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DETERMINATION OF THE COFFIN-MANSON EQUATION UNDER LOW-CYCLE FATIGUE CONDITIONS

ODREĐIVANJE KOFIN-MANSON JEDNAČINE U USLOVIMA NISKOCIKLIČNOG ZAMORA

Originalni naučni rad / Original scientific paper
UDK /UDC:

Rad primljen / Paper received: 1.12.2020

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Keywords
- Coffin-Manson equation
- low-cycle fatigue
- high strength low alloy steel
- stabilized hysteresis loop

Abstract

The cycle loading of a material results in the modification of its properties and so in this paper is presented the behaviour of the fatigue life using low-cycle fatigue parameters. By applying the Coffin-Manson equation in fatigue loading of the tested specimens, the crack initiation has been computed. The stabilized hysteresis loop is a characteristic of all hystereses and it is used to determine all of the parameters for the low cycle fatigue (LCF) assessment. The experimental results have given us important information on the understanding of fatigue behaviour of high strength low-alloyed steel (HSLA) and its welded joints.

Ključne reči
- Kofin-Manson jednačina
- niskociklični zamor
- niskolegirani čelik povišene čvrstoće
- stabilizovana histerezisna petlja

Izvod

Ciklično opterećenje materijala povlači za sobom modifikacije njegovih osobina i u ovom radu je pokazano ponašanje zamornog veka koristeći parametre niskocikličnog zamora. Koristeći Kofin-Manson jednačinu kod zamornog opterećenja na ispitivanim epruvetama, određena je inicijacija prsline. Stabilizovana histerezisna petlja je predstavnik svih histereza i koristi se za određivanje svih parametara za ocenu niskocikličnog zamora. Rezultati eksperimentalnih ispitivanja su nam dali važne podatke o razumevanju zamornog ponašanja niskolegiranog čelika povišene čvrstoće i zavarenih spojeva izrađenih od ove vrste čelika.

INTRODUCTION

High strength low-alloy (HSLA) steels are widely used structural steels for manufacturing structures especially in shipbuilding and offshore structures. For steel structures such as ship structures, the most common manufacturing process is welding. That is why HSLA steels, besides high strength, should also have good plasticity, sufficient toughness and high resistance to brittle fracture, and satisfactory workability and good weldability, /1/.

Fatigue damage is among the major issues in engineering, because it increases with the number of applied loading cycles in a cumulative manner and can lead to failure of a considered part. Therefore, the prediction of fatigue life has an outstanding importance that must be considered during the design of materials in mechanical engineering. As many other materials, HSLA steels are very often exposed to low-cycle fatigue as a consequence of the loading with variable amplitudes that create fatigue cracks. The technology of the manufacture and thermomechanical processing of Nionikral -70 steel (NN-70 steel is the former Yugoslav version of the American steel HY-100) is a result of joint research from the Military Technical Institute in Žarkovo (VTI) and ironworks 'Jesenice' from Jesenice (Slovenia), in the 1990s, /2/. Nionikral-70 is chosen as a typical representative of high strength low-alloy steels with complex microstructure and significant differences in mechanical properties and resistance to crack initiation and propagation. Steel NN-70 is intended to be shaped by welding, so that after it is successfully mastered, its suitability for welding is also subjected to assessment. There are two relations for the testing procedure of the resistance to low-cycle fatigue of welded joints made of HSLA steel: Coffin-Manson relation that represents the strain-life curve, and the Ramberg-Osgood stress-strain relation that represents cyclic stress-strain curve. This paper is based on the Coffin-Manson relation for determining parameters during the fatigue loading.

EXPERIMENTAL PROCEDURE

For the low-cycle fatigue experiment, 10 round specimens are investigated, Fig. 1, on a universal servo-hydraulic MTS testing machine, with 500 kN capacity, interfaced to a computer for machine control and data acquisition, Fig. 2. The material used in the current experimental investigation was the welded joint of high strength low-alloyed steel Nionikral-70 (NN-70), designed for ship structures and pressure vessels. The chemical composition of NN-70 is given in Table 1. An EVB 75 basic electrode is chosen for the welding of plates, Table 2.

Figure 1. Round specimens prepared for LCF testing.

Table 1. Chemical composition of NN-70 steel (wt. %).

C	Si	Mn	P	S	Cr	Ni	Cu
0.106	0.209	0.220	0.005	0.017	1.258	2.361	0.246
Al	Mo	Ti	As	V	Nb	Sn	Ca
0.007	0.305	0.002	0.017	0.052	0.007	0.014	0.0003
B	Pb	W	Sb	Ta	Co	N	/
0	0.0009	0.0109	0.007	0.0009	0.0189	0.0096	/

Table 2. Chemical composition of the filler material (wt. %).

C	Si	Mn	Ni	Mo	Cr
0.06	0.50	1.50	2.10	0.40	0.40

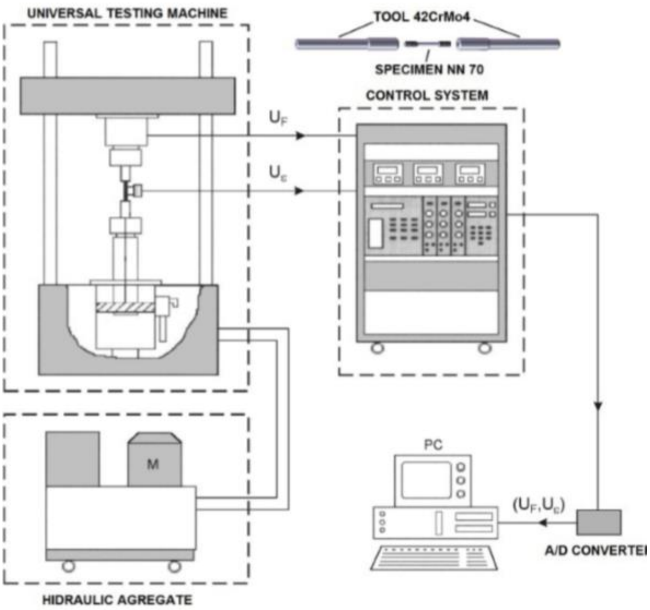

Figure 2. Overall scheme of the MTS testing system, /3/.

Ten specimens (of diameter 7 mm) taken from the welded plates are subjected to strain control under fully reversed strain $R_\varepsilon = -1$, at five levels of total strain amplitude $\Delta\varepsilon/2$ from 0.4 to 0.8 %. The frequency of load changes during the test amounted to $f = 0.233$ Hz for the period of $T = 4.30$ s.

After receiving information on the controlled strain, in order to define the cycle of the stabilized hysteresis loop, the curves of extreme stress values are constructed with a certain number of cycles to failure (cyclic stress response curves), /4/.

The hysteresis loops are measured by using the signals acquired from the load cell and the extensometer (gauge length of 25 mm) attached to each specimen, Fig. 3.

Figure 3. MTS extensometer.

The LCF has been analysed in terms of cyclic stress response and the cyclic strain life relation. The strain life curve which contains the Coffin-Manson equation was evaluated according to ASTM E 606, /5/. Values in Coffin-Manson equation are recorded at 50 % of the total fatigue life.

RESULTS AND DISCUSSION

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

The stabilized hysteresis loop is used for determining the complete strain-life curve. Plastic and elastic strain amplitudes depend on the number of cycles to failure:

$$\frac{\Delta\varepsilon_e}{2} = \varphi_1(N_f), \quad \frac{\Delta\varepsilon_p}{2} = \varphi_2(N_f)\ . \tag{1}$$

The strain-life fatigue analysis of cyclic property data is the decomposition of the total cyclic strain amplitude ($\Delta\varepsilon/2$) into its components: plastic strain amplitude ($\Delta\varepsilon_p/2$), and elastic strain amplitude ($\Delta\varepsilon_e/2$), according to the equation:

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_p}{2} + \frac{\Delta\varepsilon_e}{2}\ . \tag{2}$$

Equation (2) is decomposed more precisely, Eq.(3), and is often referred to as the Coffin-Manson equation:

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_p}{2} + \frac{\Delta\varepsilon_e}{2} = \varepsilon'_f N_f^c + \frac{\sigma'_f}{E} N_f^b\ , \tag{3}$$

where: ($\Delta\varepsilon/2$), ($\Delta\varepsilon_p/2$), and ($\Delta\varepsilon_e/2$) are the total, plastic, and elastic strain amplitudes, respectively. Equation (3) contains the fatigue parameters: ε'_f - fatigue ductility coefficient; c - fatigue ductility exponent; σ'_f - fatigue strength coefficient; and b - fatigue strength exponent.

Number of cycles to failure N_f is defined as the number of cycles corresponding to a decrease of 25 % in the stress value extrapolated over the tensile stress-number of cycles curve when the stress falls sharply, according to standard ISO 12106: 2003, /6/. The cycle of the stabilized hysteresis loop (N_s) is considered at half of the number of cycles to failure ($0.5N_f$).

Figure 4 shows the plot of one stabilized hysteresis loop for 0.70 % of total strain amplitude for the specimen with values of N_s = 207.

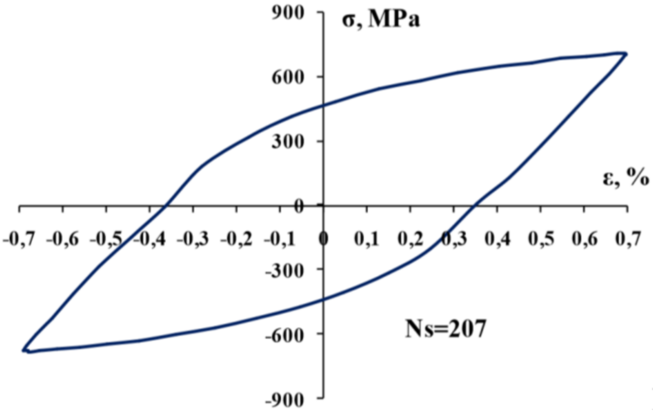

Figure 4. Example of stabilized hysteresis loop.

Table 3 shows the values for specimen of 0.70 % of total strain amplitude.

Table 3. Stabilized hysteresis values for 0.70 % of total strain amplitude.

number of cycles to failure, N_f	414
number of cycles of stabilized hysteresis loop, N_s	207
total strain amplitude, $\Delta\varepsilon/2$ (%)	0.7
plastic strain amplitude, $\Delta\varepsilon_p/2$ (%)	0.3460
elastic strain amplitude, $\Delta\varepsilon_e/2$ (%)	0.3540
maximum stress value, σ_{max} (MPa)	709.925
minimum stress value, σ_{min} (MPa)	678.43
stress amplitude, $\Delta\sigma/2$ (MPa)	694.18

The Coffin-Manson equation is linearized in the log-log system to determine ductility and strength properties and in Table 4 are given material parameters of the NN-70 steel during fatigue loading, /7-9/.

Table 4. Fatigue parameters for the welded joint of NN-70 steel.

σ'_f - fatigue strength coefficient (MPa)	994.34
b - fatigue strength exponent (-)	-0.061
ε'_f - fatigue ductility coefficient (-)	0.2312
c - fatigue ductility exponent (-)	-0.684

Finally, according to the fatigue parameters for the welded joint a final equation of the strain life curve is formed, known as the Coffin-Manson Eq.(2) for the welded joint of HSLA steel, marked as Nionikral 70 (NN-70). By using the Eq.(4), the fatigue life curve in Fig. 5, is plotted.

$$\frac{\Delta\varepsilon}{2} = 0.2312 N_f^{-0.684} + 0.0049 N_f^{-0.061}\,. \qquad (4)$$

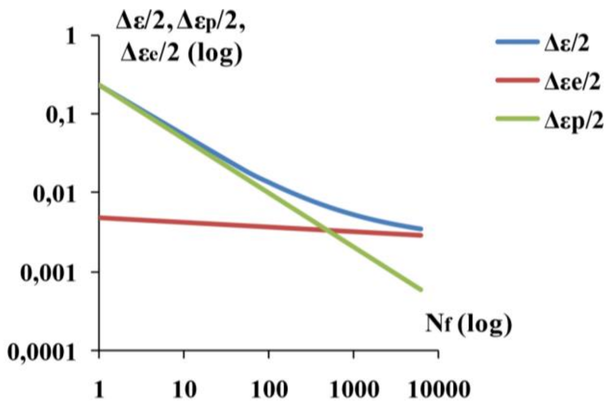

Figure 5. Fatigue life curve of NN-70.

The transition fatigue life represents the life at which the elastic and plastic curves intersect. This is the life at which the stabilized hysteresis curve has equal elastic and plastic strain components, /10/. The expression for the transition fatigue life is given by Eq.(5):

$$N_f = \left(\frac{\varepsilon'_f E}{\sigma'_f}\right)^{\frac{1}{b-c}} = 488\,. \qquad (5)$$

CONCLUSIONS

Fatigue life of the welded joint of NN-70 steel is characterized by the Coffin-Manson equation where the total strain range can be divided into the elastic and plastic range at room temperature. Fatigue parameters are important material properties and very important in performing the fatigue design. It can be concluded that the Coffin-Manson power equation can fit the test data rather well.

The results obtained in this experiment of low-cycle fatigue show real material behaviour for the future fatigue design of HSLA steel welded joints, and this testing can be used for further research on the damage and fatigue life as a function of geometry and a function of the cycle properties of the selected material.

Through analysis of the existing results of the fatigue parameters, the need arises for further research and establishment of new universal principles regarding the accuracy of the determination and calculation of parameters, using various computer applications, describing the behaviour of the material.

ACKNOWLEDGEMENTS

This research is supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia (Contract No. 451-03-68/2020-14/200012).

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