METABK 54(1) 55-58 (2015)
UDC – UDK 669.15:620.178.3:620.16=111

EFFECT OF VARIABLE LOAD ON CRACK INITIATION MICROALLOYED STEEL S 690-QL

Received – Prispjelo: 2014-02-07
Accepted – Prihvaćeno: 2014-07-15
Original Scientific Paper – Izvorni znanstveni rad

The accumulation of damage in the form of initiation and growth of micro-cracks is the first stage of destruction that ends when the merger microcracks form macro cracks. Cracks formed in the cycle number N =10^4 - 10^5 are the result of low cycle fatigue. From the need to evaluate low cycle fatigue life was carried out to investigate the low cycle fatigue microalloyed high-strength steel S690QL in the heat-treated.

Key words: microalloyed steel S690QL, low cycle fatigue, cracks, strain amplitude

INTRODUCTION

Production of lightweight and reliable structures is possible primarily by using light or high-strength materials. This special place is occupied by the microalloyed high-strength steels, due to availability of the steel as a material, and finally to their cost significantly more acceptable in comparison to other alternative materials. Namely, the use of high-strength steel may reduce the weight up to two times, and thus the costs of procurement, manufacturing, installation and testing of a steel structure. So today it is impossible to imagine the construction of mobile and fixed cranes, bridges, structures of stadiums and halls, passenger and freight cars (road or rail), or equipment for mining, without the use of high-strength steel.

Also, considering that they possess a good combination of mechanical properties, these steels find use in the construction of highly demanding structures such as pipelines in the oil and gas industry, pipelines for hydro-power plants, pressure vessels, tanks and the like. Despite its high strength, and considering the type of structures to be used for, these steels should meet essential mechanical, technological and design requirements [1].

This is particularly emhasized because of their unfavorable ratio of yield stress and tensile strength. Namely, the higher the ratio, the project codes are considered to provide greater “reserve” in case of overloading, and thus significant plastic strain that would precede the eventual fracture, or damage of a structure. Thus, in order to ensure higher safety in the application of high-strength steel, standard tensile and impact tests must be accompanied by appropriate tests in terms of fatigue and fracture mechanics. This is particularly important considering the fact that the highly efficient methods and procedures for the assessment and design of various types of structures, based on the knowledge of these parameters (Eurocode, SINTAP, FITNET) were recently developed [2 - 4].

Taking into account that the high-strength steels are predominantly used for manufacture of welded structures, the phenomenon of heterogeneity of welded joints, or so-called “mismatching” of the microstructure and mechanical properties of the three main areas of welded joint: weld metal, heat-affected zone and the base metal is of particular importance. Also, taking into account that the welded joints are well known as structural joints containing smaller (acceptable) or larger (non-allowable) defects, the application of these test methods reaches its peak [5].

The development of new methods for testing of the materials, and particularly of the methods essential for assessment of the behavior of structural materials in exploitation (low-cycle and high-cycle fatigue, fracture mechanics, etc.) enabled better characterization of the mechanical and technological properties of high-strength steel. For the necessities of assessment of the low-cycle fatigue life, the resistance of as-heat treated microalloyed high-strength steel S690QL to the low-cycle fatigue was tested.

TEST RESULTS

The procedure of testing of the resistance of as-heat treated, microalloyed high-strength steel S690QL 30 mm thick to low-cycle fatigue consisted of [6]:

- determination of the chemical composition of the tested sample,
- preparation and testing of cylindrical smooth specimens, to determine the tensile properties and

M. Burzić, University of Belgrade, I.C. Faculty of Mechanical Engineering, Belgrade, Serbia.
M. Manjgo, Faculty of Mechanical Engineering, Mostar, BiH.
J. Bernetič, Acroni d.o.o., Jesenice, Slovenia.
Z. Burzić, Military Technical Institute, Belgrade, Serbia.
M. Arsić, IMS Institute, Belgrade, Serbia.

check the target tensile strength of R_m = 850 MPa, and
- preparation and testing of cylindrical smooth specimens, to determine the characteristic parameters of low-cycle fatigue.

Determination of the chemical composition of the submitted sample was made on the JOEL quantometer, on specially prepared plates. Results of the determination of the chemical composition are given in Table 1.

Table 1 **Chemical composition / mass. % [6]**

C	Si	Mn	P	Cr	Cu	Mo	Ni	Ti
0,15	0,19	0,96	0,01	0,3	0,12	0,4	0,08	0.03

Tensile testing of the specimens taken from the sample submitted were conducted at room temperature. The tests procedure and specimen geometry are defined in the standard EN 10002-1 [7]. Results of the determination of tensile properties are given in Table 2.

Table 2 **Results of tensile test [8]**

Sample Designation	$R_{p0,2}$ / MPa	R_m / MPa	A / %	E / GPa
S690QL - 1	770	881	19,1	206,1
S690QL - 2	771	881	19,6	206,2
S690QL - 3	772	883	17,6	206,3

Typical diagram of tensile testing stress-elongation for the specimen designated as S690QL-1, tested at room temperature, is shown in Figure 1.

The procedure for determination of the low-cycle fatigue characteristics, as well as the geometry of smooth cylindrical specimen, are defined by the following standards ASTM E513 [9], ASTM E606 [10], and ASTM E739 [11]

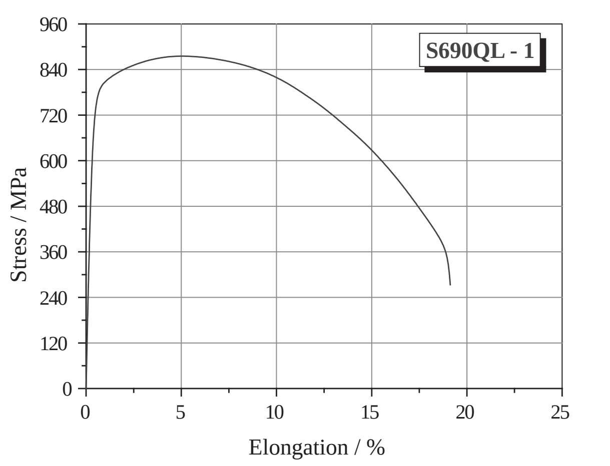

Figure 1 Diagram Stress - Elongation for the Specimen S690QL-1 [8]

Dynamic testing in order to determine the parameters of low-cycle fatigue were conducted on a servohydraulic system for testing of the materials. The strain-controlled regime was applied, with the cycle asymmetry factor R_e = -1. Law of controlled strain is defined by trigonometric function:

$$\varepsilon = \frac{\Delta\varepsilon}{2}\sin\left(\frac{2\pi}{T}t\right) \tag{1}$$

where we distinguish: the amplitude $\Delta\varepsilon$ / 2 / 2, the time, t, in seconds, and the period, T, also expressed in seconds.

The testing of the resistance of the specimens taken from microalloyed steel S690QL to low-cycle fatigue was conducted at strain amplitude levels $\Delta\varepsilon$ /2 = 0,3, 0,6, 0,8, 0,9, 1,0 and 1,2 %. The values of frequency f associated with these levels are equal to the reciprocal values of the corresponding periods, T.

To determine the elastic modulus, E, of the specimens taken from a sample of high-strength steel S690QL, tensile curves were used. The obtained values of elastic modulus were quite uniform, and the mean value of three tests amounted to 206,1 GPa.

Data on the stabilized hysteresis, supplem-ented with data on the number of cycles to crack initiation, N_f, for the specimens made of high-strength steel S690QL are given in Table 3. For the analysis, characteristic curves, i.e. one specimen for each level of strain, were used.

Step function of the stress amplitude ($\Delta\sigma$ / 2) - amplitude of plastic strain ($\Delta\varepsilon_p$ / 2) in the log-log coordinate system is linearized, i.e. transformed into the straight line equation

$$\log\frac{\Delta\sigma}{2} = n^{'}\log\frac{\Delta\varepsilon_p}{2} + \log K^{'} \tag{2}$$

in whose experimentally determined form one can observe the value of the cyclic strain-hardening exponent n', while the cyclic strength coefficient K' may be defined by inversion.

Linearized step function stress amplitude- plastic strain amplitude for high-strength steel S690QL was obtained by processing of data from columns 6 and 8, Table 3, and using the least squares method of the ORIGIN user software in the log - log coordinate system.

$$\log\left(\frac{\Delta\sigma}{2}\right)_A = 0{,}1981\log\left(\frac{\Delta\varepsilon_p}{2}\right)_A + 3{,}2542 \tag{3}$$

Table 3 **Data on the Stabilized Hysteresis of the Specimen from Exploited Material**

Specimen	$\Delta\varepsilon$ / 2	σ_{max} / MPa	σ_{min} / MPa	$\Delta\varepsilon_p$	$\Delta\varepsilon_p$ / 2	$\Delta\varepsilon_e$ / 2	$\Delta\sigma$ / 2 / MPa	N_f
1	2	3	4	5	6	7	8	9
A1	0,003	499,1	-493,5	0,003592	0,0017960	0,0012040	496,3	6 850
A4	0,005	609,2	-612,8	0,007035	0,0035177	0,0014823	611,0	2 340
A7	0,008	674,8	-668,9	0,01274	0,0063701	0,0016299	671,9	707
A10	0,009	686,2	-688,3	0,014665	0,0073327	0,0016673	687,3	523
A14	0,010	693,3	-694,9	0,016632	0,0083161	0,0016839	694,1	466
A17	0,012	695,5	-699,1	0,020617	0,0103083	0,0016917	697,3	218

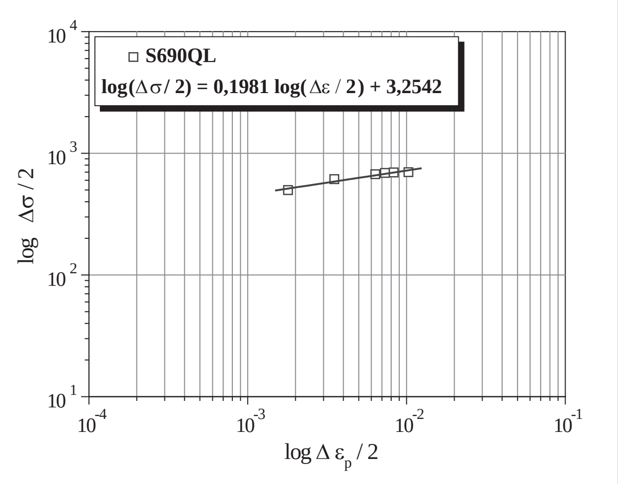

Figure 2 Linearized Step Function Stress Amplitude- Plastic Strain Amplitude for High-Strength Steel S690QL

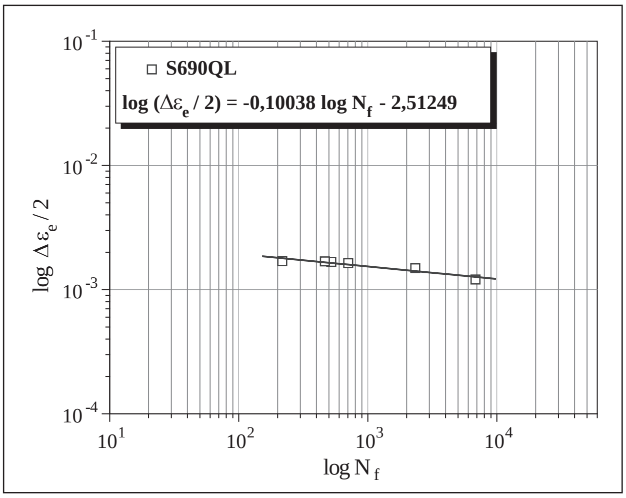

Figure 3 Linearized Elastic Component of Basic Curve of Low-Cycle Fatigue

Appearance of linearized step function stress amplitude- plastic strain amplitude for high-strength steel S690QL in the log - log diagram is given in Figure 2.

The values for high-strength steel S690QL were determined based on the general form given in Equation (2) and the obtained linearized step functions stress amplitude-plastic strain amplitude, Equation (3):

- Cyclic strain-hardening exponent $n' = 0,19812$.
- Cyclic strength coefficient $K' = 1\ 795,4$ MPa.

Linearized elastic and linearized plastic components of the basic curve of low-cycle fatigue were obtained by processing of data from columns 7 and 9, Table 3 and using the method of least squares of the ORIGIN user software in the log-log coordinate systems.

Elastic and plastic components of the total strain amplitude in the log-log coordinate systems linearize - transform into straight-line equations

$$\log \frac{\Delta \varepsilon_e}{2} = b \log N_f + \log \frac{\sigma'_f}{E} \qquad (4)$$

$$\log \frac{\Delta \varepsilon_p}{2} = c \log N_f + \log \varepsilon'_f \qquad (5)$$

from whose experimentally determined forms the coefficients and exponents necessary to define the equations of the basic curve of low-cycle fatigue are determined.

The appearance of linearized elastic and linearized plastic components of the basic curve of low-cycle fatigue in the log-log diagram for the-high strength steel S690QL is given in Figure 3 and 4.

Linearized elastic and plastic component of the basic curve of low-cycle fatigue are defined by the straight line equations. For the high-strength steel S690QL, they are given in the form of

$$\log\left(\frac{\Delta \varepsilon_e}{2}\right) = -0{,}10038 \log N_f - 2{,}51249 \qquad (6)$$

$$\log\left(\frac{\Delta \varepsilon_p}{2}\right) = -0{,}73229 \log N_f - 0{,}51763 \qquad (7)$$

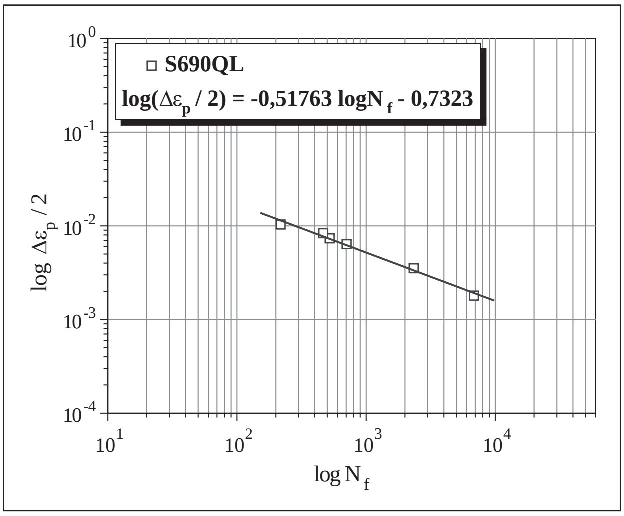

Figure 4 Linearized Plastic Component of Basic Curve of Low-Cycle Fatigue

from which, for the elastic modulus of the high-strength steel S690QL, $E = E_{sr} = 206,1$ GPa and based on the general equations (6) and (7), the following values were established:

- Fatigue strength exponent $b = -0,10038$;
- Fatigue strength coefficient $\sigma'_f = 633,3$MPa;
- Fatigue ductility exponent $c = -0,7323$;
- Fatigue ductility coefficient $\varepsilon'_f = 0,30365$.

Complete cyclic properties of high-strength steel S690QL are given in Table 4.

Table 4 **Cyclic Properties of Steel S690QL**

Property	S690QL
Elastic modulus, E / MPa	206 100
Cyclic strength coefficient, K' / MPa	1 795,4
Cyclic strain-hardening exponent, n'	0,19812
Fatigue strength coefficient, σ'_f / MPa	633,3
Fatigue strength exponent, b	-0,10038
Fatigue ductility coefficient, ε'_f	0,30365
Fatigue ductility exponent, c	-0,7323

Using the values of cyclic properties from Table 4, based on general equations

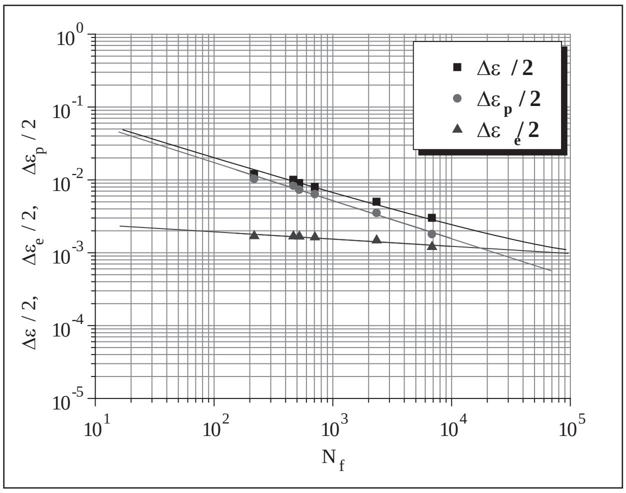

Figure 5 The Basic Curve of Low-Cycle Fatigue of High-Strength Steel S690QL

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}} \quad (8)$$

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E} N_f^b + \varepsilon'_f N_f^c \quad (9)$$

the following was obtained:

Equation for cyclic stress-strain curves for the high-strength steel S690QL

$$\frac{\Delta\varepsilon}{2} = \frac{1}{206100} \cdot \frac{\Delta\sigma}{2} + \left(\frac{1}{1795} \cdot \frac{\Delta\sigma}{2}\right)^{\frac{1}{0,19182}} \quad (10)$$

and

Equation for the basic curve of low-cycle fatigue for the high-strength steel S690QL:

$$\frac{\Delta\varepsilon}{2} = 0,00307\, N_f^{-0,0987} + 0,30365\, N_f^{-0,7323} \quad (11)$$

In Figure 5, in a log-log coordinate system, the basic curve of low-cycle fatigue (11) is shown, together with the elastic (6) and plastic component (7).

CONCLUSION

For structural steel components exposed to low cycle-fatigue, estimated low-cycle fatigue life or life to crack initiation is a key parameter. These are, as a rule, localized elastic-plastic strains occurring only in areas of stress concentration and in the welded joint as well.

Investigated microalloyed high-strength steel S690QL is intended primarily for manufacture of highly reliable welded structural elements (gantry or portal cranes). Practice has shown that the parts of welded structural elements made of high-strength microalloyed steel S690QL operate under conditions of low-cycle fatigue, where a relatively small number of cycles until their destruction can be time consuming, but it can also lead to the occurrence of local plastic strains in the critical areas of a structure, i.e. crack initiation.

The results of this study can be used for further study of the damages and fatigue life of steel structures as a function of the geometry and function of the cyclical properties of selected material, high-strength microalloyed steel S690QL. The ultimate goal of the designers should be directed towards reduction of the potential damages in critical areas of the welded steel structures, i.e. steel structures in general.

Acknowledgment

This paper is part of the research included in the project TP 36050, TP 35002, supported by the Ministry of Science and Technological Development of the Republic of Serbia, and the project Federal Ministry of Education and Science of BiH. The authors would like to thank the Ministry for the financing of this project.

REFERENCE

[1] M. Janković, Malociklusni zamor, Monografija, Mašinski fakultet, Beograd, 2001.

[2] Z. Burzić, Dž. Gačo, F. Islamović, M. Burzić, E. Bajramović, The effect of variable loading on integrity of a welded joint of high alloy-steel X20, Metalurgija, 52 (2013) 2, 181-184.

[3] A. Bukvić, Z. Burzić, R. Prokić-Cvetković, O. Popović, M. Burzić, R. Jovičić, Welding technology selection effect on fracture-toughness parameters of bi-material welded joints, Technical Gazette, 19 (2012) 1, 167-174.

[4] M. Burzić, Analysis of Crack Parameters of Welded Joint of Heat Resistant Steel, Structural Integrity and Life, 8 (2008) 1, 41-54.

[5] S. Posavljak, Istraživanje zamornog veka rotacionih diskova avionskih motora, Doktorska disertacija, Mašinski fakultet, Beograd, 2008.

[6] ACRONI, Jesenice, Born from fire, made to endure -Carbon Steel, Quenched & Tempered Heavy Plates, 2013.

[7] EN 10002-1, Metallic materials – Tensile testing, Part 1: Method of test at ambient temperature, 2010.

[8] J. Bernetič, Razvoj visokotrdne DP S690QL debelin 30 - 60 mm: kratka reziskovalna naloga, Acroni, Reziskave in razvoj, 2008.

[9] ASTM E513, Definitions of Terms Relating to Constant-Amplitude, Low-Cycle Fatigue Testing, Annual Book of ASTM Standards, 03.01, 2000.

[10] ASTM E606, Practice for Strain-Controlled Fatigue Testing, Annual Book of ASTM Standards, 03.01(2000)

[11] ASTM E739, Standard Practice for Statistical Analysis of Linear or Linearized Stress-Life (S-N) and Strain-Life (e-N) Fatigue Data, Annual Book of ASTM Standards, 03.01, 2000.

Note: The responsible translator for English language is Anđa Zorica, Belgrade, Serbia