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NEW APPROACH TO EVALUATION OF FORMABILITY OF HIGHER-STRENGTH STEEL STRIPS

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The paper analyses the material characteristics of deep-drawability of steel sheets with the thickness from 1 to 1,8 mm, the yield point above 330 MPa and the loading rate up to 150 m/min. The analysis resulted in the finding that with the loading rate up to ca 10 m/min the formability characteristics slightly increase and after exceeding this value these characteristics significantly decrease. In practice, the strain rates are below 1 s^{-1}, therefore the material characteristics determined using standard tests can be used to determine the limit states up to the above-mentioned rate.

Key words: *higher-strength steel, strips, formability, strain rate, mechanical properties*

Novi pristup prosudbi oblikovanja čeličnih traka povišenih čvrstoća. Članak analizira karakteristike duboko vučenih čeličnih traka debljine 1 do 1,8 mm s granicom razvlačenja iznad 330 MPa u rasponu brzine deformacije do 150m/min. Istraživanje je pokazalo da kod brzine deformacije 10 m/min dolazi do povećanja karakteristika oblikovanja, a po prekoračenju te brzine se vrijednosti snižavaju. U praksi dosegnute brzine deformacije su ispod 1 s^{-1}, a tada karakteristike materijala istražene normiranim probama mogu biti rabljene za ustrojstvo granice razvlačenja i brzine.

Ključne riječi: *visoko čvrst čelik, trake, oblikovanje, brzina deformacije, mehanička svojstva*

INTRODUCTION

The cold formability of sheets is defined as the ability of material to continuously change its shape and dimensions due to an action of external forces without its failure under particular conditions. The formability of materials is influenced by all factors participating in the forming process, namely the sheet material, the product type, the tool and the production technology. The formability (pressability) of steel sheets is mostly evaluated according to their behaviour during the tensile test. As the pressability criterion, the yield point, the tensile strength R_m, the elongation A, the uniform deformation A_g and the strain hardening exponent n are used, as well as other criteria derived from them, such as R_e/R_m, $(R_e/R_m)\cdot A$, etc. These criteria only apply to material and to the uniaxial scheme of main stress. The pressability of sheets under particular conditions is evaluated using technological tests, such as the cupping test. In this test, the formability criterion is the depth at which a crack is formed when a pushing a punch with a spherical end of a prescribed radius into the sheet, so-called Erichsen number IE, but also the appearance of the impressed spherical cap [2].

The material characteristics of steel sheet in the forming process are also significantly influenced by external factors. The strain rate is a significant external factor and the intensity of its influence on the behaviour of material during the forming process, and hence on the material characteristics, is a function of its internal structure [3, 4]. With increasing the strain rate, the critical slip stress increases, the yield point intensively increases, the tensile strength increases and the material strain characteristics change [5, 6]. As a result, the values of formability criteria derived from these characteristics also change. One of possibilities to increase the productivity during cold forming consists in increasing the forming (pressing) rate. Therefore it is necessary to know the behaviour of material in the forming process at increased rates, as well as its material characteristics. Measuring the material characteristics using the tensile test at high strain rates is very difficult and therefore possibilities are looked for to evaluate material characteristics using modified tests [6 - 8].

The paper is aimed at analysing the influence of the loading (strain) rate on the material characteristics and the formability of automotive surface-treated thin steel sheets.

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MATERIAL AND EXPERIMENTAL METHODS

The experiments were made on samples taken from steel strips produced by cod forming and then hot dip galvanized, grades H340LAD and H380LAD, intended for production of heavy-loaded pressings in the automotive industry. The chemical composition of tested steels is shown in Table 1.

Table 1. **Chemical composition of tested steels / %**
Tablica 1. **Kemijski sastav ispitanih čelika / %**

Steel grade	C_{max}	Si_{max}	Mn_{max}	P_{max}	S_{max}	Al_{max}	Ti_{max}	Nb_{max}	V_{max}
H340LAD	0,08	0,04	1,0	0,025	0,010	0,015	0,10	0,08	0,10
H380LAD	0,10	0,04	1,40	0,025	0,010	0,015	0,15	0,09	0,10

The microstructure of tested steel sheets is polyedric, ferritic, with a small share of fine pearlitic grains, precipitated at the boundaries of ferritic grains (Figure 1.).

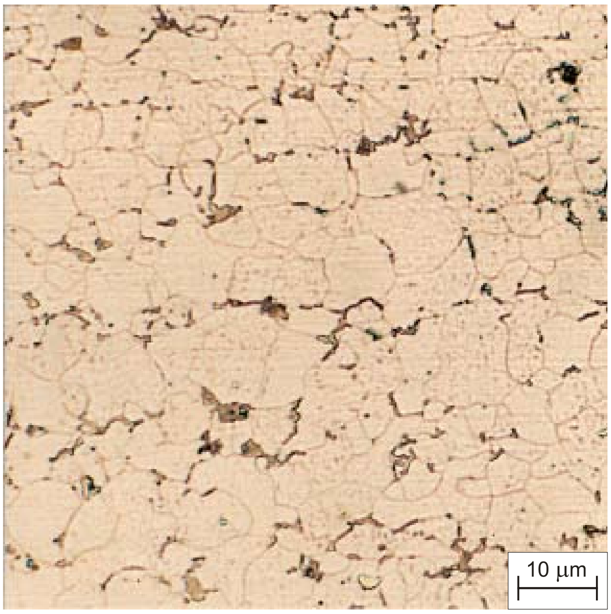

Figure 1. **Microstructure of steel strip H340LAD**
Slika 1. **Mikrostruktura čelika H340LAD**

Of the steel strips H340LAD thick 1,0; 1,5; 1,8 mm and the steel strip H380LAD thick 1,5 mm, samples were taken in the rolling direction, then flat tensile test bars with the width of 10 mm were made, as well as strips with the width of 90 mm for the cupping test were made. The tensile test was made on a tensile testing machine INSTRON 1185 with a maximum loading rate of 1 mm/min. By changing the measured length of the test bar and the loading rate in the tensile test, the test could be made at the strain rate up to 8,3 s^{-1} (which corresponds to the loading rate of 30 m/min).

The cupping test was made on the tested sheets according to STN 42 0406 Standard and also as a modified test at strain rates from 0,2 to 150 m/min. The modified cupping test was made using a fixture, whose dimensions of the spherical punch and the die were the same as for the cupping test instrument, on the tensile test machine INSTRON 1185 and on the drop tester.

In the tensile tests and the cupping tests, the force-elongation diagrams or the force-depth diagrams were recorded using PC, from which material characteristics were determined, including energy necessary for creating the impression in the cupping test.

ACHIEVED RESULTS AND THEIR ANALYSIS

The influence of the loading rate on the basic mechanical properties of steel sheet H340LAD, thick 1 mm, is documented in Figure 2. and Figure 3. In accordance with literature knowledge [3, 4], with increasing the strain rate the resistance of tested steel against plastic deformation increases.

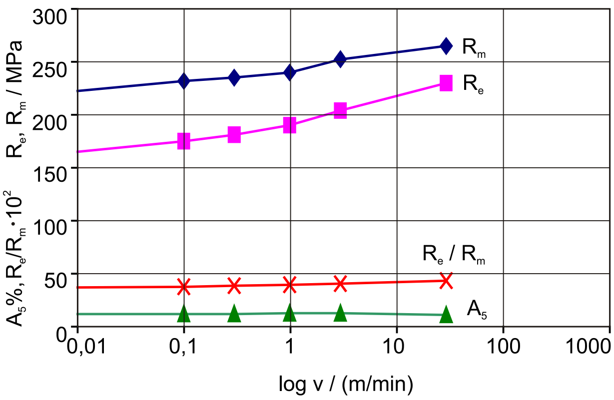

Figure 2. **Influence of the loading rate (*v*) on the yield point (R_e) and the tensile strength (R_m) and elongation A_5 of steel strip H340LAD, thick 1 mm**
Slika 2. **Utjecaj brzine deformacije (*v*) na granicu razvlačenja (R_e), vlačnu čvrstoću (R_m) i istezanjanje A_5 čeličnih traka H340LAD debljine 1 mm**

In the given loading rate interval from 0,01 to 30 m/min, the influence of the loading rate on the yield point (R_e) and the tensile strength (R_m) can be described using the following parametric equation

$$R_v = R_{v_0} + \log \frac{v}{v_0},$$

where:

R_v - the yield point (tensile strength) at the loading rate v,

R_{v_0} - the yield point (tensile strength) at the loading rate v_0 = 0,01 m/min.,

k - a material constant, whose value at R_e is higher than at R_m.

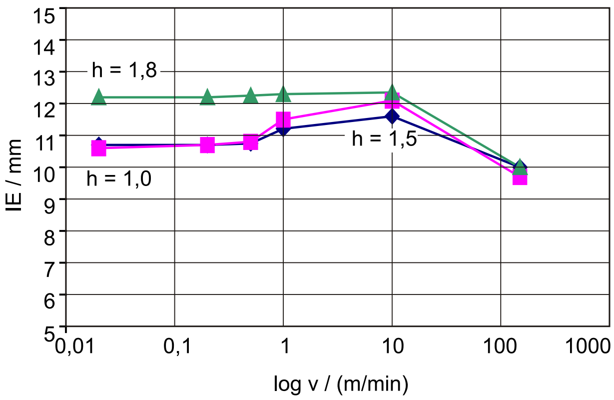

Figure 3. **Influence of the loading rate (*v*) on the elongation (A_5) and the R_e/R_m ratio of steel strip H340LAD, thick 1,0; 1,5 and 1,8 mm**

Slika 3. **Utjecaj brzine deformacije (*v*) na istezanje A_5 i odnos R_e/R_m čeličnih traka H340LAD debljine 1,0; 1,5 i 1,8 mm**

It results from the mentioned that with increasing the loading rate the R_e/R_m ratio increases, which is also documented by the measured values (Figure 3.). In fact, the elongation A_5 does not change up to the strain rate of 3 m/min, and it slightly decreases at the loading rate of as many as 30 m/min. Similar relationships were also measured on the strip thickness of 1,5 and 1,8 mm.

The results of the influence of the loading rate on the material characteristics, determined using the cupping test, are documented in Figure 4. and Figure 5. It results from the measured characteristics that the depth at which a crack is formed, IE (Erichsen number), increases with increasing the

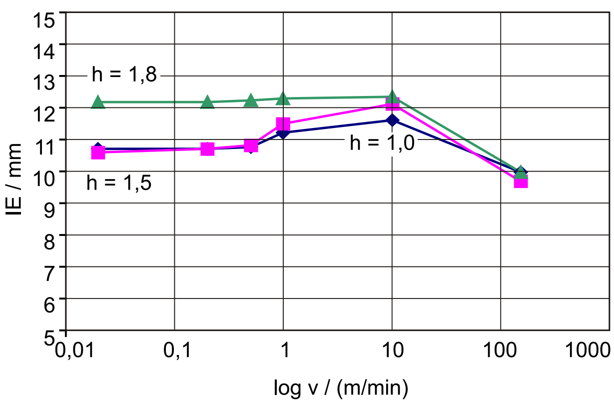

Figure 4. **Influence of the loading rate (v) on Erichsen number (IE) of steel strips H340LAD thick 1,0; 1,5 and 1,8 mm**

Slika 4. **Utjecaj brzine deformacije (*v*) na Erichsenov broj (IE) čeličnih traka H340LAD debljine 1,0; 1,5 i 1,8 mm**

loading rate up to 10 m/min and at the loading rate of 150 m/min it significantly decreases (Figure 4.). The same relationship was also determined between the loading rate and the energy necessary for creating the impression at the moment of crack formation *E* (Figure 5.). With increasing the sheet

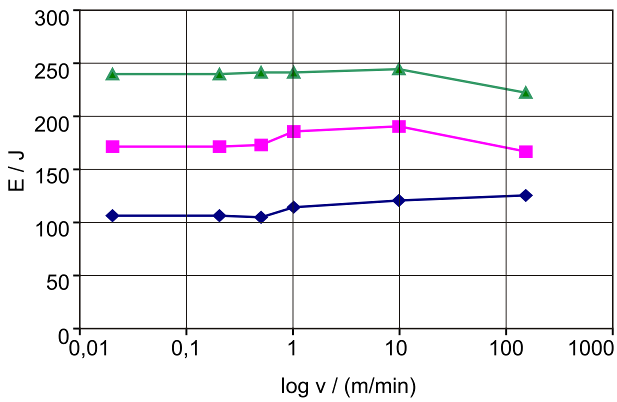

Figure 5. **Influence of the loading rate (*v*) on the deformation resistance (*E*) of steel strips H340LAD, thick 1,0; 1,5 and 1,8 mm**

Slika 5. **Utjecaj brzine deformacije (*v*) na deformacijski otpor (*E*) čeličnih traka H340LAD debljine 1,0; 1,5 i 1,8 mm**

thickness, the IE and *E* values increase. Similar relationships were also determined for the steel strip H380LAD, which has R_e = 395 MPa and R_m = 447 MPa (Figure 6.).

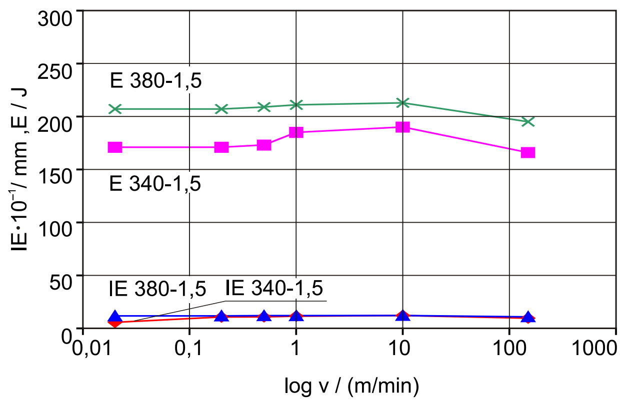

Figure 6. **Influence of the loading rate (*v*) on Erichsen number (IE) and the deformation resistance (*E*) of steel strips H340LAD and H380LAD, thick 1,5 mm**

Slika 6. **Utjecaj brzine deformacije (*v*) na Erichsenov broj (IE) i deformacijski otpor (*E*) čeličnih traka H340LAD debljine 1,5 mm**

The results of the influence of the loading rate on the material characteristics determined using the cupping test indicate that up to the loading rate of 10 m/min the IE value increase, as well as the natural deformation resistance *E* increases. At the impact loading (150 m/min), the deep-drawability of the tested sheets decreases and the nature of the failure during the cupping test also changes. During impact loading, a crack is not formed along the contour line, but in the direction parallel to the sheet plane, as documented by Figure 7., which indicates that the sheet is unsuitable for deep drawing.

Figure 7. **The crack shape in the cupping test, at the loading rate: a) $v = 0{,}01$ m/min; b) $v = 150$ m/min**

Slika 7. **Oblik pukotine pri probi po Erichsenu, pri brzini deformacije: a) $v = 0{,}01$ m/min; b) $v = 150$ m/min**

The R_e/R_m ratio is one of material characteristics controlling the deep-drawing process. For common deep-drawing steels, this ratio is 0,6. Apparently, besides the R_e/R_m ratio, the R_m–R_e difference also plays a significant role, which can eliminate, in a complex sense, material non-homogeneities. The sheets tested under static loading (0,02 m/min) had R_e/R_m = 0,74. With increasing the loading rate, this ratio increased. The cupping tests showed that after exceeding the loading rate of 10 m/min deep drawability significantly decreased. It results from comparison of the results of the tensile test (Figure 3.) and the cupping test (Figure 4.) that after reaching R_e/R_m > 0,82, which the tested steel sheets reach at the loading rate v > 3 m/min, deep-drawability decreases. The achieved results are in accordance with the results achieved in the modified notch toughness tests [8].

CONCLUSION

The paper analyses the influence of the loading rate on formability (deep drawability) of sheets made of micro-alloyed steels with higher strength properties. Based on the results of the tensile test at the loading rate from 0,01 to 30 m/min and the cupping test at the loading rate from 0,02 to 150 m/min for the tested steels H340LAD and H380LAD, the following can be stated:

- with increasing the loading rate up to ca 10 m/min, the material deep-drawing characteristics do not worse. These characteristics slightly increase, but the deformation resistance also increases.
- by shifting to impact loading (v > 10 m/min), the elongation and Erichsen number decrease, while the nature of the failure during the cupping test also changes. The cracks do not have a contour line shape any more.
- the limit state characterizing the decrease of formability due to increasing the loading rate can be evaluated on the basis of the value of the R_e/R_m ratio. For the tested sheets, this ratio is ca 0,82.

In technical practice, maximum cold forming rates are below 1 s^{-1}, which, in the tensile test made here, corresponds to the loading rate v = 4 m/min. It results from the above-mentioned that the material characteristics of cold formability determined under static conditions according to applicable standards are sufficient for evaluation of the limit state in practice.

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