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STRESS DISTRIBUTION AT DIFFERENT DEFORMATION DEGREES IN LOW CARBON STEEL DURING COLD DEFORMATION

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Abstract:

The temperature change, i.e. stresses of low carbon steel during the cold deformation process was investigated in this study. During static tensile test, temperature changes were examined using thermography at different deformation degrees. It was found that there are temperature changes in the deformation zone during the cold deformation. The increase in temperature changes in the deformation zone during cold deformation occurs with an increase in the deformation degree. The largest localization of temperature change was measured at the moment of the test sample fracture when the maximum temperature change was 8.45 °C. A higher amount of temperature change of 5.39 °C was determined at tensile strength compared to the proportionality limit amount of -0.97 °C. It was found that there are differences between the amounts of temperature changes in the range from 0.87 °C to 1.91 °C *with increasing of deformation degree of the tested steel. Calculated stress amounts proved and show the tendency that stress amounts increase as the temperature change increases in low carbon steel by increasing of deformation degree during cold deformation. It was determined deviations of the calculated stress amounts due to using the mathematical model for low carbon with niobium at the start of plastic flow.*

1 Introduction

Today, thermography finds its application in metallurgical practice during the process of cold deformation for stress determination. Namely, during the plastic deformation process of metallic materials, the temperature of the tested materials increases due to the plastic work performed [1]. Therefore, monitoring the temperature changes during the plastic deformation process is very important for determining the stress distribution and stress changes in the deformation zone during cold deformation [2]. Thermography allows the monitoring of the stress changes and stress distribution at any time during the plastic deformation unlike the conventional static tensile test method. Simultaneously, it is possible to accurately determine the amounts of temperature change at any point of the deformation zone, enabling better characterization of metallic materials [3].

Temperature changes are monitored during deformation in various metallic materials such as low carbon steels [4], stainless steels [5] and aluminium magnesium alloys [6]. Previous research [7] found the temperature rise in thermography during material testing can be related to stresses during plastic deformation. Another research indicates that the temperature change, measured by thermography, showed that it is possible to monitor and determine the temperature change distribution, i.e. stress distribution in low carbon steels with the addition and without microalloying element niobium [8]. In the same research, the possibility of quantifying the amount of temperature change during cold deformation at any point of the deformation zone was determined. It is possible to determine the start of plastic deformation, in materials that have a pronounced

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transition from elastic to plastic area [4] as well as in those that do not have a pronounced transition [9], by monitoring the temperature changes of the tested material. The influence of the testing rate was determined for low carbon steel [10] by monitoring the temperature change using thermography.

The sample preparation, i.e. coating application on the sample surface during monitoring of the temperature change, proved greatly important. In studies [11], the black matt coating proved to be very good and stable during the whole deformation process. At the same time matt coating had a uniform emissivity factor over the entire test surface and did not separate from the surface of the tested sample. The aim of this paper is to determine distribution and differences of temperature changes and calculated stress amounts at different deformation degrees. This research seeks to prove if there exist a tendency of calculated stresses increase with increasing of deformation degree in low carbon steel during cold deformation.

2 Experimental setup

Research of low carbon steel temperature change during cold deformation was carried out on tensile testing machine EU 40 mod with a nominal force value of 400kN. The stretching rate used during the static tensile test was 5 mm/min. The dimensions of the test sample are length 45 mm, width 20 mm and thickness 3 mm. The chemical composition of the tested low carbon steel is shown in Table 1.

Table 1. Chemical composition of low carbon steel (wt%).

Element	C	Mn	Si	P	S	Al
Low carbon steel	0.13	0.77	0.18	0.010	0.019	0.020

Determination of temperature change was performed with an infrared camera JENOPTIK VarioCAM®M82910. The temperature sensitivity of the infrared camera was 80 mK. A black matt coating with an emission factor of 0.95 was used during the thermographic tests.
The strain amounts for stress calculation were determined from images obtained by digital camera Blackfly S Color (FLIR) and measured with the software package MachID 2D.

3 Results and discussion

Firstly, a stress-strain graph was obtained on low carbon steel during cold deformation, Figure 1. From the stress-strain graph it is not possible to measure the stress distribution and stress amounts in random points of the deformation zone during cold deformation.

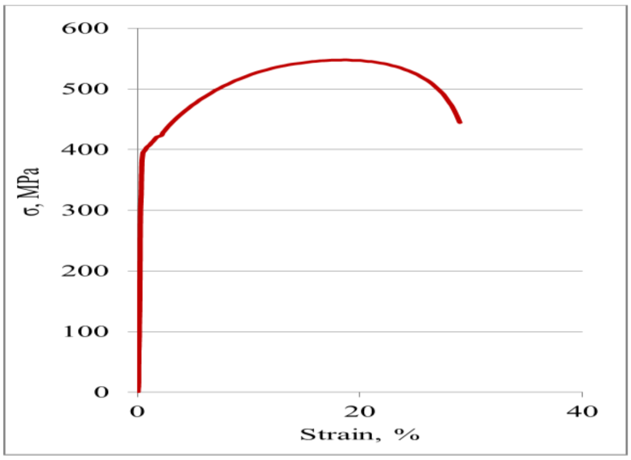

Figure 1. Dependence stress-strain in low carbon steel.

Using an infrared camera, it is possible to monitor the localization and temperature changes, i.e. stress changes at certain points in the deformation zone. Therefore, the thermography was used to determine the temperature changes of low carbon steel during cold deformation. The further behavior of low carbon steel after reaching the start of plastic flow, during cold deformation, is shown in Figure 2. Figure 2 shows the qualitative results of the temperature changes at the start of the plastic flow in low carbon steel. At the moment of reaching the proportionality limit R_p it was found that there were no temperature changes through the deformation zone, Figure 2. This is confirmed by the results obtained in the research [8].

There are significant changes in temperature, i.e. stress changes in the deformation zone of the tested low carbon steel with the progress of plastic deformation and hardening of steel (from point 1 up to the fracture of the test sample). The qualitative results in Figure 2 clearly show the increase in temperature, i.e. stress with increasing of deformation degree from point R_p to the average temperature change reached at the moment of the test sample fracture. The amounts of temperature change, at the moment of reaching the tensile strength R_m, are higher in relation to the temperature changes at the moment of proportionality limit R_p and plastic flow before reaching the tensile strength from point 1 to 3, Figure 2. However, the temperature changes through the deformation zone, at the moment of tensile strength R_m, are lower than the temperature changes at the moment before fracture from point 4 to 5 and at the fracture of the sample. In order to obtain a more accurate insight into the amounts of average temperature changes (ΔT) in the deformation zone, the amounts of temperature changes were quantitatively measured at test points from proportionality limit R_p to the fracture of the sample, determined according to Figure 2. Quantitative values of average temperature changes were taken for all test points, as shown in the Figure 3, through the entire deformation zone at the moment of reaching test point fracture. Quantitative results in the areas of temperature changes (ΔT) in the deformation zone are shown in Figure 4.

The quantitative results of the maximum temperature changes clearly confirmed the qualitatively obtained results. A constant increase in the average temperature changes was determined by the progression of plastic deformation from the point R_p to the fracture of the test sample, Figure 4. It can be seen that the amounts of temperature change (ΔT) during cold deformation are greatest at the moment of the test sample fracture in the area where is determined the greatest temperature change. The maximum temperature change was measured of 8.45 °C at the moment of test sample fracture, Figure 3 and 4. A lower amount of maximum temperature change of 5.39 °C was measured in the deformation zone at the moment of reaching the point tensile strength R_m in relation to the moment of test sample fracture, Figure 4. However, the amount of temperature change (ΔT) is higher in the point of tensile strength R_m in relation to the amount of temperature change at the point of proportionality limit R_p which is -0.97 °C.

The amounts of temperature changes in the area of plastic deformation before reaching the tensile strength R_m, from test points 1 to 3, show higher amounts of temperature changes than the amount at test point R_p. At the same time, they show lower amounts of temperature change than the amount at the test point R_m, Figure 4. In points 4 and 5, by further increasing of deformation, there are higher amounts of temperature changes of 6.67 °C and 7.54 °C, in relation to the test point R_m, Figure 4. However, the amounts of temperature change, obtained for test points 4 and 5, are lower than the amount of the test sample fracture.

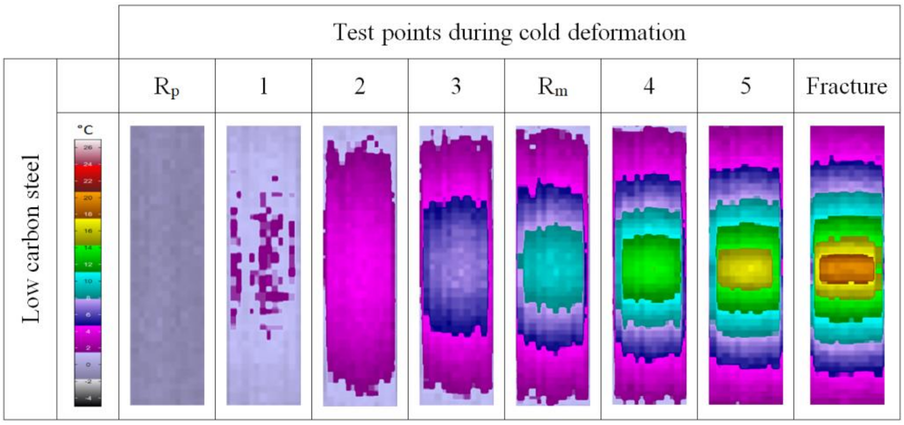

Figure 2. Distribution of temperature changes during plastic deformation in low carbon steel.

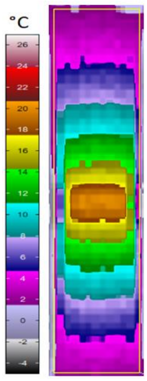

Figure 3. Area of measurement values of the temperature changes in whole deformation zone.

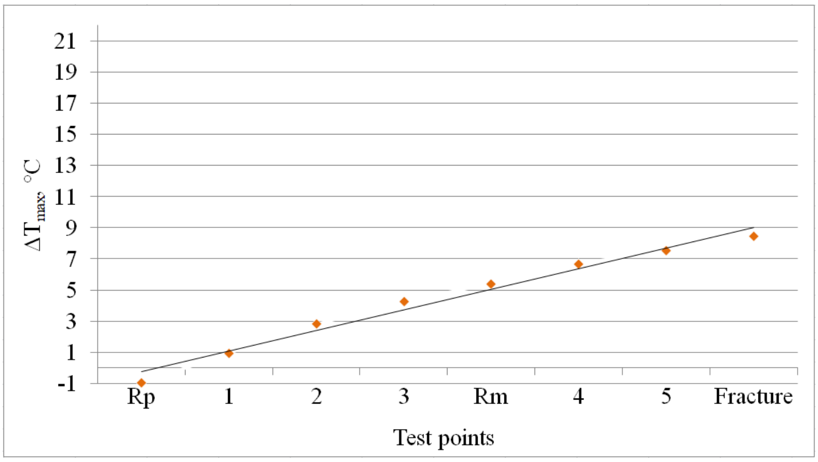

Figure 4. Quantitative results of the maximum temperature changes in the test points of low carbon steel during cold deformation.

It can be concluded, from the qualitative and quantitative results, that in the tested low carbon steel there is an increase in the amounts of temperature changes through the deformation zone with increasing deformation degree from point R_p to the test sample fracture. The obtained results show that the differences of temperature changes (ΔT) between test points during the whole plastic deformation process range from 0.87 °C to 1.91 °C. In order to prove that the temperature changes are related with the stress changes, the stress values were calculated from the measured values of temperature changes.

The test points 3, R_m, 4 and 5 were selected for stress calculation in order to observe stress changes with a significant increase in the deformation degree. Mathematical model from the research [12], obtained at the start of plastic flow on low carbon steel with the addition of 0.048% of the microalloying element niobium, is presented in form of an Equation (1):

$$\sigma = 640.894 - 90.392\Delta T_{max} - 1049.07\varepsilon_{max} - 86.8013\Delta T_{max}^2 - 399310\varepsilon_{max}^2 + 13425.7\Delta T_{max}\varepsilon_{max} \quad (1)$$

where σ is calculated stress, ΔT_{max} is maximum temperature change and ε_{max} is maximum strain.
Equation 1 from research [12] is applied for stress calculation in test points 3, R_m, 4 and 5. Figure 5 shows calculation results of stresses in selected points.

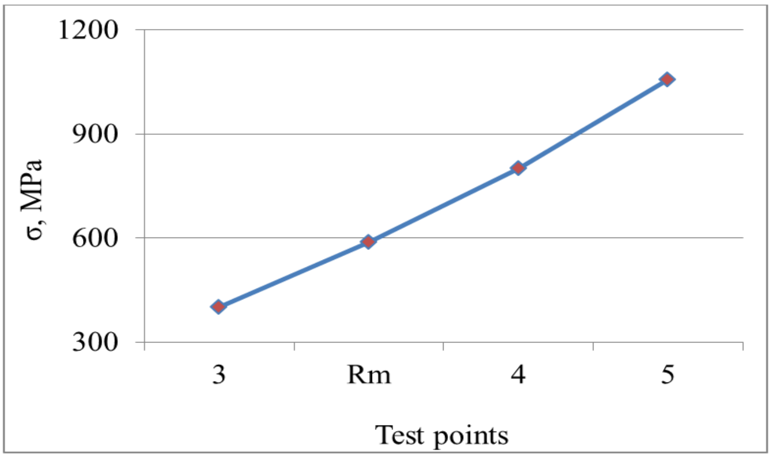

Figure 5. Calculated results of stresses in selected test points 3, R_m, 4 and 5 *in low carbon steel.*

It was proved that the higher stress amounts in the points 4 and 5, 802.08 MPa and 1057.4 MPa, are calculated, which proves that the higher amounts of temperature changes and stresses were achieved in these points at higher deformation degree. The calculated stress amount 588.07 MPa, at the point R_m, is lower than the stress amounts in the points 4 and 5. These results confirm lower amounts of temperature change in the point R_m in relation to the points 4 and 5. The calculated stress amount in point 3 showed significantly lower amount, 401.06 MPa, compared to the points R_m, 4 and 5. The same behavior of the low carbon steel was determined by measuring the temperature changes in points 3 and R_m where the amounts of the temperature changes were lower compared to the temperature changes in points 4 and 5.

The calculated stress amounts obtained by the mathematical model from Equation 1, showed deviations of the obtained results in relation to the results obtained on the stress-strain diagram, Figure 1. These deviations of the calculated stresses were obtained since the calculated stress amounts were obtained using mathematical model for the start of the plastic flow in low carbon steel with the addition of niobium. Since the tests in this research were performed on low carbon steel without niobium during the whole process of plastic deformation until the fracture of the test sample, these deviations were obtained. However, from the obtained calculated results of the stress amounts, it can be concluded that there is a tendency of the stress amounts increase with the increase of the deformation degree and temperature change increase. Future tests will provide appropriate mathematical models for the tested low carbon steel in the area up to the fracture of test sample and it will be possible to obtain good results of the calculated stress amounts which should not show the obtained deviations. It is well known that significant increase in the number of dislocations occur in steel during plastic deformation. Therefore, an increase in temperature change can be associated with an increase in the hardening by deformation degree increase of the tested low carbon steel.

There is an increase of dislocations accumulation which causes higher stresses and consequently a greater temperature changes in the deformation zone of the tested low carbon steel during the increase in the deformation degree. Higher stresses are a consequence of material hardening by the accumulation of dislocations and cause an increase in temperature changes or localization of stresses in a certain part of the deformation zone.

4 Conclusion

It was confirmed that the temperature, i.e. stress changes during cold deformation of low carbon steel increases with increasing of deformation degree. The maximum amount of temperature change in the deformation zone of 8.45 °C was obtained at the moment of the test sample fracture, while the lowest amount of temperature change of -0.97 °C was determined at the point of proportionality limit R_p. Differences in temperature changes (ΔT) between test points during the whole plastic deformation process were obtained in the range from 0.87 °C to 1.91 °C.

The obtained results lead to the conclusion that the stress amounts increase as the temperature changes increase in low carbon steel during cold deformation. It was determined deviations of the calculated stresses in relation to the results obtained on the stress-strain diagram. However, a tendency of increasing the calculated stress amounts with an increasing degree of deformation as well as increasing temperature change has been proven. Future tests with appropriate mathematical models for the tested low carbon steel will enable new results of the calculated stress amounts without large deviations.

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References

[1] Srinivasan, N., Narayanaswamy, R., Venkatraman, B.: *Advanced imaging for early prediction and characterization of zone of Lüders band nucleation associated with pre-yield microstrain*, Materials Science and Engineering: A, 561 (2013), 203-211.

[2] Rešković, S., Jandrlić, I.: *Influence of Niobium on the Beginning of the Plastic Flow of Material during Cold Deformation*, The Scientific World Journal, 2013 (2013), 723725.

[3] Srinivasan, N., Narayanaswamy, R., Venkatraman, B.: *An Insight into Lüders Deformation Using Advanced Imaging Techniques*, Journal of Materials Engineering and Performance, 22 (2013), 10, 3085-3092.

[4] Petit, J., Wagner, D., Ranc, N., Montay, G., François, M.: *Comparison of different techniques for the monitoring of the Lüders bands development*, 13th International Conference on Fracture ICF13, Beijing, China, 2013, 3797-3809.

[5] Venkatraman, B., Mukhophadyay, C.K., Raj, B.: *Prediction of tensile failure of 316 stainless steel using infrared thermography*, Experimental Techniques, 28 (2004), 35-38.

[6] Coër, J., Manach, P.Y., Laurent, H., Oliveira, M.C., Menezes, L.F.: *Piobert-Lüders plateau and Portevin-Le Chatelier effect in an Al-Mg alloy in simple shear*, Mechanics Research Communications, 48 (2013), 1-7.

[7] San Juan, M., Martín, O., Santos, F.J., De Tiedra, P., Daroca, F., López, R.: *Application of thermography to analyse the influence of the deformation speed in the forming process*, Procedia Engineering, 63 (2013), 821-828.

[8] Jandrlić, I., Rešković, S., Brlić, T.: *Distribution of Stress in Deformation Zone of Niobium Microalloyed Steel*, Metals and Materials International, 24 (2018), 4, 746-751.

[9] Kutin, M., Ristić, S., Burzić, Z., Puharić, M.: *Testing the Tensile Features of Steel Specimens by Thermography and Conventional Methods*, Scientific Technical Review, 60 (2010), 1, 66-70.

[10] Wullink, J., Van den Berg, F., Van Liempt, P., De Haas, M.: *Thermography applied to the evaluation of non-uniform deformation heat of metals*, Quantitative InfraRed Thermography Journal, 5 (2008), 1, 69-80.

[11] Lazić, L., Rešković, S., Jandrlić, I., Brlić, T.: *Determination of the emissivity of coatings for preparation of samples in thermographic testings*, Proceedings of the 25th International Conference on Ecological Truth, Vrnjačka Banja, Serbia, 2017, 100-107.

[12] Brlić, T., Rešković, S., Jurković, Z., Janeš, G.: *Mathematical modeling of influence parameters during formation and propagation of the Lüders bands*, Facta Universitatis, Series: Mechanical Engineering, 18 (2020), 4, 595-610. doi: 10.22190/FUME200416041B