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INFLUENCE OF THE STRAIN RATE ON THE NOTCH TOUGHNESS OF COLD-FORMING STEELS

The paper analyses the influence of the strain rate with loading rates of 1.7.10^{-5} – 4.8 m.s^{-1} on the notch toughness of hot-rolled microalloyed steels S 315 MC and S 460 MC and cold-rolled deep-drawing steels DC 06, H 220 B and H 220 P. It discusses a possibility of utilising a modified notched-bar impact test to predict the formability of these steels at high strain rates of thin steel sheets.

Key words: *notch toughness, strain rate, microalloyed steel, drawing steel*

1. Introduction

The influence of the strain rate in the forming process can be formulated in such a way that the resistance of metal against dislocation movement increases with an increasing strain rate, which has an impact on an increase in the yield point, the tensile strength, a change in the deformation characteristics, etc. A localization of plastic deformation can occur and at higher strain rates the whole process assumes an adiabatic character [1]. The influence of the strain rate on the strength and deformation characteristics is significantly influenced by the structure of metallic material.

The notched-bar impact test is one of the simplest tests making it possible to assess the behaviour of materials under the dynamic loading conditions and expressing the active fracture resistance in a narrow zone of the tested cross-section [1, 2]. Its disadvantage consists in the fact that it does not make it possible to obtain absolute values of material toughness that would characterize the fracture resistance. The notch toughness is influenced by the size and shape of the notch of the test bar, while their influence on the notch toughness depends on the internal structure of material. Nowadays, the test is usually made using standard tests bars with the dimensions of 10 × 10 × 55 mm and with the V notch with the depth of 2 mm, the diameter $r = 0.25$ mm and the angle of 45°. Even though there are more exact tests to determine material fracture resistance [1, 2], the notched-bar impact test is the most used one in practice for its simplicity. Its application to testing the notch toughness of semi-products and products from which standard test bars cannot be made necessitated studying the influence of the test bar thickness, the notch shape, the specimen dimensions, as well as the loading rate, etc. on the characteristics that can be obtained using the notched-bar impact test [3, 4, 5, 6, 7].

The goal of this paper is to analyse the influence of the loading rate on the notch toughness of cold-forming steels with higher tensile strength values and, based on this analysis, to assess a possibility of utilizing the notched-bar impact test to predict their formability at increased strain rates, which is necessitated by the practice at present.

2. Experiments and their analysis

The experiments were made on hot-rolled micro-alloyed steels S 315 MC and S 460 MC with the thickness of 8 mm and on cold-rolled deep-drawing steels DC 06, H 220 B and H 220 P with the thickness of 0.8 and 1 mm.

Basic mechanical properties and characteristic of tested steels — Table 1

Steel	Thickness [mm]	R_e ($R_{p0.2}$) [MPa]	R_m [MPa]	A_5 [%]	Z [%]	Characteristic of steel
S 315 MC	8.0	390	477	38	80	Micro-alloyed steel C = 0.05 %, Nb = 0.042 %, thermomechanically rolled, suitable for cold rolling
S 460 MC	8.0	537	625	30	76	Micro-alloyed steel C = 0.07 %, Nb = 0.052 %, V = 0.082 % thermomechanically rolled, suitable for cold rolling
DC 06	0.8	145	283	45	–	C < 0.015 % recrystallization annealed, extra deep-drawing
H 220 B	1.0	224	347	36	–	C < 0.06 % drawing steel, hardened during paint baking
H 220 P	1.0	250	369	31	–	C < 0.06 %, P < 0.08 %, drawing steel with increased dent resistance

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The basic mechanical properties and characteristic of the tested steels are given in Table 1.

From the strips of the tested steels, materials were taken in the rolling direction and the following test bars were made: from steels S 315 MC and S 460 MC – with the dimensions of 10 × 8 × × 55 mm and the V notch with the depth of 2 mm, and from steels DC 06, H 220 B and H 220 P – with the dimensions 8 × (sheet thickness) × 28 mm and the V notch with the depth of 4 mm. The shape and dimensions of these test bars were based on obtained practical knowledge.

The notched-bar impact test was made at two or three loading rates on different testing machines given in Table 2.

Loading rates and used notched-bar testing machines Table 2

Loading rate v [m.s^{-1}]	Strain rate $\dot{\varepsilon}$ [s^{-1}]	Used machines
$v_1 = 1.7.10^{-5}$	$1.1.10^{-3}$	Tensile testing machine ZD 100/I + fixture
$v_2 = 5.10^{-2}$	3.3	Fatigue testing machine INSTRON 8511 + fixture
$v_3 = 4.8$	$3.2.10^2$	Pendulum impact testing machine PSWO 1000

The required test bar failure energy at the loading rates (v_1 and v_2) was evaluated by planimetring the area of the force F – deflection diagram.

Fig. 1 shows the influence of the loading rate (v) during the notched-bar test on the *KCV* values at 20 °C. It results from Fig. 1 that the *KCV* values of steels S ... MC are significantly higher than that of the other tested steels, during both the static loading (v_1) and the impact loading (v_3). This is, besides different mechanical values, due to different dimensions of the test bars, which has a significant influence on the *KCV* value.

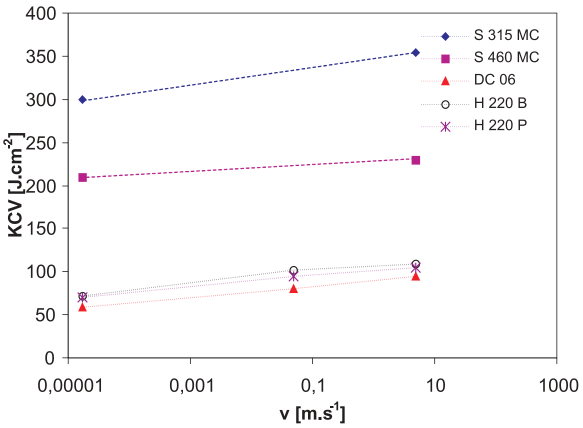

Fig. 1. Relationship between KCV and loading rate of tested steels

The evaluation of the influence of the property (structure) of the tested steels on the loading rate can be made e.g. using the following relationship

$$KCV_{v3} = k \,.\, KCV_{v1} \qquad (1)$$

where KCV_{v3} is the notch toughness at the loading rate $v_3 =$ $= 4.8$ m.s^{-1}, KCV_{v1} is the notch toughness at the loading rate $v_1 = 1.7.10^{-5}$ m.s^{-1} and k is a material constant expressing the sensitivity of steel to the change of the loading rate.

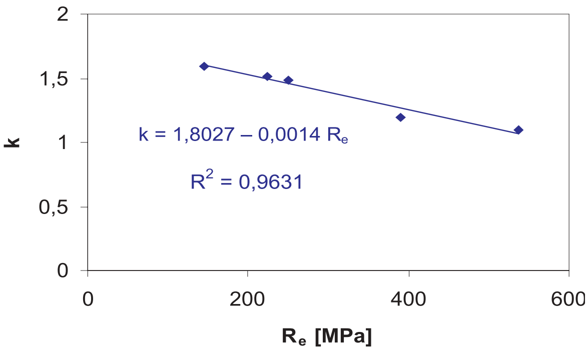

Fig. 2. Relationship between the constant of material sensitivity to the loading rate change from 1.7.10^{-5} to 4.8 m.s^{-1} and the yieald point R_e of tested steels

Fig. 2 shows the relationship between the k constant and the yield point of the tested steels, demonstrating that the higher yield point of steel the less sensitivity of steel to the strain rate. The yield point can be considered as a macroscopic structural characteristic. The matrix of all the tested steels is ferritic. The increase in the yield point of H 220 B and H 220 P steels is due to the BH effect and the phosphorus content, and that of S 315 MC and S 460 MC steels is due to fine grains and precipitation hardening. This means that the more dislocation movement obstructions in the steel structure the less sensitivity of steel to the strain rate [1, 8, 9, 10, 11]. For the tested steels, the material constant k can be analytically expressed using the following parametric equation

$$k = A - B \,.\, R_e \qquad (2)$$

For the tested steels, the constant $A = 1.8027$ and the constant $B = 0.0014$.

For S 315 MC and S 460 MC steels, a temperature dependence of the notch toughness was constructed for the static loading ($v_1 = 1.7.10^{-5}$ m.s^{-1}) and the impact loading ($v_3 = 4.8$ m.s^{-1}). The results are shown in Fig. 3 and Fig. 4. It results from the figures that at the static loading the *KCV* values in the super-transitional area are lower than at the impact loading, and the transitional temperature at the static loading is also lower. If we take the temperature at which KCVmax decreases by its half (T50) as the transitional temperature, this temperature at the static loading is 41 °C lower than at the impact loading for S 315 MC steel and as few as 19 °C lower for S 460 MC steel (see Fig. 3 and Fig. 4). The results are in accordance with literature knowledge [1] that with an increasing strain rate the susceptibility of metals to brittle failure increases and that the sensitivity to the strain rate under the same external conditions is a function of the structure.

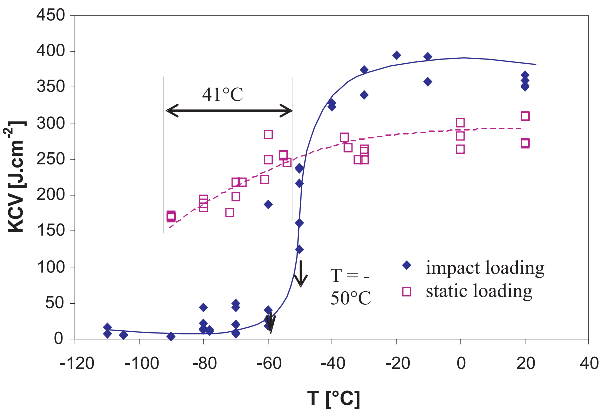

Fig. 3. Temperature dependence of KCV S 315 MC steel

It resulted from the experiments and their analysis that the notched-bar impact test can also be made, while meeting certain conditions, on thin steel sheets applied in the automotive industry. The notch toughness values in the super-transitional area are higher at a higher rate and this increase is a function of the structure, whose macroscopic characteristic is the yield point. With an increasing strain rate, the susceptibility of the tested steels to brittle failure (unstable crack propagation) increases.

The above-mentioned conclusions enable us to assume that a modified notched-bar test can serve to predict the formability of drawing steels at increased strain rates. With an increasing strain rate, the strain work increases, in dependence on the strength characteristics of steel ($k = A - B \, . \, R_e$). If the notch toughness at the required strain rate v_x (KCV_x) is higher that at the static strain rate v_s (KCV_s), at this strain rate the formability of steel sheet can be assessed according to traditional formability criteria. In case that KCV_x is less than KCV_s, at the strain rate v_x there is a risk of plastic instability and, as a result, a local failure. Such a condition may occur for example in S 315 MC steel at the temperature of -50 °C (see Fig. 3), but also when the critical strain rate is exceeded, where the relationship $KCV_x = k \, . \, KCV_s$ does not apply and where there is a risk of sudden fracture.

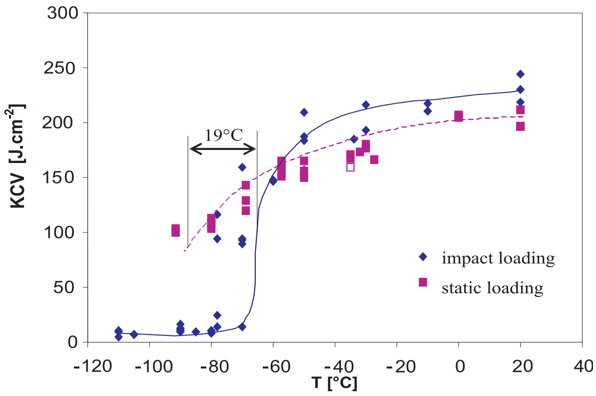

Fig. 4. Temperature dependence of KCV S 460 MC steel

3. Conclusion

The paper analyses, based on the experiments, the influence of the loading rate on the notch toughness of hot rolled microalloyed steels suitable for cold working (S 315 MC and S 460 MC) and cold rolled drawing steels (DC 06, H 220 B and H 220 P). Possibilities of utilizing the notched-bar impact test results to assess the formability of steels at higher strain rates are also discussed. It results from the analysis that:

- the notched-bar impact test can also be applied to thin sheets (~ 1 mm), but the test bar shape must meet certain conditions, in particular the bar height to the notch depth ratio,
- in the super-transitional area, the notch toughness increases with an increased loading rate in the interval from $1.7.10^{-5}$ to 4.8 m.s^{-1}, while this increase rate is a function of the structure of the tested steel,
- with an increasing loading rate, a risk of unstable crack propagation increases (the transitional temperature increases),
- a modified notched-bar impact test can serve to predict the formability of steel sheets at increased strain rates, mainly as regards the prediction of the strain resistance, the loss of plastic stability and a possibility of using traditional formability criteria at increased strain rates; standardized tests of deep-drawing properties of steel sheets are practically static ($\dot{\varepsilon} \approx 10^{-3} s^{-1}$), however, in the technical practice steel sheets are processed at rates of as many as 1 – 10 s^{-1}.

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