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ISSN 0543-5846
METABK 47(1) 19-23 (2008)
UDC - UDK 669.14-418:539.37:620.17=111

CONTRIBUTION TO EVALUATION OF MECHANICAL PROPERTIES DURING IMPACT LOADING

Received – Prispjelo: 2006-12-15
Accepted – Prihvaćeno: 2007-07-11
Original Scientific Paper – Izvorni znanstveni rad

The paper analyzes the influence of the impact rate of up to 120 ms^{-1} with a constant energy on the relative compression of high-grade unalloyed steels, Cu and Zn, and the evaluation of energy consumed during the impact bending test at the impact rate of up to 80 ms^{-1}. Based on the experiments made, relationships for the prediction of the influence of the strain rate within the range of 10^{-3} – $2.5.10^3$ s^{-1} on the mechanical properties of high-grade unalloyed steels with the yield point of 210 – 450 MPa and microalloyed steels with the yield point of 300 – 600 MPa are presented.

Key words: Impact rate, strain rate, impact energy, strength properties, strain hardening

Prilog procjeni mehaničkih svojstava pri ispitivanju udarom. Članak analizira utjecaj brzine udara do 120 ms^{-1} s stalnom energijom na relativno sabijanje visokočvrstih nelegiranih čelika, Cu i Zn, i procjena rabljene energije pri ispitivanju žilavosti pri brzini udara 80 ms^{-1}. Na temelju realiziranih eksperimenata predmjevane su relacije utjecaja brzine deformacije od 10^{-3} do $2.5.10^3$ s^{-1} na mehanička svojstva visokočvrstih nelegiranih čelika s granicom razvlačenja 210 do 450 MPa i mikrolegiranih čelika sa 300 do 600 MPa.

Ključne riječi: brzina udara, brzina deformacije, udarni rad, deformacijsko otvrđivanje

INTRODUCTION

The behaviour and properties of a material during deformation is, among others, influenced by external factors, which also include the strain rate. The strain rate has a significant effect on the material behaviour during the deformation (forming) process [1,2], as well as on the final properties of products [3,4,5]. Dynamic loading has also a significant effect on the degradation of the properties of products during their service life [6,7].

The investigation of the influence of the impact rate on the properties and behaviour of materials is experimentally very demanding. Therefore the literature has paid a great attention to a possibility to replace the strain rate with the temperature in the form of a relationship where a material property is a function of the temperature and the strain rate [8].

However, it appears that this approach makes it possible to predict the influence of the impact rate on the material properties only partially.

This is mainly due to the non-homogeneous distribution of stress and strain in a product, which increases with an increasing impact rate. This non-homogeneity during impact loading is due to the effect of additional inertial-force fields, which are formed by accelerating or decelerating the mass of a structural unit. In case of tests, it is the mass and the grade of the test specimen material, the toughness of the test equipment, etc. that makes the interpretation of the test results very difficult.

The literature [9] analyzes the temperature dependence of the impact toughness KCV during static (v=2.10^{-4} ms^{-1}) and dynamic (v=5 ms^{-1}) loading. In the subtransitional area, the KCV during static loading of the S 315MC grade was 20% lower than during dynamic loading and for the S 460MC grade it was 5% lower than during dynamic loading; this indicates that the grade of a material influences, besides its sensitivity to the strain rate, also the amount of energy lost during dynamic loading.

The paper aims to analyze the behaviour of selected materials at various loading rates in terms of energy lost during impact loading, their sensitivity on the strain rate, and the final strength properties.

ENERGY BALANCE DURING IMPACT LOADING

During tests utilizing impact energy, the kinetic energy of the hammer is consumed for the deformation and failure of the specimen, the deformation of the hammer, but its part is also consumed for lost energy (deformation of the equipment, deformation of the specimen in the impact point, energy of the flying pieces of the speci-

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men, etc.). Figure 1 shows the relative compression of cylinders Ø 8x20 mm made of steel grades C15 and C33, rolled copper and zinc, as a function of the impact rate of up to 120 ms^{-1} with a constant impact energy – for steels and Cu, E=380 J, and for Zn, E=172 J.

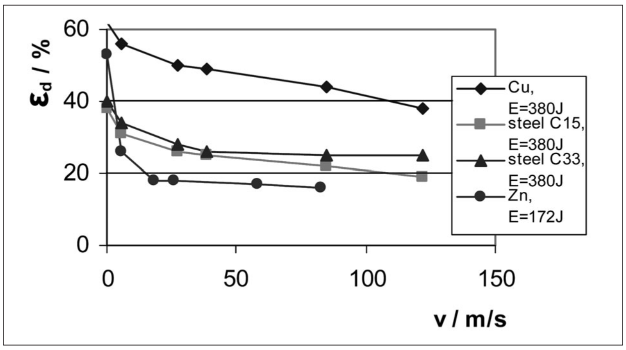

Figure1. The influence of impact rate v on the relative compression ε_d of testing cylinders Ø 8x20 mm at a constant impact energy E.

During static loading (the strain rate is considered v=0 ms^{-1}), the specimens were compressed at a tensile machine, and at the strain rate of up to 120 ms^{-1} they were compressed at a pneumatic ejection device, while the weight of the hammer was decreased with the increasing loading rate, so that the impact energy could be constant.

The results of the above-described tests show that a sudden decrease of the relative compression ε_d takes place in the point of transition from static to dynamic loading (v=5 ms^{-1}, which is the impact rate for standard impact bending tests), and the decrease of ε_d is more moderate with the further increase of the impact rate. The sensitivity of a material to the impact rate is a material function. Zn shows the highest (hexagonal lattice) and Cu the lowest (lattice K 12) sensitivity to the impact rate.

The tested unalloyed steel C15 (ferrite with the lattice K8) has a higher sensitivity to the impact rate than Cu, but is more sensitive than the steel C33, which confirms the knowledge that the more homogeneous material the higher its sensitivity to the strain rate.

As stated above, a part of impact energy is lost, and the amount of this lost energy depends, among others, on the impact rate, but also on the material grade. Since impact loading is the most used during impact bending tests, the energy balance was experimentally investigated at the impact bending test on standard test bars made of the steel C33. The impact rate ranged from 5 ms^{-1} (Charpy test) to 80 ms^{-1} (pneumatic ejection device). The total energy E consumed for deformation and failure of the test bar and the lost energy Es were evaluated. The lost energy Es was determined as the sum of energy necessary for deformation of the test bar in the point of impact of the hammer and energy of flying parts of the test bar after failure. The energy consumed for the failure of the test bar, KV, is

$$KV = E - Es\ [J] \tag{1}$$

The results of the influence of the impact rate on the consumed energy E, the lost energy Es, and the energy consumed for the failure of the test bar KV, which characterizes the material resistance to impact loading, are shown in Figure 2. The analysis of the test results shows that the lost energy Es during the standard impact bending test is negligible, but it increases with an increasing impact rate and at v= 60 ms^{-1} it is higher than KV. The reliability of the calculated KV value was verified by measuring the deformation of the test bar cross-section in the notch:

$$\Delta b = \frac{b_2 - b_1}{2}\ [mm] \tag{2}$$

where b_2 is the greatest width of the cross-section and b_1 is the least width of the cross-section

The measured results show that the course of the dependence of the deformation characteristic Δb on the impact rate is identical with the course of KV (Figure 2). The KV (and also Δb) value decreases with an increasing impact rate. This decrease is caused by increased concentration of deformation into the fracture area as a result of the increase of the strain rate with the increase of the impact rate.

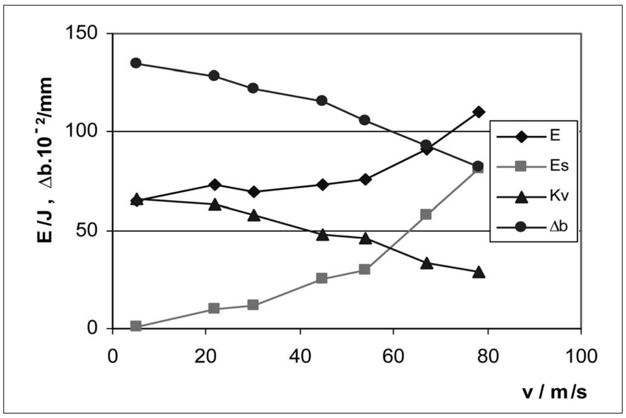

Figure 2. The influence of impact rate v on the total consumed energy E, the lost energy Es, the consumed energy to failure KV and deformation Δb at impact test of C33 steel.

INFLUENCE OF THE STRAIN RATE ON MECHANICAL PROPERTIES

In general, it can be stated that with the increase of the strain rate the resistance of materials to plastic deformation increases and the material plasticity also changes [1,3,4,9]. The intensity of the influence of the strain rate on the behaviour of a material in the impact process is a material function. During a tensile test made with various rates, the results can only be influenced by the toughness of the machine, the sensitivity of the force sensors and the force-strain recorder. It can be stated that currently these influences are significantly eliminated.

The influence of the strain rate in the range of 10^{-4} – 10^{3} s^{-1} on the strength properties of steels is the most often described using the following formulas:

$$R_{\dot{\varepsilon}}=R_1+A.\log(\dot{\varepsilon}/\dot{\varepsilon}_0), \text{ or}$$

$$R_{\dot{\varepsilon}}=R_1+A.[\log(\dot{\varepsilon}/\dot{\varepsilon}_0)]^n \qquad (3)$$

where R_{ε} is the strength characteristic at the strain rate $\dot{\varepsilon}$, R_1 is the strength characteristic at static loading at the rate $\dot{\varepsilon}_0$. *A* and *n* are material constants characterizing the sensitivity of a material to the strain rate.

The influence of the strain rate on the mechanical properties was tested by tension on tensile test bars d_0 = 4 mm, L_0 = 20 mm in the strain rate range from 10^{-3} s^{-1} to $2.5.10^{3}$ s^{-1}, which were made of high-grade unalloyed steels C4, C10, C28, C33 with R_e ranging from 210 to 450 MPa and of microalloyed (V, Nb) steels with the polyedric structure and with R_e ranging from 300 to 600 MPa. Figure 3 documents the influence of the strain rate on the basic mechanical properties of the steel C4 (R_e=210 MPa, R_m=310 MPa) and the steel C33 (R_e=450 MPa, R_m=710 MPa).

The results of tests confirm the literary knowledge that the resistance of a material to deformation increases with an increasing strain rate; this means that the yield point and the tensile strength increases and the plasticity also changes. The intensity of the influence of the strain rate, as shown in Figure 3, is a function of the material structure.

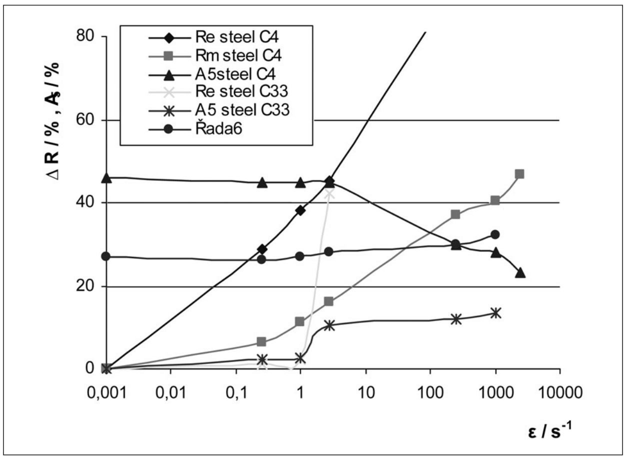

Figure 3. The influence of the strain rate $\dot{\varepsilon}$ during the tensile test on the relative increase of the yield stress ΔR_e, the ultimate strength ΔR_m and A_5 elongation of tested steels.

The structure of the steel C4 is mainly ferritic (it contains 95% of ferrite and 5% of pearlite) and is much more sensitive to the strain rate than the steel C33, which has the ferrite-pearlitic structure (it contains 48% of ferrite and 52% of pearlite). The tested micro alloyed steels, whose matrix consists of ferrite and a reduced content of pearlite, but also the precipitates of micro alloying elements, are even less sensitive to the strain rate

The influence of the strain rate on the A_5 elongation value of the tested steels is shown in Figure 3. The de-

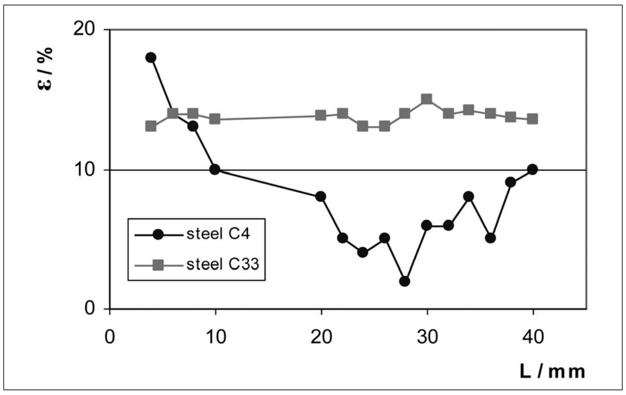

Figure 4. The distribution of plastic deformation along the testing specimen at impact loading of =10^{-2} s^{-1}.

crease of the elongation value at v >10^{2} s^{-1} of the steel C4 is due to the non-homogeneity of plastic deformation along the test bar (Figure 4).

This non-homogeneity is predominantly the result of a significant increase of R_e at v >10^{2} s^{-1}, at which R_e reaches the level of R_m (R_e=420 MPa). The steel C33 keeps the homogeneous distribution of plastic deformation along the test bar even at these rates. This steel has R_e=640 MPa and R_m=785 MPa at v=2,5.10^{2} s^{-1}, and hence no premature local loss of plastic stability takes place.

However, the literature [4] confirms that from the micro-volume point of view the homogeneity of plastic deformation increases with an increasing strain rate.

Based on the experiments made, using the method of least squares we can predict the influence of the strain rate on the strength properties for the given group of steels. The general parametric equation (Equation 3) has the following form for high-grade unalloyed subeutectoid steels

$$R_{e\dot{\varepsilon}}=R_{e\dot{\varepsilon}_0}+A.[\log(\dot{\varepsilon}/\dot{\varepsilon}_0)]^{2,49} \qquad (4)$$

$$R_{m\dot{\varepsilon}}=R_{m\dot{\varepsilon}_0}+B.[\log(\dot{\varepsilon}/\dot{\varepsilon}_0)]^{2,1} \qquad (5)$$

and for micro alloyed steels (R_e=300 – 600 MPa)

$$R_{e\dot{\varepsilon}}=R_{e\dot{\varepsilon}_0}+A.[\log(\dot{\varepsilon}/\dot{\varepsilon}_0)]^{1,64} \qquad (6)$$

$$R_{m\dot{\varepsilon}}=R_{m\dot{\varepsilon}_0}+B.[\log(\dot{\varepsilon}/\dot{\varepsilon}_0)]^{1,49} \qquad (7)$$

The material constants A and B, which express the intensity of the influence of the strain rate, are a function of the structure. R_e, but also R_m, can be considered as a

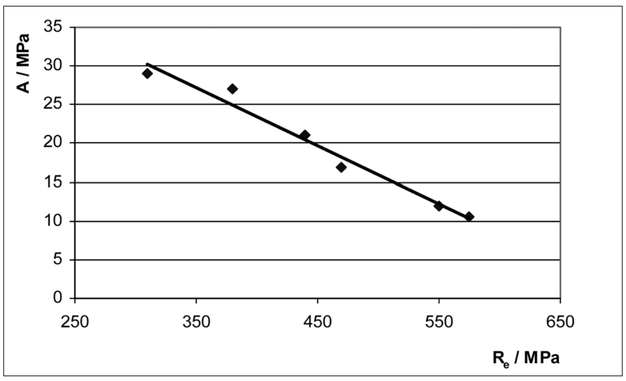

Figure 5. The relationship between the material constant A and yield stress R_e for micro alloyed steels.

macroscopic characteristic of the structure, and the relationships between A, B a R_e, R_m can be described using the linear following equations (see Figure 5)

$$A = C + D.R_e,\ B = E + R_m \qquad (8)$$

For micro alloyed steels, A= 55,5 – 0,077R_e, and

$$B = 58,3 - 0,071R_m. \qquad (9)$$

PROPERTIES OF STRAIN-HARDENED STEELS

Semi-products and products can be produced by cold forming at various strain rates. Therefore it is necessary to know whether the basic mechanical properties are influenced by the strain rate. Figure 6 shows the graph of relative differences of strength properties of the selected steels, strain-hardened to 20% statically ($\dot{\varepsilon}_1=10^{-3}\ s^{-1}$) and by impact ($\dot{\varepsilon}_2=10^{2}\ s^{-1}$) according to the relationship:

$$\Delta R = (R_{20\%\dot{\varepsilon}1} - R_{20\%\dot{\varepsilon}2}) / R_{20\%\dot{\varepsilon}1} \qquad (10)$$

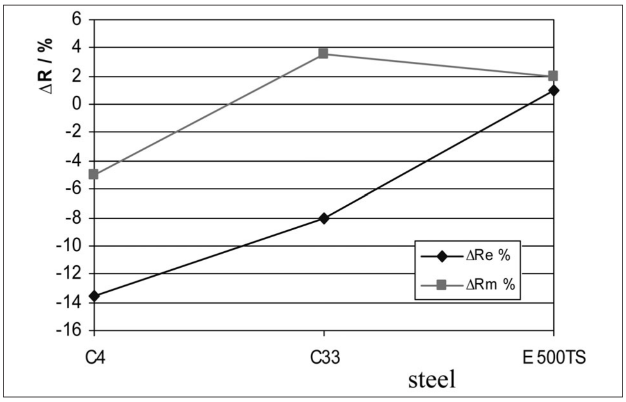

Figure.6 The relative difference of strength properties ΔR_e, ΔR_m of dynamic deformation strengthened steels $\dot{\varepsilon}=10^2\ s^{-1}$ against the static deformation of strengthened tested steels $\dot{\varepsilon}=10^{-3}\ s^{-1}$ of marks C4, C33 and E50TS to value of 20%.

The analysis of the results shows that the strength properties of strain-hardened steels are, to a certain extent, influenced by the strain hardening rate. This conclusion mainly applies to low-carbon steels and the degree of this influence is a material function. The relative change of the tensile strength R_m can be described using the formula

$$\Delta R_m = (0,53 - 10^{-3}\ R_m).\varepsilon \qquad (11)$$

where ε is the amount of reduction during forming.

The strength properties (R_e, R_m) of dynamically hardened micro alloyed steels are practically uninfluenced by the strain hardening rate. The cause of the above-mentioned facts can be attributed to the influence of dynamic deformation on the homogeneity of plastic deformation.

The dynamic hardening rate also influences the strain ageing processes. Figure 7 documents the dependence of the increment of the yield point ΔR_e on the ageing period at 100 and 200°C of test bars of the steel C4,

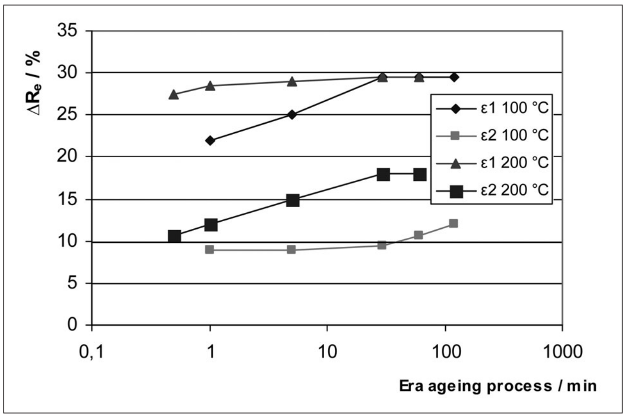

Figure 7. The dependence of the increase of yield stress ΔR on the aging time of C4 steel after 10% of static $\dot{\varepsilon}_1=10^{-3}\ s^{-1}$ and dynamic $\dot{\varepsilon}_2=10^{2}\ s^{-1}$ deformation.

statically ($\dot{\varepsilon}=10^{-3}\ s^{-1}$) and dynamically ($\dot{\varepsilon}=10^{2}\ s^{-1}$) strain hardened to 10%. The results show that the intensity of strain ageing expressed as ΔR is higher in statically strain hardened test bars, after stabilization (ageing period approx. 30 min.), than in dynamically hardened ones by approx. 65%.

The results of tests made on statically and dynamically strain hardened test bars confirm the knowledge that if the whole volume is strain hardened, plastic deformation is more homogeneous in dynamically hardened steel, dislocations are more homogeneously distributed in the volume [4,10]. Consequently, during the subsequent static tensile test, plastic deformation starts in dynamically strain hardened steel at a lower stress (see Figure 6). This effect is more marked when fewer obstructions to dislocation movement occur in the steel structure (steel C4). When the number of obstructions to dislocation movement in the structure grows, this effect decreases, even disappears (steel C33, E480TS).

Dynamically strain hardened steel, as a result of more homogeneous distribution of dislocations within the volume, has also a lower and more homogeneously distributed internal (strain) energy and hence a lower ability of diffusion of atoms (N, C), which was reflected in a decreased influence of strain ageing on the yield point when compared with static strain hardening.

CONCLUSION

The aim of the paper was to assess the influence of the impact rate on the interpretation of the test results and to analyze the influence of the strain rate on the basic mechanical properties of unalloyed high-grade steels with the carbon content from 0,04 to 0,53% and micro alloyed (Nb, V) steels with the yield point from 300 to 600 MPa. The test results and their analysis show the following.

– – The resistance of the tested materials (steels, Cu, Zn) to plastic deformation increases with an increasing impact rate. The amount of the total energy necessary for deformation increases and this increase depends on the material grade and the test conditions.

- In evaluating the impact toughness at impact rates above 5 ms^{-1}, it is necessary to consider lost energy, which does not participate in the total absorbed energy during breaking a test bar (KV).
- The sensitivity of unalloyed high-grade steels on the strain rate is a function of their internal structure. The fewer obstructions to dislocation movement occur in the structure, the higher sensitivity of the tested steels to the strain rate is. For the tested steels in the strain rate range from 10^{-4} to 10^3 s^{-1}, this sensitivity is expressed using parametric equations.
- The strain hardening (forming) rate influences the resulting properties of strain hardened steels, but also processes during strain ageing, more significantly only in steels with a low yield point, as a result of increased homogeneity of plastic deformation with an increasing strain rate.

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Note: The responsible translator for English language is Fedorčakova Melania, Košice, Slovakia