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DIGITAL IMAGE CORRELATION (DIC) SYSTEM AS A VERIFICATION TOOL FOR CONSTITUTIVE MODELS OF DEFORMATION WITH COMPLEX STRAIN PATH CHANGES

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Abstract

Effects of the strain path changes that occur during metal forming have been the subject of theoretical and experimental studies in the light of deformation inhomogeneities. Modern multiphase steels were used as their mechanical properties are very sensitive and strictly dependent on the combination of microstructure components with different levels of their mechanical responses. DIC as a precision tool has been used to investigate the deformation inhomogeneity during the tensile tests of specimens previously deformed with complex strain path history. The study was focused on the combined metal forming processes (i.e. Accumulated Angular Drawing (AAD), Wire Drawing (WD) and Wire Flattening (WF)). These processes are characterised by a combination of various deformation mechanisms (area reduction, torsion, bending, burnishing), and thus, are strongly affected by nonlinear strain path changes. Then, data provided in the experimental part of the work was used to assess the existing work hardening models in the light of their applicability for the prediction of mechanical response of materials subjected to nonlinear loading conditions. In the numerical analysis, work hardening model (i.e. Chaboche model) was investigated. The results of computer simulation were then compared with the DIC measurements and conclusions regarding applicability of the proposed approach were drawn. The comparison of the DIC data processing with tensile test data shows that correlation techniques provide results sufficiently accurate to study the inception and the evolution of the strain localization phenomena, so this methodology could be successfully applied in a more complex, as in the present investigation, forming problems.

Key words: Digital Image Correlation, work hardening models, strain path changes

1. INTRODUCTION

In recent years there has been an extensive development of bulk ultrafine-grained (UFG) and nanostructured (NS) materials. Most often these materials are produced by severe plastic deformation (SPD) methods. SPD processing produces superior strength due to a significant grain refinement. At the same time, however, a noticeable drop in ductility is observed in such materials (Sauvage et al., 2012; Murty & Torizuka, 2010; Majta & Muszka, 2012). The main reason of this situation is the effect of work hardening reduction, which is clearly observed during loading e.g. in uniaxial tensile tests. In the case of microalloyed ultrafine-grained steels, the reasonably good ductility is attributed to the finely dispersed second phase particles, which effectively increase the work hardening rate.

Nevertheless, the restricted ability to plastic deformation needs more and more exact measurements techniques to be applied in the studies of such important issues as the mechanical response of UFG and NS materials. Examples of this group of techniques are non-contact measurement methods. Thanks to the great improve-

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ment in the non-contact techniques for strain measurements (Post, 1983; Fottenburg, 1969; Lu, 1998) Digital Image Correlation (DIC) enables one to make a precise analysis of the strain fields very easily and in a very convenient manner. DIC is a non-contact optical technique based on the comparison of two images of investigated specimen acquired at different stages of loading (Wang et al., 1993; Sutton et al., 1983; Sutton et al., 1991). Originally, this technique was applied to the measurements of displacements and strains.

In the present study, two-dimensional DIC technique is also applied for strain measurements, but in severely deformed specimens as a comparison of the mechanical response of two microalloyed steels. The DIC system is employed to measure the deformation of affected by nonlinear strain path changes specimens during tensile testing. In order to determine the local accumulations of the deformation energy, the measurements of displacements and the resulting strains were used in the analyses of the mechanical properties developments. In the numerical analysis, Chaboche work hardening model was employed. The results of the computer simulations were then efficiently compared with the DIC measurements.

Table 1. *Basic chemical composition (wt. %)*

Material	C	Si	Mn	Nb	Ti	Cu	N	B	Ni	Co
Microalloyed ferritic steel	0.07	0.29	1.36	0.067	0.03	0.16	0.0098	0.002	-	-
Microalloyed austenitic steel	0.047	0.30	1.64	0.097	-	-	0.0042	-	30.8	0.022

2. EXPERIMENT

In order to evaluate the interrelationships between processing and mechanical behaviors of UFG and layered microstructures, two microalloyed steel wire rods (diameter of 6.5mm), with basic chemical composition shown in table 1, were used in the current work.

In the present work, the experimental procedure was divided into two parts: (1) complex metal forming process and (2) tensile test combined with Digital Image Correlation analysis. All experiments were carried out in order to provide data for the modeling part. Three steps of deformation were included in the complex metal forming process. In the first step, the multi-pass wire drawing process, using Accumulative Angular Drawing (AAD) method, was performed. The AAD process induces high strain accumulation in the surface layers of the wire, which allows one to achieve increased mechanical properties and ductility in the wires characterized by small diameters. The methodology employed in this process utilizes the following means of deformation: area reduction, torsion, bending and brushing due to limited metal flow. In the next step, the multi-pass linear wire drawing (WD) process was used. In the final step, the wire flattening (WF) process (figure 1a) was carried out (Majta et al., 2015).

Next, the tensile test combined with Digital Image Correlation (DIC) analysis was performed. At the beginning of the measurements, the surface of each specimen was coated with a stochastic pattern. The system of two high resolution CCD cameras enables to track the position of the same physical points (pattern) shown in the reference image and the deformed images. The digital images are recorded and processed by means of an image correlation algorithm. Many parameters are considered while obtaining accurate DIC results. Some of the parameters include speckle size, type of algorithm, subset size, subset overlap, gray level interpolation. The basic processing work is done by the software that calculates the average gray scale intensity (based on the tracking of the grey value pattern in small local neighborhoods) over the subset in the reference and deformed image and compares them. It is important, that the object surface shows enough structure to allow the algorithms to correlate identical points from both cameras. The equation 1 shows the basic form of the cross-correlation term using the two consecutive images (Yang et al., 2010).

$$c(u,v) = \sum_i \sum_j L_1(r_i, s_j) L_2(r_i + u_L, s_j + v_L) \quad (1)$$

$$u_L = u + \frac{\partial u}{\partial r}(r_L - r_C) + \frac{\partial u}{\partial s}(s_L - s_C) \quad (2)$$

$$v_L = v + \frac{\partial v}{\partial r}(r_L - r_C) + \frac{\partial v}{\partial s}(s_L - s_C) \quad (3)$$

Where: u and v are the in-plane displacements of the center points of a subset located at (r_C, s_C), and u_L and v_L are the displacements of an arbitrary point (r_L, s_L) in the subset. L_1 represents the intensity of subset pixels in the reference image. L_2 represents the intensity of pixel in the deformed image. Solving

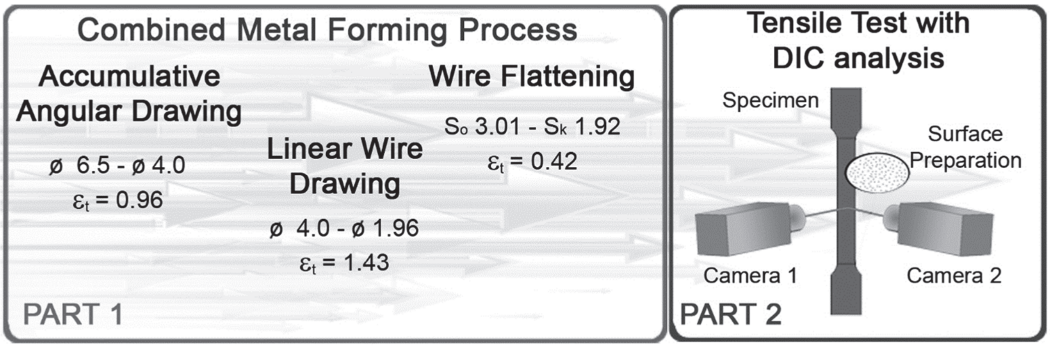

***Fig. 1.** The concept of the experimental procedure for the combined metal forming process and tensile test with attached DIC analysis.*

for the variables u gives the in-plane deformation in the x direction and v gives the in-plane deformation in the y direction. The subset size is 5n x 5n. Equation 1 gets different values at different positions in the deformed image. The maximum value of the term shows the matched position of the most similar pattern in the deformed image compared to the reference image. Highly optimized input parameters provide very accurate results. In the presented study, DIC system was utilized as the verification method of the work hardening model used in the numerical analysis.

Tensile tests were performed at room temperature with strain rate of $0.001s^{-1}$ for both analyzed materials. The deformation process and the specimens' geometries are presented in figure 2.

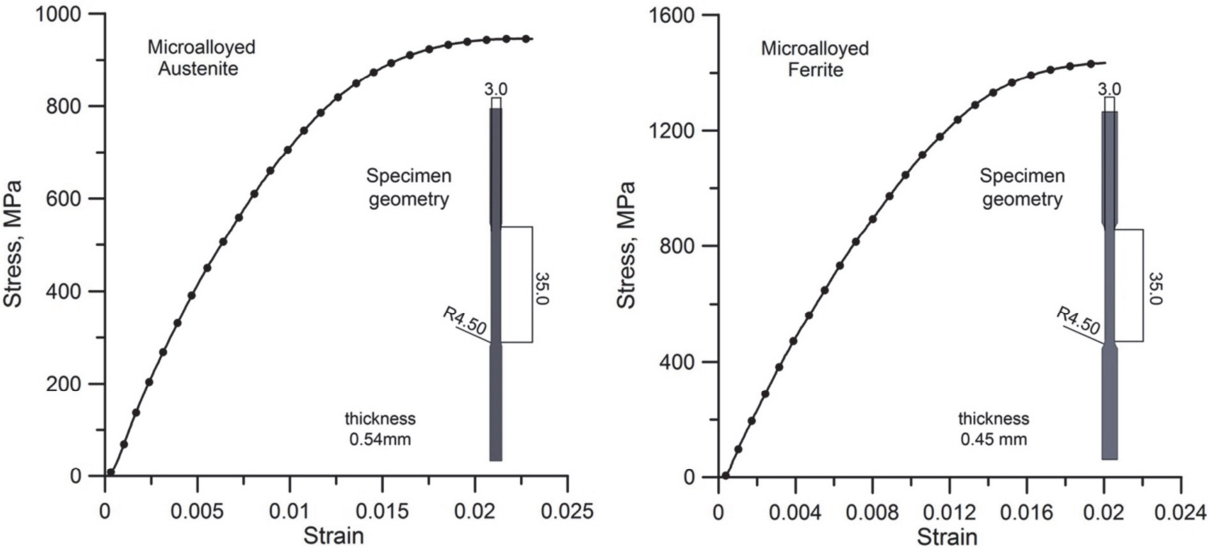

***Fig. 2.** Flow stress- strain curves recorded during tensile test and the specimens dimensions of both of the studied materials.*

3. WORK HARDENING MODEL

The main aim of the current work is verification of the existing work hardening model with the help of the Digital Image Correlation analysis. That comparison allows one to check the correct predictions of the materials behavior in the numerical simulation of the presented processes. In the case of the microalloyed steels, the effects of the interactions between recrystallization and precipitation kinetics, as well as solid solution and precipitation strengthening, are particularly important problems. Also, as already mentioned, in the current study, Digital Image Correlation is used for analysis of materials that undergo complex strain path changes - that is why the more complex hardening model was selected.

3.1. Chaboche model

The selected model is Chaboche model (Lemaitre & Chaboche, 2000). It consists not only of isotropic part of the hardening, but also of kinematic hardening component, what enables it to take into account strain path sensitivity resulting e.g. from Bauschinger effect. The isotropic component can be described by the following equation:

$$\sigma^0 = \sigma_0 + Q(1 - exp^{-b\varepsilon}) \tag{4}$$

where: σ^0– the size of the yield surface; σ_0 – yield stress; Q – maximum change in yield surface, b – rate of change of yield surface during plastic deformation; ε – strain.

Evolution law of the kinematic part of the Chaboche hardening model is described as a sum of the backstresses, which includes parameters that control the position of the stress for each backstress:

$$\dot{\boldsymbol{\alpha}} = \frac{C_k}{\sigma^0}(\boldsymbol{\sigma} - \boldsymbol{\alpha})\varepsilon - \gamma_k \boldsymbol{\alpha}\varepsilon \tag{5}$$

where: C_k – initial kinematic hardening modulus; γ_k – the rate at which the kinematic hardening modulus decreases with increasing plastic deformation; σ^0 – the size of the yield surface; σ – stress tensor; α – backstress; ε – strain.

In the current study, all models parameters were identified based on data from the experimental part. Additionally, in the simulation procedure, the elastic part was included.

This model is widely available in various finite element simulation software, one of them is Abaqus Standard package, which was used in the current work. The main advantage of the Chaboche model is its effective usage in simulations where the complex hardening modes take place.

ductile fracture (figure 3a) in the case of the microalloyed austenite and the brittle fracture (figure 3b) in the case of microalloyed ferrite were observed.

In order to analyse the Digital Image Correlation data, three points on the specimens were selected and strains at these points were tracked. Points A and C represent the two ends of the sample. The strain values at these two points are close to each other. Point B represents the region where cracks occurred. Figure 3 shows the strain *vs* time at those points for both studied materials. The strain value in point B was larger in comparison to the data in points A and C. In the case of the austenite, these differences were larger due to a strain localization in the necking area. Points A, B and C are representative points selected along the strain gauge of tensile specimen. Points A and C are the limiting points for the DIC calibration and point B is a point near the zone where failure occurred. Additionally, figure 4 presents the strain distribution along the gauge length, which shows that the strain values near the centre of the samples are similar to the values obtained in points A and C.

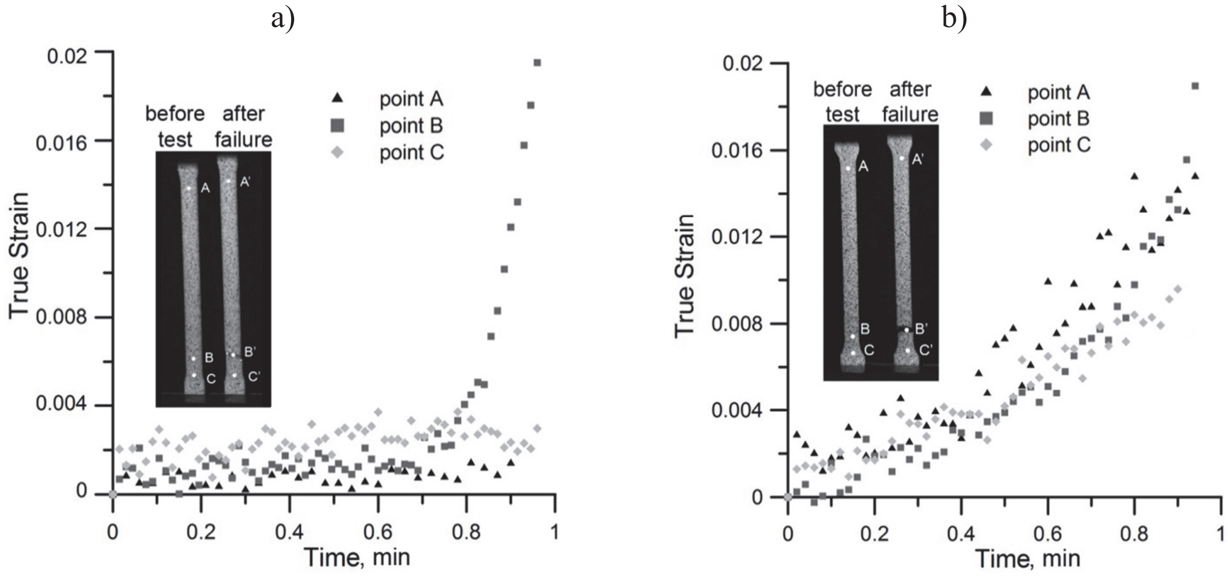
a)
b)

Fig. 3*. True strain vs displacement for three selected points and specimens' geometries before and after plastometric test with marked points for austenitic steel - a) and ferritic steel - b).*

4. RESULTS

As expected, high strain accumulation and inhomogeneity of the deformation resulting from applied history of deformation led to large work hardening of the investigated fcc and bcc materials. As a result, typical mechanical behaviour of these two materials were observed during tensile test i.e. the

Figure 4 represents the changes of the true strain levels at different times during the tension tests. The profile of the axial strain along the three points (A, B and C points from figure 3) is presented as one line in time (relative). In time steps 10-40, the differences between the points that represent the end of the sample and the crack region are smaller for both analysed materials. Only in the last time step, before failure, one could notice the clearly marked peak in point B. In the austenitic steel, this peak was more visible than in the case of the ferritic steel. The length of the time step used during the investigation in both cases was about 10 s.

Figure 5 presents the comparison of the true strain (point B) changes in time obtained in the numerical simulation and the DIC analysis for both materials. The comparison presented in the figure 5a shows good accuracy between the modelling results

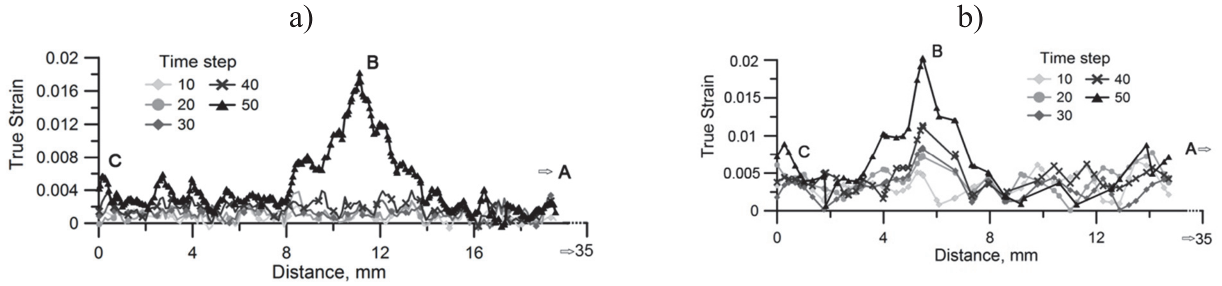

Fig. 4. True strain levels change during different DIC analysis time steps during tensile test for the austenitic steel - a) and ferritic steel - b).

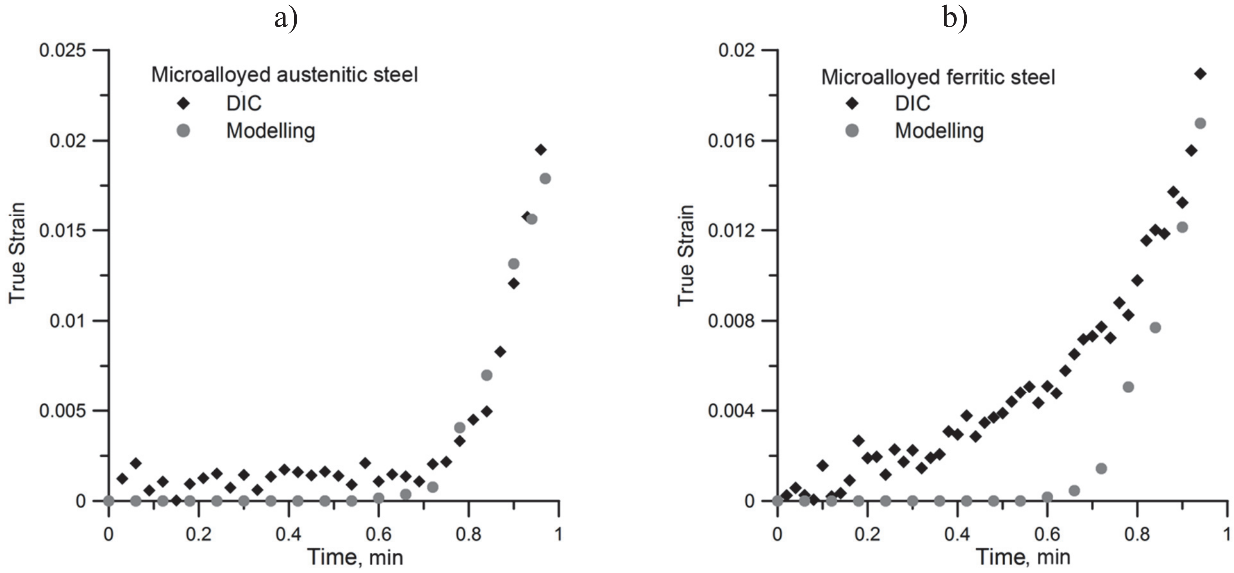

Fig. 5. Comparison of the true strain change obtained in simulation and DIC analysis at point B for the microalloyed austenitic steel - a) and microalloyed ferritic steel-b).

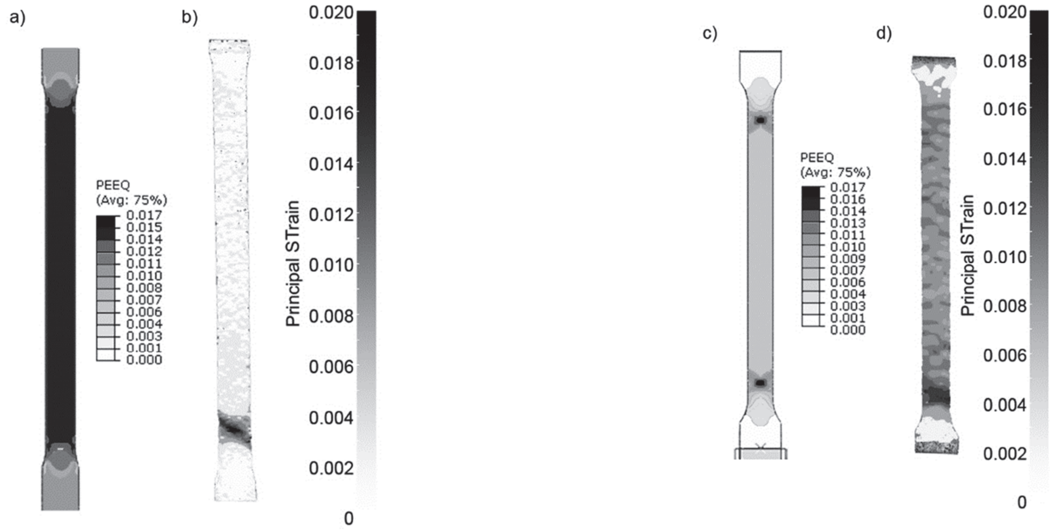

Fig. 6. Plastic strain distribution obtained in simulation and in DIC analysis for the microalloyed austenitic steel -a) b) and for the microalloyed ferritic steel -c) d).

and the results obtained in the DIC analysis. In the case of the ferritic steel, the shapes of both curves were different only below 0.01 of strain, the curve representing the numerical analysis coincides with the curve obtained in the DIC analysis. Nevertheless, the application of the combined hardening models, such as Chaboche model, is strongly recommended for a simulation of nonlinear deformation processes.

Presented in figure 6c and 6d, the comparison of calculated and measured principal strain distributions for ferritic steel demonstrates that the chosen material model captured correctly both the distribution and the concentration of the strain values. In the case of the microalloyed austenitic steel, the level of the strain had a similar values both in the numerical simulation and in the DIC analysis, but the strain localization in the numerical simulation did not occur, as it is observed in the case of the microalloyed ferritic steel. The reason for that can be attributed to differences in work hardening representations of the investigated in the present study fcc and bcc structures, i.e. the hardening mechanism in the case of fcc is much more sensitive to the processing parameters. Hence, the correct representation of the hardening in fcc materials needs more sophisticated model than in the case of bcc materials".

5. CONCLUSIONS

In the present paper, complex metal forming processes, which take advantage of the strain path changes, were presented. The tensile tests of the specimens after complex metal forming processes compared with Digital Image Correlation system were analysed in details. Based on the DIC results, applied in the computer simulations work hardening model was verified and the following major conclusions can be drawn:

Experimental approach provides the time evolution of various variables (displacement, strain, strain rate, and so on). The comparison of the DIC data processing with tensile test data shows that correlation techniques provide results sufficiently accurate to study the inception and the evolution of the strain localization phenomena, so this methodology could be successfully applied in more complex, as in the present investigation, forming problems.

Proper choice of the work hardening model that takes into consideration complex history of deformations is crucial in order to effectively model the complex strain path processes and to control strain and microstructure evolution, and thus, to optimize the properties of the final products, especially in products obtained by the SPD methods.

The presents study clearly shows that the DIC system, although more demanding compared to other methods (e.g. mechanical or laser extensometers) can be successfully implemented for the strain behaviour assessment. Characterisation of the mechanical response using this technique is more accurate as it takes into account deformation history and microstructure evolution of the analysed specimens.

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ZASTOSOWANIE SYSTEMU CYFROWEJ KORELACJI OBRAZU (DIC) DO WERYFIKACJI MODELI KONSTYTUTYWNYCH UMOCNIENIA W ZŁOŻONYCH PROCESACH ODKSZTAŁCANIA

Streszczenie

W pracy omówiono aspekty dotyczące niejednorodności odkształcenia stali mikrostopowych o podwyższonych własnościach wytrzymałościowych jako efekt zastosowania procesów charakteryzujących się zmienną ścieżką odkształcenia. Część badawcza koncentrowała się na próbie rozciągania materiałów wcześniej poddanych złożonym procesom przeróbki plastycznej (tj. proces kątowego wielostopniowego ciągnienia, ciągnienie oraz spłaszczanie drutów). Głównym narzędziem badawczym był system Cyfrowej Korelacji Obrazu (DIC), który wykorzystany został do analizy niejednorodności odkształcenia w omawianych procesach. W dalszej części pracy przeprowadzona została symulacja numeryczna z zastosowaniem modelu Chabocha do opisu umocnienia odkształceniowego. Wyniki uzyskane za pomocą systemu Cyfrowej Korelacji Obrazu poddano szczegółowej analizie oraz porównano z rezultatami uzyskanymi z modelowania komputerowego. Na tej drodze sformułowano wnioski dotyczące skuteczności działania zastosowanych równań konstytutywnych do przewidywania zmian w charakterystyce mechanicznej materiałów poddanych przeróbce plastycznej ze złożoną odkształcenia.

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