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Material Characteristics of Plastic Deformation in High-Strength Steel

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Abstract:

The paper is concerned with material characteristics of plastic deformation, relating to the occurrence and development of plastic deformation, proof stress and strain hardening exponent with changing testing temperature, in high-strength low-alloy steels. The material characteristics of plastic deformation were measured experimentally by means of a tensile test in the temperature range from –80 °C to +100 °C; subsequently, a fractographic analysis of fracture surfaces was carried out in order to evaluate failure mechanisms of the steels studied.

Keywords:

high-strength low-alloy steel, proof stress, strain hardening exponent, fractographic analysis, transcrystalline ductile failure

1. Introduction

The study of material characteristics of plastic deformation under various temperature conditions is of cardinal importance for the evaluation of basic mechanical properties of steels utilised in engineering production. Based on the experiment, the authors of the paper set a goal to enhance the contemporary knowledge of the material characteristics behaviour by the findings on the effects of temperature on the values of the material characteristics in the range of test temperatures –80 °C to +100 °C, which are temperatures not commonly applied in steel testing. The testing temperature has significant influence on the degradation processes in materials, and is thus one of critical factors directly determining the values of the material characteristics measured. High-strength low-alloy steel ARMOX 500T was selected for the experimental testing, as the steel is utilised, for its very high strength and hardness, in industries, where the requirements for materials are dictated by high product service load.

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2. Experimental

High-strength low-alloy steel ARMOX 500T was selected for the evaluation of characteristics of plastic deformation. Chemical composition and basic mechanical properties of the steel are stated in Tab. 1 and Tab. 2, respectively.

Tab. 1 Chemical composition (weight %) of the steel studied (heat no. 074218-445917)

Steel/Element	C	Mn	Si	Cr	Ni	Mo	Al
ARMOX 500T	0.28	0.85	0.26	0.49	0.88	0.345	0.057

Tab. 2 Values of basic mechanical properties of ARMOX steel

Steel/Element	$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]	HBW [Brinell]	*KV –40 °C* [J]
ARMOX 500T	1399	1634	min. 10	533	min. 23

2.1. Tensile Test

Flat test specimens were utilised for tensile tests. The specimens including specified dimensions for high-strength materials are shown in Fig. 1. The tensile test was carried out as per ISO 6892-1 [1] (test method at room temperature) and EN ISO 6892-2 [2] (tensile test at elevated temperature).

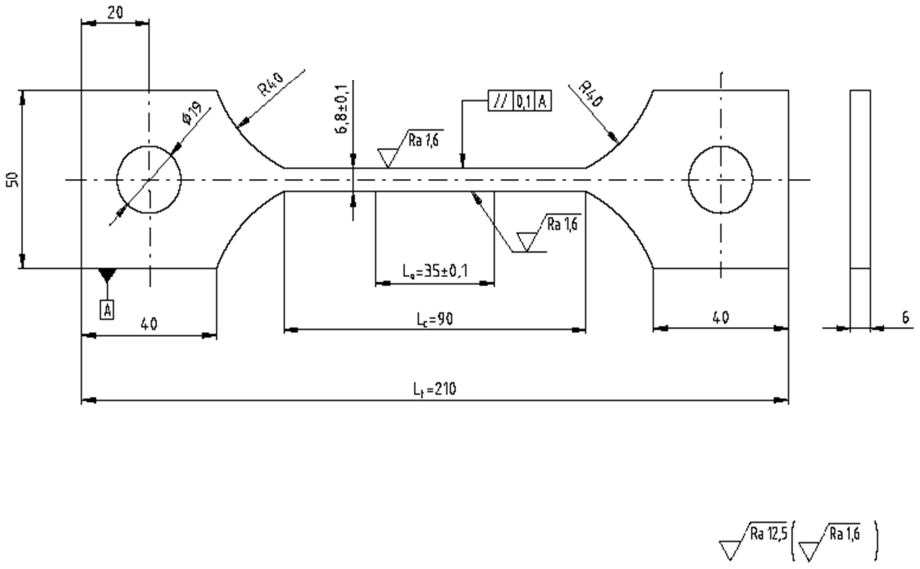

Fig. 1 Drawing of flat test bars

Tensile tests on ARMOX 500T steel specimens were carried out using a universal test machine Zwick at constant crosshead separation rate 2 mm/min. In the elastic area of the tensile test, corresponding stress rate $\dot{\sigma} \approx 60$ MPa s^{-1} and strain rate $\dot{\varepsilon} = 3 \times 10^{-4}$ s^{-1} were applied. The deformation was scanned by extensometer SANDNER EXA 50-5o

with measured length of the extensometer L_e = 50 mm and range 5 mm. During measuring, force F, elongation ΔL_e and time t were recorded. The evaluation of proof stress $R_{p0.2}$ characteristics was carried out by common methods (ISO 6892-1, ISO 6892-2). The strain hardening exponent n was determined using ISO 10275 [3].

2.2. Fractographic Analysis of Fracture Surfaces after a Tensile Test

The fractographic analysis of fracture surfaces was carried out by means of a scanning electron microscope JSM 840 (JEOL); photographs were taken in digital format using TS 12211 (TESCAN) device. The goal of the fractographic analysis of fracture surfaces was to evaluate the effects of testing temperature on the character of fracture surfaces after a tensile test.

3. Results and Discussion of the Results Obtained

Based on the comparison of the results (Fig. 2) for ARMOX 500T steel obtained in the test temperature range –80 °C to +100 °C, changes in measured values $R_{p0.2}$ can be observed at test temperatures –80 °C and –60 °C, if compared to the values read at +20 °C. In ARMOX 500T steel (Fig. 2), the $R_{p0.2}$ values increased at –60 °C (approx. +5 %) and –80 °C (approx. +5.3 %) [4, 5].

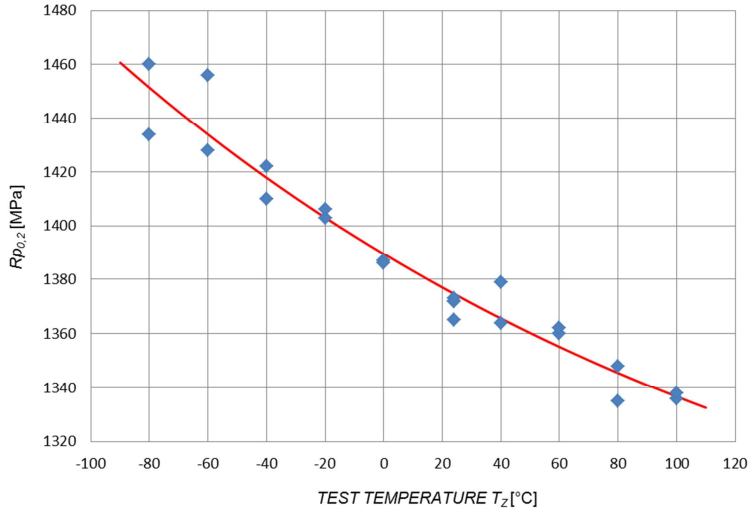

Fig. 2 The effect of the temperature on the proof stress $R_{p0.2}$

The growth of the $R_{p0.2}$ quantity with decreasing test temperatures –60 °C and –80 °C is a consequence of the growth of critical resolved shear stress value with decreasing temperature, in particular in metals with BBC crystal lattice [6].

Experimental results of $R_{p0.2}$ limit determination in dependence on temperature were fitted using Eq. (15) in paper [7] simplified in form

$$R_{p0.2}(t) = \sigma_G + \sigma_0 \exp(-kt) \tag{1}$$

taking into account that only the dependence on test temperature t (not on strain rate) is considered. Least square method performed by MS Excel tool *Solver* led to the values of

regression parameters σ_G = 1237.83 MPa, σ_0 = 151.83 MPa and k = 0.004278 K^{-1}. The fit with determination coefficient 0.948 can be considered as successful.

Rather substantive effect of the test temperature on the values of plastic deformation characteristics was observed in case of strain hardening exponent *n* (Fig. 3), where, based on the comparison of individual results for ARMOX 500T steel, a different course of its values in the temperature range from +60 °C to +100 °C can be seen, in particular as against the area of negative values. In this temperature range, the level increased, if compared to the value obtained at +20 °C, by 11.7 % at +80 °C, and by 25.8 % at +100 °C, whereas in the area of negative temperatures up to –80 °C, the level decreased on average by approx. 11 %.

For fit of temperature dependence of hardening exponent *n* regression function similar to Eq. (1) was used (only increasing exponential function was applied instead of decreasing one)

$$n(t) = n_G + n_0 \exp(ct) \tag{2}$$

with the values of regression parameters n_G = 0.05104, n_0 = 0.00149 and c = 0.02719 K^{-1} and determination coefficient 0.919.

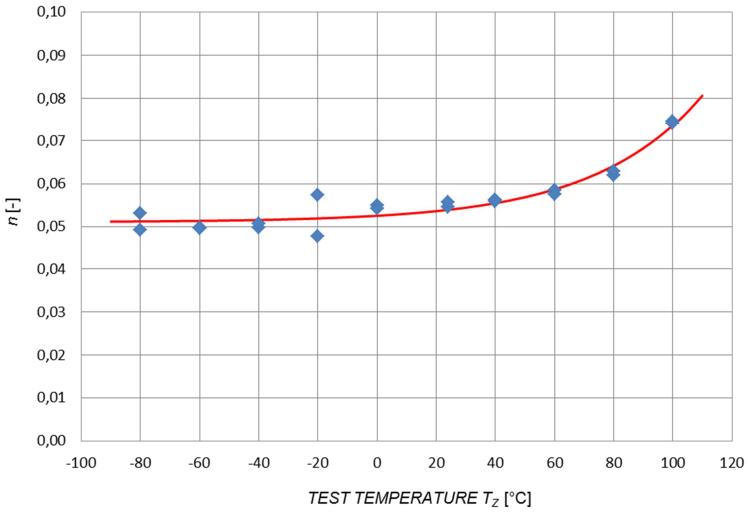

Fig. 3 Temperature dependence of the hardening exponent

The value of hardening exponent *n* can be, based on classical approximations of the theory of plasticity, correlated for uniaxial tension loading to the value of maximum uniform deformation A_g at the moment of plastic instability origin. This also corresponds with the point of reaching the maximum force in the tensile diagram and the occurrence of three-dimensional stress, resulting in the formation of a “neck” on the test bar. This situation is a consequence of the “saturation” of dislocation substructure, and can be connected with another very difficult realization of plastic deformation mechanisms, with the occurrence of cohesion failures in initiation centres, mostly accompanied by the occurrence of inclusions [8].

This rather substantive increase of the hardening exponent value in the area of temperatures above +60 °C thus suggests corresponding increase of the “critical” amount of uniform, i.e. stable deformation. This can be caused by thermal activation of the

recovery (softening) submicrostructural processes, which is not a common phenomenon at these relatively low temperatures.

3.1. Fractographic Analysis

The effect of testing temperature, at which the failure mechanism may change and thus affect material characteristics of plastic deformation after a tensile test, was determined on specimens after a tensile test by means of a fractographic analysis.

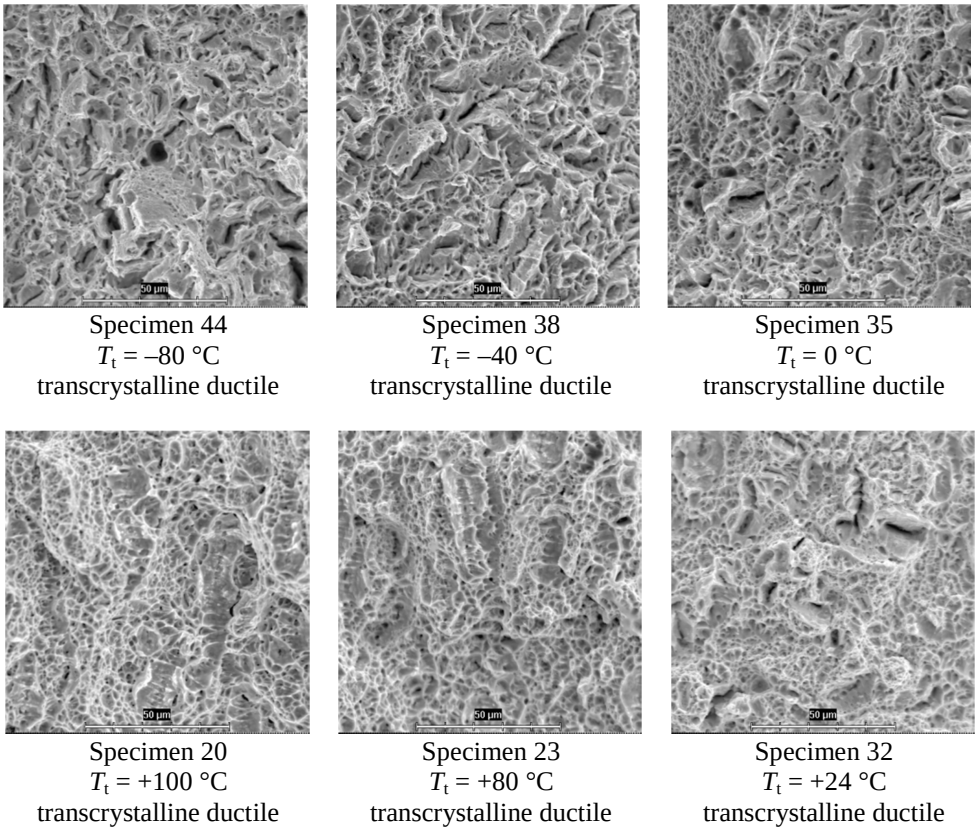

Fig. 4 Morphology of ARMOX 500T steel fracture surface

The results of the fractographic analysis carried out on ARMOX 500T specimens after the tensile test over the entire range of test temperatures from –80 °C to +100 °C proved that the failure mechanism is of transcrystalline ductile type with very fine dimple morphology without substantive variation at individual temperatures. Also, there are secondary cracks in the fracture surfaces, which are perpendicular to the fracture plane. The cracks were created by a shear mechanism, as could be deduced from the appearance of areas around individual secondary cracks. These are the surfaces created by the opening of secondary cracks in the fracture area as a result of three-dimensional deformation in the stage of final failure in the process of plastic instability [9].

The number of these secondary cracks changes considerably with the temperature. The proportion of secondary cracks can be expressed by the sum of their length l in a square-shaped unit u having the area of 100 μm^2:

$$p = \frac{l}{u} \quad \frac{[\mu\text{m}]}{[100\,\mu\text{m}^2]} = [10^{-2}\ \mu\text{m}^{-1}] \tag{3}$$

and can be called *crack density*.

The value of this proportion depends, in case of fractographically evaluated fractures, on temperature; the course of the strong relation is shown in Fig. 5 and proves growing plasticity of steel matrix of low-tempered martensite, or bainite with growing temperature in the range from –80 °C to +80 °C. At this temperature as well as at +100 °C, secondary cracks only occur sporadically.

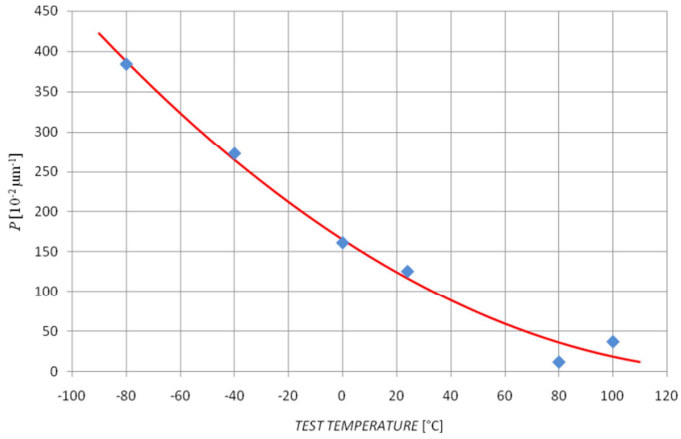

Fig. 5 Proportion of secondary cracks in relation to temperature

For the fit of this dependence no suitable published regression function was found and also the fit using regression function (1) was not successful. Therefore, the simplest phenomenological function was used – parabola with the peak on temperature axis, which can be expressed as

$$\rho(t) = a\,(t-b)^2\,. \tag{4}$$

Regression calculations led to the values of regression parameters a = 0.007298 μm/100 μm^2/K^2 and b = 150.7 °C. The value of determination coefficient 0.989 indicates very good fit of experimental data.

4. Conclusion

The paper states the results of measuring material characteristics of plastic deformation obtained in the temperature range –80 °C to +100 °C from ARMOX 500T low-alloy steel. The experiment was followed by a fractographic analysis of fracture surfaces for the purpose of evaluation of the testing temperature effect on failure mechanisms having direct influence on material characteristics. The results obtained from the experimental data can be summarized as follows:

- the decrease of the test temperature below 0 °C resulted in the increase of proof stress, which can be explained by the increase of the critical resolved shear stress for the beginning of the plastic deformation;

- the substantive effect of temperature on the development of plastic deformation was identified by determining the strain hardening exponent *n*; rather substantive increase of *n* was proved at temperatures +80 °C and +100 °C, if compared to the value determined at test temperature +24 °C. This phenomenon can result from the occurrence of recovery softening processes;
- transcrystalline ductile failure mechanism was proved on fracture surfaces after a tensile test on ARMOX 500T steel in the temperature range from –80 °C to +100 °C;
- plastic properties of the microstructural steel matrix formed by low-tempered martensite and bainite depend substantively on the test temperature. The low plasticity results, in the area of negative values, in the occurrence of a considerable number of secondary cracks. If they occur even before reaching the point of instability, characterised by the level of stress R_m, their proportion can also affect the strain hardening exponent value.

Acknowledgements

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References

[1] ISO 6892-1:2009 *Metallic Materials – Tensile Testing – Part 1: Method of Test at Room Temperature*.

[2] ISO 6892-2:2011 *Metallic Materials – Tensile Testing – Part 2: Method of Test at Elevated Temperature*.

[3] ISO 10275:2007 *Metallic Materials – Sheet and Strip – Determination of Tensile Strain Hardening Exponent*.

[4] ZAKI FARAHAT, AI., EL-BITAR, T. and EL-SHENAWY, E. Austenitic stainless steel bearing Nb compositional and plastic deformation effects. *Mater. Sci. Eng. A.*, 2008, vol. 492, no. 1-2, p. 161-167.

[5] SURESH, MR. et al. Study of welding characteristics of 0.3C-CrMoV(ESR) ultrahigh strength steel. *J. Mater. Sci.*, 2007, vol. 42, no. 14, p. 5602-5612.

[6] MIAO C. et. al. Effect of Strain Rate on the Deformation-Induced Martensite Transformation and Mechanical Behavior of Austenitic Stainless Steel for Cold Stretched Pressure Vessels. In *ASME 2010 Pressure Vessels and Piping Division/K-PVP Conference*, vol. 1, p. 737-742. ISBN 978-0-7918-4920-0.

[7] KOHOUT, J. and HRUBÝ, V. Mutual reciprocal interconnection of relations describing creep, yield stress and stress relaxation. *Komunikácie* (*Communications*), 2010, no. 4, p. 40-44. ISSN 1335-4205.

[8] MA, L. et. al. Nonlinear Analysis of Pressure Strengthening for Austenitic Stainless Steel Pressure Vessel. In *ASME 2008 Pressure Vessels and Piping Conference*, vol. 3 (Design and Analysis), p. 493-498. ISBN 978-0-7918-4826-5.

[9] DYJA, D., STRADOMSKI, Z. and PIREK, A. Microstructural and Fracture Analysis of Aged Cast Duplex Steel. *Strength of Materials*, 2008, vol. 40, no. 1, p. 122-125.