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Low cycle fatigue of weldments produced of a high strength low alloyed steel

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Abstract

A quenched and tempered high strength low alloy steel NIONIKRAL 70 for producing welded pressure vessels, where high resistance to fatigue crack propagation and high tolerance of damage are of high importance, has been investigated. Low cycle fatigue tests were conducting on several series of uniaxial cylindrical smooth specimens under strain control. The cycle behavior of the material is characterized using Coffin-Manson relation.
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*Keywords:*low cycle fatigue, high strength low alloyed steel, material parameters

1. Introduction

To produce safe and economic pressurized equipment such as hydraulic and gas cylinders, pressure vessels and pressure pipes, high strength low alloyed (HSLA) steels have been developed. Extensive studies have been conducted to understand the fatigue behavior of HSLA steels over the years. The fatigue process consists of crack initiation and crack propagation to failure. Smooth specimens are usually used to study the crack initiation behavior.

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Fatigue lives are related to the stress and strain quantities as described in Posavljak (2009), Wanhill (2009), Barter (2009),Petrašković (2009) and Čamagić et al. (2010).

Pressure vessels are often subjected to cyclically varying loads or deformations due to pressure fluctuations and external loads, which induce fatigue damage at the highly stressed locations, leading frequently to premature failures in equipment intended for long life application. In order to design against failure under fatigue actions, designers need some material data such as the stress and strain amplitude versus life curve for a given material.

The pressure equipment used in fossil power and hydroelectric power plant, refinery and chemical industry, operates in the wide range of pressures and temperatures and it is exposed to environmental impact, see Jesus et al. (2006). In the majority of reactors and reservoirs as well as in the majority of pipelines, the effect of fatigue loading is a special problem, and it is especially significant in the gas fluid equipment and gas fluids liquefied under pressure.

In the event that the material has the crack-like defect, low-cycle fatigue may, in relatively short period of time, lead to its critical value, and if the component also works at low temperature (the example of pressure vessels made of HSLA steels), brittle fracture must be taken into account as well.

This paper presents a part of extensive researches of the cyclic behavior of the HSLA steel NIONIKRAL 70 (NN-70) which is used extensively in Serbian petrochemical industry and is based on Coffin-Manson relation for determine fatigue loading parameters of welded joint at room temperatures as described in Hales et al. (2002).

2. Experimental details

2.1. Material

The material used in the current experimental investigation was high strength low alloyed steel NN-70, designed for ship structures and pressure vessels as described by Milović et al. (2011) and Zrilić et al. (2007). The chemical composition of the investigated material is given in Table 1. The steel was produced in electro furnace, casted and rolled into slabs and plates of 45 mm thickness. High strength was achieved by quenching and tempering which resulted in grain refinement, due to optimal combination of chemical composition and precipitation kinetics.

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

C	Si	Mn	P	S	Cr	Ni	Cu	Al	Mo	Ti	As
0,106	0,209	0,220	0,005	0,0172	1,2575	2,361	0,246	0,007	0,305	0,002	0,017
V	Nb	Sn	Ca	B	Pb	W	Sb	Ta	Co	N	
0,052	0,007	0,014	0,0003	0	0,0009	0,0109	0,007	0,0009	0,0189	0,0096	

The chemical composition was carefully selected in order to provide the optimal combination of strength and toughness, plasticity, resistance to crack initiation and/or growth, low temperature service and good resistance to fatigue and stress corrosion. Apart from these properties, technological requirements as formability and especially weldability had to be fulfilled.

The mechanical properties of parent material are listed in Table 2. This steel is weldable fine grain carbon low alloy steel, delivered in the normalized condition and intended for the manufacture of pressure equipment. Despite of the extensive use of this steel in Serbian petrochemical industry, very limited data exists on its fatigue behavior.

Table 2. Static material properties of NN-70 steel.

Elasticity modulus, E	209 GPa
Poisson's ratio, μ	0.3
Yield stress, $R_{p0.2}$	805 MPa
Ultimate strength, R_m	853 MPa
Charpy V adsorbed total energy, E_{tot}(at 20° C)	96.83 J

In order to investigate the behaviour of welded components made of NN-70 steel in low cycle fatigue conditions, we welded two plates 21 mm thick by manual arc welding (MAW) following a defined proper Welding Procedure Specification (WPS) so that we produced the defect-free welded joint, see Fig. 1. The shape of the welded joint, e.g. K-weld, was designed to enable and facilitate the analysis of the behaviour inside the heat affected zone of the joint. The preheating temperature was 170° C and we welded plates with the electrodes EVB 75 (classification according to AWS A-5.5: E 10018-G) whose chemical composition is given in Table 3. Welding was performed in five to seven passes depending on the plate's sides.

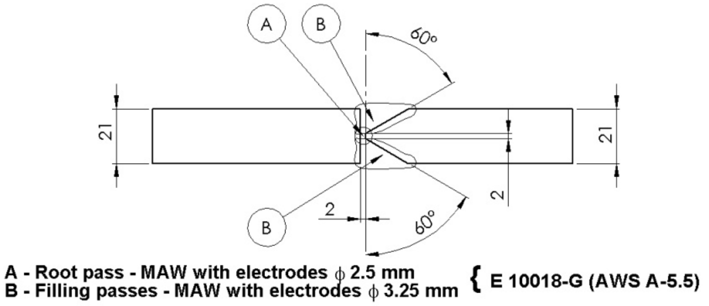

Fig. 1. Schematic representation of welded plates

Table 3. Chemical composition of the weld metal (wt %).

Electrode	C	Mn	Si	Cr	Ni	Mo
EVB 75	0.06	1.50	0.50	0.40	2.1	0.40

Table 4. Tensile properties of the welded joint specimens.

Weld metal	
Elasticity modulus, E	203.5 GPa
Yield stress, $R_{p0.2}$	645.4 MPa
Ultimate strength, R_m	914.3 MPa

The results of the tensile tests of the weld metal (WM) are shown in Table 5. The specimens started to yield at around 640 MPa indicated that strength under-matching of the welded joint was obtained.

2.2. Specimens and experiments

For the investigations of the behavior of welded pressure equipment under low cycle fatigue conditions, we designed specimens that can provide the desired data. Smooth specimen with threaded ends shown in Fig. 2 is a typical specimen which we use for strain control tests. The MTS test system that we employ is a universal servo hydraulic test machine with load capacity t 500 kN. A general scheme of this machine is shown in Fig. 3.

Our low cycle fatigue research has been carried out at room temperature in air. The strain-controlled tests have been done for the determination of uniaxial deformation characterized by the cyclic stress-strain curve (CSS). For our investigated material we employed a sine strain-time wave form with a constant strain rate 0.233 s^{-1} and the strain ratio R_ε=-1. For the measurement and control of strain we used the longitudinal MTS extensometer with 25 mm gage length.

3. Results and discussion

Ten specimens taken from the welded plates were subjected to strain control under fully reversed strain R_ε=-1, at five levels of total strain amplitude $\Delta\varepsilon/2$ from 0.4% to 0.8%. Data for one of stabilized hysteresis along with number of cycles to failure are given in Table 5. In Table 6 cyclic characteristic values for investigated material during fatigue loading are given.

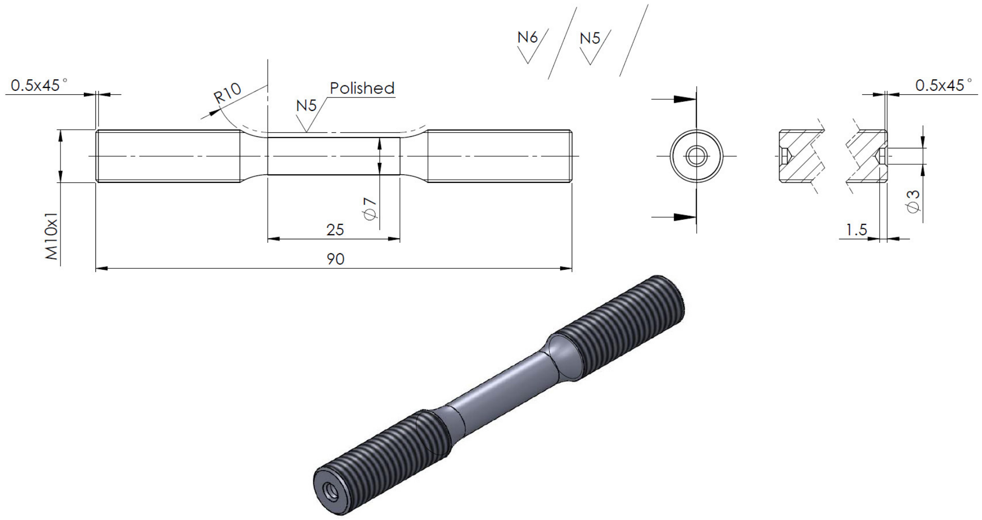

Fig. 2. Type of specimen employed in our fatigue testing.

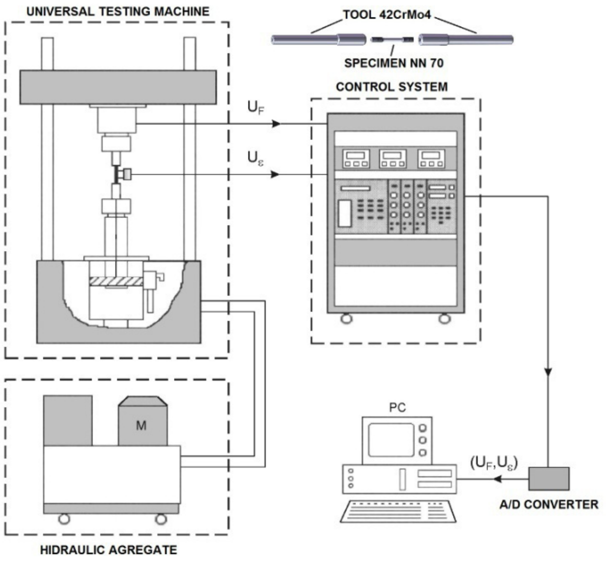

Fig. 3.Overall scheme of MTS testing system on which we have tested our specimens.

Table 5. Stabilized hysteresis data for total strain amplitude of 0.7%.

Maximum stress, σ_{max}	710 MPa
Minimum stress, σ_{min}	678 MPa
Plastic strain amplitude, $\Delta\varepsilon_p/2$	0.003815 mm
Elastic strain amplitude, $\Delta\varepsilon_e/2$	0.003540 mm
Stress amplitude, $\Delta\sigma/2$	694 MPa
Number of cycles to failure, N_f	414

Table 6. Cyclic characteristic values ofmaterial investigated.

Cyclic strength coefficient, K'	MPa
Fatigue strength coefficient, σ_f'	994.3MPa
Fatigue strength exponent, b	-0.061
Fatigue ductility coefficient, ε_f'	0.2312
Fatigue ductility exponent, c	-0.684

The CSS relationship is determined using the least squares fitting technique applied to the experimental data and taking into account the constitutive equation

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

A fundamental step in the strain-life fatigue analysis of cyclic property data is the decomposition of the total cyclic strain amplitude ($\Delta\varepsilon/2$) into plastic strain amplitude ($\Delta\varepsilon_p/2$) and elastic strain amplitude ($\Delta\varepsilon_e/2$) according to the Coffin-Manson relationship given by equation

$$\frac{\Delta\varepsilon}{2}=\frac{\Delta\varepsilon_p}{2}+\frac{\Delta\varepsilon_e}{2}=\varepsilon'_f\cdot N_c^f+\frac{\sigma'_f}{E}\cdot N_b^f \tag{2}$$

In this experiment, number of cycles to failureN_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(E). Cycle of stabilized hysteresis loop (N_s) was considered at half of number of cycles to failure ($0{,}5N_f$). Characteristics of the quantities of the stabilized hysteresis loop were used for developing the basic fatigue characteristics of investigated material. In Figure 4 one stabilized hysteresis loop for 0.70% of total strain amplitude for specimen with values of N_s=207 is plotted.

Using welded joint cyclic characteristic values given in Table 6 and the Eqs. (1) and (2), the final equation of strain life curve, known as Coffin-Manson relationship, is given by

$$\frac{\Delta\varepsilon}{2}=0.2312\cdot N_f^{-0.684}+0.00763\cdot N_b^{-0.061} \tag{3}$$

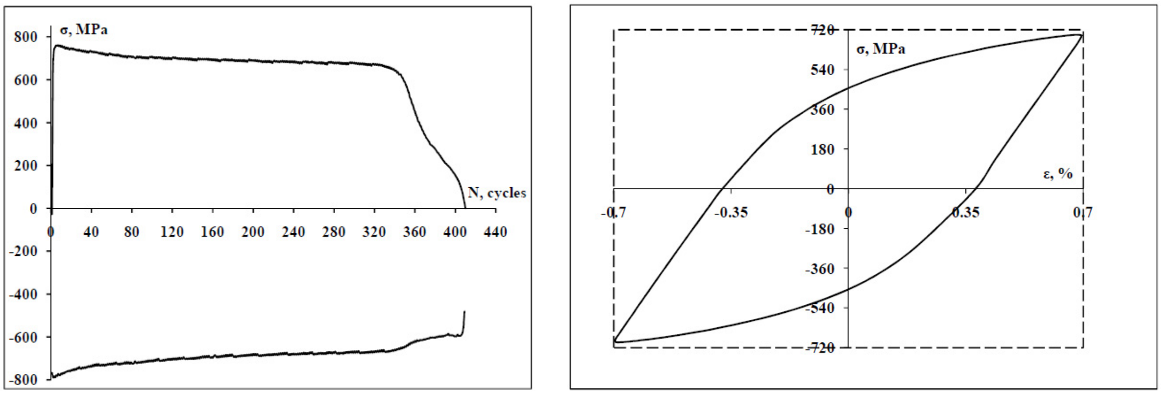

Fig. 4. Stress-life curve and the stabilized hysteresis loop for total strain amplitude value 0.7%.

Using Eq. (3), the fatigue life curve shown in Fig. 5 is plotted.

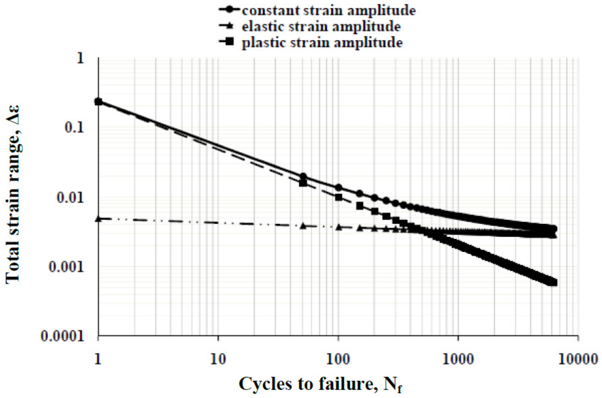

Fig. 5. Fatigue life curve of material investigated.

4. Conclusion remarque

The behavior of welded NN-70 steel under low cycle fatigue loading conditions was characterized. The importance of the strain-life curve, using Coffin-Manson relationship, was discussed showing the low cycle fatigue parameters for welded joint of high strength low-alloy steel at room temperature. These parameters are one of the important material properties and very important to perform the fatigue design. Analysis applied to fatigue crack initiation assume that a unique relation exists which describes the strain path of cyclic loading. Thus, fatigue life is characterized by Coffin-Manson relationship where the total strain range can be divided into elastic and plastic range. It can be concluded that Coffin-Manson power equation can fit the test data rather well. The results obtained in this experiment of low cycle fatigue show the real material behaviour for future fatigue design of a HSLA steel welded joints.

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References

Posavljak, S., 2009. Damages Computation of Aircraft Engine Disks. Structural Integrity and Life 9. 2 113-124.

Wanhill, R., 2009. Some Notable Aircraft Service Failures Investigated by the National Aerospace Laboratory (NLR). Structural Integrity and Life 9. 2 71-87.

Barter, S.A., Molent, L., White, P., Dixon, B., 2009. Recent Australian Full-Scale F/A-18 Fatigue Tests. Structural Integrity and Life 9. 2 89-112.

Petrašković, Z., 2009. Analysis of Hysteresis in Low Cycle Fatigue of Steel Dampers for Earthquake Application. Structural Integrity and Life 9. 3 181-192.

Čamagić, I., Vasić, N., Ćirković, B., Cvetković, S., Vasić, Z., 2010. Variable and Impact Load Testing of HSLA Steel Welds. Structural Integrity and Life 10. 3 231-234.

Hales, R., Holdsworth, S.R., O'Donnell, M.P., Perrin, I.J., Skelton, R.P., 2002. A Code of Practice for the Determination of Cyclic Stress-Strain Data. Materials at High Temperatures 19.4 165-185.

Jesus, A.M.P., Ribeiro, A.S., Fernandes, A.A., 2006. Low and High Cycle Fatigue and Cyclic Elasto-Plastic Behavior of the P355NL1 Steel. Transactions of the ASME 128 298-304.

Milović, L., Vuherer, T., Zrilić, M., Momčilović, D., Jaković, D., 2011. Structural Integrity Assessment of Welded Pressure Vessel Produced of HSLA Steel. Journal of Iron and Steel Research International 18 888-892.

Zrilić, M., Grabulov, V., Burzić, Z., Arsić, M., Sedmak, S., 2007. Static and Impact Crack Properties of a high-strength steel welded joint. International Journal of Pressure Vessels and Piping 84.3 139-150..