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IMPACT OF CHOICE OF STABILIZED HYSTERESIS LOOP ON THE END RESULT OF INVESTIGATION OF HIGH-STRENGTH LOW-ALLOY (HSLA) STEEL ON LOW CYCLE FATIGUE

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High strength low-alloy steel under low cycle fatigue at a certain level of strain controlled achieve stabilized condition. During the fatigue loading stabilized hysteresis loop is determined, which typical cycle of stabilization is calculated as half number of cycles to failure. Stabilized hysteresis loop is a representative of all hysteresis and it's used to determine all of the parameters for the assessment of low cycle fatigue. This paper shows comparison of complete strain-life curves of low cycle fatigue for two chosen stabilized hysteresis loop cycles of base metal HSLA steel marked as Nionikral 70.

Key words: HSLA steel, mechanical properties, low cycle fatigue, stabilized hysteresis loop

INTRODUCTION

HSLA steels [1], as many other mechanical materials, that are used in shipbuilding, energy sector, and in airline and process industry, are very often exposed to low cycle fatigue as a consequence of the loading with variable amplitudes which arise due to fatigue cracks. Main procedure of the testing of material resistance to low cycle fatigue (LCF) is to determine the share of the total elastic and plastic strain amplitudes [2]. Therefore, it is important to determine the characteristic cycle of stabilized hysteresis loop. This experiment is based on comparison of two different stabilized hysteresis loops and then comparison of obtained complete strain-life curves.

EXPERIMENTAL PROCEDURE

The material used in this study was base metal of Nionikral-70 (NN-70), a high strength low alloyed steel (HSLA). Properties of NN-70 are given in Table 1 and its chemical composition steel is presented in Table 2. For this experiment of LCF 9 specimens of NN-70 steel were investigated. The LCF test, at room temperature, was performed on a universal servo-hydraulic MTS machine (rating 500 kN).

This test is frequently conducted in strain-control using an extensometer (gauge length is 25 mm) attached to the specimen (diameter 7 mm). More precisely total strain controlled LCF test has been conducted under fully-reversed tension-compression loading [3], $R_\varepsilon=\varepsilon_{min}/\varepsilon_{max}= -1$.

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Table 1 **Mechanical properties of NN-70**

R_m / MPa	$R_{p0,2}$ / MPa	E / GPa
850	805	209

Table 2 **Chemical composition /% wt**

C	Si	Mn	P	S	Cr
0,106	0,209	0,220	0,005	0,017	1,258

Table 3 contains data for base metal NN-70 during strain-controlled LCF test for 9 specimens. Also, Table 3 shows that experiment on total strain amplitudes ranging from ± 0,35 % to ± 0,80 % was performed. After getting information about controlled strains in order to define cycle of stabilized hysteresis loop, curves of extreme stress values have been constructed with a certain number of cycles to failure (cyclic stress response curves) [4]. With these curves, stabilized hysteresis loops were defined, in order to form complete strain-life curves for two chosen versions in field of stabilization.

Table 3 **Data of base metal NN-70**

Spec.	Total strain amplitude $\Delta\varepsilon/2$ / %	Elongation of gauge length Δl / mm	Total strain $\Delta\varepsilon$ / %	Period T / s
1	0,35	0,0875	0,70	4,20
2	0,35	0,0875	0,70	4,20
3	0,45	0,1125	0,90	4,20
4	0,50	0,1250	1,00	4,30
5	0,60	0,1500	1,20	4,30
6	0,60	0,1500	1,20	4,30
7	0,70	0,1750	1,40	4,30
8	0,70	0,1750	1,40	4,30
9	0,80	0,2000	1,60	4,20

RESULTS AND DISCUSSION

Beside mechanical properties, important parameter which appears in further calculations is elastic modulus. It's evaluated by parts of monotonic stress strain curves for 9 specimens and its arithmetic mean is 209 GPa [5]. Extreme stress values (σ_{max} i σ_{min}) that belong to upper and lower points of hysteresis loops, with stress-strain response for all cycles, show that NN-70 decreases when exposed to LCF. Positive extreme stress values curves are used for determine number of cycles to failure (N_f). Significant stress drops are apparent in positive extreme stress values curves ($\sigma_{max)}$ as they sudden and pronounced change shape in comparison to negative extreme stress values curves. In Figure 1 is example of specimen 4 which shows cyclic stress response curve with its positive and negative stress values.

Cycle of Stabilized hysteresis loop is equal 0,5 N_f (see Figure 1) and this diagram shows two different versions cycles to failure (N_f) [6]. On the example of spec. 4, for first version is taken N_{f-1}= 662, the number of cycles which was moved to the middle of diagram. For second version is determined real number of cycles N_{f-2}= 1323, and crack initiation appeared during the testing. After testing, first version will show if it is possible to choose any other values of cycle in horizontal central part of positive curve for determination of stabilized hysteresis [7]. Only after comparative examination, it can be concluded how choice of cycle of stabilized hysteresis affects on values of plastic and elastic components during fatigue loading.

After defined cycles to failure (N_f), cycles of stabilized hysteresis loop (N_s) were determined (as half of N_f). In case of specimen 4 values of cycles are N_{s-1} = 331 and N_{s-2} = 662 (both versions). Table 4 shows data of cycles for all 9 investigated specimens.

Based on cycle of stabilized condition were formed stabilized hysteresis loop for both versions. In Figure 2 is illustrated hysteresis loop for specimen 4 for cycle N_{s-2} = 662.

Using hysteresis loops, values of plastic, elastic and total strain amplitudes as well as total strains were determined. From hysteresis loops were obtained values of maximum and minimum stress and in the end stress amplitude was obtained for given cycles.

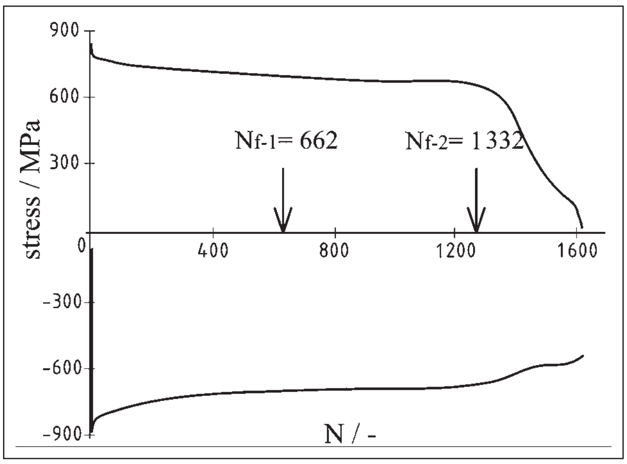

Figure 1 Cyclic stress response curve with extreme stress values

Table 4 **Data of cycles N_f and N_s**

Version	I		II	
Spec.	N_{f-1}	N_{s-1}= N_{f-1}/2	N_{f-2}	N_{s-2}= N_{f-2}/2
1	3 520	1 760	7 040	3 520
2	2 275	1 138	4 550	2 275
3	580	290	1 160	580
4	662	331	1 323	662
5	235	118	470	235
6	195	98	390	195
7	89	44	177	89
8	170	85	340	170
9	85	43	170	85

The parameters of stabilized hysteresis loop were determined for all 9 specimens. In Table 5, for example, values of parameters for spec. 4 (second version) are illustrated.

Table 5 **Stabilized hysteresis parameters for specimen 4**

number of cycles to failure, N_{f-2} / -	1 323
total strain amplitude, $\Delta\varepsilon/2$ / %	0,50
plastic strain amplitude, $\Delta\varepsilon_p/2$ / %	0,18
elastic strain amplitude, $\Delta\varepsilon_e/2$ / %	0,32
plastic strain range, $\Delta\varepsilon_p$ / %	0,36
maximum stress value, σ_{max} / MPa	706,21
minimum stress value, σ_{min} / MPa	708,37
stress amplitude, $\Delta\sigma/2$ / MPa	707,29

Complete strain-life curve [8] respresents relationship between total strain amplitude ($\Delta\varepsilon/2$) and number of cycle to failure (N_f) and this curve can be used for determination part of plastic and elastic component during LCF loading:

$$\frac{\Delta\varepsilon}{2} = \varphi\ (N_f) \qquad (1)$$

Stabilized hysteresis loop was used for determination complete strain-life curve. Plastic and elastic strain amplitudes depend on number of cycles to failure:

$$\frac{\Delta\varepsilon_e}{2} = \varphi_1\ (N_f) \qquad \frac{\Delta\varepsilon_p}{2} = \varphi_2\ (N_f) \qquad (2)$$

After determination dependence between elastic and plastic strain amplitudes and N_f, in calculation S-N curve was used and it's was linearized in the relation:

$$\frac{\Delta\sigma}{2} = \sigma_f' N_f^b \qquad (3)$$

where are: $\Delta\sigma/2$ - stress amplitude, σ'_f - fatigue strength coefficient, N_f - number of cycles to failure, b - fatigue strength exponent

Inserting the relation (3) in Hooke's law, it's obtained as follows

$$\frac{\Delta\varepsilon_e}{2} = \frac{\sigma_f'}{E} N_f^b \qquad (4)$$

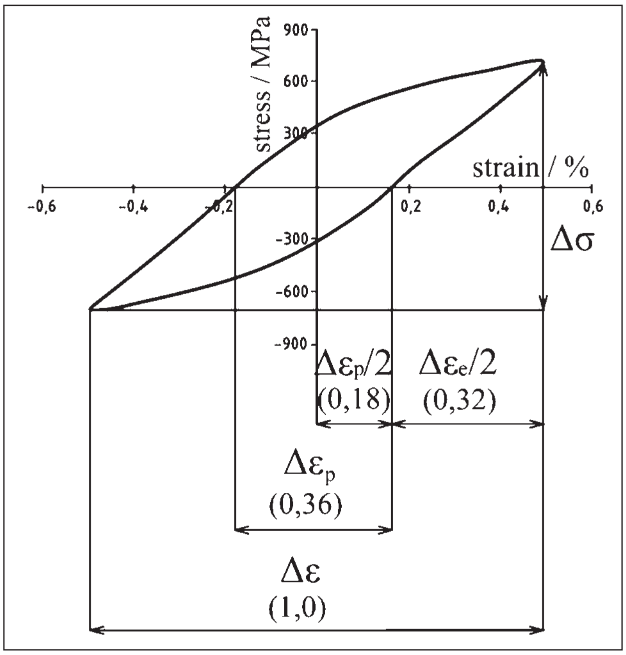

Figure 2 Stabilized hysteresis loop for spec. 4

and in the end respresents a form of dependence $\Delta\varepsilon_e/2 = \varphi_1(N_f)$.

LCF behavior of this material was analyzed using the Coffin-Manson relation [8], between the plastic strain amplitude ($\Delta\varepsilon_p/2$) and the number of cycles to failure (N_f):

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f^{'} N_f^c \tag{5}$$

where are: $\varepsilon_f^{'}$ - fatigue ductility coefficient, c - fatigue ductility exponent

Elastic (4) i plastic (5) components were linearized in log-log system and transformed in equation form y = kx + n (relation 6 and 7), for easier determination coefficients and exponents of complete strain-life curve, see Figure 3.

$$\log\frac{\Delta\varepsilon_e}{2} = b\ \log\ N_f + \log\ \frac{\sigma_f^{'}}{E} \tag{6}$$

$$\log\frac{\Delta\varepsilon_p}{2} = c\ \log\ N_f + \log\ \varepsilon_f^{'} \tag{7}$$

Using number of cycle to failure and plastic strain amplitude was obtained linearized plastic component of strain-life curve in Figure 3(a).

Also, using number of cycle to failure and elastic strain amplitude was obtained linearized elastic component of complete strain-life curve, in Figure 3(b), for second version of choice of stabilized hysteresis. After constructing linearized components of complete strain-life curve (Figure 3) and putting them into relations (6 and 7) in Table 6 are given cyclic properties (I and II version), calculated during LCF test.

By adding two expressions (4) and (5), final equation of complete strain-life curve is obtained:

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f^{'}}{E} N_f^b + \varepsilon_f^{'}\ N_f^c \tag{8}$$

that represents the basic form of (1).

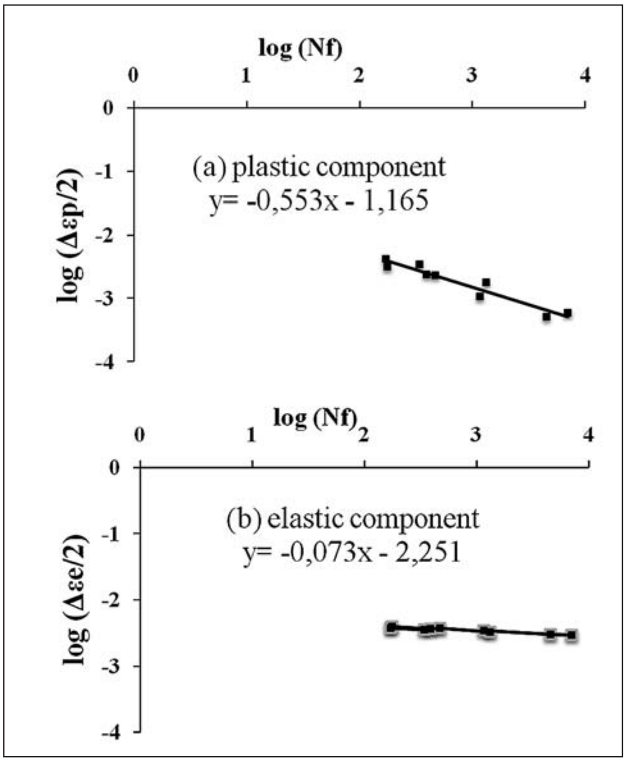

Figure 3 Linearized plastic (a) and elastic (b) component for second version

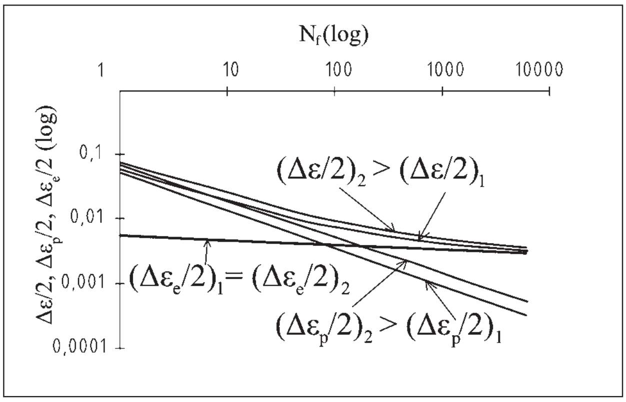

Figure 4 Strain-life curves for both versions

Table 6 **Cyclic properties for I and II version**

	E / GPa	σ'_f / MPa	b / -	$\varepsilon_f^{'}$ / -	c / -
I	209	1 137	-0,072	0,0525	-0,584
II	209	1 174	-0,073	0,0684	-0,553

The values of the coefficients and exponents related to the elastic and plastic components are inserted in complete strain-life curve (8).

After that these data have formed the formula (9) for the first version and the formula (10) for the second version of calculation, see Figure 4.

$$\left(\frac{\Delta\varepsilon}{2}\right)_1 = 0{,}0054\ N_f^{-0{,}072} + 0{,}0525\ N_f^{-0{,}584} \tag{9}$$

$$\left(\frac{\Delta\varepsilon}{2}\right)_2 = 0{,}0056\ N_f^{-0{,}073} + 0{,}0684\ N_f^{-0{,}553} \tag{10}$$

In Figure 4 represents elastic and plastic components with complete strain-life curves for both versions of choice of stabilized hysteresis. Comparing both strain-life curves, could be seen that elastic component of base metal is equal for both versions while plastic component is different. For second version, plastic component is higher than the plastic component for first version, which means that second version is closer to the final fracture of material. For example, from Figure 4, for $N_f = 100$, value of plastic component of second version is for 33 % higher than value of plastic component for first version.

CONCLUSION

Experiment showed comparison of stress-strain response in the points of expected crack initiation for base metal with calculation of parameters that are required for assessment of cycle life.

Impact of choice of stabilized hysteresis loop on the end result of investigation was defined which is most expressed on the difference of plastic components.

This testing of the behavior of material on LCF can be used for further investigations of damage and fatigue life of HSLA steel as a function of the geometry and function of the cycle properties of selected material.

Based on differences in the results, especially for plastic components, it is important to determine the start of crack initiation.

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Note: The responsible for english: prof. Anđa Zorica, professional translator from Belgrade, Serbia