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INFLUENCE OF THE STRAIN RATE ON THE MECHANICAL AND TECHNOLOGICAL PROPERTIES OF STEEL SHEETS

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The paper analyses the influence of strain rate on the behaviour of un-alloyed steels with R_e (yield strength) in the range of 210 ... 550 MPa in the deformation process. It analyses the results of the influence of strain rate ranging from 10^{-3} to $2{,}5 \cdot 10^2$ s^{-1} on the yield strength, the ultimate tensile strength (R_m), the elongation (A) and the reduction of area (Z). Achieved results of strain rate in relationship on values of Erichsen number I_E are also given. By increasing of strain rate ranging from 10^{-3} to $2{,}5 \cdot 10^2$ s^{-1} the ratio R_e/R_m is increased, whereas it was observed more intensively for steels with the lower value of R_e. By increasing of strain rate up to 1 s^{-1} are I_E values of tested steels increased, whereas the ratio R_e/R_m was equal 0,82. After exceeding of this strain rate was the ratio R_e/R_m increased and I_E value is remarkable decreased.

Key words: Plastic deformation, Erichsen number IE, tensile tests

Utjecaj brzine deformacije na mehanička i tehnološka svojstva čeličnih traka. U članku se analizira utjecaj brzine deformacije na ponašanje nelegiranog čelika s R_e (granica razvlačenja) 210 do 550 MPa tijekom deformacije. Motre se rezultati utjecaja brzine deformacije u rasponu 10^{-3} do $2{,}5 \cdot 10^2$ s^{-1} na granicu razvlačenja, vlačnu čvrstoću (R_m) istezanja (A) i kontrakciju (Z). Dodatno se prikazuje utjecaj brzine deformacije na vrijednost Erichsenovog broja I_E. Povećanjem brzine deformacije u intervalu 10^{-3} do $2{,}5 \cdot 10^2$ s^{-1} povećava se odnos R_e/R_m i to intenzivnije za čelik s nižom vrijednošću R_e. Povećanjem brzine deformacije do cca 1 s^{-1} povećava se I_E ispitivanog čelika pri čemu R_e/R_m = 0,82. Iznad te brzine odnos R_e/R_m se povećava, a I_E izrazito se smanjuje.

Ključne riječi: plastična deformacije, Erichsen broj I_E, vlačni pokus

INTRODUCTION

Increasing of strain rate during forming of semi products or products is one of the ways of production intensification. Therefore an attention is paid to the study of the influence of the strain rate on the material behaviour in the deformation process, but also on the methodology of evaluation of formability at increased strain rates (including impact) [1,2]. In general, it applies that increased strain rates result in increased strength characteristics of materials, while the yield stress is rising up more intensively than the tensile strength [3]. As a result, increased strain rate results in an increased R_e/R_m ratio, and for certain materials is ratio $R_e/R_m > 1$. This fact significantly influences the formability (especially compressibility) of materials due to of localization of plastic deformation to "suitable" areas.

Plastic deformation is characterized by the fact that its development is markedly non-homogeneous. The degree of non-homogeneity is a function of internal and external factors. The internal factors are internal mikrostructure of material, as follows: number and structure of phases, grain size and structure type. By increasing of grain size and number of phases, non-homogeneity of plastic deformation significantly increased. The temperature, strain rate and the stress state are crucial external factors [4,5].

The sensitivity of materials on strain rate during the forming process is, as it was mentioned earlier, a function of material, and therefore it is beneficial to analyze this sensitivity, especially for new developed materials intended for the cold forming. This is necessary in order to determine the limit state, as well as the properties of the final product.

The main aim of the paper is to extend the knowledge and to mention on certain problems occurring during forming at increased rates (up to impact loadings).

EXPERIMENTAL MATERIAL AND METHODS

Experimental programme was realized on samples taken from stripes produced of un-alloyed high-grade and micro-alloyed cold rolled steels with yield stress ranged from 210 to 550 MPa. Cut-outs from the steel sheet and flat test specimens oriented in the rolling direction were machined out for the tensile test. The same procedure was applied for the samples used in Erichsen deep-drawing tests.

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For static tensile tests a universal test machine INSTRON 1185 was used and this machine was used retooled with an Erichsen test fixture for the deep-drawing tests in the press tool velocity interval from $3{,}3\cdot10^{-3}$ $m\cdot s^{-1}$ to $1{,}10^{-1}$ $m\cdot s^{-1}$. Deep-drawing tests with speed punch up to $2{,}5$ $m\cdot s^{-1}$ were done by drop tower.

EXPERIMENTAL RESULTS AND DISCUSSION

The influence of strain rate on the basic mechanical properties of tested steel C4 is shown in Figure 1, which indicates that increased strain rates result in increased strength properties, whereas the intensity of growth of R_e is higher than of R_m. The dependence of the strength properties on the strain rate for un-alloyed high-grade steels in the range from 10^{-3} to 10^3 s^{-1} was described using parametric equations, mostly in the form presented in [4,6,8],

$$R_{e\dot{\varepsilon}} = R_{e\dot{\varepsilon}_0} + k\cdot\ln(\dot{\varepsilon}/\dot{\varepsilon}_0)$$

$$R_{m\dot{\varepsilon}} = R_{m\dot{\varepsilon}_0} + k\cdot\ln(\dot{\varepsilon}/\dot{\varepsilon}_0)$$

where R_e, R_m are the yield strength and the ultimate tensile strength at the given strain rate $\dot{\varepsilon}$, $R_{e\dot{\varepsilon}_0}$ and $R_{m\dot{\varepsilon}_0}$, are the yield strength and the tensile strength at the static strain rate (10^{-3} s^{-1}).

When the material is more homogeneous and there is the lower amount of obstacles for dislocations movement, the more sensitive to the strain rate is. Figure 2 shows the influence of the strain rate on the increment of the yield strength ΔR_e of C33 steel after various heat treatments.

The as-quenched steel has the lowest sensitivity to $\dot{\varepsilon}$, because the martensitic makrostructure has the highest number of obstacles to dislocations movement, and the as-normalized steel has the highest sensitivity.

Similarly, Figure 3 documents the influence of $\dot{\varepsilon}$ on ΔR_e and ΔR_m values of C4 and E500TS steels with different grain size.

The grain boundaries are insuperable obstacles to dislocation movement, therefore the finer grain caused the more obstructions, and the steel is less sensitive to the strain rate $\dot{\varepsilon}$. In terms of assessment of formability, the R_e/R_m ratio is the most important criterion.

Test results realized on different steel grades confirmed fact that by increasing of strain rate the ratio

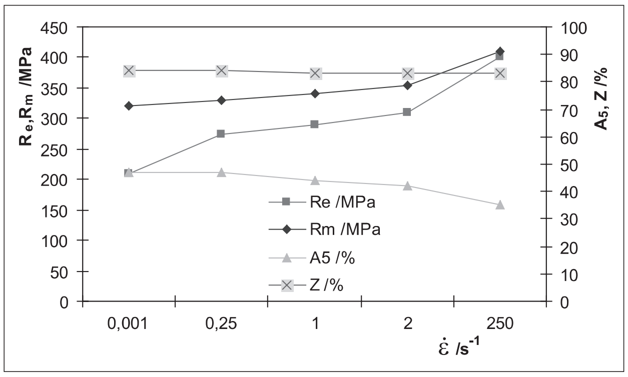

Figure 1 Influence of the strain rate $\dot{\varepsilon}$ on mechanical properties of steel C4.

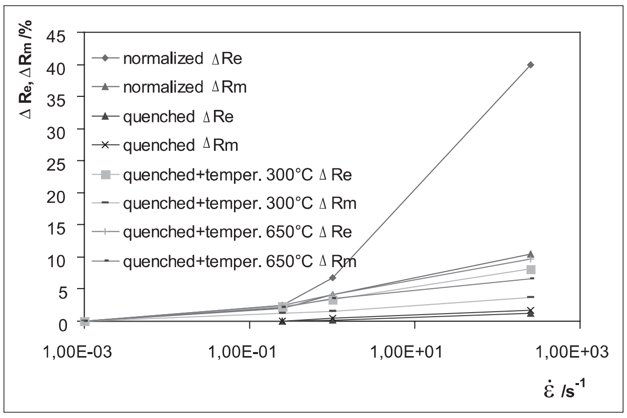

Figure 2 Influence of the strain rate $\dot{\varepsilon}$ on the increment of strength properties ΔR_e or ΔR_m, after heat treatment, compared with the initial state ($\dot{\varepsilon}=10^{-3}$ s^{-1}) of steel C33, after various heat treatments.

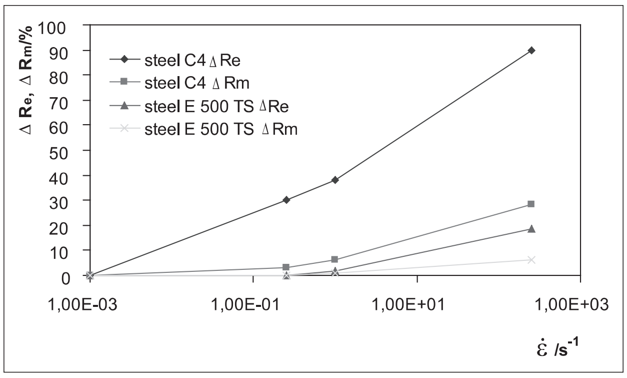

Figure 3 Influence of the strain rate $\dot{\varepsilon}$ on the increment of strength properties ΔR_e or ΔR_m, compared with the initial state at $\dot{\varepsilon}=10^{-3}$ s^{-1} for various steel grades.

R_e/R_m is also increased and the intensity of that increase is a function of material. The lower amount of obstructions for dislocations movement in material causes the more remarkable influence of $\dot{\varepsilon}$. Figure 4 shows an example of influence of grain size to ratio R_e/R_m for different strain rates.

Analysis of achieved results of strength properties (R_e, R_m) showed that un-alloyed high-grade steels dedicated for cold forming up to critical strain rate $\dot{\varepsilon}_{kr}$ allocated the ratio $R_e/R_m < 1$ and from the view of macro volume up to that strain rate should be keeping the plastic stability till deformation responded to stress R_m.

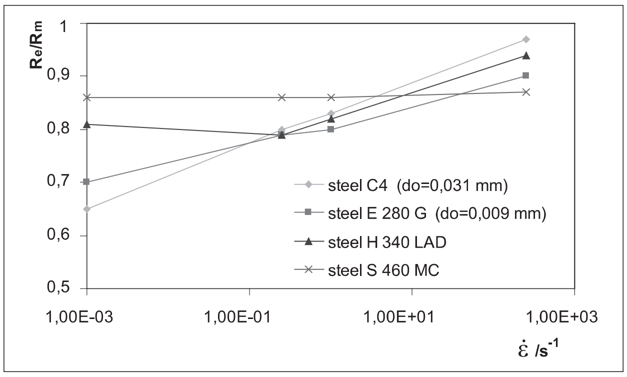

Figure 4 Influence of the strain rate $\dot{\varepsilon}$ on R_e/R_m for various steel grades.

The critical value $\dot{\varepsilon}_{kr}$ is affected by internal structure of material and commonly should be stated that by increasing R_e value also the value $\dot{\varepsilon}_{kr}$ increase. Table 1 shows values of R_e, R_m, R_e/R_m of tested steels at characteristic strain rates as well as the characteristics of its state (carbon content, content of micro-alloying elements and grain size).

Based on the R_e/R_m ratio obtained from the static tensile tests, the tested steels can be divided into three groups: steels with $R_e < 300$ MPa and $R_e/R_m < 0{,}7$, steels with $R_e > 300$ MPa and $R_e/R_m > 0{,}7$, and the third group consists by steels with $R_e > 500$ MPa and $R_e/R_m > 0{,}8$. Figure 5 shows the graphic relationships $\dot{\varepsilon}$ vs. A and $\dot{\varepsilon}$ vs. Z of tested steels. *A* decrease of the elongation with an increase of $\dot{\varepsilon}$ value is only shown for steels with $R_e < 300$ MPa after exceeding of ratio $R_e/R_m > 0{,}82$. Steels with a higher yield stress maintain or even increase their elongation at ratio $R_e/R_m > 0{,}82$.

Results of Erichsen deep-drawing tests showed that the indentation depth up to the fracture of the indented cup (I_E) is actually the same for both used steel grades, although there are big differences in elongation A_{80}. This can be related to the changes in the stress distribution during the Erichsen deep-drawing test on the one side and during tensile test on the other.

Basic information about the formability of the steel sheet can be obtained by tensile test. However, the compressibility of the sheet is affected by a number of factors arising from the applied production technology [1,2,6]. Important characteristics of compressibility can be obtained by the technological tests. In Table 2 are summarized the results of Erichsen deep-drawing test (I_E - is the Erichsen number) for different movement rate of punch knife.

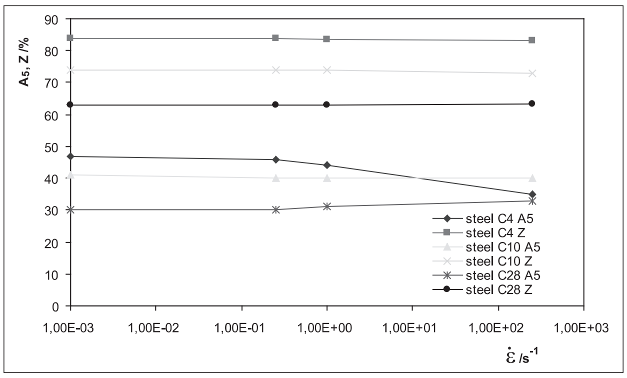

Figure 5 Influence of the strain rate $\dot{\varepsilon}$ on the elongation A_5 and the reduction of area *Z* of various tested steel grades.

The influence of strain rate on the I_E values is plotted in Figure 6. As can be seen that by increasing of the loading rate up to about $v = 0{,}2$ m·s^{-1} is a slight growth of the I_E, then there is a slight decrease of the I_E value.

For the highest loading rate of 2,5 m·s^{-1} is that decrease more remarkable. The loading rate of 0,2 m·s^{-1} which marked the start of I_E decrease, roughly corre-

Table 1 **Mechanical properties of tested steels at characteristic strain rates**

Tested steels	Material characteristics	/s^{-1}			
		10^{-3}	$2{,}5 \cdot 10^{-1}$	1	$2{,}5–10^{2}$
C4	R_e /MPa	210	275	290	400
C < 0,04%	R_e/R_m	0,65	0,8	0,83	0,93
d = 0,031 mm	A_5 /%	47	46	44	35
E280G	R_e /MPa	295	340	350	459
C < 0,04 %	R_e/R_m	0,70	0,79	0,80	0,9
d = 0,009 mm	A_5 /%	30	27	25	22
H340LAD	R_e /MPa	350	380	430	540
Nb, V < 0,1 %	R_e/R_m	0,81	0,79	0,82	0,94
d = 0,008 mm	A_5 /%	26	26	26	24
C33	R_e /MPa	440	451	470	630
C < 0,33 %	R_e/R_m	0,62	0,62	0,63	0,80
d = 0.012 mm	A_5 /%	27	26	26	27
C33	R_e /MPa	1910	1910	1910	1935
quenched	R_e/R_m	0,81	0,81	0,83	0,81
C33 quenched + tempered 300 °C	R_e /MPa	1480	1525	1540	1600
	R_e/R_m	0,92	0,95	0,95	1,0
C33 quenched + tempered 550 °C	R_e /MPa	820	840	845	900
	R_e/R_m	0,90	0,90	0,90	0,90
S460 MC	R_e /MPa	537	550	592	700
C < 0,07 % Nb	R_e/R_m	0,86	0,86	0,86	0,87
d = 0,006 mm	A_5 /%	30	30	30	29
E500TS C < 0,08 %, Nb,Ti	R_e /MPa	540	540	550	640
d = 0,0056 mm	R_e/R_m	0,84	0,84	0,85	0,94
	A_5 /%	39	39	39,5	40

Table 2 **Results of Erichsen deep-drawing test for different movement rate of punch knife**

Mark of steels	v /m·s^{-1}	$3{,}3\cdot10^{-3}$	$8{,}34\cdot10^{-3}$	$1{,}6\cdot10^{-2}$	$2{,}0\cdot10^{-1}$	2,5
H220YD	I_E /mm	12,5	12,6	13,0	12,7	11,2
H340LAD		12,4	12,5	12,8	12,6	11,3
H380LAD		12,4	12,5	12,6	12,5	11,5

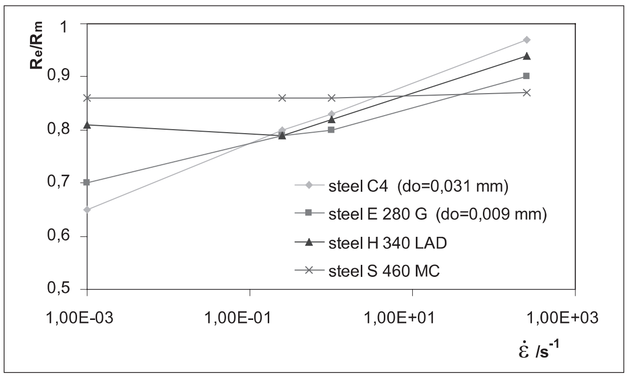

Figure 6 Influence of pressing tool velocity on Erichsen number I_E for investigated steel.

sponded to the strain rate 1 s^{-1}. The experiments are in good agreement with data reported in references [1,6,7,9], declaring that up to the strain rate of about 1 s^{-1} there is no significant decrease of steel sheet formability by the increase of the loading rate, and therefore in this zone the traditional deep-drawing criteria can be applied. At this strain rate is ratio R_e/R_m for H340LAD steel equal 0,82. At strain rate of $2\cdot10^2$ s^{-1} is ratio R_e/R_m = 0,9.

During testing, but also during production by forming is deformation rate due to inhomogeneous process of plastic deformation changing and instantaneous deformation speed of particular position is almost higher than the mean deformation strain rates.

The outstanding decrease of I_E value at impact loading (v = 2,5 m·s^{-1}, $\dot{\varepsilon}\sim10^2$ s^{-1}) is caused due to different factors. We assume that the decisive factor is the increase of macro heterogeneity of plastic deformation of the cup by deformation rate increasing and also deformation localization into the critical parts of the cup. This can results in a decrease of the total value of plasticity. Changes of the friction between the tool and sheet should have an influence, too [9,10].

CONCLUSIONS

The aim of the paper was to judge the influence of strain rate in the range from 10^{-3} to $2{,}5\cdot10^2$ s^{-1} on the mechanical properties, with regards to the plasticity of un-alloyed high-grade steels with the yield strength ranged from 210 to 550 MPa. Based on the analysis of experimental results obtained from a long time period and literature sources, the following conclusions can be stated:

– The resistance of material to plastic deformation is increases with strain rate increasing, herewith the strength properties of tested steels as well as ratio R_e/R_m are increased.
– The intensity of increase of ratio R_e/R_m with an increasing strain rate is a function of the internal structure of material. The intensity of increase in ratio R_e/R_m with an increasing strain rate is the highest for steels with R_e < 300 MPa, lower for steels with R_e < 500 MPa, and slightly for steels with R_e > 500 MPa.
– The influence of the strain rate on the plasticity characteristics (elongation and reduction of area) is related to the ratio R_e/R_m. Only steels with R_e < 300 MPa exhibit a decreasing elongation in the studied strain rate interval, and it from the strain rate where ratio R_e/R_m > 0,82. Steels with the higher values of yield stress are keeping or increasing its elongation, respectively.
– Movement rate of punch knife during the stamping process (Erichsen deep-drawing test) up to rate about 0,2 m·s^{-1} what responds to average strain rate about 0,1 m·s^{-1} causes the slight increase of deep-drawing. Exceeding of this rate leads to the decrease of deep-drawing, whereas it was more intensive for steel sheet with the lower yield stress.
– The decrease of Erichsen number was observed at strain rate for ratio R_e/R_m > 0,82.

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