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APPROPRIATE MATHEMATICAL MODEL FOR STRESS CALCULATION BASED ON THE MEASURED VALUES OF DEFORMATION AND TEMPERATURE CHANGES

Ivan Jandrlić[1*], Stoja Rešković[1], Ladislav Lazić[1], Tin Brlić[1], Dušan Ćurčija[2]

[1] University of Zagreb Faculty of Metallurgy, Sisak, Croatia
[2] Croatian Metallurgical Society, Zagreb, Croatia

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Abstract

Presented mathematical model determines the stresses depending on the measured temperature changes and the associated deformations of the samples. Investigations were conducted by tensile testing machine Zwick 50 kN on the samples from low-carbon niobium microalloyed steel. The values of measured parameters were determined by using the methods of thermography and digital image correlation. The model is formulated on the basis of a multiple regression analysis of the relations between measured and calculated parameters. Verification and validation of the model showed a good agreement between the model and the system modeled.

Keywords: *stress, mathematical model, thermography, digital image correlation*

Corresponding author: ijandrli@simet.hr*

INTRODUCTION

The rapid development of technologies requires manufacturers to quickly adapt to new products, which have to meet the growing demands of the market. The development of materials used in the production of components goes hand in hand with development of the technologies. The best example for this is the automotive industry which, in addition to maintaining or increasing safety and dimensions, also requires a lower mass of the final product. For this reason, manufacturers are increasingly turning to the new types of materials. To maintain the reliability of the built-in components, it is of utmost importance to conduct detailed mechanical testings of newly installed components. Along with the application of different testing methods, the modeling and testing of components by using models formulated on the basis of the finite element method are increasingly in use [1-3].

Models for modeling mechanical behavior of various metal system components that are under load are especially complex. These models have certain limitations in terms of predicting all factors that may affect final values. They require knowledge of a significant number of parameters of the material to simulate the real behavior of certain components in the system as accurately as possible [4-8]. In order to obtain the reliable information of the material, there are also different models used in research to determine the interdependence between different parameters [4,5]. The wide knowledge on the material flow and stress distribution in the observed sample under load is also necessary [6,9]. Existing modeling methods are constantly subjected to improvements [8,9], as well as the ability of devices for the model verification [7]. What is valid for all models is a large number of metal testing, such as static tensile test, shear test, or some other method.

From the literature it is evident that there is a need for extensive research in order to develop the reliable models for determining stress distribution in the deformation zone. Lately the idea and need for a different and perhaps simpler approach to the modeling have emerged. It is well known that during the plastic deformation of the metals there is a change in the internal energy of the deformed metal, and this is manifested with the temperature change of the test sample in the deformation zone [10,11]. This change can be detected and measured by an infrared camera, and subsequent thermal analysis provides a clearer picture of the temperature distribution, i.e. the metal flow, throughout the deformation zone [11-14]. Thermography thus provides rapid and accurate measurements from which the distribution of temperature can be analyzed, and thus stress and deformation distribution during deformation of the test samples may be determined [13,14].

It is a reasonable assumption that the maximum temperature change occurs at the place of the maximum deformation. For this reason, it is necessary to obtain the accurate information on deformation distribution throughout the deformation zone. This can be achieved by the method of Digital Image Correlation (DIC), which is frequently used today as a method for displacement and deformation analysis [15-17]. With this method it is possible to measure very small changes in displacements, thus measuring very small non-homogeneous deformations [14,15]. The advantage of the method is also the insensitivity of the method considering the shape of the sample and it is possible to conduct the testings on the samples with non-standard shapes and sizes [18]. The method has been developed to such an extent that it begins to be used for the validation of models tested in real conditions [16].

The aim of this paper is to formulate a mathematical model which will be able to calculate the values of acting stresses from the experimentally determined values of deformation (strains) and corresponding temperature changes. The model will be formulated on the basis of experimentally determined values of strain and temperature changes detected by the methods of Digital Image Correlation and thermography. Maximum values of strains, temperature changes and stresses determined by a static tensile test, were used for the modeling. It is realistic to assume that they occur in places of maximum acting stresses. Once formulated, the model will be validated and verified by experimentally measured values.

MATERIALS AND METHODS

For the proposed model, at first it was necessary to experimentally determine the stresses, strains and temperature changes in the deformation zone during the stretching of samples. For this purpose, at the same time, during the static tensile testing on the Zwick 50 kN testing machine, the deformation of samples was recorded with an infrared and optical digital camera. The maximum stress values during the experiment were obtained from the diagram recorded by the static tensile testing machine. By a subsequent analysis of recorded deformations, using the methods of thermography and DIC, the values of temperature changes and strains were determined during the testing period. The maximum values of temperature changes and strains at the points of maximum stresses were determined. The arrangement of the measuring equipment as well as the deformation zone analyzed by the thermography and DIC methods are shown in Figure 1.

Figure 1. The arrangement of the measuring equipment as well as the deformation zone analyzed by the thermography and DIC methods

Tests were performed at two different testing speeds of 10 and 15 mm · min^{-1}. The samples for static tensile testing were taken in the rolling direction from a 3 mm thick hot-rolled strip. Tests were performed on samples with rectangular cross-section, with gauge length of 45 mm and gauge width of 20 mm. The chemical composition of the tested steel is given in Table 1.

Table 1. Chemical composition of the tested steel, wt. %

Element	C	Mn	Si	P	S	Al	Nb	N
Micro-alloyed steel	0.12	0.78	0.18	0.011	0.018	0.02	0.048	0.008

To formulate the model, it was necessary to determine the interdependence of the measured values using the MathCAD and OriginPro software packages. Data obtained from the thermography and Digital Image Correlation analysis, due to the high frequency of measurement, had a certain noise, which would present a problem during the modeling process. Therefore, a certain smoothing of the measured values of measured strains and temperature changes was made before the modeling with the use of the Savitzky - Golay method within OriginPro, and the fourth-order polynomial function. Subsequently, the multiple linear regression analysis with the application programs was performed on adjusted values of measurement results.

RESULTS AND DISCUSSION

In the first step of formulating the model, the interdependence of measured values was studied. First, the influence of temperature change on the increase of strain during stretching of samples was determined. The analysis was performed at both used testing speeds. The results are shown in Figure 2.

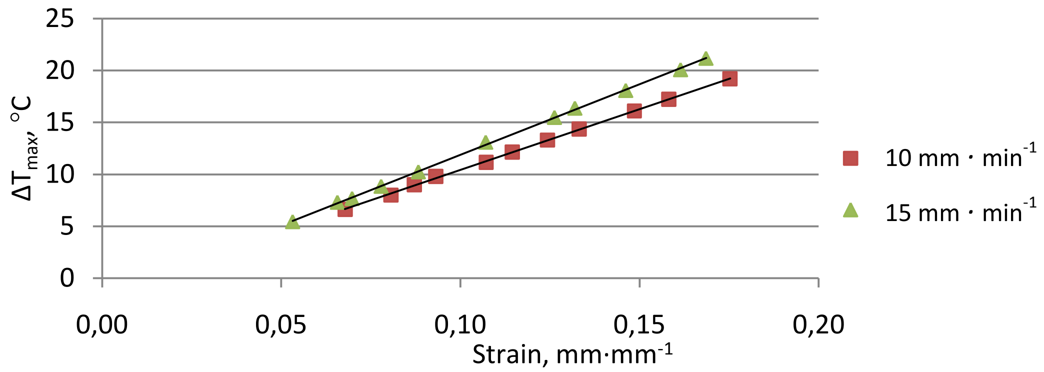

Figure 2. Dependence of temperature change on strain at different testing speeds

The analysis of the influence of the increase in strains on the temperature change during the stretching of samples, made of 0.048% Nb microalloyed steel, shows that the increase in strain causes an increase of the temperature changes. From the obtained diagrams it is clear that the increase in temperature is linear in relation to the strains increase. Linear growth indicates a close association of strains and temperature changes. It is logical to conclude that a greater amount of deformation causes a greater temperature change.
Linear growth was achieved at both used testing speeds. In the case of 15 mm · min^{-1}, the temperature increase is higher than at the lower testing speed (10 mm · min^{-1}). This indicates that the testing speed has an effect on the temperature change. It is expected that this increment will grow with a further increase in the testing speed, which should be explored in further research.
However, the question is how the temperature change is influenced by the increase in stress. For this reason, this dependence was also examined. The obtained diagram of the dependence of the temperature change on the increase in stress is shown in Figure 3.

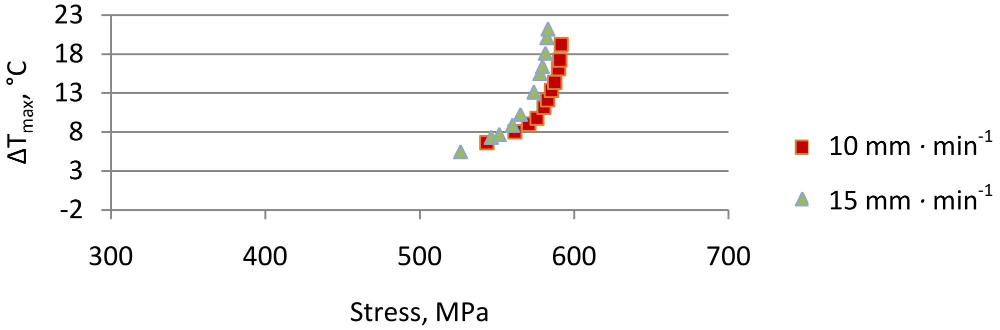

Figure 3. Dependence of the temperature change on the stress at different test speeds

As can be seen in the above correlation diagram, the increase in stress has a significant effect on the temperature change. This functional relationship is represented by an exponential function. The influence of deformation velocity is in this case weaker, but is still present.

From the analysis as well as previous investigations, it can be concluded that the measured temperature changes are closely related to the values of stresses and strains achieved during the tensile test. Accordingly, the following relation can be set:

$$\Delta T = f(\sigma, \varepsilon) \tag{1}$$

where: σ – stress,
ε – strain (i.e. deformation).

Starting from this assumption, using the multiple linear regression analysis, the functional relationships between the temperature change on one side and the strain and stress on the other side, at both the test speeds, were determined separately. The following general function dependency was obtained:

$$\Delta T = a + b \cdot \varepsilon + c \cdot \sigma \tag{2}$$

From this function, we gain two separate functions for each testing speed:

$$\Delta T = 1.6 + 140.2 \cdot \varepsilon - 0.0077 \cdot \sigma \tag{3}$$

$$\Delta T = 2 + 157.2 \cdot \varepsilon - 0.0104 \cdot \sigma \tag{4}$$

Depending on the used testing speed, different parameter values of *a*, *b*, *c* were achieved, Table 2.

Table 2. Parameter values *a, b* and *c* at different testing speeds

Testing speed (mm ·min^{-1})	*a*	*b*	*c*
10	1.6	140.2	-0.0077
15	2	157.2	-0.0104

By transformation of equation 4, it is possible to express the stress as the function of temperature change and achieved deformation:

$$\sigma = \frac{\Delta T - (a + b \cdot \varepsilon)}{c} \tag{5}$$

By entering the parameters assigned to each test speed, the following equations are achieved:

$$\sigma = \frac{\Delta T - (1.6 + 140.2 \cdot \varepsilon)}{-0.0077} \tag{6}$$

$$\sigma = \frac{\Delta T - (2 + 157.2 \cdot \varepsilon)}{-0.0104} \tag{7}$$

The mathematical model for the stress calculation formulated on the basis of the above achieved regression equations was validated and verified with the measured values of deformations and temperature changes. It has been achieved a good agreement between computed values by the developed model and the experimentally measured values of maximum stresses, for both of the used testing speeds.

CONCLUSIONS

By the experimental studies and analysis of obtained data on the adequate application programs it was established that there is interdependence between temperature changes, strains (i.e. deformations) and stresses in the deformation zone of the tested samples.

Using multiple linear regression analysis, the functional relationships between the two independent (predictive) variables, the temperature changes and strains, and the dependent (criterion) variable – stresses, were determined.

The mathematical model formulated on the basis of the achieved regression equations enables the calculation of stresses knowing the experimentally measured values of temperature changes and deformations in the deformation zone. Model was validated and verified by comparing the calculated and experimentally determined values.

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REFERENCES

[1] M. Seif, J. Main, J. Weigand, T. P. McAllister, W. Luecke, Finite element modeling of structural steel component failure at elevated temperatures, Structures 6(2016), pp. 134-145.
[2] S. Izadpanah, S. Hadi Ghaderi, M. Gerdooei, Material parameters identification procedure for BBC2003 yield criterion and earing prediction in deep drawing, International Journal of Mechanical Sciences, 115–116(2016), pp. 552-563.
[3] R. Padma Priya, S. Kandasamy, Study on the behavior of cold-formed steel angle tension members, 20th International Specialty Conference on Cold-Formed Steel Structures, (Roger A. LaBoube and Wei-Wen Yu), Department of Civil, Architectural & Environmental Engineering Missouri University of Science and Technology, November 3 & 4, 2010, St. Louis, Missouri, pp. 589-604.
[4] M. Abspoel, M. E. Scholting, M. Lansbergen, Y. An, H. Vegter, A new method for predicting advanced yield criteria input parameters from mechanical properties, Journal of Materials Processing Technology, 248(2017), pp. 161-177.
[5] C. Li, E. Daxin, N. Yi, Analysis on fracture initiation and fracture angle in ductile sheet metal under uniaxial tension by experiments and finite element simulations, Journal of Materials Research, 31(2016)24, pp. 3991-3999.
[6] A. Nasser, A. Yadav, P. Pathak, T. Altan, Determination of the flow stress of five AHSS sheet materials (DP 600, DP 780, DP 780-CR, DP 780-HY and TRIP 780) using the uniaxial tensile and the biaxial Viscous Pressure Bulge (VPB) tests, Journal of Materials Processing Technology, 210(2010)3, pp. 429-436.
[7] M. Merklein, M. Biasutti, Development of a biaxial tensile machine for characterization of sheet metals, Journal of Materials Processing Technology, 213(2013)6, pp. 939-946.
[8] Y. Ling, Uniaxial true stress-strain after necking, AMP Journal of Technology, 5(1996), pp. 37-48.
[9] H. Vegter, H. Mulder, P. van Liempt, J. Heijne, Work hardening descriptions in simulation of sheet metal forming tailored to material type and processing, International Journal of Plasticity, 80(2016), pp. 204-221.
[10] A. Rusinek, J. R. Klepaczko, Experiments on heat generated during plastic deformation and stored energy for TRIP steels, Materials and Design, 30(2009), pp. 35-48.
[11] M. M. Kutin, S. S. Ristić, M. R. Prvulović, M. M. Prokolab, N. M. Marković, M. R. Radosavljević; Application of Thermography during Tensile Testing of Butt Welded Joints, FME Transactions, 39(2011), pp. 133-138.

[12] J. Hyun Ryu, J. In Kim,H. S. Kim, C. S. Oh, H. K. D. H. Bhadeshia, D.-W. Suh, Austenite stability and heterogeneous deformation in fine-grained transformation-induced plasticity assisted steel, Scripta Materialia, 68(2013), pp. 933-936.
[13] T. Brlić, S. Rešković, I. Jandrlić, Study of inhomogeneous plastic deformation using thermography, 16th International Scientific Conference on Production Engineering - CIM 2017, (E. Abele, T. Udiljak, D. Ciglar), Zagreb: HUPS, 08-10.06., 2017, Zadar, Croatia, pp. 65-68.
[14] I. Jandrlić, S. Rešković, T. Brlić, Distribution of stress in deformation zone of niobium microalloyed steel, Metals and Materials International, 24(2018)4, pp. 746-751.
[15] M. Eskandari, A. Zarei-Hanzaki, M. Yadegari, N. Soltani, A. Asghari, In situ identification of elastic–plastic strain distribution in a microalloyed transformation induced plasticity steel using digital image correlation, Optics and Lasers in Engineering, 54(2014), pp. 79-87.
[16] P. Lava, S. Cooreman, D. Debruyne, Study of systematic errors in strain fields obtained via DIC using heterogeneous deformation generated by plastic FEA, Optics and Lasers in Engineering, 48(2010)4, pp. 457-468.
[17] I. Jandrlić, S. Rešković, T. Brlić, L. Lazić, T. Aleksandrov Fabijanić, Investigation of deformation by digital image correlation, 16th International Foundrymen Conference, Global Foundry Industry - Perspectives for the Future, (Z. Zovko Brodarac, N. Dolić, A. Begić Hadžipašić), University of Zagreb Faculty of Metallurgy, 15.-17.05.2017, pp. 115-121.
[18] P. Lava, S. Coppieters, R. Van Hecke, P. Van Houtte and D. Debruyne, Digital image correlation in the classroom: determining stress concentration factors with webcams, http://www.matchid.org/pascal/Articles/plava_classroomfinal2.pdf (25.3.2015)