DOI: 10.1515/adms-2017-0015

T. Brynk

Warsaw University of Technology, Faculty of Materials Science and Engineering, 02-507 Warsaw, Poland
tbrynk@inmat.pw.edu.pl

APPLICATION OF 3D DIC DISPLACEMENT FIELD MEASUREMENT IN RESIDUAL STRESS CALCULATIONS

ABSTRACT

The knowledge of residual stress distribution is of great importance from the viewpoint of both, industrial and basal research. The most commonly utilized method of residual stress determination is based on strain measurements near the drilled holes of known geometry made by means of tensometric rosettes. An alternative to tensometers way of strain measurement is Digital Image Correlation (DIC). This optical method utilizes digital images registered during observed object deformation and delivers results in the form of displacement field maps consisting of hundreds or thousands of data points. Therefore, it is possible to deliver much more data in comparison to rosettes (only 3 or 6 tensometers, usually) and use them in the inverse method numeric procedure for residual stress calculations. In the paper the experimental stand consisting of micro driller and stereo imaging system for 3D DIC measurement and its application to residual stress estimation in prestrained steel samples are presented followed by obtained results discussion.

Keywords: *residual stress, Digital Image Correlation (DIC), inverse method*

INTRODUCTION

Residual stress presence in materials might be caused by numerous factors related to its processing as well as service and is the reason of many failures [1]. The most popular method of their determination, so called Mathar's method [1,2,3,4], is based on precise strain measurement near the drilled small holes by means of tensometric rosettes of defined geometry. Drilling process induces stress relaxation which is accompanied by displacements in the hole neighborhood. Basing on strain gauges readings mounted round the hole it is possible to estimate residual stress amount and direction. This method is well known and normalized (ASTM E837) however it has some drawbacks related with the need of specified tensometric rosettes usage. Their fixing takes long time and requires some training form the operator. Moreover, the method is fragile to eccentricity of rosettes location and hole diameters are limited only to ones available on a market and number of strain measurements is limited, usually to 3 or 6.

An alternative way of precise displacement/strain measurement is the use of optical methods like Electronic Speckle Pattern Interferometry (ESPI) [5] or Digital Image Correlation (DIC) [6]. The latter method is more suitable for research in question due to is

lower sensitivity to vibrations and quite easy adaptation to mounting with micro driller. The results delivered from optical methods are in the form of hundreds or thousands of data points arrays defining displacement fields in the area of interest. Large number of data points gives an opportunity to apply collected data in an inverse method based calculations [7]. In such a method, a set of initially defined model parameters describing displacement fields near the hole is optimized to decrease the difference between this model and measurement results, usually in an iterative procedure. If inverse method is applied in residuals stress estimation, besides residual stress components additional parameters, for example coordinates of the hole, might be added to the optimization procedure increasing a method accuracy.
The aim of the paper is to demonstrate the applicability of DIC measurements results and inverse method calculation algorithms to determine residuals stress components in steel samples. For this purpose, experimental testing stand was designed and build and measurements and calculations performed.

METHODOLOGY

3D DIC method [8] has been selected to perform displacement fields measurements resulted from hole drilling related stress relaxation. Two cameras oriented symmetrically to the micro driller and with some angle to the observed sample area were used. The set-up of 3D DIC system gave an opportunity for placing the head of micro driller between them, therefore there was no need to move the optical system for the drilling time. Prior to undeformed (registered before drilling) and deformed (registered after drilling) images registration calibration procedure has been applied. The series of images of calibration gird consisting of 9x9 dots array with 0.49 mm spacing (Fig. 1a) was recorder with its different positioning to both cameras. Subsequently, triangulation procedure was done in Vic3d software (Correlated Solutions, USA) resulting in precise determination of cameras distance to the object and lens distortions. The same software has been used to displacement fields data processing. Samples' surface was prepared for DIC measurements by black and white paint spraying (Fig. 1b).

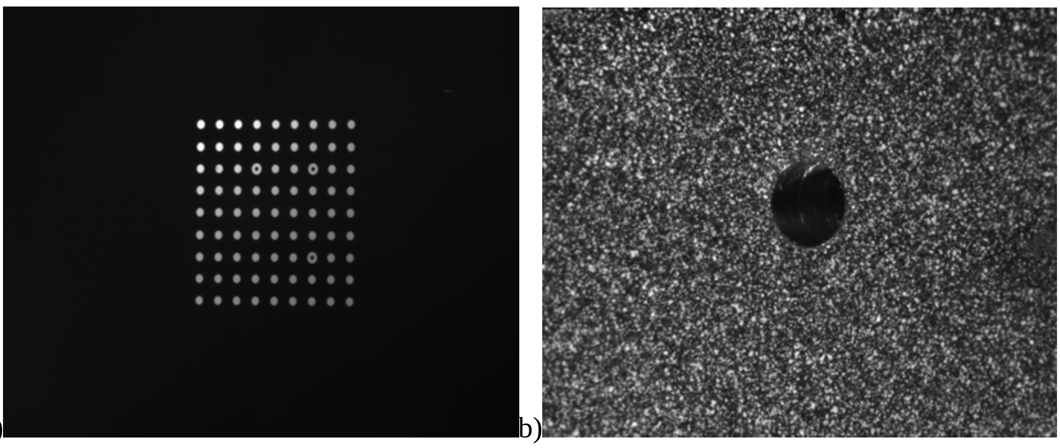
a)  b)

Fig. 1. Exemplary, actual images of: a) calibration grid and b) sample surface prepared for DIC measurements after 1.5 mm diameter circular hole drilling

The testing stand consisting of aluminum profiles frame, micro driller, cameras and lightening (see Fig. 2) has been built to determine displacement fields near the drilled hole of

1.5mm diameter in 18G2A steel samples bended in tensile (convex, Fig. 3a) and compressive (concave, Fig 3b) modes.

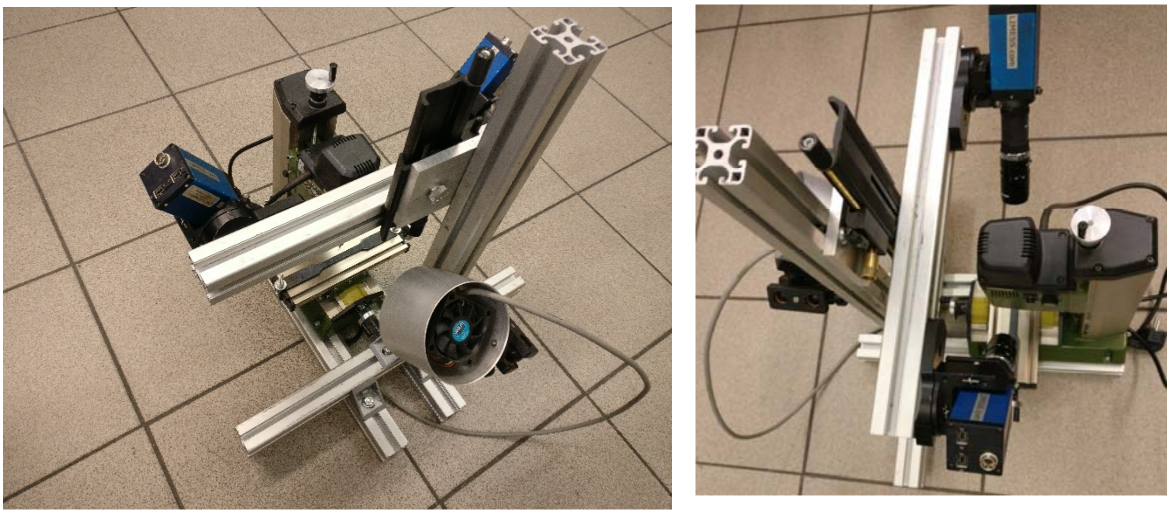
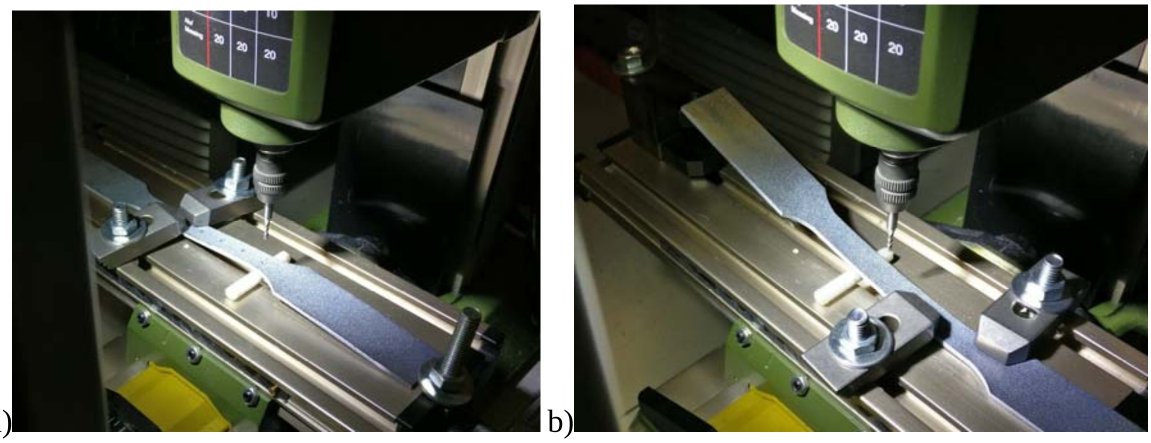


Fig. 2. Testing set-up with micro driller, two cameras translation table and lightening



a) b)

Fig. 3. Sample in a) convex and b) concave loading mode after hole drilling

DIC measurements data have been used as the input data for the iterative algorithm for model parameters fitting in similar way as presented in [9] for stress intensity factor determination. The following analytical model delivering horizontal and vertical components of displacement field near through hole was used [5]:

$$u_k(r_k,\theta_k)=\frac{(1+v)a^2}{Er_k}\left\{\begin{aligned}&\left(\frac{\sigma_x+\sigma_y}{2}\right)\cos\theta+\left(\frac{\sigma_x-\sigma_y}{2}\right)\left[\left(1-\frac{a^2}{r_k^2}\right)\cos 3\theta_k+\kappa\cos\theta_k\right]+\\&+\tau_{xy}\left[\left(1-\frac{a^2}{r_k^2}\right)\sin 3\theta_k+\kappa\sin\theta_k\right]\end{aligned}\right\} \quad (1)$$

$$v_k(r_k,\theta_k)=\frac{(1+v)a^2}{Er_k}\left\{\begin{aligned}&\left(\frac{\sigma_x+\sigma_y}{2}\right)\sin\theta+\left(\frac{\sigma_x-\sigma_y}{2}\right)\left[\left(1-\frac{a^2}{r_k^2}\right)\sin 3\theta-\kappa\sin\theta\right]+\\&-\tau_{xy}\left[\left(1-\frac{a^2}{r_k^2}\right)\cos 3\theta-\kappa\cos\theta\right]\end{aligned}\right\} \quad (2)$$

where:
$\kappa=3\text{-}4v$, v- Poisson's ratio,
E-Young's modulus,
a – hole diameter,
σ_x, σ_x, τ_{xy} -residual stress components,
(r_k, θ_k) -coordinates of k-th data point in polar system.

Polar to cartesian coordinates transformation has been applied:

$$r_k = \sqrt{(x_k - x_0)^2 + (y_k - y_0)^2} \tag{3}$$

$$\theta_k = \tan^{-1}\left(\frac{y_k - y_0}{x_k - x_0}\right) \tag{4}$$

where (x_0, y_0) are coordinates of a hole center.

This translation allowed easy implement hole center coordinates as parameters being optimized in an iterative procedure. Besides, three additional parameters defining rigid body movement (T_x and T_y) and rotation (R) were included in optimization procedure enabling successful calculations even for cases when the sample was slightly moved between registration of undeformed and deformed images. Fitting procedure was stopped when appropriate value of error function has been achieved. Calculated σ_x, σ_y and τ_{xy} for the set of one reference and tree deformed (registered with a few seconds intervals after hole drilling and drilling head removal from the field of view) images were averaged and are presented in the results section.

It should be kept in mind that equations 1 and 2 are valid for flat surfaces. In the investigated cased samples were bent and convex or concave areas were observed, therefore the results of calculations contain some bias related to surface topology. Nonetheless the aim of presented work was to show the applicability of DIC measurements in residual stress estimation, at first attempt for relatively high stress values. Presented methodology is planned to be developed for more complex cases including more practical blind holes drilling.

RESULTS

The results of DIC measurements for two bending cases are presented in Fig. 4. Hole drilling accompanied stress relaxation resulted in clearly visible surface displacement in the direction out of hole center for convex case and opposite for concave case.

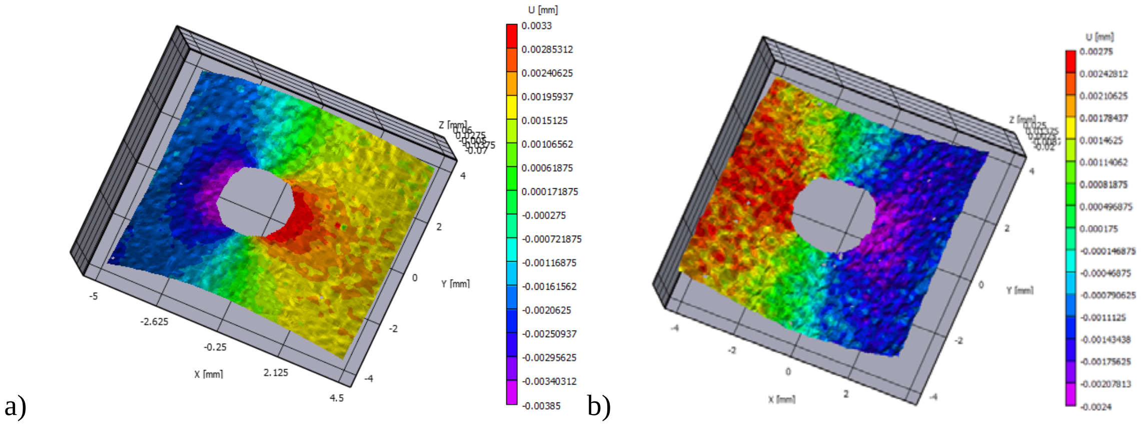


Fig. 4. Results of 3D DIC horizontal displacement fields measurement for a) convex and b) concave cases of sample loading presented in Fig. 3

Fig. 5 and 6 show exemplary DIC measurements results compared to results delivered from the model after parameters optimization procedure. Displacement components distribution and extreme values are in good accordance when comparing two neighborhood images, especially for horizontal components where displacements were the highest. Due to data filtration use based on threshold values of correlation coefficient some missing points are visible on presented maps as white islands.

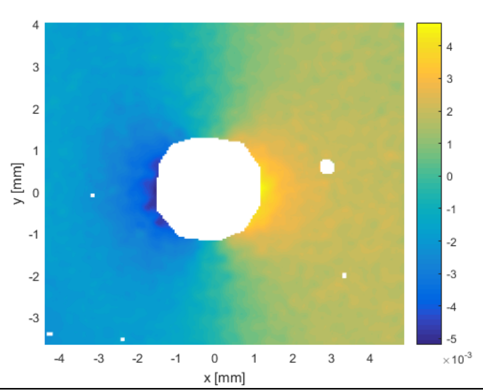
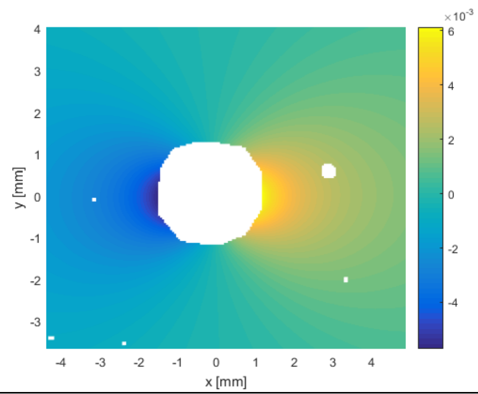
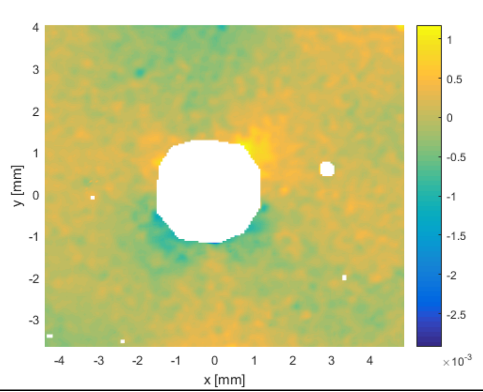
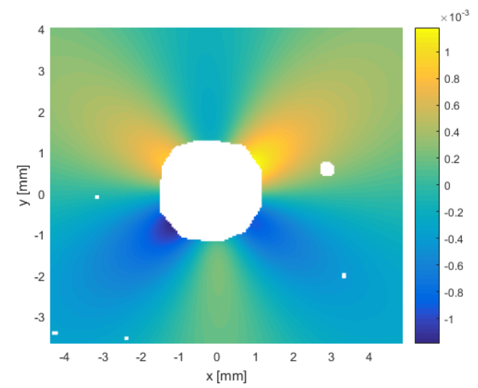
	DIC measurement	Analytical model (Eq. 1 or 2) after parameters fitting
Horizontal direction		
Vertical direction		

Fig. 5. Exemplary results of DIC displacement fields measurements and analytical model after paramaters fiting for convex loading case

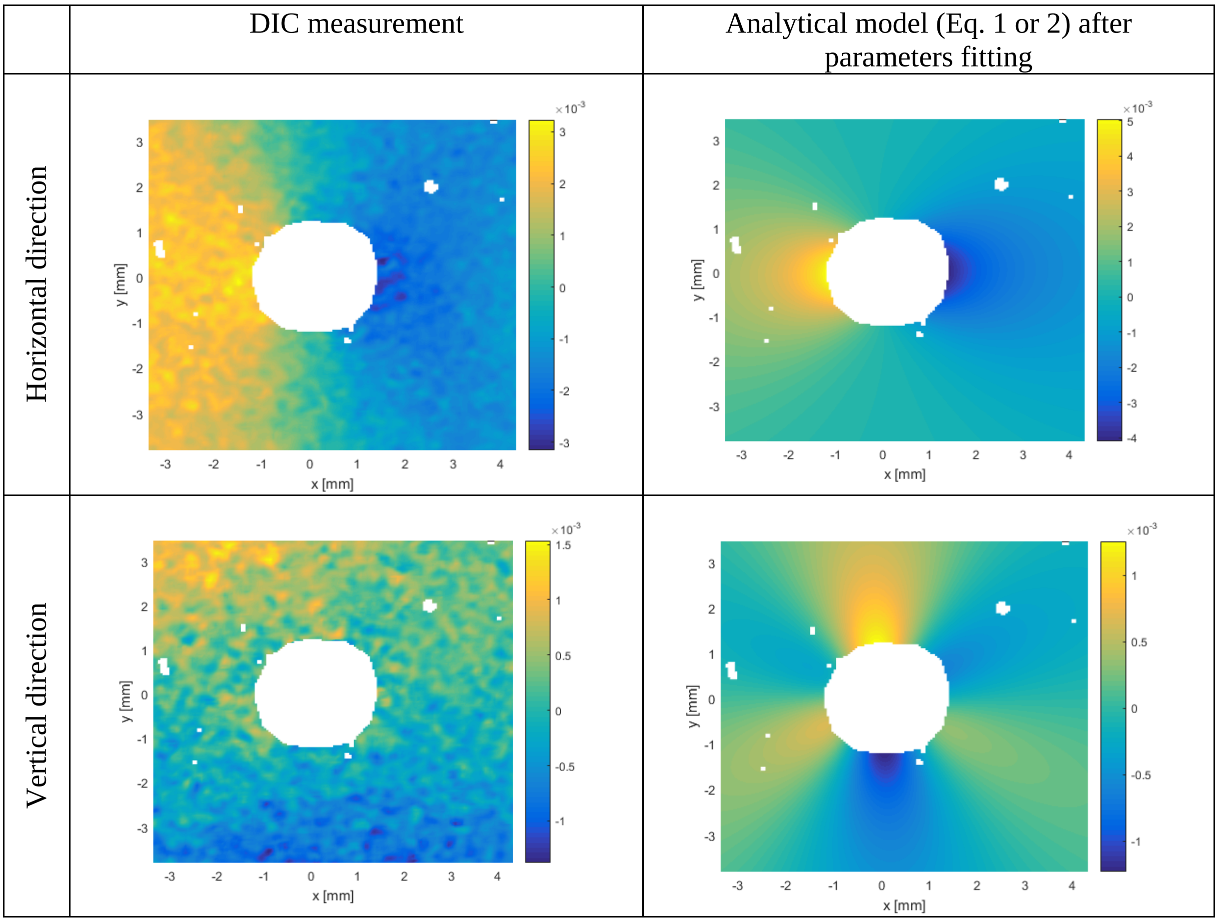


Fig. 6. Exemplary results of DIC displacement fields measurements and analytical model after parameters fitting for concave loading case

Measurements data coming from areas having the worst correlation resulted from speckle pattern changes by drilling crisps deposition has not been taken into account during calculations. Thus, measurement data filtration allows to perform residuals stress calculations, even if some part of pattern necessary for DIC measurements is lost.

Averaged values of residual stress components for both analyzed load cases are presented in Fig. 7. As anticipated, determined values are high due not flat samples' surface topology, however stress distribution is in accordance to expected from applied loading modes. Relatively high error bars suggest the need for more rugged cameras fixing. Cameras fixing solution applied in reported investigation was based on three points support and puling springs making cameras positioning easy but DIC measurement more prone to vibrations.

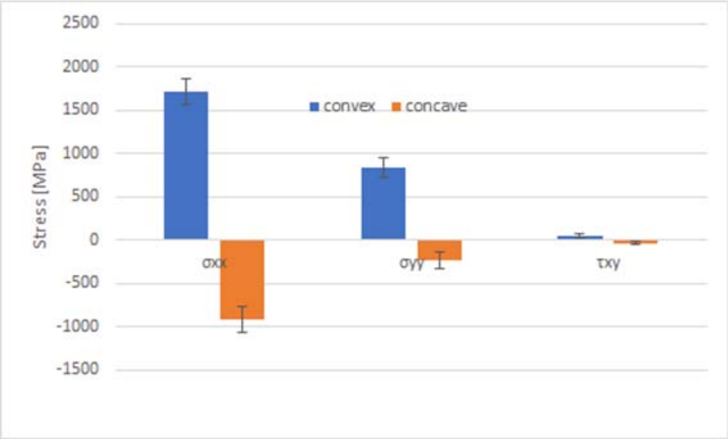


Fig. 7. Results of DIC based residual stress measurements

CONCLUSIONS

The promising methodology of residual stress measurements based on inverse method calculations and 3D DIC displacement fields measurements near drilled holes has been developed. Testing set-up was used to determine residual stress distribution in two loading cases attained by samples' bending and obtained results were in accordance to anticipated from the applied loading mode. Planned improvements of the stand and methodology are expected to make the calculations more repeatable (reduce scattering) allowing determination of residual stresses of smaller degree and for more practical blind hole drilling case. The method accuracy is planned to be tested for samples loaded to the determined strain/stress level in tension.

ACKNOWLEDGEMENT

This work was supported by The National Science Center under contract 2016/21/D/ST8/02019.

REFERENCES

1. Wither P.J., Residual stress and its role in failure. Reports on Progress in Physics, 70 (2007) 2211–2264.
2. Rossini N.S., Dassisti M., Benyounis K.Y., Olabi A.G., Methods of measuring residual stresses in components. Materials & Design, 35 (2012) 572–588
3. Mathar J., Determination of Initial Stresses by Measuring the Deformation Around Drilled Holes. Trans.,ASME 56 (1934) 249-254.
4. Huang X.; Liu Z. & Xie H., Recent progress in residual stress measurement techniques. Acta Mechanica Solida Sinica, 26 (2013) 570 – 583.

5. Gao J., Shang H., Deformation-pattern-based digital image correlation method and its application to residual stress measurement. Applied Optics, 48 (2009) 1371-1381.
6. Lord J.D., Penn D., Whitehead P.: The Application of Digital Image Correlation for Measuring Residual Stress by Incremental Hole Drilling. Applied Mechanics and Materials, 13-14 (2008) 65-73.
7. Cooreman S., Lecompte D., Sol H., Vantomme J., Debruyne D., Identification of Mechanical Material Behavior Through Inverse Modeling and DIC, Experimental Mechanics, 48 (2008) 421–43.
8. Helm J.D., McNeill S.R., Sutton M.A., Improved three-dimensional image correlation for surface displacement measurement. Opt. Eng., 35 (1996) 1911–1920.
9. Brynk T., Pakiela Z., Kulczyk M., Kurzydlowski K.J., Fatigue crack growth rate inultrafine-grained Al 5483 and 7475 alloys processed by hydro-extrusion. Mechanics of Materials, 67 (2013) 46–52.