FATIGUE PROPERTIES OF LOW CARBON STEEL STRENGTHENED BY STATIC OR DYNAMIC WORK HARDENING

UTRUJENOSTNE LASTNOSTI MALOOGLJIČNEGA JEKLA UTRJENEGA S STATIČNO IN DINAMIČNO DEFORMACIJO

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The influence of strain rate on mechanical properties and fatigue resistance of low carbon steel (C content 0.04%) is shown. Experimental results are analyzed and relations derived describing the dependence of yield strength and ultimate tensile strength on prior strain rate in the range from 10^{-3} to 10^3 s^{-1}. The effect on fatigue resistance was analyzed, too. The impact hardened steel showed higher fatigue properties. Explanations are sought analyzing differences in microstructure and substructure of steel work hardened by static or impact strain.

Key words: low carbon steel, static and dynamic work hardening, static properties, fatigue properties

Določen je vpliv hitrosti hladne utrditve na mehanske lastnosti in odpornost proti utrujenosti za jeklo 0,04% C. Analizirani so eksperimentalni rezultati in razvite so enačbe, ki povezujejo mejo plastičnosti in natezno trdnost s hitrostjo predhodne hladne deformacije v razponu od 10^{-3} do 10^3 s^{-1}. Tudi vpliv na odpornost proti utrujenosti je analiziran. Udarno deformirano jeklo je pokazalo večje utrujenostne lastnosti. Razlaga se išče v razliki v mikrostrukturi in podstrukturi jekla, ki je bilo statično in dinamično deformacijsko utrjeno.

Ključne besede: malo ogljično jeklo, statična in dinamična deformacijska utrditev, statične lastnosti, utrujenostne lastnosti

1 INTRODUCTION

The loading rate influences the deformation process and changes the final properties of the metal. The strain resistance is growing with the increase of the strain rate. The loading rate changes also the plastic properties and the microstructure of the deformed material[1,6,10,11,12].

Several works reported on the dependence of fatigue resistance on the previous plastic deformation. In general, plastic deformation influences the quality of the surface and affects throught it the fatigue process[2,3]. Furtherly, plastic deformation changes the structure and the mechanical properties of the material, and changes the stress distribution in the product too[3,4,5]. Generally, higher work hardening increases the fatigue limit, though it does not always improve other fatigue properties. The influence depends also on the amount of straining applied. For low amounts of deformation the influence is ambiguous[1,3,6].

The aim of the work was to show the importance of work hardening strain rate. The strain rate affects surface quality, microstructure, and stress distribution in the work hardened material, and consequently, also the fatigue resistance.

2 EXPERIMENTAL MATERIAL AND METHODS

The experiments were performed on low carbon steel (C 0.04%) rods with an initial diameter of 16 mm. The heat treatment consisted of the annealing at 950°C for 60 min and air cooling. It produced a polyhedral ferrite-pearlite microstructure, with a mean ferrite grain size of 0.031 mm and 5 vol.% of lamellar pearlite. The mechanical properties were as follows: R_e = 210 MPa, R_m = 310 MPa, A_5 = 46%, Z = 84%.

Rods of 12 mm in diameter were drawn with 10% reduction and two strain rates: ε_s=2.10^{-2} s^{-1} on a universal tensile test machine ZDM10, and ε_d=2.10^2 s^{-1} on a drop weight impact test machine. The work hardened rods were then machined into test pieces and fatigue tested. The fatigue limit (σ_{CO}) was determined by rotational bending with the frequency of 24 Hz. Tensile test pieces were loaded with symmetric cycling σ_a = ± 150 MPa at 16.6 Hz to 10^4 and 5.10^4 cycles. After fatigue loading the tensile testing was applied to evaluate the influence of cycling testing on mechanical properties. By tensile testing test pieces d_0 = 4 mm and L_0 = 20 mm, and different strain rates, from ε = 10^{-3} s^{-1} to ε = 2,5 10^3 s^{-1} were used.

3 RESULTS

The mechanical properties: yield strength R_e, ultimate tensile strength R_m, elongation A_5 and reduction of area Z are plotted in **Figure 1** in dependence on the work hardening strain rate. The strength grows with the growth of strain rate, and the growth is faster at higher dynamic strain rates (ε > 1 s^{-1}). While the reduction of area Z did not show significant changes, the elongation A_5 decreased for high strain rates ε > 1 s^{-1}.
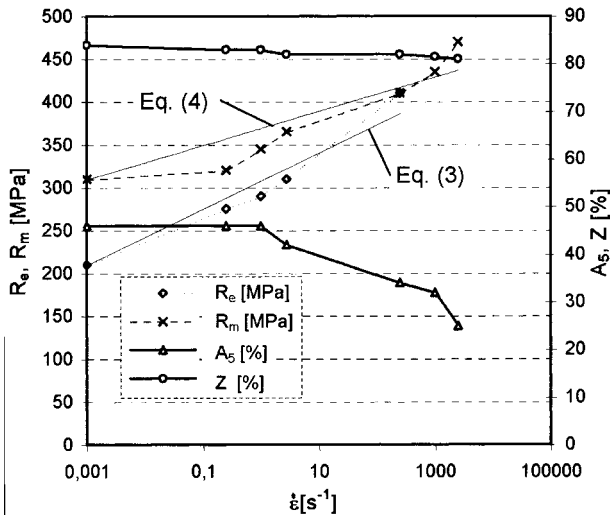
Figure 1: Dependence of mechanical properties on work hardening strain rate for a low carbon steel
Slika 1: Vpliv hitrosti deformacijske utrditve na mehanske lastnosti maloogljičnega jekla

The aim of this contribution was also to find a mathematic description of the influence of strain rate on mechanical properties. Different formulas are proposed in references: The best fits were obtained with equations:

$$R_\varepsilon = R_{\varepsilon 0} + A \log(\varepsilon/\varepsilon_0) \quad (1)$$

$$R_\varepsilon = R_{\varepsilon 0} + K.\log(\varepsilon/\varepsilon_0)^n \quad (2)$$

with:

R_ε the strength (R_e, or R_m) at the strain rate ε,

$R_{\varepsilon 0}$ the strengt for the static strain ε_0,

A, K and n are constants of rate induced stress increase

For the tested steel the equations (1) and (2) into the form correspond with a correlation coefficient 0.95 into the form:
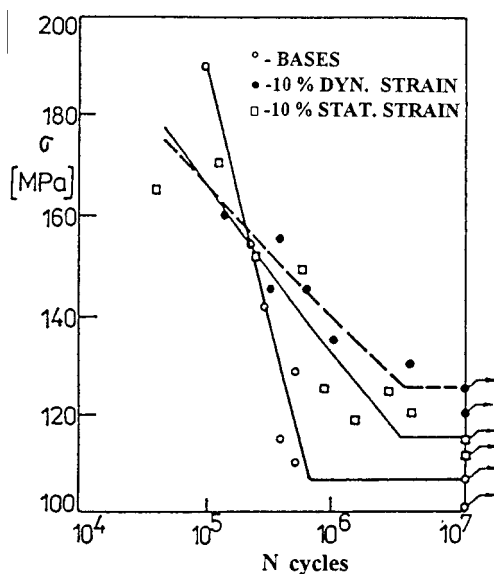

Figure 2: Woehler curves for a low carbon steel
Slika 2: Wöhlerjeva krivulja za maloogljično jeklo

$$R_{e\varepsilon} = 210+32.7 \log(\varepsilon/\varepsilon_0); \ R_{e\varepsilon} = 210+19.8 \log(\varepsilon/\varepsilon_0)^{2.49} \quad (3)$$

$$R_{m\varepsilon} = 310+20.0 \log(\varepsilon/\varepsilon_0); \ R_{m\varepsilon} = 310+9.4 \log(\varepsilon/\varepsilon_0)^{2.1} \quad (4)$$

In the interval of tested strain rate from $\varepsilon=10^{-3}$ s^{-1} to $\varepsilon=10^3$ s^{-1} the value of R_e and R_m can be predicted by these equations with small deviations.

The fatigue properties of the tested steel σ_h - N (Woehler curve) in dependence on the previous static ($\varepsilon_s = 2.10^{-2}$ s^{-1}) and dynamic ($\varepsilon_d = 2.10^2$ s^{-1}) work hardening are shown in **Figure 2**. As shown the 10% tensile plastic deformation increased the fatigue limit σ_{C0}, changed the slope of the Woehler curve and increased the scatter. The changes are influenced by the work hardening strain rate. The declined part of the Woehler's curve is typically expressed by a relation of the form logN = a + b.σ. The statistics of the influence are in **Table 1**.

Table 1: Fatigue statistics parameters of the tested steel

Condition	a	b	σ_{C0} (MPa)	$\Delta\sigma_{C0}$ (MPa)	$\Delta\sigma_{C0}$ (%)
initial	6,935	-0,0103	±107	-	-
10% dynamic strainε_s=2.10^{-2}s^{-1}	10,115	-0,0313	±116	9	8
10% static strain ε_d=2.10^{2}s^{-1}	11,334	-0,0384	±126	19	15

The stress - strain curves in **Figure 3** were obtained by tensile testing the material previously work hardened and then fatigue tested with symmetric tension/compression $\sigma_a = \pm 150$ MPa at 16.6 Hz to 10^4 and 5.10^4 cycles. The steel was softened (ΔR) by the long time cycling (to N = 10^4, and 5.10^4 cycles). The softening ΔR was measured at tensile testing to 0.5% and 3% strain. The dependence of softening ΔR on the number of cycles N applied is in **Figure 4**. It shows that ΔR depends on both, the number of cycles and the rate of previous work hardening. The saturation of softening is apparent at 5.10^4 cycles. To this limit are related the measured softening values given in **Table 2**.

Table 2: Softening by cycling of the tested work hardened steel

Condition	$R_{0.5}$ (MPa)	R_3 (MPa)	$\Delta R_{0.5}$ (MPa)	ΔR_3 (MPa)	$\Delta R_{0.5}$ (MPa)	ΔR_3 (%)
10% stat.strain N=0	365	400	-	-	-	-
10% stat.strain N=5.10^4	270	323	95	77	26	19
10% dyn.strain N=0	303	372	-	-	-	-
10% dyn.strain N=5.10^4	233	320	70	52	23	14

The cycling softening is stronger by the deformation level of 0.5%, while around the yield point, the higher is the strain the less distinct is the softening. UTS practically is not affected by cycling. The relative softening
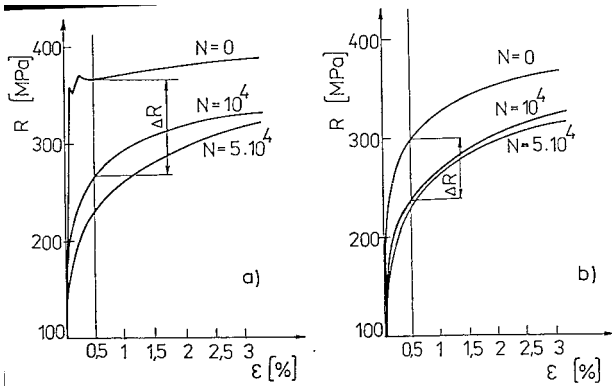
Figure 3: Stress-strain curves in tension for a low carbon steel after static (3a) and dynamic (3b) work hardening by cycling at $\sigma_a = \pm150$ MPa

Slika 3: Krivulje napetost-deformacija za nateg za maloogljično jeklo po statični (3a) in dinamični (3b) deformacijski utrditvi s cikliranjem pri $\sigma_a = \pm150$ MPa

ΔR is from 3% to 5% lesser in impact work hardened steel.

4 DISCUSSION

The results confirm the general rule - increasing the work hardening strain rate yield strength R_e and tensile strength R_m are increased also. The effect of strain rate is strongly dependent on steel microstructure. In equation (1) the strain rate intensity is expressed through the parameter A. If the values R_e and R_m represent the tested volume of the solid, then A can be calculated as function of R_e or R_m. Since values of $A_e = 31$ for R_e and $A_m = 15$ for R_m were obtained, it is than calculated:

$$A_e/R_e = 0.7 - 0.238 \cdot \log R_e \quad (5)$$

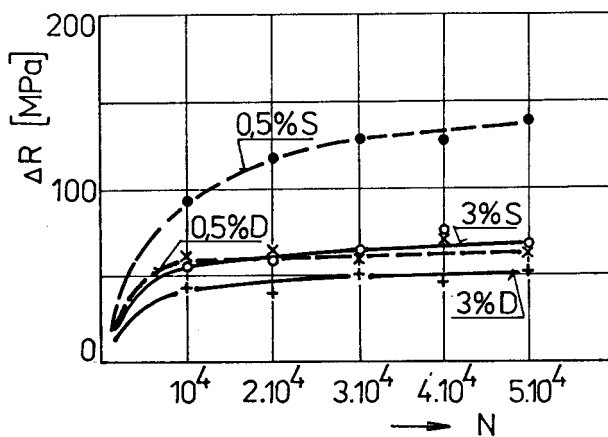$$A_m/R_m = 0.237 - 0.076 \cdot \log R_m \quad (6)$$

Figure 4: Cycling softening ΔR influenced by static (S) and dynamic (D) work hardening. Low carbon steel

Slika 4: Ciklično mehčanje ΔR v odvisnosti od statične (S) in dinamične (D) deformacijske utrditve. Maloogljično jeklo

Both equations describe the relative influence of strain rate on strength values. The higher the strength, the lower is the relative influence of strain rate.

Previous 10% strain increased fatigue limit and it causened also softening by cycling, all in good agreement with reported data. Our results show that these caracteristics are also strain rate dependent.

The plastic deformation is not uniform all over the deformed body, which yields in bands between not deformed areas[7,8]. The deformation is influenced by internal and external factors. To the external factors belong temperature, strain rate, and the applied amount of strain, while the internal factors are the properties of the work hardened material, strain process, and microstructure.

Therefore, the answer to the question, why is the fatigue limit σ_{C0} of the dynamic work hardened steel 7% higher than that of the static work hardened, is to be sought in the micro structure and substructure of the steel. As already reported[7,9], the dynamic plastic deformation is more uniform from the point of view of microstructure and substructure. This is shown also by the micrographs in **Figure 5 and 8**. The sub-micrographs show that after 10% of static strain cell pattern are well developed and the dislocation distribution in the cells is not uniform. After 10% of dynamic strain cell pattern are not completely developed, the cells are smaller and contain fewer dislocations. The mean cell size is for static strain 950 nm, and that for dynamic strain 615 nm. Cell pattern develop by greater deformation. By 25% of strain the
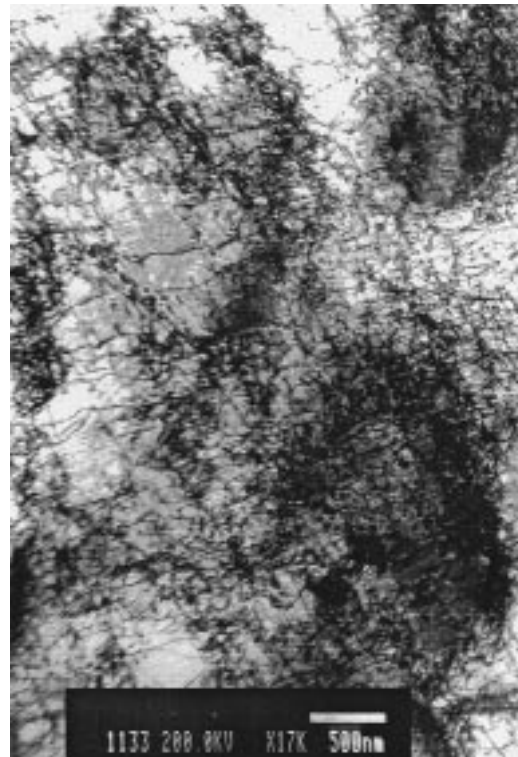

Figure 5: Substructure of a low carbon steel after static elongation 10% in tension

Slika 5: Podstruktura maloogljičnega jekla po 10% statičnem raztegu
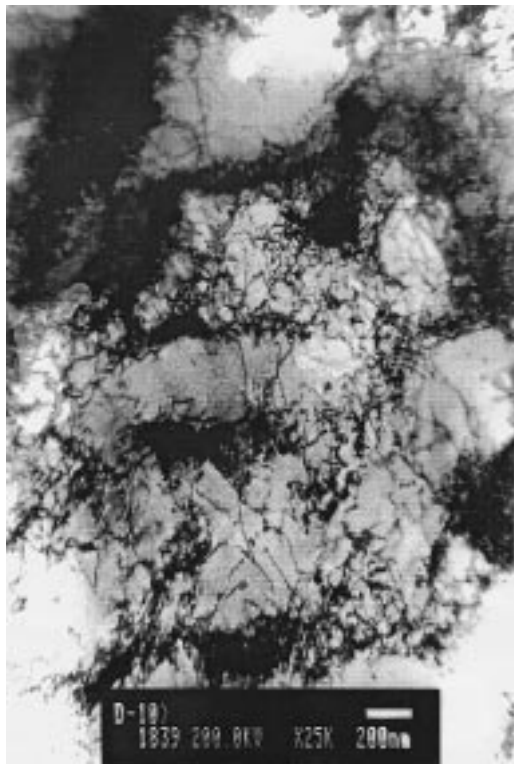
Figure 6: Substructure of a low carbon steel after dynamic elongation 10% in tension
Slika 6: Podstruktura maloogljičnega jekla po dinamičnem 10% raztegu

Figure 8: Microstructure of a low carbon steel after dynamic elongation 10% in tension
Slika 8: Mikrostruktura maloogljičnega jekla po 10% dinamičnem raztegu

Figure 7: Microstructure of a low carbon steel after static elongation 10% in tension
Slika 7: Mikrostruktura maloogljičnega jekla po 10% statičnem raztegu
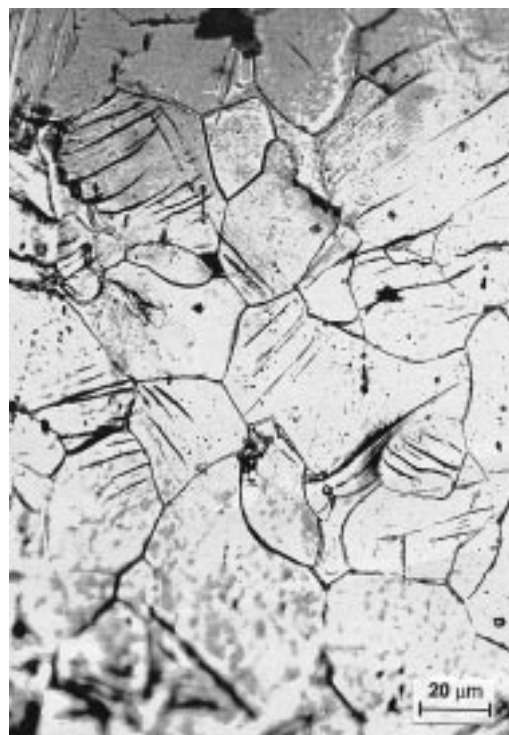

Figure 9: Microstructure of a low carbon steel after dynamic elongation 10% in tension and subsequent fatigue testing at $\sigma_a = \pm150$ MPa for $N = 6.10^4$ cycles
Slika 9: Mikrostruktura maloogljičnega jekla po dinamičnem 10% raztegu in po utrujenostnem obremenjevanju pri $\sigma_a = \pm150$ MPa z $N = 6.10^4$ ciklov

mean cell size decreased to 615 nm for static and 480 nm for dynamic strain and the distribution of dislocations in the cells is more uniform. The sliding bands are finer after dynamic plastic deformation **(Figure 7)**, and cover a larger area (more grains), than after static deformation **(Figure 8)**. In cycling work strengthened steel fatigue slide bands after dynamic strain are wider due to the more uniform plastic deformation, as shown in **Figure 9**. In steel work hardened by static strain new fatigue slide bands were not found. It is supposed that such bands developed inside the wide slide bands due to the previous static strain.

5 CONCLUSIONS

The aim of this paper was to analyze the influence of strain rate by work hardening on mechanical and fatigue properties of a low carbon steel.

Taking into account the results and discussion it is concluded:

– at tensile testing the increase of strain rate from static $\varepsilon = 10^{-3}$ s^{-1} to impact $\varepsilon = 2.10^2$ s^{-1} increased the yield point by 95%, UTS by 32%, elongation decreased by 26%, while the reduction of area did not change;

– the work hardening increased both, the short time as well as the conventional fatigue limits. The increase is work hardening strain rate dependent. A 10% static work hardening increased the fatigue limit by 8%, while by dynamic work hardening the increase was of 15%;

– the softening is observed in cycling work hardened steel. It increases grows with the number of cycles applied to a saturation limit. The value depends on the previous work hardening strain rate. Impact hardened steel is prone to softening;

– the influence of work hardening strain rate on fatigue properties is due to the increase of homogeneity of deformation distribution with the increase of strain rate; and

– the higher the strain rate at work hardening, the higher the beneficial effect on fatigue properties.

6 REFERENCES

[1] L. O. Sokolov, Soprotivlenije metallov plastitseskoj deformácii, Nauka, Moskva 1963

[2] V. Sedláçek: Unava hliníkovych a titanovych slitin, SNTL, Praha, 1989

[3] A. Puskár: Vysokofrekvencná unava materiálov, DU, Zilina, 1997

[4] K. Klesnil, P. Lukás: Unava kovovych materiálu, AKADEMIA Praha 1975

[5] L. Kunz: Mikrostrukturní aspekty kovu, Thesis work, Brno, 1996

[6] J. Michel, M. Bursák, I. Mamuzić: *Metalurgija*, 35 (1996) 2, 69-72

[7] V. Sedlácek: Nehomogenita plasticke deformace. In. "Deformácia a lom kovovych sustav", DT CSVTS Kosice 1989

[8] A. Puskár: Mikroplasticnost a porusenie kovovych materiálov, VEDA Bratislava, 1986

[9] J. Michel: *Materiálove inzinierstvo*, 3 (1996) 2, 22

[10] Metals Handbook, Vol 8, ASME, ISBN 0-87170-007-7, USA, 1985

[11] T. Kvackaj, I. Pokorny: Mathematical model of stress - strain curves, *Metalurgija*, 4 (1995) 145-149

[12] T. Kvackaj: Tepelne deformacny rezim v priebehu prvej fázy riadeneho valcovania, *Hutnik* 2 (1985) 50-53