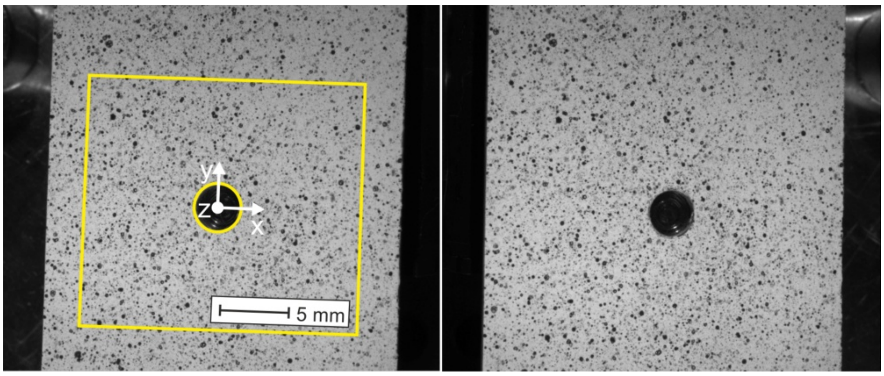
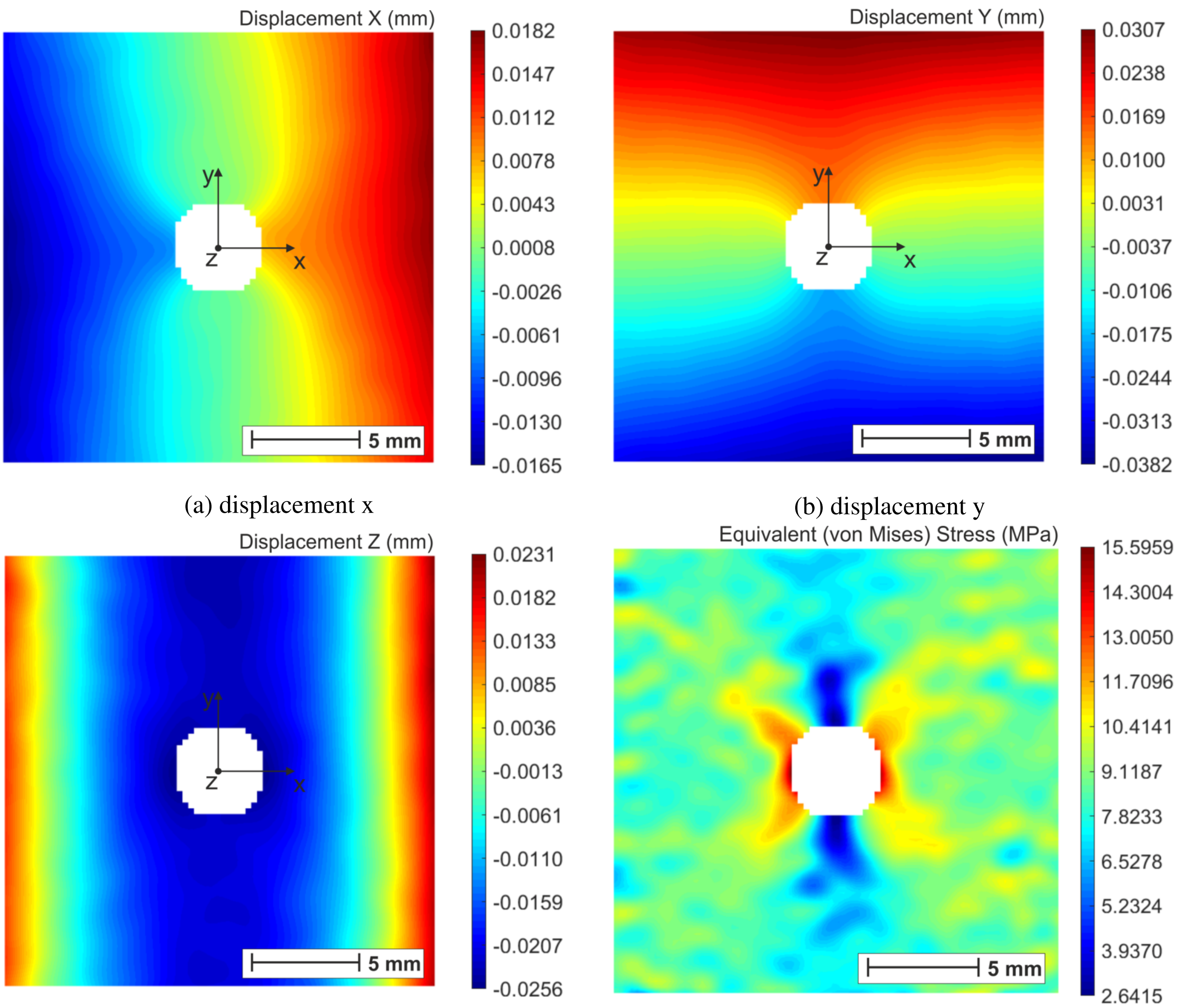


Fig. 3: Reference images captured by a Dantec Dynamics Q-400 stereo camera correlation system with a marked area of evaluation.

The analysed specimen was loaded in 10 steps (1 step corresponded to a force increase of 12 N) with a tensile force that gradually increased from a value of 0 N to a final value of 120 N. It has been shown that the results of strain-stress analyses performed by digital image correlation systems depend significantly on the size of the facet, which has to ensure that each correlated part is unique (i.e. each facet has to contain a unique part of black-and-white speckle pattern created at the surface of the specimen) and on a corresponding level of smoothing that can be set in the Istra4D software supplied with the Dantec Dynamics correlation systems [10]. In Fig. 4, the displacement fields and the equivalent von Mises stress field obtained by the MOSTRAN v.1.0 software developed at the authors' department can be seen for a chosen facet size of 28×28 px. The 6 px overlapping of the facets ensured that the data, determined at the centre of each facet, was acquired with a higher resolution.

By the above-mentioned procedure, a stress state characterizing the simulated (residual) stress was induced in the specimen material. In the next phase of the measurement, such a procedure was implemented to simulate the process used to quantify the residual stresses in thick specimens, i.e. drilling a blind hole and sequentially recording the released strains in 20 steps until a drilled hole depth of 2 mm was reached. This approach thus leads to 20 mutual position changes between the milling cutter (MC) and the correlation system (Fig. 5).

Under ideal conditions, i.e. if the correlation system still returned exactly to its initial position (or did not



(a) displacement x

(b) displacement y

(c) displacement z

(d) equivalent von Mises stress

Fig. 4: Displacement and stress fields obtained after maximum loading of the specimen.

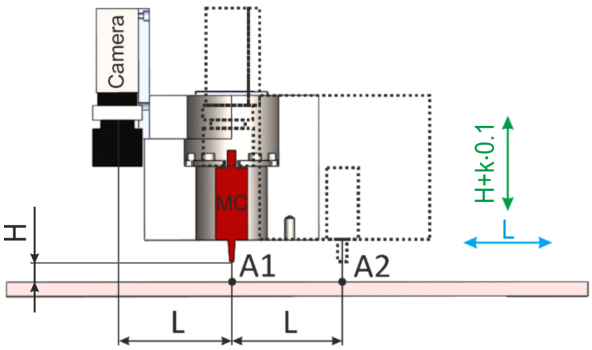


Fig. 5: The mutual position between the milling cutter (MC) and camera system and their necessary movements in the horizontal and vertical direction.

move from it), the digital image correlation system should evaluate approximately the same displacement and strain fields as in the analysis described above (the mean relative deviation found by the authors is approximately 1% and 3% for the displacement and strain fields, respectively, when capturing 30 images under the same loading and measurement conditions). The entire drilling/measuring system was moved in two directions – in the horizontal one (forward and backward) by a distance L = 150 mm, which characterizes the distance between the milling cutter axis and the focus of the camera lenses, and in the vertical one (down and up) by a distance $H + k \cdot 0.1$ mm, where H = 10 mm is the distance of the milling cutter from the specimen surface, k is the measurement step number, and 0.1 mm is the increment of material being removed at each measurement step (Fig. 5). After each return of the camera system to the starting position, images of the analyzed specimen were captured by the digital image correlation system.

As the measurement continued under the same conditions as the above-mentioned displacement/stress analysis, information on the accuracy with which the camera system returned to its original position was provided by the correlation system itself, based on the comparison of the 3D coordinates of the evaluated surface points of the specimen. This process has already been used and verified in the initial testing phase of the drilling device when the results obtained by the correlation system were compared with the deviations recorded by the inductive displacement sensor and have achieved a high level of similarity [11]. Fig. 6 shows the mean deviations of the specimen surface points' 3D coordinates compared against the condition at the specimen maximum loading. Based on the presented plot, it can be concluded that the camera system returned to its original position with an evaluated maximum deviation of approximately 10 μm, observed in the direction of the largest drilling/measuring device shift, which corresponds to the positioning accuracy already established [11].

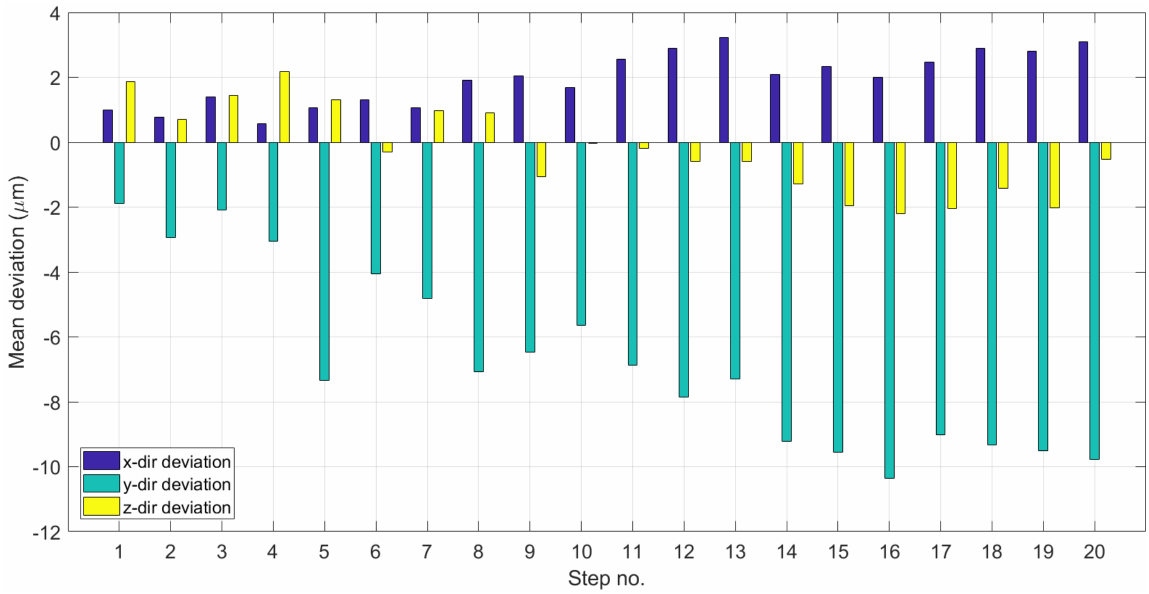


Fig. 6: The mean deviations from the initial position of the correlation system obtained at each measurement step after the necessary change of position between the drilling and measuring device has been carried out.

The obtained 20 images were correlated under the same above-mentioned conditions and the acquired displacement or equivalent von Mises stress fields were compared with the results obtained at the maximum loading of the specimen. It should be noted that rigid motions were filtered out from the fields of the individual components of displacement and thus the compared fields should not be affected by the motion of the stereo camera system, but should only correspond to the deformation of the specimen itself. The relative deviations of the displacement components and the equivalent von Mises stress obtained as mean values from the whole evaluated specimen area are shown in Fig. 7 and Fig. 8. While the maximum deviations in the measured displacement components reach higher levels (ca. 10%) for displacement x and z, respectively, the smallest deviation is observed for displacements obtained in the loading direction of the specimen, i.e. in the y-direction. The mean deviations observed in the equivalent von Mises stress reach levels between 4–6%, which can be considered acceptable when expecting the value of about 3%.

To find the optimal region around the hole, which could be further used for residual stress quantification through the proposed system, the obtained deviations were subjected to an analysis that documents how the investigated quantities change as a function of the distance from the center of the drilled hole. The relative deviations of the compared quantities obtained in 20 measurement steps were averaged over 15 concentric areas A_i with a width of 2 facets, i.e. approximately 0.5 mm (see Fig. 9d). Based on the obtained results, it can be concluded that the mean deviation acquired in the displacement x (Fig. 9a), displacement z (Fig. 9c) and equivalent von Mises stresses (Fig. 9d), respectively, increases with an increasing distance from the center of the hole. When analyzing the deviations in the displacement y (Fig. 9b), the same conclusion cannot be established. However, in this case, the level of deviations is significantly lower than in the other ones.

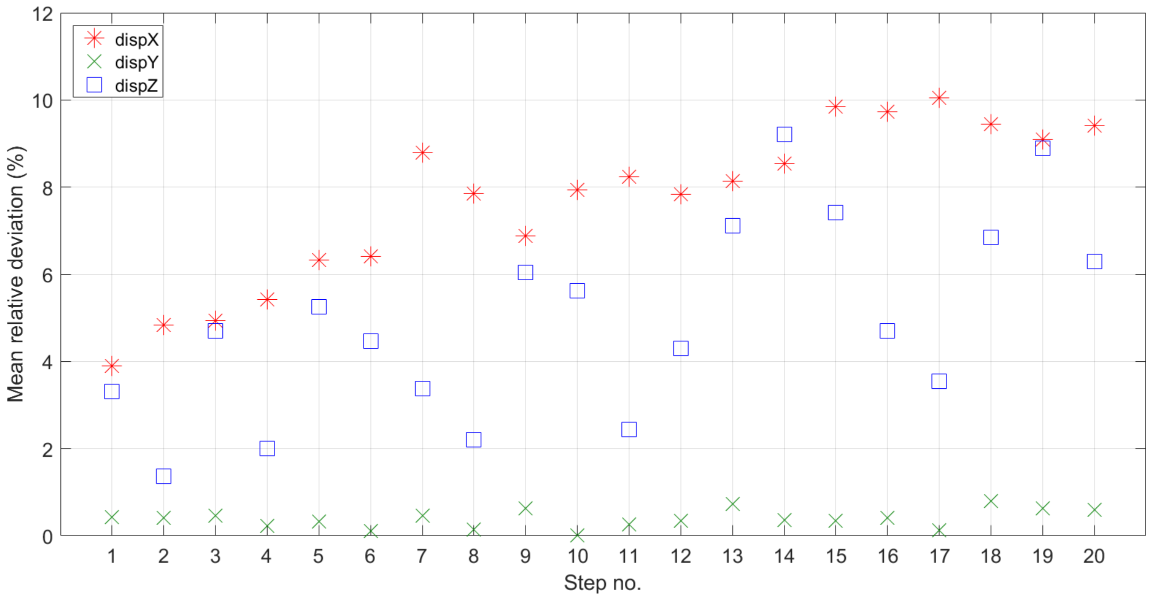


Fig. 7: The mean relative deviations of the displacement components obtained on the evaluated specimen area at each measurement step after the necessary change of position between the drilling and measuring device has been carried out.

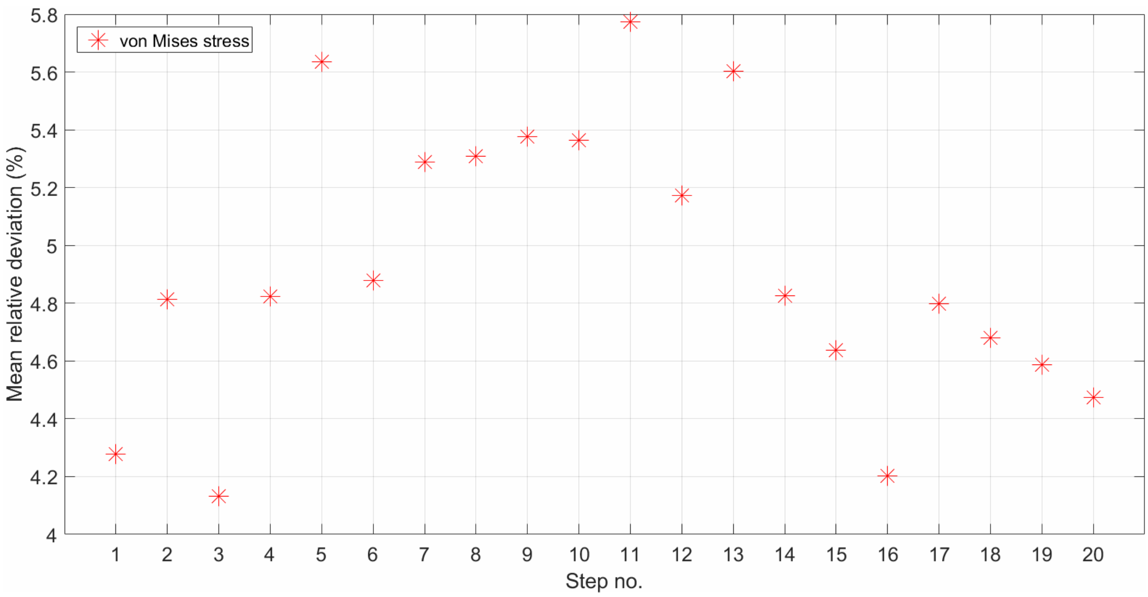
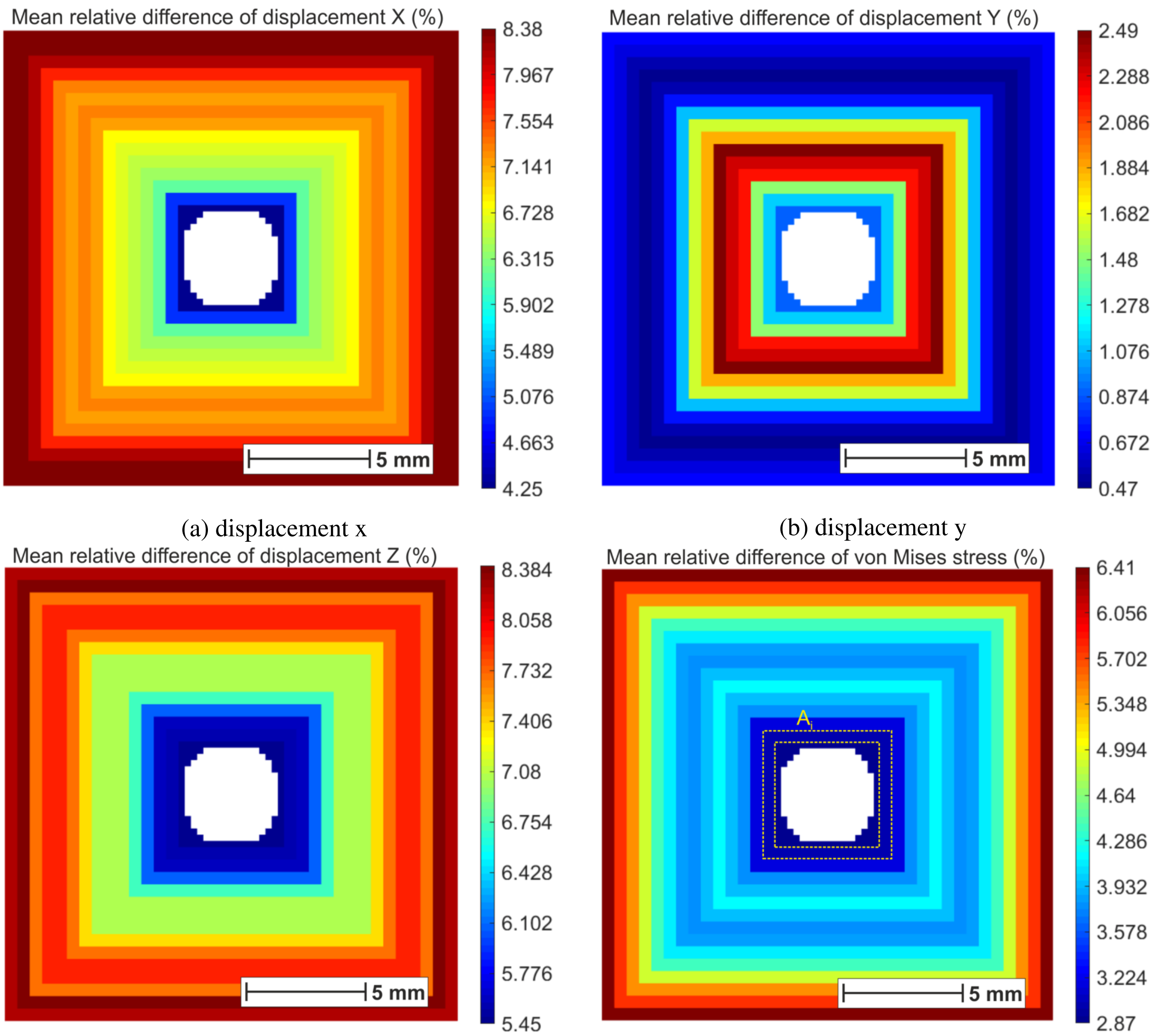


Fig. 8: The mean relative deviations of the equivalent von Mises stress obtained on the evaluated specimen surface at each measurement step after the necessary change of position between the drilling and measuring equipment has been carried out.

3 Conclusion

The paper describes the possibilities of performing analysis of the released full-field deformations or stresses in the vicinity of the hole using a custom drilling device combined with a stereo camera digital image correlation system Q-400 Dantec Dynamics on thick specimens when a blind hole is milled in the analysed material in a stepwise manner. In previous analyses, it has been shown by the authors that even a small change in the position (rotation) of the correlation systems can result in significant correlation errors that negatively affect the results of the analyses. For this reason, it was necessary to design the drilling/measuring device so that when the position between the milling cutter and the correlation system is changed relative to each other (to ensure milling the hole and capturing the images in each of twenty measurement steps), the measuring system returns to the initial position as accurately as possible. The results obtained show that even if the correlation system returns to its original position with a deviation of the order of a few μm, the evaluated displacement,



(a) displacement x

(b) displacement y

(c) displacement z

(d) equivalent von Mises stress

Fig. 9: Planar distribution of mean relative deviations as a function of distance from the centre of the drilled hole.

strain or stress fields will be affected. However, in the case of a stereo camera system, this deviation is not so significant that the moving camera approach (which allows the recording of images with the required quality for any shape and thickness of the specimens) cannot be used for the analysis of residual stresses.

As the use of a stereo camera digital image correlation system always introduces some image distortion into the measurements, the authors plan to perform the same analysis using a single camera system. It will also be necessary to perform similar analyses for other types of stress states, e.g. biaxial stress state. Once the above-mentioned analyses have been performed, it will be possible to decide more accurately which type of digital image correlation system is preferable to use for image capturing, how large the area evaluated in the vicinity of the drilled hole is appropriate to use for calculating residual stresses, and from what quantities (i.e. displacements or strains) the residual stress values will be determined.

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