E. ČIŽMÁROVÁ, J. MICHEĽ, I. MAMUZIĆ, M. BURŠÁK

ISSN 0543-5846
METABK 41 (4) 285 (2002)
UDC - UDK 669.14.018.262:620.17=20

INFLUENCE OF STRAIN RATE ON PROPERTIES OF MICROALLOYED S-MC STEEL GRADES

Received - Primljeno: 2001-02-20
Accepted - Prihvaćeno: 2002-07-10
Original Scientific Paper - Izvorni znanstveni rad

The influence of strain rate on properties of microalloyed steel for cold drawing of S 315 MC and S 460 MC grades was analysed. It has been shown by testing these steel that strain rates in the range from 10^{-3} up to 1 s^{-1} do not influence the mechanical properties significantly. Significant strengthening started at strain rates exceeding 2 s^{-1}. It has been shown also that the basic mechanical properties of the coldworked tested steel by 5 to 25 % were not influenced by prestrain at 10^{-3} to 10^{3} s^{-1} strain rates. It is supposed according to the results, that the susceptibility to cold work of these steel was not influenced significantly by the strain rates usually used at coldwork (less than 1 s^{-1}) and that the products after coldwork maintain their mechanical properties.

Key words: *strain rate, mechanical properties, microalloyed steel*

Utjecaj brzine naprezanja na svojstva mikrolegiranog čelika S-MC gradacije. Analiziran je utjecaj brzine naprezanja na svojstva mikrolegiranog čelika za hladno izvlačenje gradacije S 315 MC i S 460 MC. Pokazano je testiranjem tih čelika da brzine naprezanja u opsegu 10^{-3} do 1 s^{-1} ne utječu značajno na mehanička svojstva. Značajno očvršćivanje započinje kod brzina naprezanja iznad 2 s^{-1}. Također je pokazano da osnovna mehanička svojstva hladno obrađenih čelika testiranih pri 5 do 25% ne zavise o prednaprezanju pri 10^{-3} do 10^{3} s^{-1} brzinama naprezanja. Pretpostavljeno je na osnovi rezultata, da osjetljivost na hladnu preradu tih čelika ne zavisi značajno o brzinama naprezanja, koje se uobičajeno koriste pri hladnoj preradi (manje od 1 s^{-1}) i da produkti zadržavaju svoja mehanička svojstva nakon hladne prerade.

Ključne riječi: *brzina naprezanja, mehanička svojstva, mikrolegirani čelik*

INTRODUCTION

The properties of metallic materials are mostly influenced by the applied strain and strain rate. As described in literature the resistance to dislocation movement in the atomic lattice of metallic materials is growing with the growth of the strain rate applied. The result is higher strength properties for higher strain rates, but so the plastic properties are influenced as well [1-4]. The result is a higher probability of strain localisation and fracturing. Deep draw steel plates are classified nowadays by properties as ductility, or deformation strengthening exponent, which given for static strain rates at about 10^{-3} s^{-1}. However, new processing technologies use deformations up to 1 s^{-1}, or higher, and for these it is a need to know „the dynamic" properties of the deep-draw material [5].

E. Čižmárová, J. Micheľ, M. Buršák, Faculty of Metallurgy, Technical University of Košice, Košice, Slovakia, I. Mamuzić, Faculty of Metallurgy, University of Zagreb, Sisak, Croatia

The properties of the final product depend always on the production technology applied, and so also on the strain rate applied either at hot forming or at coldwork [6-8, 11, 12]. The homogeneity of the strain is influenced by the strain rate applied in both macro and microscopic levels [2, 9, 7]. Uneven deformation distribution can lead to quality control problems of product.

The aim of this work is to analyse the influence of strain rate on the susceptibility to deformation and on the final mechanical properties. S-MC steel grades are produced first for coldworked products. We suppose that any data about the influence of strain rate on their properties can be valuable for the application.

EXPERIMENTAL MATERIAL AND METHODS

Hot rolled steel sheets 8 mm thick were tested. The materials used are microalloyed steel grades S 315 MC and S 460 MC. The chemistry and basic mechanical properties are shown in Table 1. and Table 2..

Table 1. **Chemical composition of tested steel [%]**
Tablica 1. **Kemijski sastav ispitanih čelika [%]**

Material	C	Mn	Si	P	S
S 315 MC	0.05	0.87	0.02	0.011	0.007
S 460 MC	0.07	1.53	0.02	0.011	0.004
	Al	Ti	Nb	V	
S 315 MC	0.042	0.011	0.042	-	
S 460 MC	0.050	0.015	0.051	0.082	

Table 2. **Mechanical properties and microstructural parameters of tested steel**
Tablica 2. **Mehanička svojstva i mikrostrukturni parametri ispitanih čelika**

Material	R_e [MPa]	R_m [MPa]	A_5 [%]	Z [%]	KCV [Jcm^{-2}]
S 315 MC	390	477	38	80	360
S 460 MC	537	625	30	76	207
	d [μm]	λ [μm]	P [%]	R_Z [MPa]	R_{PR} [MPa]
S 315 MC	9.0	0.10	3	211	78
S 460 MC	6.0	0.72	1	258	150

The low content of C, P, S and Si, in these steels is the basic condition for good susceptibility to coldwork. The yield strength R_e, ductility A_5 and reduction of area Z are high due to the excellent microstructure design. In fact the tested steel have a microstructure near to one of ferrite, with an even distribution of the precipitates of micro alloying elements in the ferrite matrix as shown in Figure 1. and Figure 2.. The pearlite content (P), and grain size (d) and the mean distance between the precipitates (λ) are given in Table 2.. The yield strength is high due to the ingrain strengthening (R_Z) and precipitation strengthening (R_{PR}), and the values are shown in Table 2.. The adverse influence of precipitates on ductility and toughness is decreased by the very fine grain of the tested steel. The microstructure is appropriate for coldworked products [10].

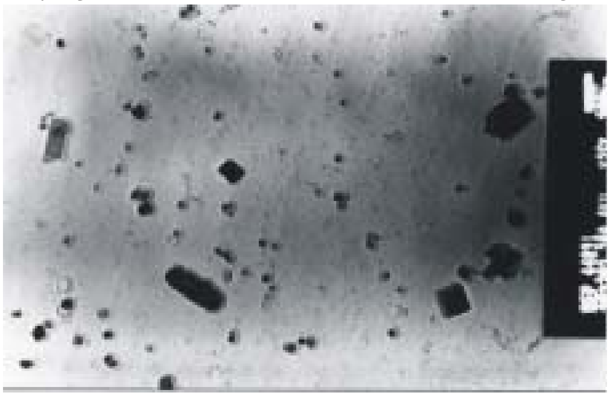

Figure 1. **Substructure of S 315 MC steel**
Slika 1. **Substruktura S 315 MC čelika**

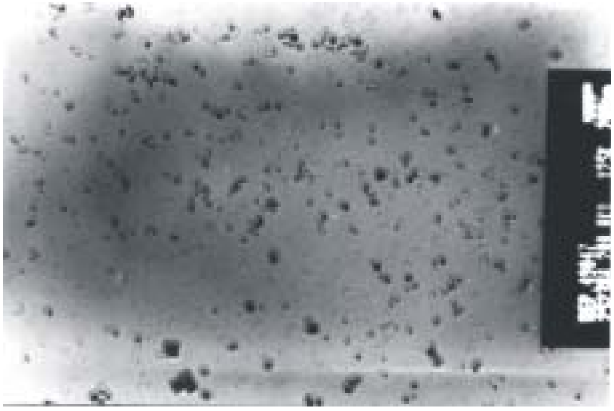

Figure 2. **Substructure of S 460 MC steel**
Slika 2. **Substruktura S 460 MC čelika**

Test plates were cut from the middle of the sheets and test pieces were machined for tensile testing, impact energy testing and fatigue testing. The influence of strain rate on properties was tested by:

- static tensile testing at strain rates from $\dot{\varepsilon} = 3.3x10^{-3}\ s^{-1}$ to $\dot{\varepsilon} = 1\ s^{-1}$ using an universal tester INSTRON 1185,
- tensile testing at $\dot{\varepsilon} = 2.6\ s^{-1}$ on a fatigue tester INSTRON 8511 with test piece of d_0 = 4 mm diameter and L_0 = 20 mm length,
- impact fracture energy testing at up to $2x10^{-4}$ m/s speed using static tester INSTRON 1185,
- impact fracture energy testing at up to 5 m/s speed by Charpy impact tester PSW with test piece of 10x8x55 mm dimension with a V notch,

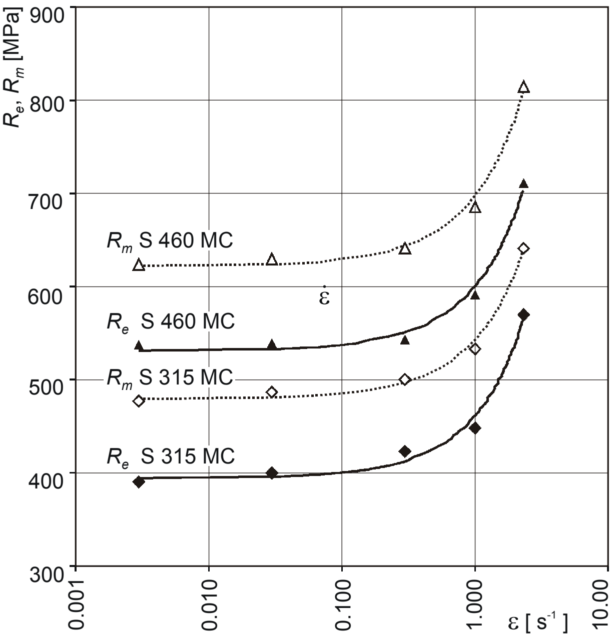

Figure 3. **The influence of strain rate $\dot{\varepsilon}$ on the yield strength and UTS R_m**
Slika 3. **Utjecaj brzine naprezanja $\dot{\varepsilon}$ na brzinu popuštanja i UTS R_m**

- fatigue testing in symmetric tension compression at 30 Hz frequency on the fatigue tester INSTRON 8511.

The influence of the strain rate on the final properties of the tested steel was determined by:

- deformation homogeneity after static tensile strain at the strain rate of 10^{-3} s^{-1} (INSTRON 1185) along the test piece gauge length, and the same for dynamic tensile strain at a strain rate 10^2 s^{-1} (in a special fixture on an PSW impact tester) to total plastic strains of 5, 10, 15, 20, 25 % on test pieces with d_0 = 6 mm, L_0 = 50 mm dimensions,
- static tensile test results ($\dot{\varepsilon}$ =10^{-3}s^{-1}) obtained on predeformed test pieces with different strains (about 5, 10, 15, 20, 25%) and different predeformation loading conditions (static $\dot{\varepsilon}$ =10^{-3}s^{-1} and dynamic $\dot{\varepsilon}$ =10^2 s^{-1}).

RESULTS AND DISCUSSION

The influence of strain rate on strength properties of the tested steel is given in Figure 3. and on deformation properties in Figure 4.. The obtained results are in good agreement with the reparted results. With higher strain rates strengthening was observed for both yield strength R_e and ultimate tensile strength R_m.

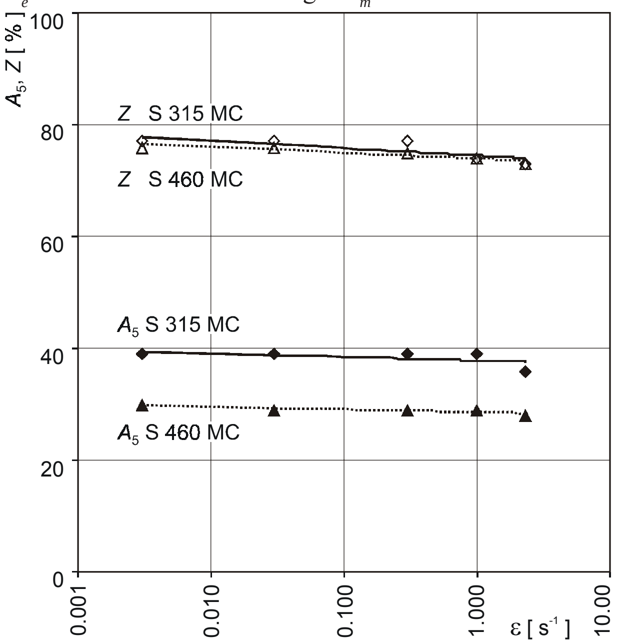

Figure 4. **The influence of strain rate $\dot{\varepsilon}$ on the ductility A_5 and contraction Z**

Slika 4. **Utjecaj brzine naprezanja $\dot{\varepsilon}$ na rastezljivost (ductilnost) A_5 i stezanje Z**

The influence of the strain rate in the range from 10^{-4} to 10^1 s^{-1} on the strength is described by relations:

$$R_e\dot{\varepsilon} = R_e\dot{\varepsilon}_1 e^{C\ln\dot{\varepsilon}}$$

$$R_m\dot{\varepsilon} = R_m\dot{\varepsilon}_1 e^{D\ln\dot{\varepsilon}}$$

where $R_e\dot{\varepsilon}_1 (R_m\dot{\varepsilon}_1)$ is the yield strength at strain rate, C and D are material constants giving the sensitivity of the material to the strain rate. For steel grade S 315 MC they amount: C = 0.1511 and D = 0.1234 and for steel S 460 MC they are C = 0.1155 and D = 0.112 by the fit with a correlation index of 0.95. The steel S 315 MC (softer) is more sensitive to strain rate than the stronger steel grade S 460 MC. An increase of strain rate to 1 s^{-1} from 3.3 10^{-3} s^{-1} for steel S 315 MC led to the yield strength increase from 5 %, to 14 %, while for steel grade S460 MC the yield strength R_e, increased to 11 % from 5 % by the same increase of strain rate. For the strain rate 2.3 s^{-1} the increase of R_e, is 46 % and the increase of R_m is 35 % for steel grade S 315 MC. For the same strain rate for steel grade S 460 MC the increase of R_e is 32 %, and the increase of R_m is 30 %.

A small decrease of ductility A_5 and reduction of area Z was observed with the increase of the strain rate in the applied range (Figure 4.), and for strain rates used in the majority of coldwork (up to 1 s^{-1}) the growth of strength properties is not markedly high.

So we can conclude that the required forming energy will not change significantly for strain rates $\dot{\varepsilon}$ applied by the usual technological forming operations (pressing, deep drawing).

Impact energy on notched specimens was tested by standard Charpy impact test (up to speed of v = 5 m/s) and a comparison was made by static testing (v = 2x10^{-4} m/s) for temperatures ranging from -110 to 20 ° C. The results are shown in Figure 5.. Three test pieces were tested for every temperature and the points in the plot are the calculated mean values.

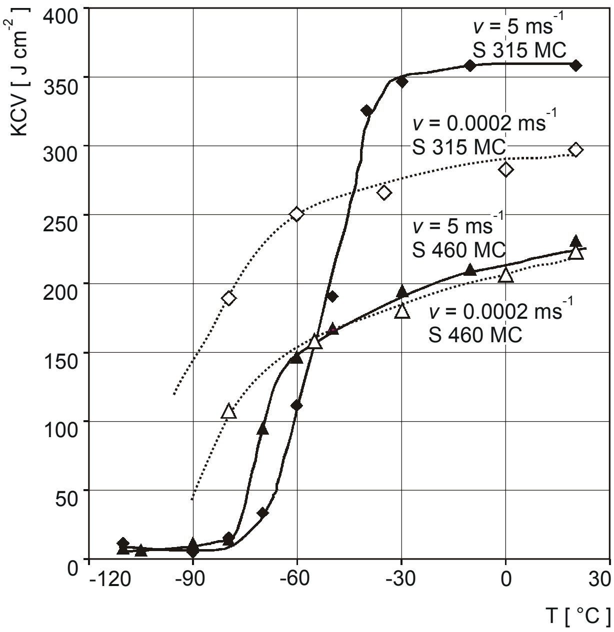

Figure 5. **The temperature dependence of notch toughness KCV**

Slika 5. **Temperaturna zavisnost zarezne čvrstoće KVC**

The deformation energy to fracture at static loading conditions (KCV_s) is for steel S 315 MC 17 % lower and for steel S 460 MC 4 % lower than the impact energy by Charpy test (KCV) at temperatures higher than the transition temperature. The transition temperatures at static loading are markedly lower.

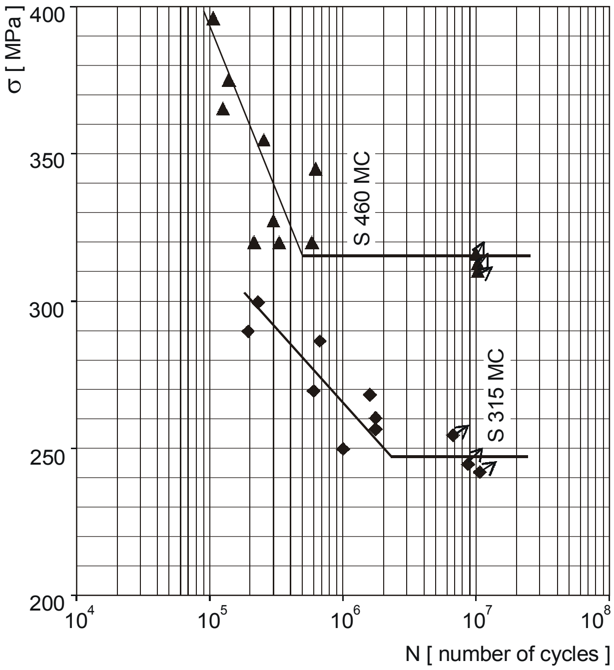

Figure 6. **Wöhler curve et symmetric cycle tension - compression**
Slika 6. **Wöhlerova krivulja simetričnoga ciklusa istezanje - sabijanje**

The sensitivity of the steel to changes in loading speed is expressed by the material constant B from the relation:

$$KCV = B \cdot KCV_s$$

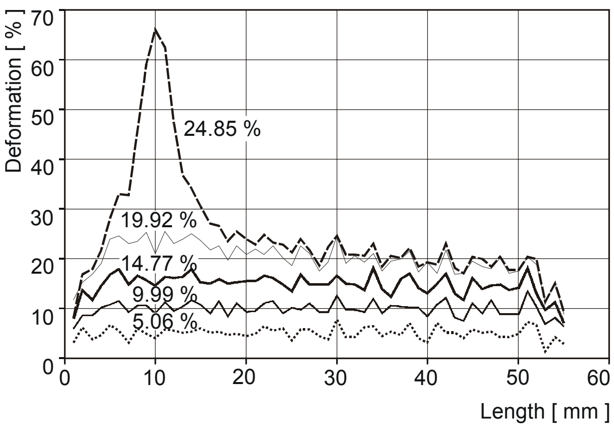

Figure 7. **The distribution of deformation on the length of specimen of S 315 MC steel at different strain degree at static loading**
Slika 7. **Zavisnost raspodjela deformacija od duljine uzorka S 315 MC čelika pri raznim stupnjevima naprezanja statičnog opterećenja**

For steel grade S 315 MC we have got B = 1.2 and for steel S 460 B = 1.036.

The tests on notched specimens showed that higher deformation energy is consumed for forming at dynamic loading conditions. The increase is material dependent. The higher the prime strength of the material the less sensitive it is to dynamic loads. The tests showed also that for the tested materials the transition temperatures are on the safe side from the usual forming temperatures and there is no danger of fast crack propagation.

The fatigue test results are in Figure 6. showing the dependence of the upper stress level s on the number of cycles to fracture N. The fatigue limit was defined as 10^7 at 30 Hz.

Table 3. **Fatigue test results of tested steel**
Tablica 3. **Rezultati ispitivanja zamora čelika**

Steel	R_e [MPa]	At 30 Hz		
		σ_C [MPa]	σ_C / R_e	σ_C / R_m
S 315 MC	390	+248	0.64	0.52
S 460 MC	537	+318	0.59	0.51

The fatigue properties of the tested steel are good, as the results show. The calculated rates σ_C/R_e, and σ_C/R_m are high, due first to the fine grained microstructure.

The influence of the strain rate on the final properties of the tested steel was determined by mechanical properties after prestrain and also by deformation homogeneity evaluation along the test piece gauge length after tensile strain. In Figure 7. the dependence of deformation homogeneity along the test piece gauge length after static de-

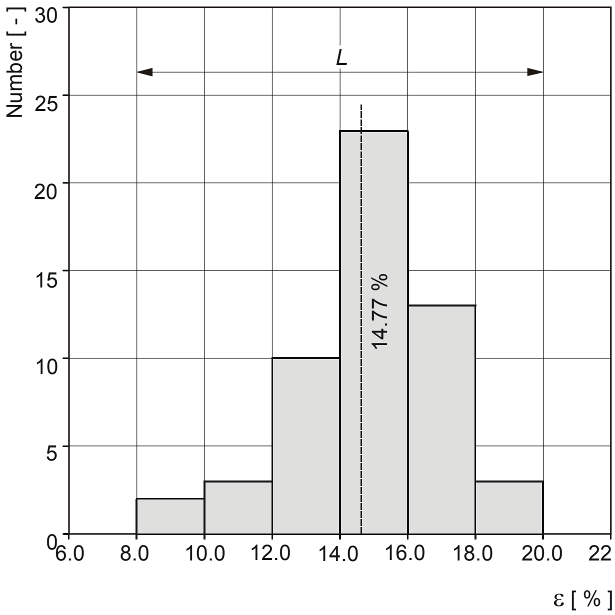

Figure 8. **The histogram of deformation distribution of the length of specimen at medium deformation ε of S 315 MC steel**
Slika 8. **Histogram raspodjele deformacija duljine uzorka pri srednjoj deformaciji ε S 315 MC čelika**

formation (10^{-3} s^{-1}) for different final deformations of the steel grade S 315 MC is given. In Figure 8. the histogram of deformation homogeneity for these steel for a static deformation 14.77 % is presented.

To classify the deformation homogeneity for different mean deformations ε, the mean deviation from homogeneity *M* and the value of variation range of the statistical set *L* (Figure 8.) was used. The M value was calculated from:

$$M = \frac{\sum_{i}^{n} U_x m_x}{n} \quad [\%]$$

where U_x is the deviation in the x-th classified interval of deformation from the interval with the mean value, m_x is the number of elements in the classified interval with deviation U_x, n is the number of elements in the statistical set. The deformation interval 2 % was selected (Figure 9.).

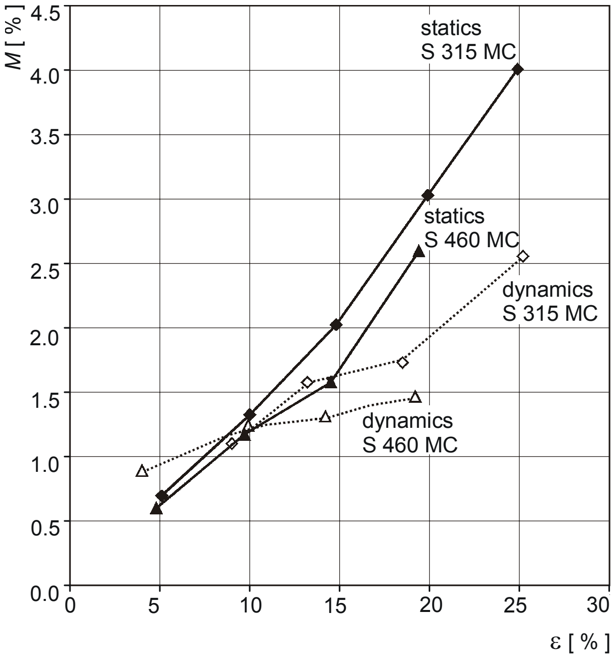

Figure 9. **The dependence of non - uniformity of deformation *M* of the length of specimen at medium degree of deformation ε**

Slika 9. **Zavisnost odstupanja od homogenosti *M* duljine uzorka pri srednjem stupnju deformacije ε**

In Figure 9. and Figure 10. the dependence of the deviation criteria *M* and *L* on the mean deformation for the tested steel are plotted. The analysis showed that the deviation increased with the increase of the mean deformation, and more for S 460 MC steel. For the impact tests the deviation from deformation homogeneity along the test piece for higher mean deformations is lower than for static loading. At tested steel the deformation is not localised into a small area at impact loading (10^2 s^{-1}), which is a valuable property for material produced for coldworked products.

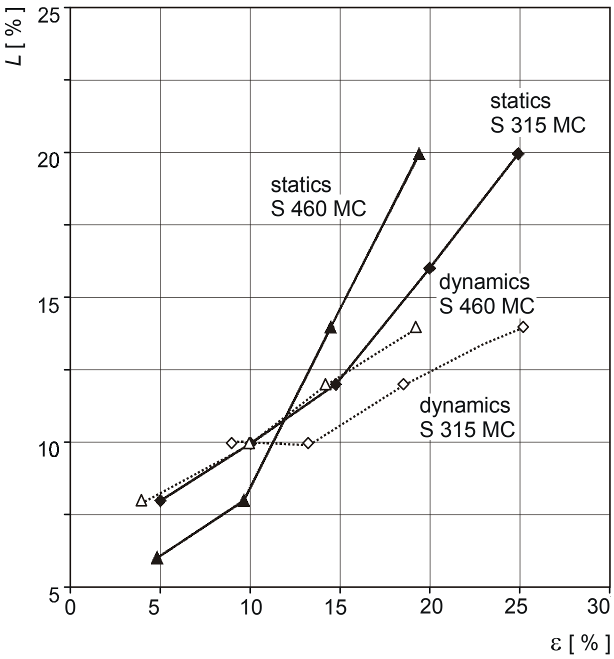

Figure 10. **The dependence of variational interval *L* or on the length of specimen at medium degree of deformation ε**

Slika 10. **Zavisnost varijacijskog intervala *L* duljine uzorka pri srednjem stupnju deformacije ε**

The mechanical properties of the final product are very important. In Figure 11. and Figure 12. are the strength and deformation properties determined by static tensile tests on test pieces prestrained by static (10^{-3} s^{-1}) and dy-

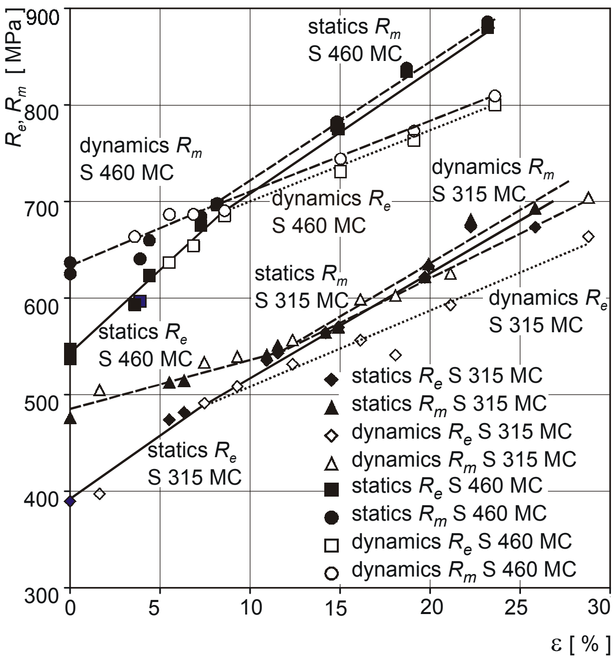

Figure 11. **The dependence of yield strength R_e and UTS R_m on degree of deformation strain hardening**

Slika 11. **Zavisnost brzine popuštanja R_e i UTS R_m od stupnja deformacijskog povećanja tvrdoće naprezanja** namic (10^2 s^{-1}) strain to different mean deformations from 5 to 25 % are given. In Figure 11. it is shown, that with the increase of prestrain ε the strength values R_e and R_m have increased. For small values of prestrain (up to 10%) the values of R_e and R_m are not influenced by the strain rate at predeformation. For higher prestrain values there are differences between R_e and R_m and the values are smaller for the impact prestrain ($\dot{\varepsilon} = 10^2$ s^{-1}). The uneven deformation is generally caused by the applied strain rate [7], but it does not influence the strength value of the prestrained tested steel significantly. The strength values (R_e and R_m) of the tested steel predeformed by static strain to 20 %, are only about 4 to 8 % higher than the strength values of the steel predeformed by dynamic strain.

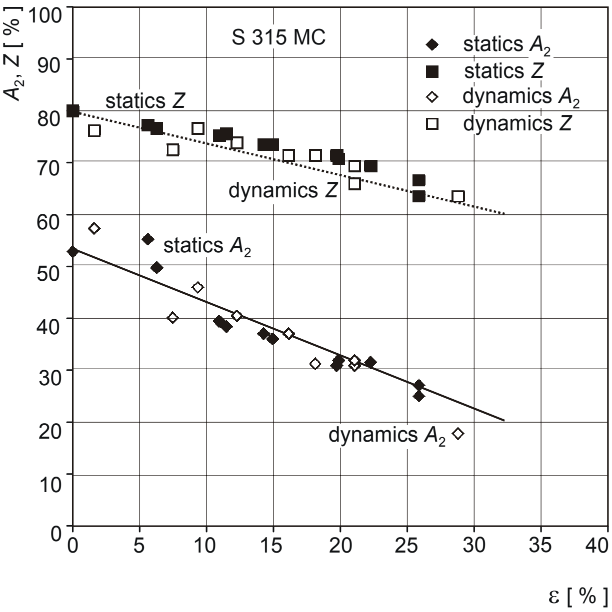

Figure 12. **The dependence of ductility A_2 and contraction Z on the degree of deformation strain hardening of S 315 MC steel**

Slika 12. **Zavisnost rastezljivosti A_2 i stezanja Z od stupnja deformacijskog povećanja tvrdoće naprezanjem za S 315 MC čelik**

The plastic properties are in fact not sensitive to the strain rate applied at predeformation, their dependence on the mean predeformation value ε is shown in Figure 12. and can be expressed by the theoretic at relation:

$$A_2' = A_2 - \varepsilon; \quad Z' = Z\left(1 - \frac{\varepsilon}{1+\varepsilon}\right)$$

where A_2, and Z are the prime values for the material before predeformation.

The experiments showed that the final mechanical properties of the tested steel are not influenced significantly by the strain rate at predeformation in the range from 10^{-3} to 10^2 s^{-1}.

CONCLUSION

The aim of this article was to analyse the influence of strain rate on the properties of S-MC steel grades which prepared for coldworked products. Two steel grades S 315 MC and S 460 MC were tested. The analyses showed:

- the microstructure of these steels is fine grained near to ferrite one phase microstructure with an even distribution of the precipitates of microalloying elements in the ferrite matrix. This microstructure warranted high strength (R_e = 390 MPa, and R_e = 537 MPa) and plasticity (A_5 > 30 %), and high fatigue properties (σ_C/R_e = 0.64, and 0.59),
- for the generally used strain rates from 10^{-4} to 1 s^{-1} only a slight strength growth was measured (R_e, R_m) with the strain rate increase, with no significant change in ductility and reduction of area. So the important property: the deformation energy, is not influenced by strain rate in the given range,
- the change of strain rate from static (10 mm/min) to impact (5 m/s) changed the measured deformation energy to fracture. At temperatures exceeding the transition temperature the Charpy standard impact energy KCV (at 5 m/s) was 17% higher for steel grade S 315 MC), and 4 % higher for steel S 460 MC than the one determined by static loading (at 2x10^{-4} m/s),
- the basic mechanical properties (R_e, R_m, Z, A) of the tested steel prestrained to a mean value of deformation from 5 to 25 % were not influenced significantly by the strain ra-te applied at the prestrain in the range from 10^{-4} to 10^3 s^{-1}.

REFERENCES

1. P. Veles: Mechanické vlastnosti a skúšanie kovov, Alfa, Bratislava, 1989
2. J. Micheľ: Materiálové inžinierstvo, 3 (1996) 2, 22
3. J. Micheľ, I. Mamuzić, M. Buršák: Metallurgy, 35 (1996) 2, 69
4. Metals Handbook, ASME, ISBNO-87170-007-7, Vol. 8, USA, 1985, 187
5. J. Janovec, J. Ziegelheim: Růst užitných vlastnosti automobilových plechů. in: Technológia ´99, Bratislava, Slovakia, 1999, 319
6. J. Elfmark: Plasticita kovů, VŠB, Ostrava, 1984
7. J. Micheľ, E. Čižmárová, S. Oružinská: Kovové materiály 37, 1999
8. L. D. Sokolov: Soprotivlenie metallov plastičesko deformacii, Nauka, Moskva, 1963
9. J. Švejcar: Plastická deformace a zpevnění monokrystalu Fe-36 Ni pri zatežování vysokými rychlostmi. Kandidátska dizertační práce, Brno, Czech Rep., 1986
10. E. Čižmárová, J. Micheľ: Mikrolegované ocele tvárniteľné za studena. in: Transfer 2001, Trenčín, Slovakia, 2001, 119
11. A. Pietriková: Advanced Steels for Railway Carriages, Materiálové inžinierstvo, 1995, 4, 57
12. T. Kvačkaj, at all: Effect of production technological parameters of seamless angle pipes on final quality, Acta Metallurgica Slovaca, 8 (2002) 1, 170