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The Effect of Strain Rate on Mechanical Properties in Microalloyed Steels, Grade S 315 MC and S 460 MC

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Abstract

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

Key words: microalloyed steel, mechanical properties, strain rate

Introduction

The mechanical properties of metallic materials are in majority influenced by the applied strain and strain rate. As it is described in the literature, the resistance to the 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 providing higher strain rates but also the plastic properties are influenced(1-3). The obtained result is a higher probability of strain localisation and fracturing. Deep drawing steel plates are classified nowadays by properties such as ductility or deformation strengthening exponent, which are listed for static strain rates at about 10^{-3} s^{-1}. However, new processing technologies use deformations of products up to 1 s^{-1} or higher and for these it is a must to know “the dynamic” properties of the deep drawing material(4).

The properties of the final product depend always on the production technology applied, and also on the strain rate applied either at hot forming or at cold work(5).

The homogeneity of the strain is influenced by the strain rate applied in both macro and microscopic levels(6-7). Uneven deformation distribution can lead to the final product to quality control problems.

The aim of this work is to analyse the influence of strain rate on the susceptibility to deformation and on the final mechanical properties. Steel grades S-MC are produced previously for cold worked products. We suppose any data about the influence of strain rate on their properties can be valuable for the users.

Materials and Experimental Proceolwa

Hot rolled steel sheets with 8 mm in thickness were tested. The tested materials were microalloyed steel grades S 315 MC and S 460 MC. The chemical compositions and basic mechanical properties are shown in Tables 1 and 2. respectively The low content of C, P, S and Si, in these steels is the basic condition for good susceptibility to cold work. The yield strength Re, ductility A_5 and reduction of area Z are high due to the excellent microstructure design. In fact the tested steels are nearly a one phase microstructure, ferrite, with an even distribution of the precipitates of microalloying elements in the ferrite matrix as shown in Figures 1 and 2.

Table1 Chemical compositions of tested steel

Material	C[%]	Mn[%]	Si[%]	P[%]	S[%]	Al[%]	Ti[%]	Nb[%]	V[%]
S 315 MC	0,05	0,87	0,02	0,011	0,007	0,042	0,011	0,042	-
S 460 MC	0,07	1,53	0,02	0,011	0,004	0,05	0,015	0,051	0,082

Table2 Mechanical properties and microstructural parameters of tested steel.

Material	Re [MPa]	Rm [MPa]	A_5 [%]	Z [%]	KCV [Jcm^{-2}]	d [μm]	λ [μm]	P [%]	R_Z [MPa]	R_{PR} [MPa]
S 315 MC	390	477	38	80	360	9,0	0,10	3	211	78
S 460 MC	537	625	30	76	207	6,0	0,72	1	258	150

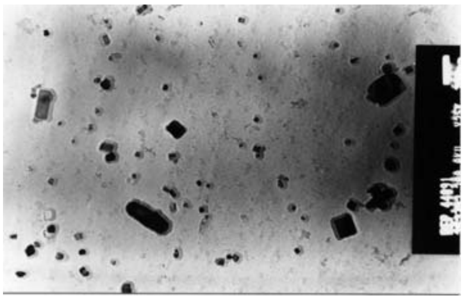

Figure 1. Substructure of S 315 MC steel

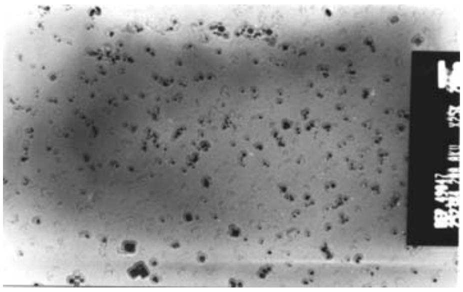

Figure 2. Substructure of S 460 MC steel

The pearlite content (P), and grain size (d) and the mean distance between the precipitates (λ) are shewn in Table2. The yield strength is high due to the in-grain strengthening (R_Z) and precipitation strengthening (R_{PR}), shown in Table 2. The adverse influence of precipitates on ductility and toughness is decreased by the very fine grain in the tested steels. The microstructures are appropriate enough for cold worked products(8).

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

- Static tensile testiat strain rate from $\dot{\varepsilon}$ =3,3.10^{-3} s^{-1} to $\dot{\varepsilon}$ = 1 s^{-1} on an universal tester INSTRON 1185
- Tensile test at $\dot{\varepsilon}$ =2,6 s^{-1} on a fatigue tester INSTRON 8511 with test piece dimension for both steels : diameter d_0 = 4 mm and length L_0 = 20 mm,
- Impact fracture energy test at a top speed of 2.10^{-4} m s^{-1} on a static tester INSTRON 1185,
- Impact fracture energy testing at a top speed of 5 m s^{-1} on a Charpy impact tester PSW with test piece dimension for both steels 10x8x55 mm with a V notch,
- 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 of 10^2 s^{-1} (in a special fixture on an PSW impact tester) to total plastic strains 5, 10, 15, 20, 25 % on test pieces with dimensions d_0 = 6 mm, L_0 = 50 mm
- Static tensile test results ($\dot{\varepsilon}$=$10^{-3}s^{-1}$) obtained on pre-deformed test pieces with different strains (about 5, 10, 15, 20, 25%) and different pre-deformation 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 $\dot{\varepsilon}$ on strength properties of the tested steel is shown shown in Figure 3 and on deformation properties illustrated in Figure 4. The results are in good agreement with the results in references: With higher strain rates $\dot{\varepsilon}$ strengthening was observed for both yield strength R_e and ultimate tensile strength R_m.

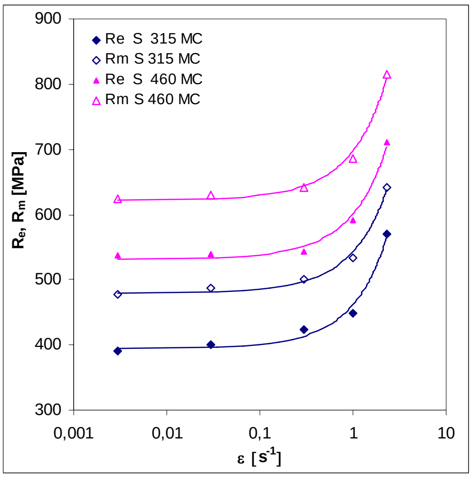

Figure3. The influence of strain rate $\dot{\varepsilon}$ on the yield strength and UTS R_m

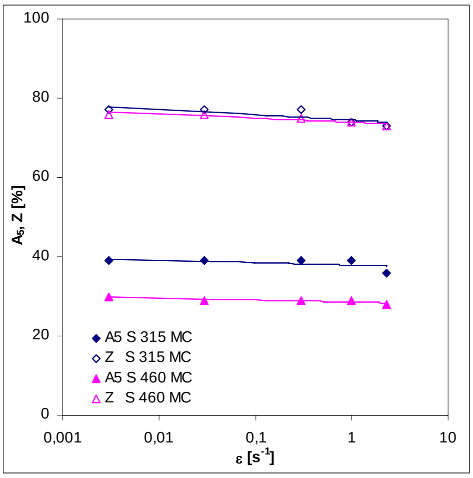

Figure 4. The influence of strain rate $\dot{\varepsilon}$ on the ductility A_5 and contraction Z

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

$$R_{e\,\dot{\varepsilon}} = R_e\dot{\varepsilon}_1\ e^{C\ln\dot{\varepsilon}} \qquad (1)$$

$$R_m\dot{\varepsilon} = R_m\dot{\varepsilon}_1\ e^{D\ln\dot{\varepsilon}} \qquad (2)$$

where $R_e\dot{\varepsilon}_1$ ($R_m\dot{\varepsilon}_1$) is the yield strength at strain rate $\dot{\varepsilon}_1$, C and D are material constants giving the sensitivity of the material to the strain rate. For steel grade S 315 MC C = 0.1511 and D = 0.1234 and for steel S 460 MC 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 % at the same increase of strain rate. For the strain rate 2.3 s^{-1} the increase of R_e, was 46 % and the increase of R_m was 35 % for steel grade S 315 MC. For the same strain rate of steel grade S 460 MC the increase of R_e, was 32 %, and the increase of R_m was 30 %.

A slight decrease of ductility A5 and reduction of area Z was observed with the increase of the strain rate $\dot{\varepsilon}$ in the applied range Figure 4. For strain rates used in the majority of cold work up to 1 s^{-1} the increase of strength properties is not markedly high. Therefore, it can be concluded that the required forming energy will not change significantly for strain rates $\dot{\varepsilon}$ applied in the usual technological forming operations (pressing, deep drawing).

Impact energy on notched specimens was tested by the standard Charpy impact test (top speed v =5 m s^{-1}) and a comparison was made at static testing (v = 2.10^{-4} m s^{-1}) 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.

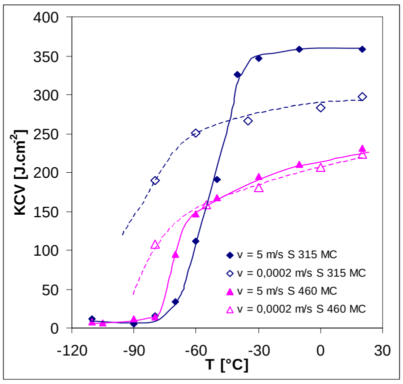

Figure 5. The temperature dependence of notch toughness KCV

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

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

$$KCV = B.\, KCV_s \qquad (3)$$

For steel grade S 315 MC 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 provides the less sensitive to dynamic loads it is. 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 in Figure 6 showed the dependence of the upper stress level σ on the number of cycles to fracture N. The fatigue limit was defined as 10^7 at 30 Hz. The fatigue properties of the tested steel are good as shown. The calculated rates σ_C/R_e, and σ_C/R_m are high, due first to the fine grained microstructure.

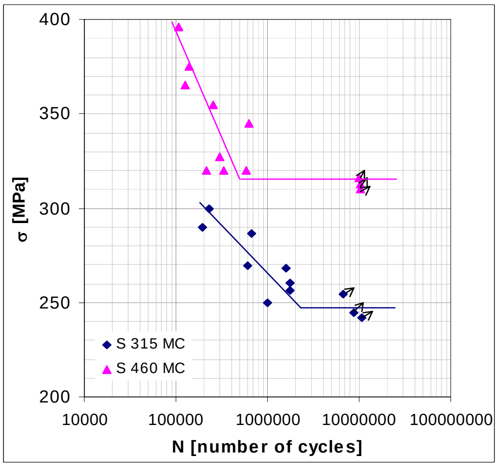

Figure 6. Wöhler curve et symmetric cycle tension – compression

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. Figure 7 is the dependence of deformation homogeneity along the test piece gauge length after static deformation (10^{-3} s^{-1}) for different final deformations of the steel grade S 315 MC. Figure 8 is the histogram of deformation homogeneity for these steels for a static deformation of 14.77 %.

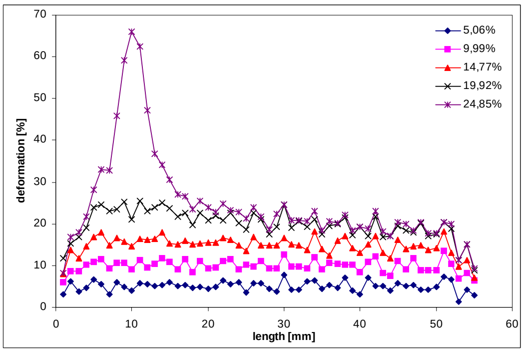

Figure7. The distribution of deformation on the length of specimen of S 315 MC steel at different strain degree at static loading

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 was calculated from

$$M = \frac{\Sigma_i^n U_x m_x}{n} \qquad [\,\%\,] \qquad (4)$$

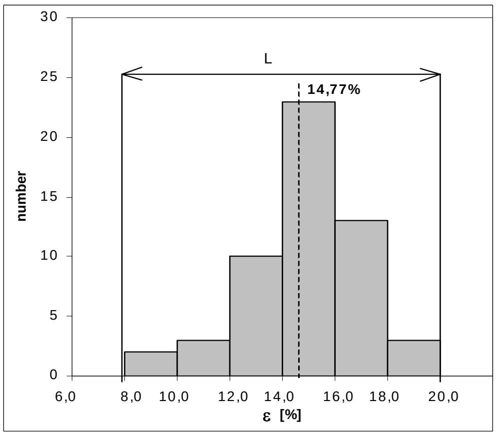

Figure 8. The histogram of deformation distribution on the length of specimen at medium deformation ε = 14,77% of S 315 MC steel

where U_x is the deviation in the x-t 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 and n is the number of elements in the statistical set. The deformation interval 2 % was selected Figure 9.

In Figures 9 and 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 steel S 460 MC. For the impact tests the deviation from deformation homogeneity along the test piece for higher mean deformations is lower than for static loading. In the tested steel, the deformation is not localized into a small area at impact loading ($10^2 s^{-1}$), a valuable property for material produced for cold worked products.

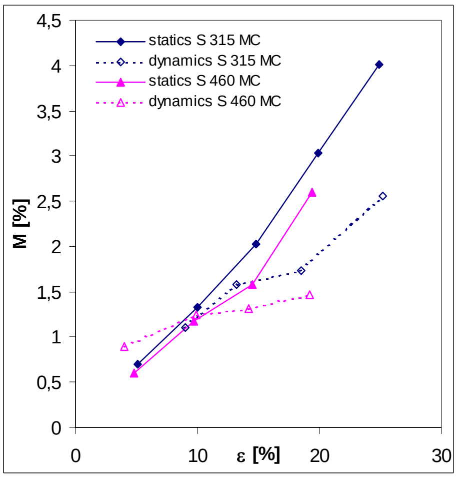

Figure 9. The dependence of deviation from homogeneity M or on the length of specimen at medium degree of deformation ε

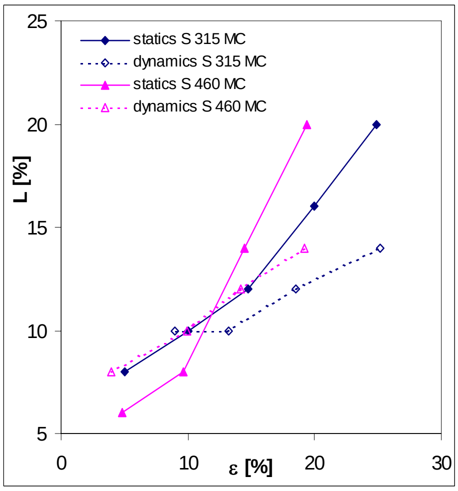

Figure10. The dependence of variational interval L or on the length of specimen at medium degree of deformation ε

Table 3. Fatigue test results of tested steel

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 mechanical properties of the final product are very important. Figures 11 and 12. show the strength and deformation properties determined by static tensile tests on test pieces prestrained by static ($10^{-3}s^{-1}$) and dynamic ($10^2 s^{-1}$) strain to different mean deformations from 5 to 25 %. Figure 11 shows, that the increase of prestrain ε results in the strength values R_e and R_m being 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 in general caused by the applied strain rate $\dot{\varepsilon}^{(9)}$, but it does not influence on 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.

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 relation:

$$A'_2 = A_2 - \varepsilon\,, \qquad Z' = Z\,(1 - \frac{\varepsilon}{1+\varepsilon}),$$

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 $10^{2}s^{-1}$.

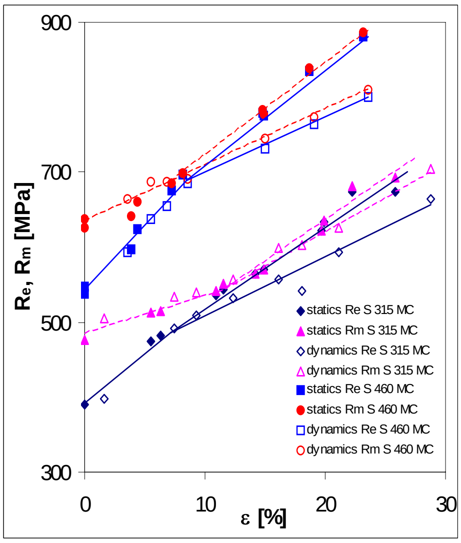

Figure11. The dependence of yield strength R_e an UTS R_m on degree of deformation strain

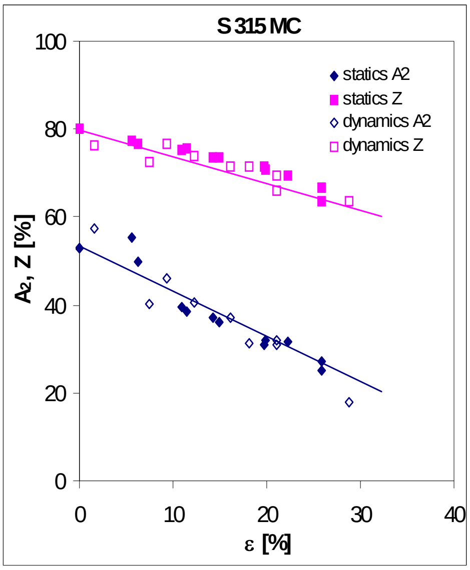

Figure12. The dependence of ductility A_2 and contraction Z on the degree of hardening deformation strain hardening of S 315 MC

Conclusion

The aim of this work was to determine the influence of strain rate on the properties of steel grades S-MC which are produced for cold-worked products. Two steel grades were tested, S315 MC and S 460 MC. The reselts showed that:

1. The microstructure of these steels is fine grain, nearly a one phase microstructure, ferrite, with an even distribution of the precipitates of microalloying elements in the ferrite matrix. This microstructure design 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).

2. For the generally used strain rates from 10^{-4} to1 s^{-1}, only a slight strength increase is measured (R_e, R_m), and with a the strain rate increase, there is no significant change in ductility and reduction of area. This important property shows that the deformation energy is not influenced by strain rate in the given range.

3. The change of strain rate from static (10 mm/min) to impact (5 m/s^{-1}) changed the measured deformation energy to fracture. At temperatures exceeding the transition temperature the Charpy standard impact energy KCV (at 5.m/s^{-1}) was 17% higher for steel grade S 315 MC), and 4 % higher for steel S 460 MC than that determined by static loading (at 2.10^{-4} ms^{-1}).

4. 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 rate applied at the prestrain in the range from 10^{-4} to 10^{3} s^{-1}.

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