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ESTIMATION OF CYCLIC STRESS-STRAIN CURVES FOR LOW-ALLOY STEEL FROM HARDNESS

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This article describes investigations into the existence of correlation between experimentally determined cyclic parameters and hardness of quenched and tempered representative low-alloy steel 42CrMo4. A good correlation was found to exist between cyclic strength coefficient *K'* and Brinell hardness *HB*, but not between cyclic strain hardening exponent *nž* and hardness *HB*. Nevertheless, good agreement between calculated and experimental cyclic stress-strain curves shows that cyclic parameters i.e. cyclic stress-strain curves of the investigated steel can be successfully estimated from its hardness.

Key words: cyclic loading, stress-strain curves, hardness, estimation

Procjena cikličkih krivulja naprezanje-deformacija niskolegiranog čelika na osnovi tvrdoće. U radu je istraženo postojanje korelacije između eksperimentalnih vrijednosti cikličkih parametara i tvrdoće poboljšanog niskolegiranog čelika 42CrMo4. Ustanovljena je dobra koreliranost koeficijenta cikličke čvrstoće *K'* i Brinellove tvrdoće *HB*, ali ne i eksponenta cikličkog deformacijskog očvršćivanja *n'* i tvrdoću *HB*. Usprkos tome, dobivenim cikličkim krivuljama naprezanje-deformacija pokazano je da se ciklički parametri i njima definirane cikličke krivulje naprezanje-deformacija ispitivanog čelika sa zadovoljavajućom točnošću mogu procjenjivati već i samo na osnovi njegove tvrdoće.

Ključne riječi: cikličko opterećenje, krivulje naprezanje-deformacija, tvrdoća, procjena

INTRODUCTION

In order to shorten product development time and cut down expenses, simulations and virtual testing of product models are increasingly being performed during early stages of product development cycle, while different versions are still being considered. One of the most important design decisions which must be made at that point is the proper choice of material. For modelling and simulation of response of dynamically loaded structures and components, cyclic and fatigue properties which describe material behaviour must be known. The experiment-based determination of their values is certainly the most accurate one. However, due to complexities and high costs of cyclic experiments, especially if more materials are taken into consideration, it quickly becomes prohibitive. Since monotonic experiments are simple, inexpensive and usually readily available, advantages of using simple tensile data and hardness for estimation of cyclic and fatigue properties is obvious. For estimation of strain-based approach fatigue properties from monotonic material properties, number of methods were suggested [1-5] and reviewed [5-7].

This points to the fact that the need for such solutions exists. Although no suggestions were given for direct estimation of cyclic properties i.e. cyclic material behaviour from monotonic properties, such possibility would certainly contribute to improve product design, especially in early stages of development. This work describes investigations of correlations between experimentally determined cyclic parameters and hardness of low-alloy steel 42CrMo4.

CYCLIC STRESS-STRAIN CURVES

Stress-strain response of cyclically loaded material can be quite different from the one when it is loaded monotonically. During loading, material can exhibit strain hardening, strain softening, its response can be stable and in some cases it can even behave differently in various loading phases. The well accepted and widely used method of describing stress-strain response of most cyclically loaded metal materials is stabilized or mid-life true stress - true strain curve. It can be determined from strain-controlled cyclic experiments performed on a number of standard material specimens [8]. The set of representative hysteresis curves, resulting cyclic stress-strain curve and monotonic stress-strain curve are shown in Figure 1.

General methodology and exact procedure for determination of material stress-strain response to completely reversed, cyclic, uniaxial, tensile-compressive

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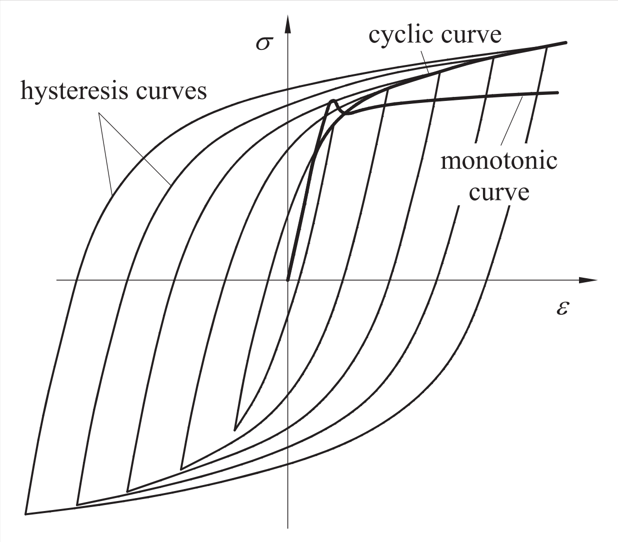

Figure 1. Stress-strain curves

loading are given in [9]. Cyclic stress-strain curves of most metals can be successfully represented with Ramberg-Osgood equation [8]:

$$\frac{\Delta\varepsilon}{2}=\frac{\Delta\varepsilon_e}{2}+\frac{\Delta\varepsilon_p}{2}=\frac{\Delta\sigma}{2E}+\left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}} \qquad (1)$$

where: $\Delta\varepsilon$ - true total strain range, $\Delta\varepsilon_e$ - true elastic strain range, $\Delta\varepsilon_p$ - true plastic strain range, $\Delta\sigma$ - stress range, E - modulus of elasticity, $K'=\frac{\Delta\sigma}{2}+\left(\frac{\Delta\varepsilon_p}{2}\right)^{-n'}$ - cyclic strength coefficient, n' - cyclic strain hardening exponent.

MATERIAL DATA

The chosen material is high-strength low-alloy steel 42CrMo4 (ISO 683/1; AISI4140; W.Nr. 1.7225) which is typically used for production of various highly-loaded machine components and elements such as gears, rolling bearings, shafts and cams. Its chemical composition is given in Table 1.

Table 1. **Chemical composition of steel 42CrMo4 / wt. %**

C	Si	Mn	P	S	Cr
0,43	0,26	0,65	0,015	0,021	1,07
Ni	Mo	Cu	Al	Sn	
0,19	0,16	0,16	0,021	0,006	

Required data i.e. hardness, monotonic and cyclic properties, determined from results of own experiments [10] were supplemented with those acquired from available literature [11-15]. In total, necessary data were gathered for 40 normalized and quenched and tempered 42CrMo4 steels.

Values of Brinell hardness *HB* cover rather wide range, starting from 186 HB and ending with 670 HB. Hardness *HB*, ultimate strength R_m, cyclic strength coefficient K' and cyclic strain hardening exponent n' are given in Table 2.

Table 2. **Hardness, monotonic and cyclic parameters of steel 42CrMo4**

HB	E/MPa	R_m/MPA	K'/MPa	n'/-
186	205000	665	957	0,1808
220	190500	740	673	0,115
220	190500	740	637	0,097
199	190500	735	807	0,087
276	206000	925	1448	0,16
282	197000	900	1062	0,0866
290	190500	940	1086	0,079
290	190500	940	789	0,054
293	207000	848	1084	0,082
332	190500	1120	1234	0,065
332	190500	1120	1097	0,067
332	211400	1111	1367	0,104
332	211400	1111	2400	0,206
332	211400	1111	1146	0,084
343	206000	1100	1420	0,12
359	206000	1102	1670	0,16
381	206842	1410	1974	0,14
381	207000	1413	2266	0,124
400	200000	1551	1756	0,098
400	199000	1550	1556	0,07
430	206000	1402	2243	0,17
450	206842	1760	2251	0,12
450	207000	1758	1997	0,088
450	200000	1929	1910	0,088
450	206000	1757	2359	0,11
450	199000	1929	2000	0,1
475	206842	1930	3208	0,14
475	200000	1929	2399	0,094
475	206000	1929	2713	0,11
475	199000	2032	2073	0,08
475	200000	2033	1974	0,081
505	197000	1750	2483	0,1128
526	212000	1890	3599	0,1283
526	201000	1789	2708	0,12
560	199948	2240	3413	0,11
560	206000	2239	4222	0,13
568	196000	1900	2412	0,09
670	200000	2248	7119	0,179
670	199000	2446	3484	0,07
670	199000	2447	2821	0,05

RESULTS

The approach in which direct relationship between material parameters of interest is characterized, is widely used [1-4]. Due to its practicality, this approach was chosen for estimation of cyclic stress-strain curves parameters K' and n' from Brinell hardness HB in this work as well.

Two separate nonlinear regressions without weight factors have been performed on two data sets consisting of Brinell hardnesses *HB,* as independent variables and corresponding values of cyclic strength coefficient K' and cyclic strain hardening exponent n' as dependent variables. The relationship which was found to exist between HB and K' can be described rather well with a simple expression:

$$K' = 0{,}009(HB)^2 + 0{,}1173(HB) + 376{,}75 \qquad (2)$$

for which the square of correlation coefficient was found to be R^2 = 0,703. No such correlation could be found between HB and n' so that strain hardening exponent was approximated with constant value n' = 0,1087. This was calculated middle value of n' for all materials considered.

Experimental values of K' and n' with superimposed corresponding calculated values are shown in diagrams in Figures 2 and 3.

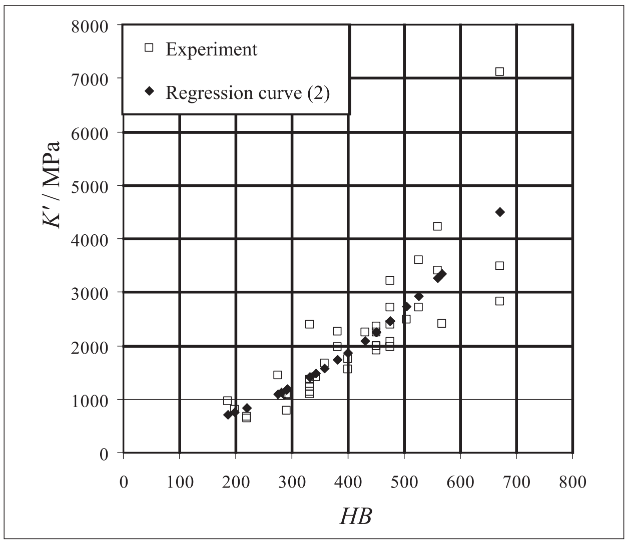

Figure 2. Experimental and calculated values of *K'*

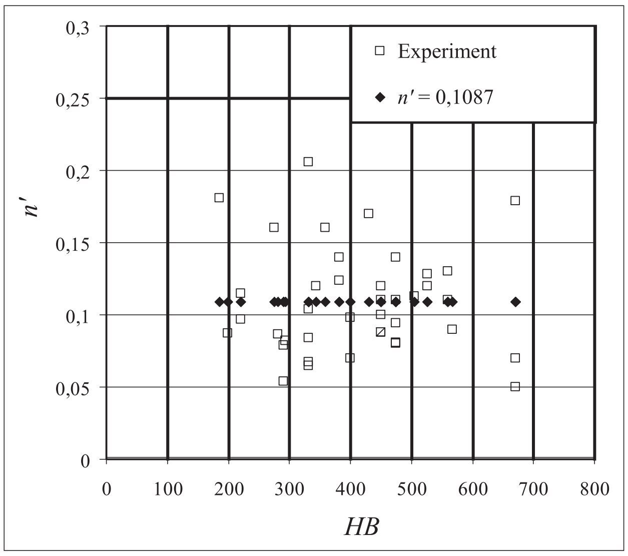

Figure 3. Experimental and calculated values of *n'*

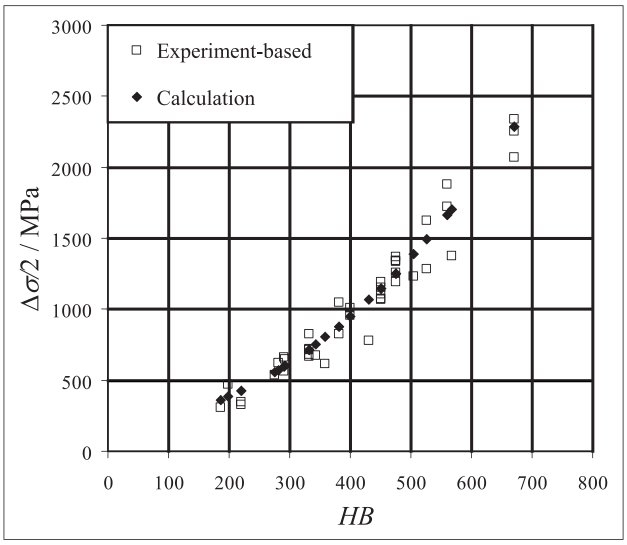

Figure 4. Values of $\Delta\sigma/2$ calculated for $\Delta\varepsilon_p/2$ = 0,2 %

Using both experiment-based and hardness-based values of K' and n' and "plastic" part of expression (1), values of σ were calculated for following values of $\Delta\varepsilon_p/2$: 0,1 %, 0,2 %, 1 % and 2 %. Results obtained for 0,2 % and 2 % are given in form of diagrams in Figures 4 and 5.

To evaluate predictive accuracy of the proposed estimation method, the error criterion [6] was used and fractions i.e. percentages of calculated values falling within scatterband of specified width factor s, $E_f(s)$ were determined. Percentages of calculated stress amplitudes $\Delta\sigma/2$ which from experimental values deviate less than 10 %, between 10 and 20 % between 20 and 30 % and more than 30 % are given in diagram in Figure 6.

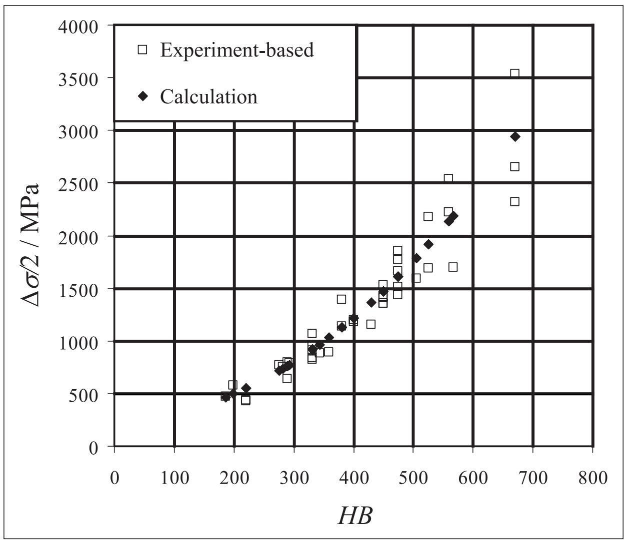

Figure 5. Values of Δ /2 calculated for Δ $_p$/2 = 2 %

To fully define the relationship between cyclic strain and stress amplitudes (1), apart from the values K' and n', the value of modulus of elasticity E is also required. However, since its exact value can be easily obtained from a simple test, "elastic" part of expression (1) was not included in the analysis. It can be noted from avail-

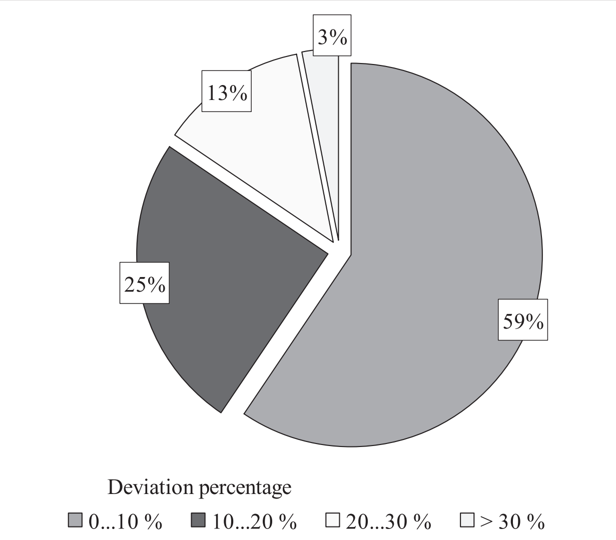

Figure 6. Percentage of estimated values of stress amplitude $\Delta\sigma/2$ which from experiment-based values deviate up to 10 %, 10 to 20 %, 20 to 30 % and more than 30 %

able material data (Table 2) that a number of steels with identical hardness (for example, 400 HB and 450 HB) have somewhat different ultimate strength R_m. This, along with information presented in [16] indicates possibility for improving accuracy of cyclic properties estimation by taking into account material microstructure and other material properties such as monotonic yield stress R_e, ultimate strength R_m or the difference between them.

CONCLUSION

This work describes the investigation of correlations between experimentally determined cyclic strength coefficient K' and Brinell hardness *HB* and between cyclic strain hardening exponent n' and hardness *HB* of quenched and tempered low-alloy steel 42CrMo4. A rather good correlation was found to exist between *K' and HB* so that a simple expression characterizing their relationship was proposed. As no correlation could be determined between n' and *HB*, n' was approximated with a constant value. Calculated and experimental cyclic stress-strain curves are in good agreement. This confirms that cyclic parameters i.e. cyclic stress-strain curves can be successfully estimated from hardness only and that estimation procedure proposed for investigated low-alloy steel 42CrMo4 is valid.

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REFERENCES

[1] S.S. Manson, Exp Mech SESA, 5, 7 (1965), 193-226.
[2] J.H. Ong, International Journal of Fatigue, 15 (1993), 213-219.
[3] M.L. Roessle, A. Fatemi, International Journal of Fatigue, 22 (2000), 495-511.
[4] M.A. Meggiolaro, J.T.P. Castro, International Journal of Fatigue, 26 (2004), 463-476.
[5] R. Basan, Zamor i oštećenje materijala boka zuba zupčanika, Disertacija, Tehnički fakultet - Sveučilište u Rijeci, Rijeka, 2009
[6] J.H. Park, J.H. Song, International Journal of Fatigue, 15 (1995), 365-373.
[7] K.S. Lee, J.H. Song, International Journal of Fatigue, 28 (2006), 386-400.
[8] N.E. Dowling, Mechanical Behavior of Materials: Engineering Methods for Deformation, Fracture and Fatigue. Prentice Hall International, New Jersey, 2006.
[9] ASTM Standard E606, 1992 (1998)
[10] R. Basan, M. Franulović, R. Kunc, Engineering Review, 28 (2008) 2, 23-30.
[11] R.W. Landgraf, Cyclic deformation and fatigue behavior of hardened steels, T.&A.M. Report No. 320, University of Illinois, Urbana, 1968
[12] P.N. Thielen, Fatigue studies on 4140 quenched and tempered steel, Dissertation, Northwestern University, Evanston, 1975
[13] SAE Standard J1099, 1998
[14] L. Reis, B. Li, M. Freitas, Fatigue & Fracture of Engineering Materials & Structures, 27 (2004), 775-784.
[15] R. Kunc, I. Prebil, J. Korelc, T. Rodič, M. Torkar, Materials and Technology, 35 (2001), 107-112.
[16] B. Smoljan, S. Smokvina Hanza, D. Iljkić, G.E. Totten, I. Felde, Computer simulation of mechanical properties of steel dies, 2nd International Conference on Heat Treatment and Surface Engineering of Tools and Dies: Extended abstracts in Materials and Technology (ISSN 1580-2949); 42 (2008) (Special issue) / Leskovšek, V.; Smoljan, B.; Jager, H.; Jenko, M. (ur.). Ljubljana : Institute of Metals and Technology, (2008), 154-155.

Note: Linguistic advisor for English language is Ksenija Mance, Faculty of Engineering, Rijeka.