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THE INFLUENCE OF THE LOADING RATE ON THE NOTCH TOUGHNESS OF LIGHT-GAUGE DRAWN STEEL SHEETS

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The paper assesses a possibility of implementing the notch toughness test on drawing sheets with the gauge up to 1 mm, the influence of the loading rate on the results, as well as a possibility of using this test to evaluate formability. Experiments were made on drawing steel sheets with a yield point from 145 to 250 MPa; the notch toughness test was made with the loading rates $v_1 = 1.7 \cdot 10^{-5}$ ms^{-1}, $v_2 = 5 \cdot 10^{-2}$ ms^{-1} and $v_3 = 4.8$ ms^{-1}. The tests have shown that reproducible results can be achieved on light-gauge drawing sheets under defined conditions. The notch toughness values, as well as the force and deformation characteristics obtained in the notch toughness test can be used to supplement and make more exact the traditional characteristics in evaluating formability at increased sheet processing speeds, which are demanded in practice.

Key words: *notch toughness, loading rate, drawing steels, formability characteristics*

Utjecaj brzine zatezanja na žilavost tankog vučenog lima. Rad procjenjuje mogućnost primjene testa žilavosti na vučene limove debljine do 1 mm, utjecaj brzine zatezanja na rezultate, kao i mogućnost uporabe tog testa za procjenu kovkosti. Vršeni su eksperimenti na čeličnim limovima s granicom razvlačenja od 145 do 250 MPa; test na žilavost napravljen je brzinom zatezanja $v_1 = 1,7 \cdot 10^{-5}$ ms^{-1}, $v_2 = 5 \cdot 10^{-2}$ ms^{-1} i $v_3 = 4,8$ ms^{-1}. Testovi su pokazali da se mogu dobiti rezultati koji se mogu postići i u proizvodnji tankih vučenih limova pod nekim određenim okolnostima. Vrijednost žilavosti, kao i sila i karakteristike deformacije dobivane u testu žilavosti mogu se koristiti za nadopunu tradicionalnih karakteristika i njihov točniji prikaz u procijenjivanju kovkosti pri povećanim brzinama obrade koje se traže u praksi.

Ključne riječi: *žilavost, brzina zatezanja, vučeni čelici, svojstva kovkosti*

INTRODUCTION

The impact bending test (notch toughness test) is the simplest testing method expressing the active failure resistance of a material in a narrow zone of the tested section [1, 2]. Its disadvantage consists the fact that it does not make possible to obtain absolute in toughness values of a material that would characterize its failure resistance. The notch toughness is influenced by the dimensions and the shape of the testing specimen, while their influence on the notch toughness depends on the internal structure of the material. Today, the test is usually made on standard specimens with dimensions of 10x10x55 mm and the V notch with the depth of 2 mm, the radius $r = 0.25$ mm and the angle of 45^o. Although there are more exact tests to determine the failure resistance of materials [2, 12], the notch toughness test is the most used in practice even today for its simplicity. To extend this test to semi-products and products from which standard specimens cannot be made, it necessitated studying the influence of the specimen thickness, the notch shape, the specimen dimensions, as well as the loading rate, etc. on the characteristics that can be obtained by the notch toughness test [3-7]. The notch toughness testing device is being modernized and it makes it possible to record a loading diagram from which further material failure resistance characteristics can be determined.

The aim of the paper is to assess a possibility of implementing the notch roughness test on drawing steel sheets with the gauge up to 1 mm and utilize the obtained results to assess their formability. It is very complicated to determine material characteristics at increased rates [8, 9], therefore efforts are made to determine these characteristics using simpler tests, such as the notch toughness test.

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EXPERIMENTS AND ANALYSIS

The experiments were made on steel sheets intended for cold working with a gauge from 0.8 to 1.0 mm. The characteristics and basic mechanical properties of the tested sheets are given in Table 1.

Table 1. **Basic mechanical properties and characteristics of tested steels**
Tablica 1. **Osnovna mehanička svojstva i karakteristike ispitivanih čelika**

Steel	Gauge [mm]	$Rp_{0.2}$ [mm]	R_m [mm]	A_5 [%]	n
DC 06	0.8	145	283	46.0	0.235
DC05D+Z	0.8	155	287	44.9	0.23
H 220 B	1.0	224	347	36.0	0.20
H 220 P	1.0	250	369	31.0	0.193
	Steel characteristic				
DC 06	C < 0.05 % recrystallization annealed, extra deep - drawing				
DC05D+Z	C < 0.015 % deep-drawing microalloyed steel with small texture of Zn layer, recrystallization annealed, extra deep-drawing for specially shaped car bodies				
H 220 B	C < 0.06 % drawing steel with hardening during paint baking, for pressing large-size pressings				
H 220 P	C <0.06 %, P < 0.08 %, drawing steel with increased dent resistance				

Tensile and notch toughness test specimens were cut from these steels. Based on knowledge of the notch toughness test, the test specimens were made with the dimensions shown in Figure 1. The distance of supports was 26 mm.

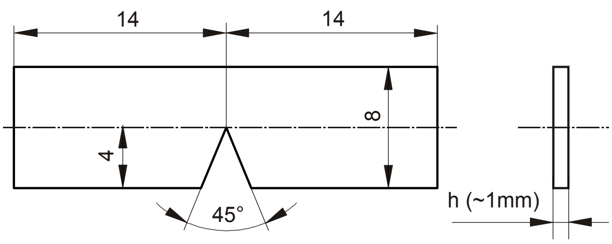

Figure 1. **Notch toughness test specimen**
Slika 1. **Uzorak za ispitivanje žilavosti**

The static tensile test was made on standardized specimens, on the tensile testing machine INSTRON 1185. Its results are given in Table 1. The notch toughness test was made at three loading rates - on the tensile testing machine ZD 1000 at $v_1 = 1.7 \cdot 10^{-5}$ ms^{-1}, on the fatigue testing machine INSTRON 8511 at $v_2 = 5.10^{-2}$ ms^{-1} and on the pendulum impact testing machine PSWO 1000 at $v_3 = 4.8$ ms^{-1} with a max. impact energy of 50 J.

The specimen failure energy in the tests made on the tensile testing machine and on the fatigue testing machine was evaluated by planimetring the area of the force F - deflection diagram.

The results of the notch toughness tests at the observed loading rates are shown in Figure 2.; the results show that the notch toughness KCV increases with an increasing loading rate.

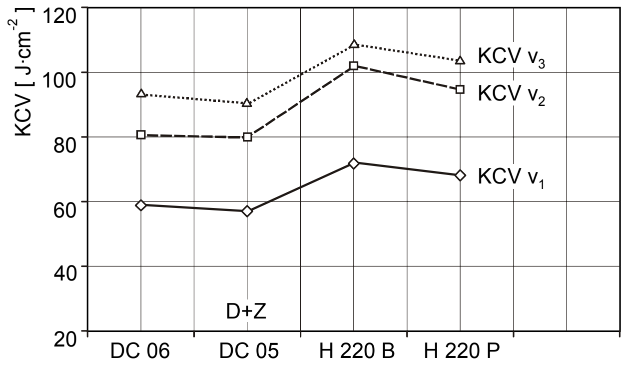

Figure 2. **Influence of the loading rate on the notch toughness KCV of tested steels: $v_1 = 1.7 \cdot 10^{-5}$ ms^{-1}, $v_2 = 5 \cdot 10^{-2}$ ms^{-1}, $v_3 = 4.8$ ms^{-1}**
Slika 2. **Utjecaj brzine opterećivanja na žilavost KCV ispitivanih čelika ($v_1 = 1.7 \cdot 10^{-5}$ ms^{-1}, $v_2 = 5 \cdot 10^{-2}$ ms^{-1}, $v_3 = 4.8$ ms^{-1})**

This increase is more marked after changing the static loading rate v_1 ($\varepsilon_1 = 1.1 \cdot 10^{-3}$ s^{-1}) to the quasi-dynamic loading rate v_2 ($\varepsilon_2 = 4.5$ s^{-1}).

The influence of the loading rate on notch toughness in the dependence on the tested steel (its yield point) is

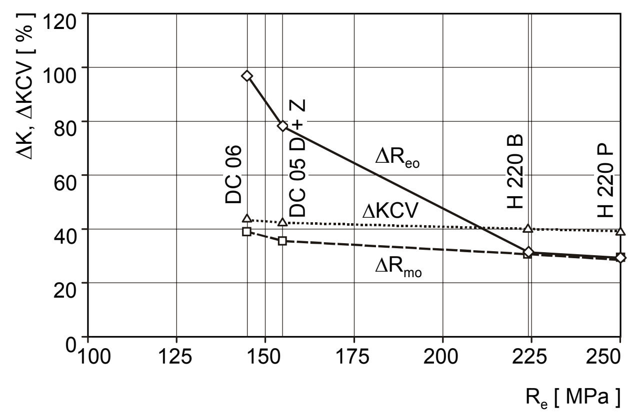

Figure 3. **Relative increase of the notch toughness ΔKCV, the yield point in bending ΔR_{eo} and the ultimate bending strength ΔR_{mo} of tested steels after changing the loading rate from v_1 to v_2**
Slika 3. **Relativan porast žilavosti ΔKCV, granice razvlačenja u svinutom ΔR_{eo} i maksimalne savojne čvrstoće ΔR_{mo} ispitivanih čelika nakon promjene brzine opterećivanja s v_1 na v_2**

better documented by the dependence of the relative increase in KCV of the tested steel. Figure 3. shows the relative increase in KCV after changing v_1 to v_2:

$$\Delta KCV = (KCVv_2 - KCVv_1) / KCVv_1$$

It results from the literature [6, 8-10] that the sensitivity of steels to the loading rate decreases with increasing steel strength (which is the function of the structure). This knowledge is also confirmed by the results of the notch toughness test made on the tested steels. DC 06 steel with the lowest yield point (145 MPa) shows the highest sensitivity to the loading rate and H 220 P steel with the highest yield point (250 MPa) shows the lowest sensitivity.

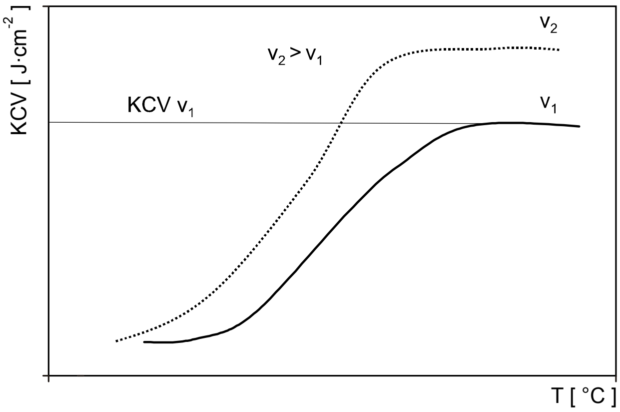

Figure 4. **Temperature - KCV relationship at the loading rates v_1 and v_2**

Slika 4. **Odnos temperature - KCV pri brzinama opterećivanja v_1 i v_2**

The influence of the loading rate on the course of the notch toughness KCV - temperature *T* relationship is shown in Figure 4. [12]. It results from the Figure that in the supertransition area the notch toughness is higher at the higher loading rate (KCVv_2 > KCVv_1). If KCVv_2 = KCVv_1, at the loading rate v_2 we get to the transition area and there is a danger of quick fracture. It applies to the tested steels that KCVv_3 > KCVv_2 > KCVv_1, therefore we can assume that in cold working at the strain rate of as many as $10^2 s^{-1}$ there is no danger of plastic stability failure.

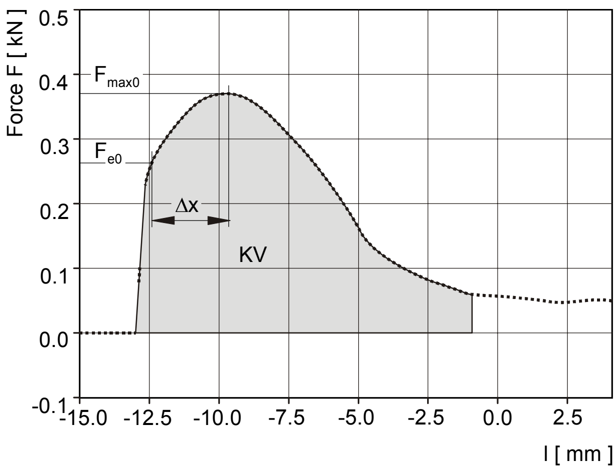

Figure 5. **Bending loading diagram at $v_2 = 5 \cdot 10^{-2} ms^{-1}$ for steel DC 06**

Slika 5. **Dijagram savijanja pod opterećenjem pri brzini $v_2 = 5 \cdot 10^{-2} ms^{-1}$ za čelik DC 06**

Considering the fact that sheet processing speeds are about $\varepsilon \sim 1 \cdot s^{-1}$ in practice, there arises a demand to assess the sheet formability at increased strain rates. Such tests should respect the sheet gauge, the behaviour of a material during being worked and a possibility of constructing correlations with the classical formability criteria [11]. A modified notch toughness test including a loading diagram could be one of the possibilities. In the notch toughness tests with the loading rates v_1 and v_2, loading diagrams were made with the coordinates force *F* - deflection; classical tensile tests were also made, where the basic formability characteristics were determined (see Table 1.), which gives us a possibility to construct the correlation between the classical plasticity criteria (R_e/R_m, n) and similar criteria determined by the notch toughness tests. Figure 5. shows a loading diagram in the notch toughness test with the loading rate v_2, as well as characteristics read from

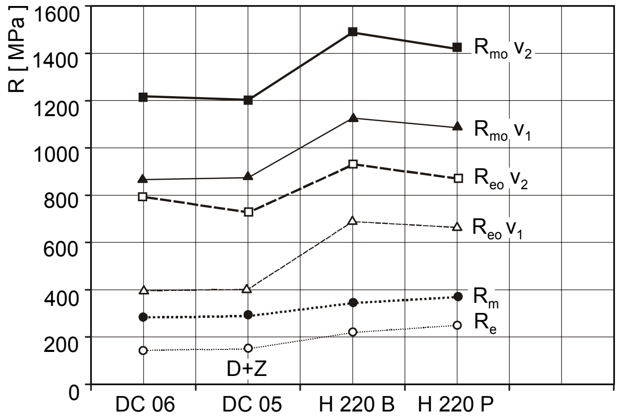

Figure 6. **Yield point R_e and ultimate strength R_m values under various loading conditions of tested steels**

Slika 6. **Vrijednost granice razvlačenja R_e i zatezne čvrstoće R_m pri različitim uvjetima opterećivanja ispitivanih čelika**

the diagram (F_{eo}, F_{maxo}, Δx). Figure 6. shows the graph of the strength characteristics - yield point and tensile strength - determined by the tensile test (R_e, R_m) and by the notch toughness test (bending R_{eo}, R_{mo}) at the loading rates v_1 and v_2, and Figure 7. shows the strain hardening exponent n and the deflection Δx at F_{maxo} in the notch toughness test. It results from these Figures that $R_{eo}v_1$, $R_{mo}v_1$ of the tested steels are higher than R_e, R_m determined by the static test, which is due to the notch effect, as well as due to the strain rate, much higher in the notched specimen than in the smooth specimen at the same loading rate v_1 because of the strain concentration around the notch, as well as due to the loading method. The influence of the loading rate on the strength properties can be assessed by comparing the results determined in the notch toughness test. As it results from Figure 6., R_{eo}, R_{mo} are higher at the loading rate v_2 than at the loading rate v_1 for all the tested steels. It results from Figure 3. that the influence of the loading rate on the relative increase of the yield point $R_{eo} = (R_{eo}v_2)/R_{eo}v_1$

[100 %] and of the ultimate strength decreases with an increasing yield point of the tested steels, while the decrease of ΔR_{eo} is more intensive than ΔR_{mo}, which is in accordance with the literature. The Δx characteristic determined in the notch toughness tests is greater at the loading rate v_1 than at the loading rate v_2 (Figure 7.), and it

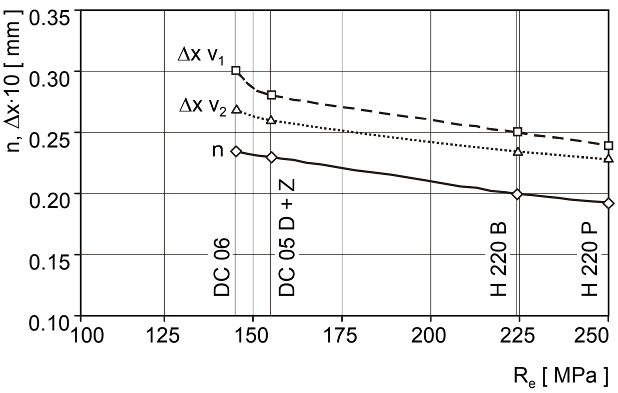

Figure 7. **Dependence of the strain hardening exponent n and the deflection Δx at F_{maxo} on the yield point R_e of tested steels**

Slika 7. **Ovisnost eksponenata hladnog očvršćavanja n i ogiba Δx na F_{maxo} pri granici razvlačenja R_e ispitivanih čelika**

results from their course that their correlation with the strain hardening exponent n is possible. The influence of the loading rate on the R_e/R_m ratio - as another formability characteristic - is rather significant. As it results from Figure 8, the R_e/R_m ratio at the loading rate v_1 (notch toughness test) has a similar course as this ratio in the tensile test. However, this does not apply at the loading rate v_2.

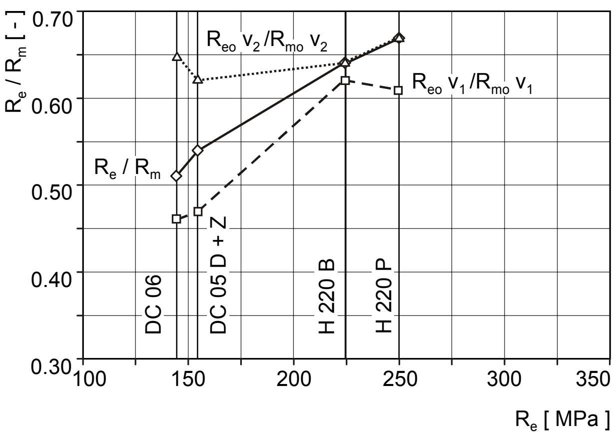

Figure 8. **Dependence of the R_e/R_m ratio on the yield point R_e of tested steels in the tensile test and the notch toughness test at the loading rates v_1 and v_2**

Slika 8. **Ovisnost omjera R_e/R_m u točki granice popuštanja R_e/R_m ispitivanih čelika na vlak i žilavost pri brzinama opterećivanja v_1 i v_2**

To assess the sensitivity of the tested steels to the change of the loading rate in the notch toughness test, the relationships between the relative increases or decreases of the observed characteristics and the yield point R_e of the tested steels were constructed, which are presented in Figure 9., where

$$\Delta(\Delta R) = \frac{\frac{R_{eo}v_2}{R_{mo}v_2} - \frac{R_{eo}v_1}{R_{mo}v_1}}{\frac{R_{eo}v_1}{R_{mo}v_1}} \cdot 100\,[\%],$$

$$\Delta(\Delta x) = \frac{\Delta x v_2 - \Delta x v_1}{\Delta x v_1} \cdot 100\,[\%].$$

The results show that the influence of the loading rate on the plasticity characteristics R_e/R_m and Δx decreases with the increasing yield point (strength characteristics) of the tested steels and for H 220 P steel these plasticity characteristics are not influenced by the change of the loading rate from v_1 to v_2. We find it important to determine the permissible R_e/R_m ratio at the required loading rate so as to avoid the local plastic stability loss.

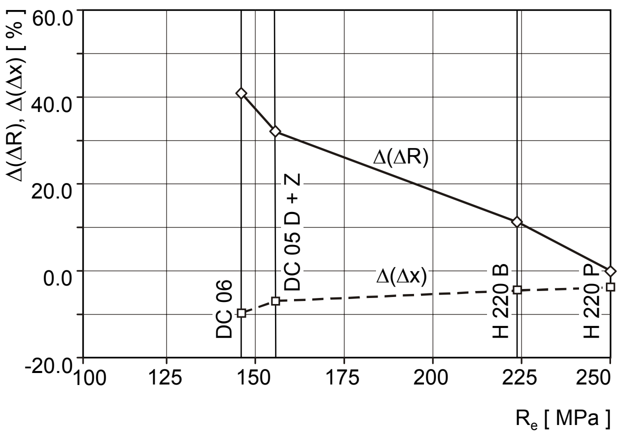

Figure 9. **Dependence of the relative change of the R_e/R_m ratio ($\Delta(\Delta R)$) and the deflection Δx ($\Delta(\Delta x)$) after changing the loading rate from v_1 to v_2 on the yield point of tested steels**

Slika 9. **Ovisnost relativne promjene omjera R_e/R_m ($\Delta(\Delta R)$) i ogiba Δx ($\Delta(\Delta x)$) nakon promjene brzine opterećivanja od v_1 do v_2 u točki granice popuštanja ispitivanih čelika**

The notch toughness test was made at the static loading and at the required loading rate, so that it can be used in assessing whether the local plastic stability loss can occur in a material at the required loading rate. The results of the modified notch toughness test show that if KCV is higher at the required loading rate than at the static loading rate, no local plastic stability loss will occur. Consequently, after determining the optimum conditions the modified notch toughness test could give an answer whether the criteria determined in the static tensile test also apply at the required loading rate.

CONCLUSION

The aim of the paper was to assess a possibility of implementing the notch toughness test to light-gauge drawn sheets, to assess the influence of the loading rate on the test results, as well as a possibility of using this test to evaluate formability. Drawing steel sheets with a gauge from 0.8 mm to 1 mm and a yield point from 145 to 250 MPa were used for experiments. The experiments and their analysis resulted in the following conclusions:

- reproducible notch toughness values can be obtained on specimens with the dimensions: gauge x 8 x 28 mm and with the *V* notch ca 4 mm deep,
- the notch toughness values of the tested steels increase with the increasing loading rate, while this increase is more intensive for steel with a lower yield point. If the loading rate changes from $1.7 \cdot 10^{-5}$ ms^{-1} (static loading) to $5 \cdot 10^{-2}$ ms^{-1}, the notch toughness increases by ca 40 %, and at the loading rate of 4.8 ms^{-1} it increases by ca 60%,
- the change of the loading rate from $1.7 \cdot 10^{-5}$ ms^{-1} to $5 \cdot 10^{-2}$ ms^{-1} significantly influences the yield point in bending and the ultimate bending strength determined by the notch toughness test and, consequently, on their ratio as one of the formability characteristics, too. For the steel with the yield point 145 MPa this ratio increases by 41%, but for the steel with the yield point 250 MPa this ratio does not change. The loading rate influences the deflection of the specimen at the plastic stability loss limit only slightly,
- the analysis has shown that if the notch toughness value is higher at the selected loading rate than at the static loading rate, the formability of tested steels at the selected loading rate could be evaluated according to classical criteria,
- the notch toughness test of light-gauge sheets can be used to supplement and make more exact the traditional criteria for evaluating the formability of light-gauge sheets at increased sheet processing speeds, which are demanded in practice.

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