CIP - Каталогизација у публикацији
Народна и универзитетска библиотека
Републике Српске, Бања Лука

621.3(082)(086.76)
621(082)(086.76)

МЕЂУНАРОДНА конференција о достигнућима у машинству и индустријском инжењерству (16 ; 2023 ; Бања Лука)
Proceedings [Електронски извор] : DEMI 2023 / [16th international conference on accomplishments in mechanical and industrial engineering, Banja Luka, Jun 2023 ; editor in chief Petar Gvero]. - El. zbornik. - Banja Luka : Faculty of Mechanical Engineering, 2023. - 1 електронски оптички диск (CD-ROM) : слика ; 12 cm

Систематски захтјеви: нису наведени. - Насл. са насл. екрана. - Ел. публикација у ПДФ формату опсега 533 стр. - Опис извора дана 7. 06. 2023. - Библиографија уз сваки рад.

ISBN 978-99976-11-04-8

COBISS.RS-ID 138545409

University of Banja Luka
Faculty of Mechanical Engineering

PROCEEDINGS

DEMI 2023

Banja Luka, Jun 2023

16TH INTERNATIONAL CONFERENCE ON ACCOMPLISHMENTS IN MECHANICAL AND INDUSTRIAL ENGINEERING

DEMI 2023

Supported by:
MINISTRY FOR SCIENTIFIC AND TECHNOLOGICAL DEVELOPMENT, HIGHER EDUCATION AND INFORMATION SOCIETY
OF THE REPUBLIC OF SRPSKA

Organizer and publisher:
FACULTY OF MECHANICAL ENGINEERING UNIVERSITY OF BANJA LUKA

Co-organizer:
FACULTY OF MECHANICAL ENGINEERING UNIVERSITY OF NIŠ, SERBIA

FACULTY OF MECHANICAL ENGINEERING UNIVERSITY OF PODGORICA, MONTENEGRO

FACULTY OF ENGINEERING HUNEDOARA
UNIVERSITY POLITEHNICA TIMIŞOARA, ROMANIA REYKJAVIK

UNIVERSITY, ICELAND

For publisher:
Full Prof. Aleksandar Milašinović, PhD

Editor of chief:
Full Prof. Petar Gvero, PhD

Executive editor:
Biljana Prochaska, PhD
Milivoj Stipanović, BsC

ORGANIZING COMMITTEE

Prof. Petar Gvero, PhD
Chairman of Organizing and Scientific Committee
Faculty of Mechanical Engineering, University of Banja Luka

Prof. Aleksandar Milašinović,
PhD Prof. Zorana Tanasić, PhD
Assoc. Prof. Stevo Borojević, PhD
Assoc. Prof. Goran Janjić, PhD
Assist. Prof. Dejan Branković, PhD
Prof. Uroš Karadžić, PhD
(Faculty of Mechanical Engineering, Podgorica)
Assoc. Prof. Dejan Mitrović, PhD
(Faculty of Mechanical Engineering, Niš)
Assoc. Prof. Sorin Ioan Deaconu, PhD
(Faculty of Engineering Hunedoara, Romania)
Assist. Prof. David C. Finger, PhD
School of Science and Engineering University of Reykjavik, Iceland
Goran Jotić, Senior Assistant, MSc
Saša Tešić, Assistant, MSc
Gordana Tošić, Assistant, MSc
Ivana Savković, Assistant, MSc
Dijana Đeorđić, Assistant, MSc
Biljana Prochaska, PhD
Sanja Maglov, MA+
Boro Marić, BA Law
Nedeljka Sladojević Putnik, BA Economics
Milivoj Stipanović, BSc
Zoran Grahovac, Assistant, MSc
Milisav Marković, Senior Assistant, MSc

SCIENTIFIC COMMITTEE

Prof. Darko Knežević, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Prof. Radivoje Mitrović, PhD Faculty of
Mechanical Engineering University of
Belgrade

Prof. Vlastimir Nikolić, PhD Faculty of
Mechanical Engineering University of Niš

Prof. Nenad T. Pavlović, PhD Faculty of
Mechanical Engineering University of Niš

Prof. Igor Vušanović, PhD
Faculty of Mechanical Engineering
Podgorica, University of Montenegro

Prof. Gelu Ovidiu Tirian, PhD University
Politehnica Timisoara Romania

Prof. Dejan Lukić, PhD Faculty of Technical
Sciences University of Novi Sad

Prof. Saša Živanović, PhD
Faculty of Mechanical Engineering
University of Belgrade

Prof. Mijodrag Milošević, PhD Faculty of
Technical Sciences University of Novi Sad

Prof. Aleksandar Milašinović, PhD Faculty of
Mechanical Engineering University of Banja
Luka

Prof. Milan Tica, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Prof. Izet Bjelonja, PhD
Faculty of Mechanical Engineering
University of Sarajevo

Prof. Milan Zeljković, PhD Faculty of
Technical Sciences University of Novi Sad

Prof. Slobodan Tabaković, PhD Faculty of
Technical Sciences University of Novi Sad

Prof. Franci Pušavec, PhD
Faculty of Mechanical Engineering
University of Ljubljana

Prof. Miodrag Manić, PhD
Faculty of Mechanical Engineering
University of Niš

Prof. Milenko Sekulić, PhD Faculty of
Technical Sciences University of Novi Sad

Prof. Mileta Janjić, PhD
Faculty of Mechanical Engineering
Podgorica, University of Montenegro

Assist. Prof. Davorin Kramar, PhD University
of Ljubljana, Slovenia

Prof. Simo Jokanović, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Prof. Gordana Globočki-Lakić, PhD Faculty of
Mechanical Engineering University of Banja
Luka

Prof. Ardelean Erika, PhD University
Politehnica Timisoara Romania

Prof. Petar Gvero, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Prof. Slobodan Lubura, PhD
Faculty of Electrical Engineering University
of East Sarajevo

Prof. Sanda Midžić – Kurtagić, PhD Faculty of
Mechanical Engineering University of
Sarajevo

Assoc. Prof. Srđan Vasković, PhD Faculty of
Mechanical Engineering University of East
Sarajevo

Prof. Bratislav Blagojević, PhD Faculty of
Mechanical Engineering University of Niš

Prof. Milan Radovanović, PhD Faculty of
Mechanical Engineering University of
Belgrade

Prof. Dragoslava Stojiljković, PhD Faculty of
Mechanical Engineering University of
Belgrade

Prof. Nebojša Manić, PhD
Faculty of Mechanical Engineering
University of Belgrade

Prof. Milan Lečić, PhD
Faculty of Mechanical Engineering
University of Belgrade

Prof. Neven Duić, PhD
Faculty of Mechanical Engineering and Naval
Architecture
University of Zagreb

Prof. Vojislav Novaković, PhD NTNU, Norway

Prof. Milan Rackov, PhD Faculty of Technical
Sciences University of Novi Sad

Prof. Mirko Blagojević, PhD Faculty of
Engineering Sciences University of
Kragujevac

Prof. Sanjin Troha, PhD

Faculty of Engineering University of Rijeka,
Croatia

Prof. Nebojša Rašović, PhD
Faculty of Mechanical Engineering,
Computing and Electrical Engineering,
University of Mostar

Prof. Miroslav Milutinović, PhD Faculty of
Mechanical Engineering University of
University of East Sarajevo

Prof. Nataša Trišović, PhD
Faculty of Mechanical Engineering
University of Belgrade

Prof. Mladomir Milutinović, PhD Faculty of
Technical Science University of Novi Sad

Prof. Dražan Kozak, PhD
University of Josip Juraj Strossmayer in
Osijek, Croatia

Prof. Dragan Milčić, PhD
Faculty of Mechanical Engineering
University of Niš

Prof. Radoslav Tomović, PhD
Faculty of Mechanical Engineering
Podgorica, University of Montenegro

Prof. Janko Jovanović, PhD
Faculty of Mechanical Engineering
Podgorica, University of Montenegro

Prof. Nebojša Radić, PhD
Faculty of Mechanical Engineering
University of East Sarajevo

Prof. Tomaž Berlec, PhD
Faculty of Mechanical Engineering
University of Ljubljana

Prof. Janez Kušar, PhD
Faculty of Mechanical Engineering
University of Ljubljana

Prof. Platon Sovilj, PhD Faculty of Technical
Sciences University of Novi Sad

Prof. Gordana Stefanović, PhD Faculty of
Mechanical Engineering University of Niš

Prof. Miladin Stefanović, PhD Faculty of
Engineering Sciences University of
Kragujevac

Prof. Vlado Medaković, PhD Faculty of
Mechanical Engineering University of East
Sarajevo

Prof. Valentina Golubović-Bugarski, PhD,
Faculty of Mechanical Engineering, University
of Banja Luka

Prof. Strain Posavljak, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Prof. Vid Jovišević, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Prof. Živko Babić, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Prof. Atul Bhaskar, PhD University of
Southampton United Kingdom

Prof. Socalici Ana, PhD University
Politehnica Timisoara Romania

Prof. Milan Banić, PhD
Faculty of Mechanical Engineering
University of Niš

Prof. Aleksandar Sedmak, PhD Faculty of
Mechanical Engineering University of
Belgrade

Prof. Branko Blanuša, PhD Faculty of
Electrical Engineering University of Banja
Luka

Assist. Prof. Srđan Savić, PhD Faculty of
Technical Sciences University of Novi Sad

Prof. Dejan Mitrović, PhD
Faculty of Mechanical Engineering
University of Niš

Prof. Goran Janevski, PhD
Faculty of Mechanical Engineering
University of Niš

Prof. Uroš Karadžić, PhD
Faculty of Mechanical Engineering
Podgorica, University of Montenegro

Prof. Deaconu Sorin, PhD University
Politehnica Timisoara Romania

Prof. Bordeasu Ilare, PhD University
Politehnica Timisoara Romania

Assist. Prof. Dejan Branković, PhD Faculty of
Mechanical Engineering University of Banja
Luka

Prof. Vinko Babić, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Prof. Jovanka Lukić, PhD Faculty of
Engineering Sciences University of
Kragujevac

Prof. Goran Petrović, PhD
Faculty of Mechanical Engineering
University of Niš

Prof. Radoje Vujadinović, PhD Faculty of
Mechanical Engineering Podgorica,
University of Montenegro

Prof. Snežana Petković, PhD Faculty of
Mechanical Engineering University of Banja
Luka

Prof. Miodrag Hadžistević, PhD Faculty of
Technical Sciences University of Novi Sad

Prof. Branko Štrbac, PhD, PhD Faculty of
Technical Sciences University of Novi Sad

Prof. Bratislav Blagojević, PhD Faculty of
Mechanical Engineering University of Niš

Prof. Peđa Milosavljević, PhD Faculty of
Mechanical Engineering University of Niš

Prof. Jelena Šaković Jovanović, PhD Faculty
of Mechanical Engineering Podgorica,
University of Montenegro

Prof. Mladen Todić, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Prof. Milija Krajišnik, PhD
Faculty of Mechanical Engineering
University of East Sarajevo

Prof. Ilija Ćosić, Emeritus Faculty of
Technical Sciences University of Novi Sad

Prof. Zorana Tanasić, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Prof. Mirko Soković, PhD
University of Ljubljana, Slovenia

Prof. Miroslav Bobrek, PhD Faculty of
Mechanical Engineering University of Banja
Luka

Prof. Goran Janjić, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Prof. Igor Budak, PhD Faculty of Technical
Sciences University of Novi Sad

Prof. Tihomir Latinović, PhD Faculty of
Mechanical Engineering University of Banja
Luka

Assist. Prof. Bojan Knežević, PhD Faculty of
Mechanical Engineering University of Banja
Luka

Prof. Sead Pašić, PhD
Faculty of Mechanical Engineering, “Džemal
Bijedić”, University in Mostar

Prof. Borut Kosec, PhD
Faculty of Natural Sciences and Engineering,
University of Ljubljana

Prof. Darko Bajić, PhD
Faculty of Mechanical Engineering
Podgorica, University of Montenegro

Prof. Dragoslav Dobraš, PhD Faculty of
Mechanical Engineering University of Banja
Luka

Senior Scient. Eng. Milica Grahovac, PhD,
Lawrence Berkeley National Laboratory,
USA

Prof. Doina Frunzaverde, PhD Faculty of
Engineering Resita Babeș-Bolyai University

Prof. Mihajlo Stojčić, PhD
Faculty of Mechanical Engineering
University of Banja Luka

Assist. Prof. Esad Tombarević, PhD Faculty
of Mechanical Engineering Podgorica,
University of Montenegro

Assist. Prof. Boško Matović, PhD Faculty of
Mechanical Engineering Podgorica,
University of Montenegro

Materials and Welding

DEMI 2023

16th International Conference on Accomplishments in Mechanical and Industrial Engineering

Banja Luka
1–2 Jun 2023.

www.demi.mf.unibl.org

Life assessment using the finite element method of high-strength low-alloy steel samples exposed to low-cycle fatigue

V. Aleksić[a], S. Bulatović[a], B Zečević[b], A. Maksimović[b], Lj. Milović[c]

[a] *Institute for testing of materials-IMS Institute, Bulevar vojvode Mišića 43, 11000 Belgrade, Serbia*
[b] *Innovation Centre of the Faculty of Technology and Metallurgy, Karnegijeva 4, 11120 Belgrade, Serbia*
[c] *University of Belgrade, Faculty of Technology and Metallurgy, Karnegijeva 4, 11120 Belgrade, Serbia*

Abstract

In the paper, based on the results of experimental research on the behavior of samples in the form of round smooth test specimens (STS) made of high-strength low-alloy steel (HSLA), Nionikral 70 (NN-70), under conditions of low-cycle fatigue (LCF), a computational stress analysis was performed using numerical methods.

Experimental investigations of the behavior of the samples were performed with controlled and fully reversible deformation ($\Delta\varepsilon/2$ = const, $R\varepsilon = \varepsilon min/\varepsilon max = -1$), according to the ISO 12106:2003 (E) standard.

For computational analyses, the method of least squares (in the Excel program) and the finite element method (FEM) (in the SolidWorks program) were used. The behavior of HSLA steel during low cycle fatigue (LCF) simulation was analyzed in the Cosmos module of the SolidWorks program.

On the basis of the analysis of the results of the stress-deformation state and the determination of the life span through the isolines of the life span and comparison with the results of experimental tests, a graphic representation is given. Specific load cycles involving the entire round smooth test specimen ligament for a specific load in a wide range of LCF loads were analyzed.

The analyzes showed the justification of the effort to solve the life assessment of steel subjected to low cycle fatigue (LCF) numerically. The results of experimental tests and simulation tests also gave us important data on understanding the LCF behavior of HSLA steel NN-70.

Keywords *HSLA, STS, LCF, Experiment, Excel, SolidWorks, FEM*

1. UVOD

In the field of engineering structures and constructions, exposed to variable stresses (σ), two types of fatigue are distinguished [1], high cycle fatigue (HCF) (high number of cycles (N) until failure) which is lower than the limit state σ_T and low cycle fatigue (LCF), with a low number of cycles to failure, but in the domain of plastic stresses.

Low-cycle fatigue of material means low-frequency material fatigue in which the appearance of microcracks and fractures occurs during repeated plastic strain with the number of cycles to failure $N=5x10^4$ changes. Low-cycle fatigue is often referred to as statistical endurance under repeated static loads. The characteristics of the fatigue process during low-cycle fatigue differ from the

Corresponding author

Phd, Vujadin Aleksić, IWE, Research Associate
vujadin.aleksic@institutims.co.yu

Institute for testing of materials-IMS Institute
Bulevar vojvode Mišića 43
Belgrade, Serbia

characteristics of the fatigue process during high-cycle fatigue for the same load levels, so the assessment of the suitability of the material for long-term work must include two types of tests: high-cycle fatigue with high frequency (high frequency value) and low-cycle fatigue at lower frequency values.

Experiences have shown that the time of crack initiation is relatively short, so the life of the structure is usually determined according to the time of crack propagation, or more precisely, according to the time of propagation to the critical crack length.

High strength low alloy steels (HSLA) (Arctic steel [2]) were developed during the 1960s and 1970s to address the welding problems of conventional structural steels and the brittle fracture accidents caused by low temperatures [3]. For these constructions, the most commonly applied shaping procedure is joining by welding. The base material (BM) of high strength low alloy steels, intended for the construction of welded structures in addition to high strength, should have good plasticity, sufficient impact toughness, high resistance to brittle sheet metal, satisfactory machinability, good weldability, and the production process should be economical.

2. PROPERTIES OF HSLA STEEL NN-70

HSLA steel, NN-70 [4] is the Yugoslav version of the American steel HY-100. HSLA steels are generally being used for producing of ship and pressure equipment. The most significant component that influences steel selection is the suitable strength-to-weight proportion of HSLA steels compared with regular low-carbon steels. Ship structures are most commonly being produced by welding. For this reason high strength low-alloy (HSLA) steels, besides high strength as the main properties, should also have exceptional plasticity, adequate toughness and high resistance to brittle damage, as well as adequate workability and good welding performance [5-8].

Due to exposure to complex loading with constant cycles during exploitation, a basic understanding of material behavior and damage mechanisms under fatigue conditions is important. Tables 1 and 2 show the chemical composition and mechanical properties of HSLA steel NN-70 at room temperature [9-33].

Table 1. Chemical composition (%wt) of NN-70 [9–33]

C	Si	Mn	P	S	Cr	Ni	Mo	V	Al	As	Sn
0.106	0.209	0.220	0.005	0.0172	1.2575	2.361	0.305	0.052	0.007	0.017	0.014
Cu	Ti	Nb	Ca	B	Pb	W	Sb	Ta	Co	N	C_{eq}
0.246	0.002	0.007	0.0003	0	0.0009	0.0109	0.007	0.0009	0.0189	0.0096	0.542

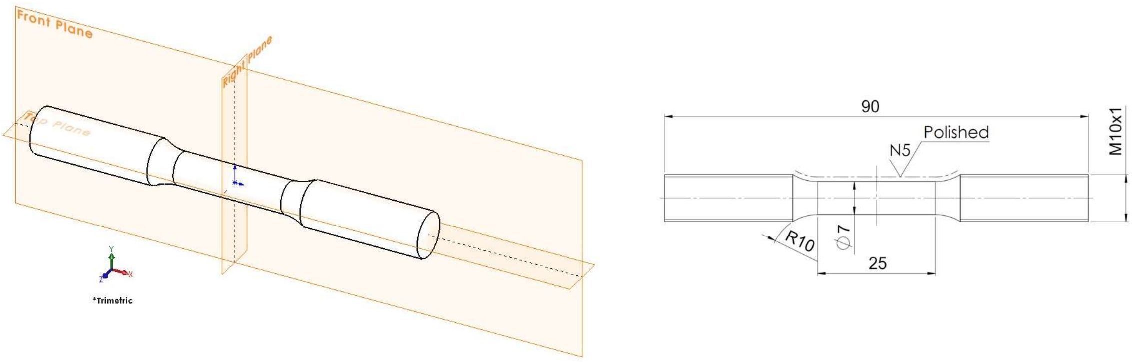
$C_{eq} = C + Mn/6 + Si/24 + Ni/40 + Cr/5 + Mo/4 + V/14$.

Table 2. Mechanical properties of NN-70 at room temperature, 20 °C, [9–33]

Microstructure		Tempered martensite + tempered bainite
Ultimate tensile stress, R_m, MPa		854.8
Yield stress, $R_{p0.2}$, MPa		813.4
Modulus of elasticity, E, GPa	static	211.5
	dynamic, LCF	**221.4**
Percent elongation, A_5, %		18.4
Impact toughness, J/cm^2		96.83
Crack initiation energy, J/cm^2		39.60
Crack propagation energy, J/cm^2		57.23
Hardness	plate	245-269 HV30
	LCF specimen	252-262 HV10

3. LCF TESTING OF HSLA NN-70 SAMPLES

Tests of steel, NN-70, by low-cycle fatigue with half-amplitude of controlled deformation, $\Delta\varepsilon/2=0.35 – 0.80$, were performed on 10 round smooth test specimens (STS), fig. 1a, made of sticks, 11x11x95 mm from steel plate NN-70, processed according to the drawing from fig. 1b.



a) Symmetry in three planes b) Dimensions of STS steel NN-70

Fig. 1. Specimen for LCF test of steel NN-70 [9–33]

Low cycle fatigue test, in accordance with ISO 12106:2017 (E) [34], was performed on a universal servo-hydraulic MTS machine (rating 500 kN), in the Military Technical Institute in Žarkovo [13, 21]. The test results of 4 specimens with controlled strain regimes shown in Table 3 were considered.

Table 3. Basic data on controlled strain regimes of LCF test NN-70 [21]

Specimen (Sp)	1	2	3	4	5	6	7
	$\Delta\varepsilon/2$ [%]	$\Delta\varepsilon/2$ [V]	$\Delta\varepsilon/2$ [mm/mm]	Δl [mm]	$\Delta\varepsilon$ [%]	T [s]	f [Hz]
	experiment	$\varepsilon[\%]=\varepsilon[V]\cdot 0.2$	1/100	3*25	1*2	experiment	1/6
09	0.35	1.75	0.0035	0.0875	0.70	4.30	0.2326
03	0.50	2.50	0.0050	0.1250	1.00	4.30	0.2326
06	0.60	3.00	0.0060	0.1500	1.20	4.30	0.2326
08	0.80	4.00	0.0080	0.2000	1.60	4.30	0.2326

4. PROCESSING OF TEST RESULTS IN THE EXCEL PROGRAM

Processing of test results was done in the EXCEL program [18, 19, 21, 30]. The results of that processing are shown in Tables 4 and 5 and in Fig. 2, 3 and 4.

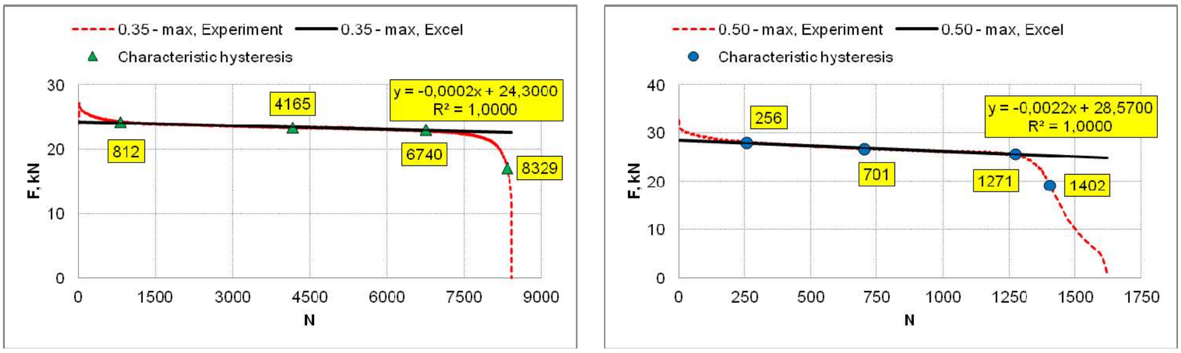
Table. 4 Characteristic processed test data of LCF steel NN-70 [29, 30]

LCF NN-70, ISO 12106/03 [34]		Stabilization regions		Characteristic cycles of stabilization			
Sp	$\Delta\varepsilon/2$, %	y=F, kN; x=N	R^2	N_{bs}	N_{es}	N_f	$N_s = N_f/2$
09	0.35	F=-0.0002N+24.30	0.95	812	6740	8329	4165
03	0.50	F=-0.0022N+28.57	0.97	256	1271	1402	701
06	0.60	F=-0.0057N+29.66	0.94	127	415	501	251
08	0.80	F=-0.0162N+30.83	0.94	50	165	207	104

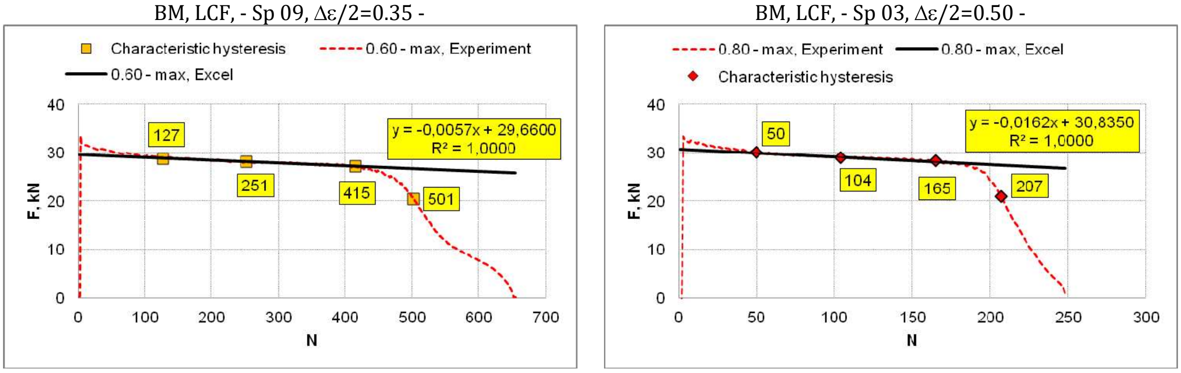
N_{bs} –The beginning of stabilization; N_{es} – End of stabilization; N_f – Cycle of failure; N_s – Characteristic stabilization cycle

Table 5. Data of characteristic stabilized hysteresis, N_s, of HSLA steel NN-70 [29, 30]

Sp	y=mx-b; y=F, kN; x=$\Delta\varepsilon_p/2$ F=0; $\Delta\varepsilon_p/2$=b/m $\Delta\varepsilon_e/2=\Delta\varepsilon/2-\Delta\varepsilon_p/2$	N_s	$\Delta\varepsilon/2$	$\Delta\varepsilon_p/2$	$\Delta\varepsilon_e/2$	σ_{max}, MPa	σ_{min}, MPa	$\Delta\sigma/2$, MPa
09	$\Delta\varepsilon_p/2$=(3.04/61.38)/100	4165	0.0035	0.000495	0.003005	608.14	-689.48	648.81
03	$\Delta\varepsilon_p/2$=(18.74/109.15)/100	701	0.0050	0.001717	0.003283	702.84	-707.19	705.01
06	$\Delta\varepsilon_p/2$=(16.93/76.92)/100	251	0.0060	0.002201	0.003799	736.15	-698.00	717.07
08	$\Delta\varepsilon_p/2$=(27.97/65.04)/100	104	0.0080	0.004301	0.003699	761.87	-709.04	735.46



BM, LCF, - Sp 09, Δε/2=0.35 - BM, LCF, - Sp 03, Δε/2=0.50 -



BM, LCF, - Sp 06, Δε/2=0.60 - BM, LCF, - Sp 08, Δε/2=0.80 -

Fig. 2. Graphical results of LCF test of NN-70 steel specimens [29, 30]

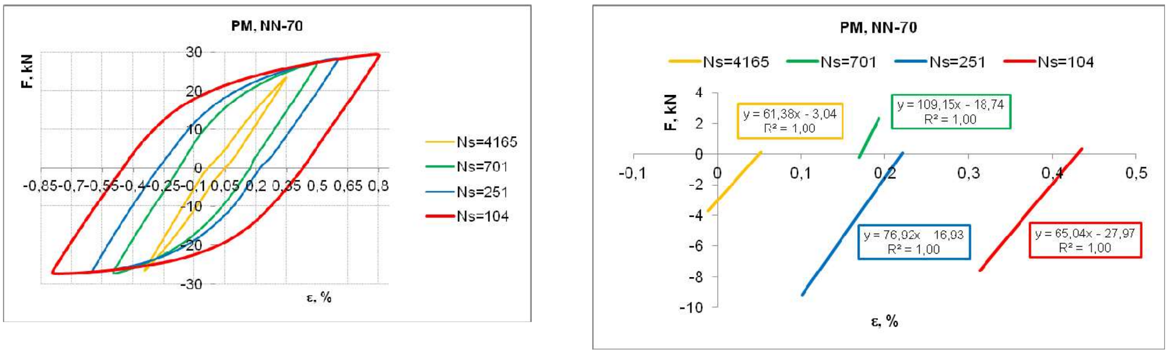


Fig. 3. Graphic view of processed stabilized hysteresis, N_s, LCF testing of HSLA steel NN-70 [29, 30]

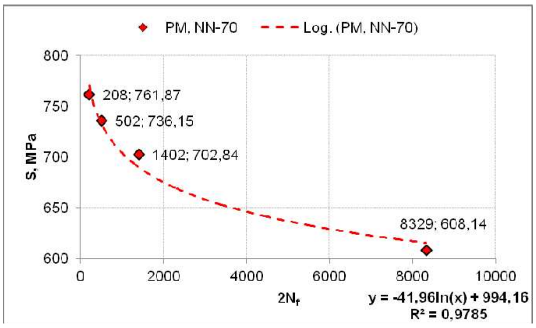
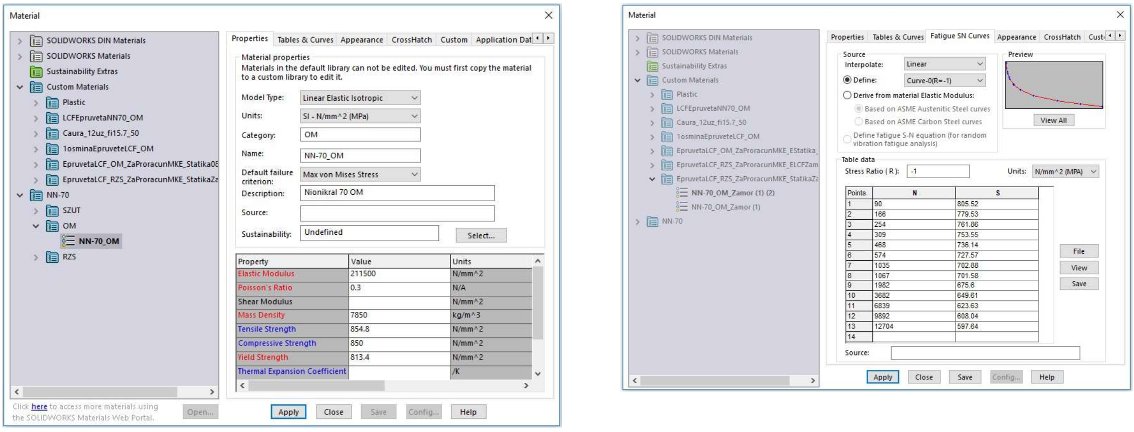


Fig. 4. Dependence S(σ)-2N$_f$ obtained in EXCEL by the method of least squares [29, 30]

5. PREPARATION FOR STATIC AND FATIGUE CALCULATION OF FEM IN SOLIDWORKS

Data from Table 2 and data obtained by processing the results of the LCF test into the EXCEL program, Fig. 4, were used for the static and fatigue calculation of the FEM of the BM specimen model in the Cosmos module of the SolidWorks parametric program, and their input is shown in Fig. 5. Initial data on the model, boundary conditions and finite element mesh are shown in Fig. 6.



Material properties
Materials in the default library can not be edited. You must first copy the material to a custom library to edit it.

Model Type: Linear Elastic Isotropic
Units: SI - N/mm^2 (MPa)
Category: OM
Name: NN-70_OM
Default failure criterion: Max von Mises Stress
Description: Nionikral 70 OM
Source:
Sustainability: Undefined

Property	Value	Units
Elastic Modulus	211500	N/mm^2
Poisson's Ratio	0.3	N/A
Shear Modulus		N/mm^2
Mass Density	7850	kg/m^3
Tensile Strength	854.8	N/mm^2
Compressive Strength	850	N/mm^2
Yield Strength	813.4	N/mm^2
Thermal Expansion Coefficient		/K

Source
Interpolate: Linear
● Define: Curve-0(R=-1)
○ Derive from material Elastic Modulus:
● Based on ASME Austenitic Steel curves
○ Based on ASME Carbon Steel curves
○ Define fatigue S-N equation (for random vibration fatigue analysis)

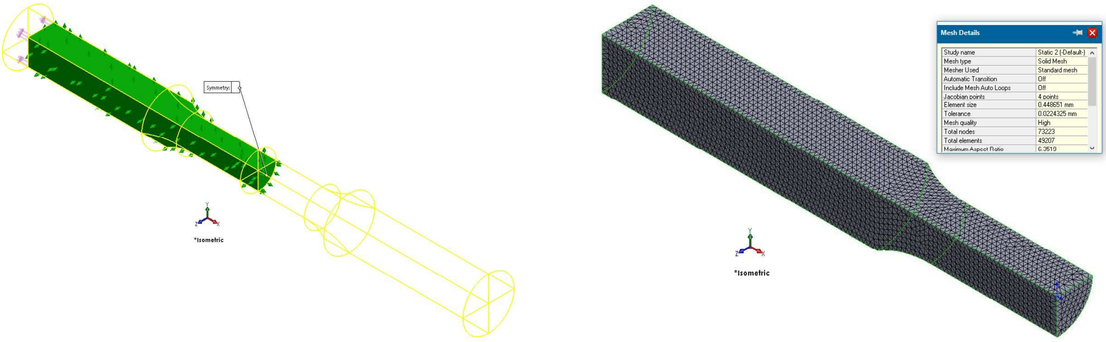
Table data
Stress Ratio (R): -1
Units: N/mm^2 (MPA)

Points	N	S
1	90	805.52
2	166	779.53
3	254	761.86
4	309	753.55
5	468	736.14
6	574	727.57
7	1035	702.88
8	1067	701.58
9	1982	675.6
10	3682	649.61
11	6839	623.63
12	9892	608.04
13	12704	597.64
14		

Source:

a) Input data for static calculation b) Input data for LCF

Fig. 5. Data for FEM calculation static and dynamic behaviour of HSLA steel NN-70



Study name	Static 2 (-Default-)
Mesh type	Solid Mesh
Mesher Used	Standard mesh
Automatic Transition	Off
Include Mesh Auto Loops	Off
Jacobian points	4 points
Element size	0.448651 mm
Tolerance	0.0224325 mm
Mesh quality	High
Total nodes	73223
Total elements	49207
Maximum Aspect Ratio	6.3519

Boundary conditions part of BM specimen Finite element mesh BM specimen

Fig. 6. Initial data on models, boundary conditions and finite element mesh of NN-70 specimen

6. RESULTS OF STATIC AND FATIGUE CALCULATION OF FEM IN SOLIDWORKS

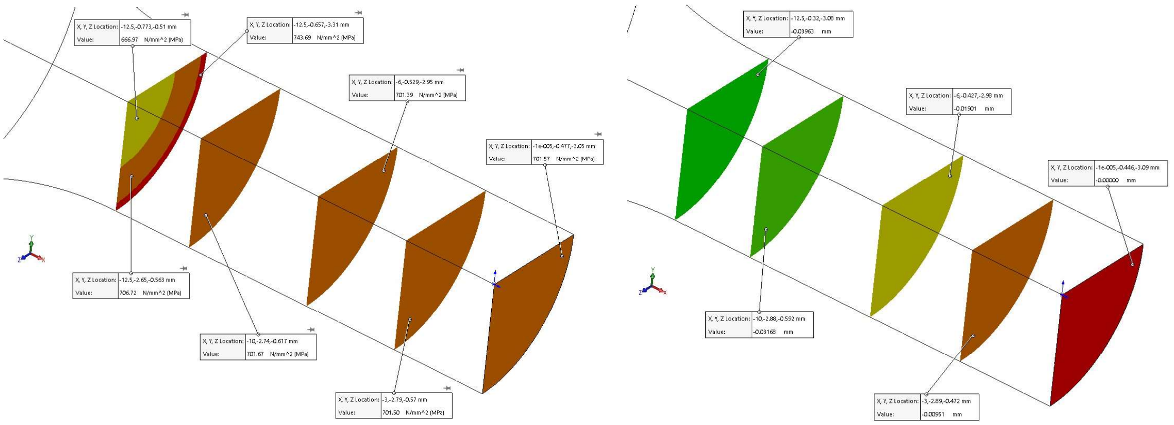
An illustration of the results of the static calculation for a load of 27 kN is shown in Fig. 7 and Table 6.

An illustration of the results of the FEM fatigue test simulation is shown in Fig. 8-10.

Table 6. Results of static calculation and simulation of LCF fatigue FEM in SolidWorks, specimen of steel NN-70

Testing specimen, cross section = 38.5 mm²							**FEM**		
	LCF, experiment		Excel		F, kN	S_{Nf}, MPa	N_{fFEM}, fracture in BM	S_{NfFEM}, max, MPa	
	Δε/2	N_f						von Mises	Normal
BM, NN-70			$N_f = e^{(994.15 - SNf)/41.96}$	90	31.00	805.52	91	872.08	898.71
				166	30.00	779.53	166	843.94	869.72
	0.80	208		254	29.32	761.87	254	824.81	850.01
				309	29.00	753.55	309	815.81	840.73
	0.60	502		468	28.33	736.15	468	796.96	821.31
				574	28.00	727.57	573	787.68	811.74
	0.50	1402		1035	27.05	702.84	1034	760,96	784.20
				1067	27.00	701.58	1065	759.55	782.75
				1982	26.00	675.60	1979	731.42	753.76
				3682	25.00	649.61	3676	703.29	724.77
				6839	24.00	623.63	6829	675.16	695.78
	0.35	8329		9892	23.40	608.14	9876	658.28	678.38
				12704	23.00	597.64	12681	647.02	666.79

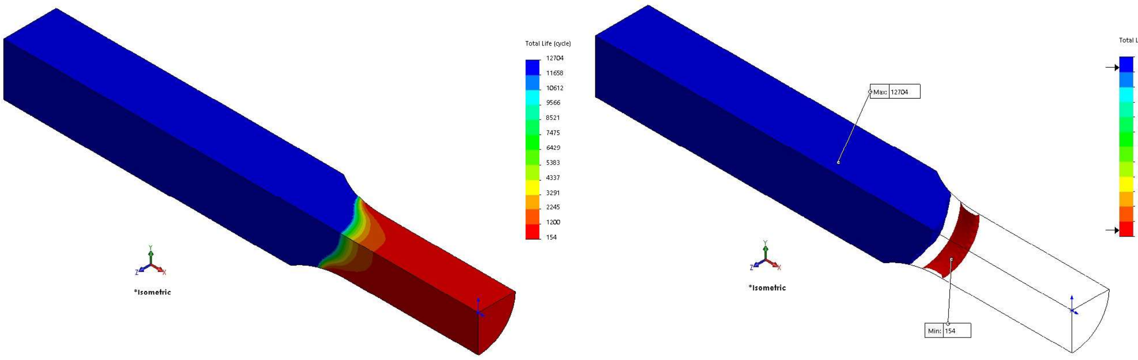
$S_{Nf} = -41{,}96\ln(N_f) + 994{,}15$ (from formula in Fig. 4)



Values of normal stresses in sections along the x axis,0 , 3, 6, 10 and 12.5 mm, BM Sp of HSLA steel NN-70

Elongation values in x-axis sections, 0 , 3, 6, 10 and 12.5 mm BM Sp of HSLA steel NN-70

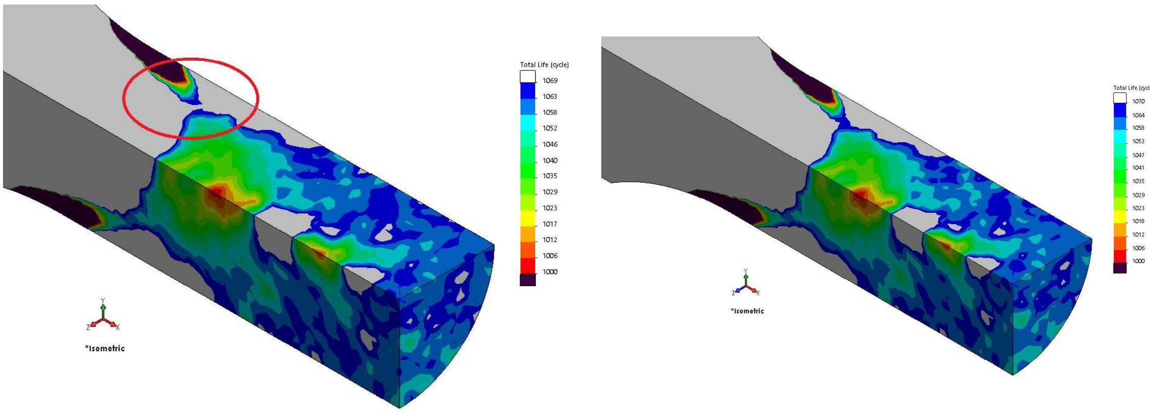
Fig. 7. Results of static calculation of FEM specimen for load 27 kN, HSLA steel of NN-70 (see Table 6)



Isolines of life, BM

Isolines of life, BM, Min i Max

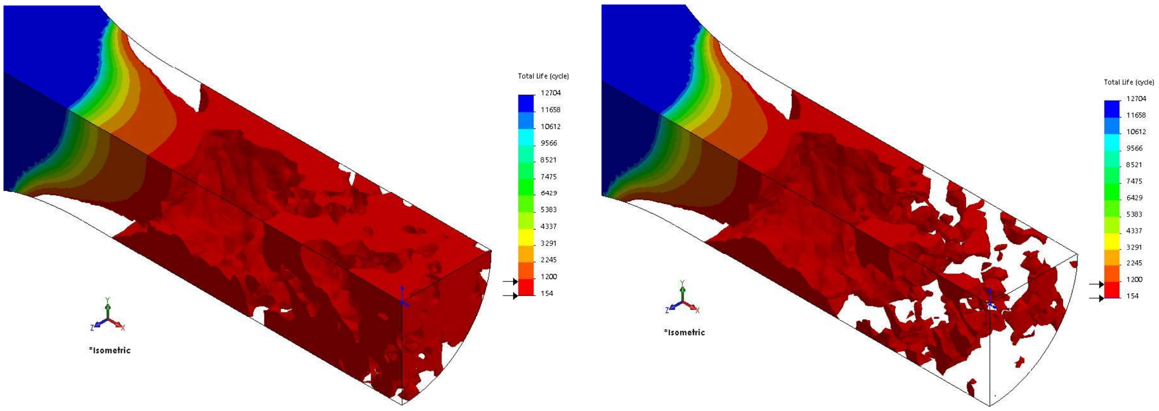
Fig. 8. Isolines of lifetime by section of STS HSLA steel NN-70 for a load of 27 kN



The cycle preceding the breaking cycle, 1069

The cycle of fracture, 1070

Fig. 9. Determination of the failure cycle of STS BM steel NN-70 by reading isosurfaces for a load of 27 kN (see table 6)



Five cycles before breaking, 1060 The cycle of fracture, 1065

Fig. 10. Determining the failure cycle of STS BM steel NN-70 by reading isovolumes for a load of 27kN (see table 6)

In the case of FEM static calculation, the SolidWorks program, in addition to the analysis of the distribution of von Mises stresses, enables the analysis of the results of the calculation of normal stresses (Table 6) as well as the analysis of strains and elongations.

The fatigue calculation, in addition to the min and max number of iso-sections of the life cycle, also gives us the percentage of damage to a specific section of the test specimen.

The methodology for determining the number of cycles for a round smooth test specimen in which the parts of the test tube separate, i.e. break, for a certain load is shown in Fig. 9 and 10, and the results of the applied methodology are shown in Table 6. Iso-section (surface or volume) of the life cycle that covers the entire ligament of the test specimen, and it is located between the min and max number of cycles of the life cycle, which is the cycle in which the fracture of the test specimen occurs.

7. DISCUSSION OF RESULTS

By processing the results of the LCF test and calculations in the EXCEL programs, using the least squares method and SolidWorks program using the finite element method, we obtained the necessary data for determining:

1. Cyclic stress-strain curve (1), Table 7 and Fig. 11,
2. Fatigue life curve (2) and transition fatigue life (3), N_{fT}, Table 8 and Fig. 12.

Table 7. Data for Cyclic stress-strain curve (1) of HSLA steel NN-70

$\Delta\varepsilon = \frac{\Delta\sigma}{E} + 2\left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}}$ (1)	Method	n'	K', MPa	E, MPa, (determined from cycle $N_{1/4}$)
	Standard [34]	0.047	946.2	221378 (**221.4 GPa**)

Table 8. Data for fatigue life curve (2) and transition fatigue life (3) of HSLA steel NN-70

$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E} N_f^b + \varepsilon'_f N_f^c$ (2) $N_{fT} = \left(\frac{\varepsilon'_f \cdot E}{\sigma'_f}\right)^{\frac{1}{b-c}}$ (3)	Method	elastic part			plastic part		
		E, MPa	σ'f, MPa	b	ε'f	c	**N_{fT}**
	Standard [34]	221378	1153.8	-0.060	0.1045	-0.594	274

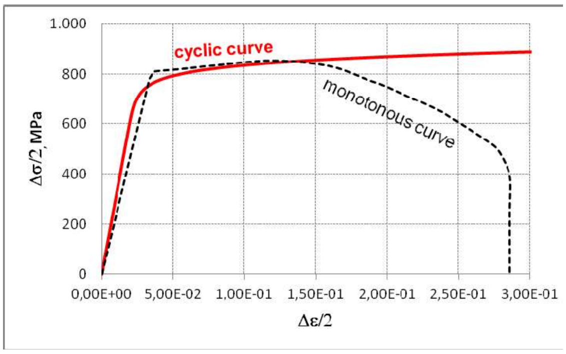


Fig. 11. Cyclic stress-strain curve (1) of HSLA steel NN-70

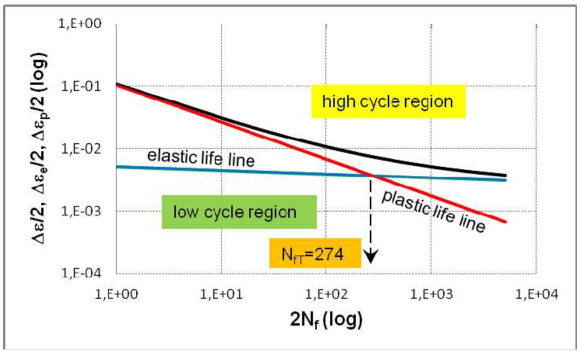


Fig. 12. Fatigue life curve (2) and transition fatigue life (3) of HSLA steel NN-70

8. CONCLUSION

The paper presents the results of the fatigue test (LCF) on a round smooth test specimen, for base metal of HSLA steel NN-70, which was used as input data for the low-cycle fatigue simulation on those test specimens and the FEM calculation in SolidWorks with the aim of obtaining comparative results of the lifetime assessment by testing and FEM calculation.

The methodology for determining the number of cycles during which the parts of the test specimen separate (specimen fracture) applied in this paper enables the calculation, FEM, of the fracture cycle to be determined on other elements made of base metal of HSLA steel NN-70 exposed to low cycle fatigue load (LCF).

As one of the very interesting and promising directions of future research, the application of the presented methodologies is imposed in order to define the size of the fatigue crack, as the main parameter for characterizing the existence of fatigue, under conditions of variable loading, in order to determine the fatigue life, cycle to failure, and assess the resistance of the material to the crack initiation, the development of which can also be followed by NDT methods.

The stabilization area during LCF test of all samples of base metal of HSLA steel NN-70 shows a high degree of agreement with the general equation of the straight line, y (F or σ) = m x (N) + b, whose coefficients m and b can be determined by linearization and show the weakening of base metal of HSLA steel NN-70.

The obtained results represent a practical contribution to the assessment of the behavior of high strength low-alloy NN-70 under LCF operating conditions.

Acknowledgement

This work was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Contracts: No. 451-03-47/2023-02/200012 and No. 451-03-47/2023-01/200287).

REFERENCES

[1] Aleksić, V., Aleksić, B., Prodanović, A., Milović, Lj. (2020). HSLA Steel-Simulation of fatigue, *New Technologies, Development And Application, Lecture Notes in Networks And Systems, Sarajevo*, vol 128. Springer, p. 314 – 321.

[2] Barsom, J. M. (1987). Fracture mechanics retrospective: early classic papers 1913-1965, *Edited By Barsom J. M.*, ASTM.

[3] Almar-Naess, A. (1985). Fatigue Handbook: Offshore Steel Structures, by Tapir, Trondheim, Norway

[4] Radović, A., Marković, D. (1984). Osvajanje Brodograđevnog Čelika Povišene Čvrstoće-Nionikral-70, VTI, Beograd.

[5] Arpan, Das., Tamshuk, Chowdhury., Soumitra. Tarafder. (2014). Ductile fracture micro-mechanisms of high strength low alloy steels, *Materials and Design*, vol. 54, p. 1002–1009.

[6] Tomasz, Ślęzaka., Lucjan, Śnieżeka., (2015). A Comparative LCF Study of S960QL High Strength Steel and S355J2 Mild Steel, *1st International Conference on Structural Integrity, Procedia Engineering, vol. 114*, p. 78– 85.

[7] Abílio, M. P., De Jesus, A., Ribeiro, S., António, A. Fernandes. (2006). Low And High Cycle Fatigue and Cyclic Elastic-Plastic Behavior Of The P355nl1 Steel, *Journal of Engineering Materials and Technology, Transactions of the ASME*, vol. 128, p. 298-304.

[8] Alang, N.A., Davies, C.M., Nikbin. K.M. (2016). Low cycle fatigue behaviour of ex-service P92 steel at elevated temperature, *21st European Conference on Fracture, ECF21*, Catania, Italy, Procedia Structural Integrity, vol. 2, p. 3177–3184.

[9] Milović, Lj., Vuherer, T., Radaković, Z., Petrovski, B., Janković, M., Zrilić, M., Daničić, D. (2011). Determination of fatigue crack growth parameters in welded joint of hsla steel, *Structural integrity and life*, vol.11, no.3, p. 183-187.

[10] Milović, Lj., Bulatović, S., Radaković, Z., Aleksić, V., Sedmak, S., Marković, S., Manjgo, M. (2012). Assessment of the behaviour of fatigue loaded HSLA welded steel joint by applying fracture mechanics parameters, *Structural integrity and life*, vol. 12, no. 3, p. 175–181.

[11] Bulatović, S., Burzić, Z., Aleksić, V., Sedmak, A., Milović, Lj. (2014). Impact of choice of stabilized hysteresis loop on the end result of investigation of High-strength low-alloy (HSLA) steel on low cycle fatigue, *Metalurgija,* vol. 53, no. 4, p. 477–480.

[12] Milović, Lj., Bulatović, S., Aleksić, V., Burzić, Z. (2014). Low cycle fatigue of weldments produced of a High strength low alloyed steel, *20th European Conference On Fracture (ECF 20), Procedia Materials Science* 3, p. 1429–1434.

[13] Bulatović, S. (2014). *Elasto-plastično ponašanje zavarenog spoja od niskolegiranog čelika povišene čvrstoće u uslovima niskocikličnog zamora*, (In Serbian). PhD thesis. Mašinski Fakulktet Univerziteta u Beogradu.

[14] Aleksić, V., Aleksić, B., Milović, Lj. (2016). Methodology for determining the region of stabiliyation of low-cycle fatigue, *Book Of Abstracts, 16th International Conference On New Trends In Fatigue And Fracture (NT2F16),* Dubrovnik, Croatia, p. 189–190.

[15] Aleksić, V., Milović, Lj., Aleksić, B., Abubkr, M. Hemer. (2016). Indicators of HSLA steel behavior under low cycle fatigue loading, *21st European Conference on Fracture, ECF21*, Catania, Italy, Procedia Structural Integrity, vol. 2, p. 3313–3321.

[16] Aleksić, V., Dojčinović, M., Milović, Lj., Samardžić, I. (2016). Cavitation damages morphology of HSLA Steel, *Metalurgija*, vol. 55, no. 3, p. 423–425.

[17] Aleksić, V., Milović, Lj., Aleksić, B., Bulatović, S., Burzić, Z., Hemer, A.M. (2017) Behaviour Of Nionikral-70 In Low-Cycle Fatigue, *Structural integrity and life*, vol. 17, no. 1, p. 61–73.

[18] Aleksić, V., Aleksić, B., Milović, Lj. (2017). Metodologija određivanja pokazatelja ponašanja hsla čelika pri delovanju niskocikličnog zamora, *V Međunarodni Kongres „Inženjerstvo, Ekologija I Materijali U Procesnoj Industriji"*, Jahorina, Bosna I Hercegovina, p. 1123-1135.

[19] Aleksić, B., Aleksić, V., Hemer, A., Milović, Lj., Grbović, A. (2018). Determination Of The Region Of Stabilization Of Low-Cycle Fatigue HSLA Steel From Test Data. In: Proceedings Of The 17th International Conference On New Trends In Fatigue And Fracture, Eds: Ricardo R. Ambriz, David Jaramillo, Gabriel Plascencia And Moussa Nait Abdelaziz, Springer, p. 101–113.

[20] Aleksić, B., Aleksić, V., Milović, Lj., Hemer, A., Prodanović, A. (2018). Determination of polynomial depending between hardness and cooling time $\Delta t_{8/5}$ of steel Nionicral 70 heat affected zone, *18th International Conference on New Trends in Fatigue and Fracture NT2F18*, Lisbon, Portugal, p. 87–90.

[21] Aleksić, V. (2019). *Niskociklični Zamor Niskolegiranih Čelika Povišene Čvrstoće*, (In Serbian). PhD thesis. Tehnološko – Metalurški Fakultet Univerziteta U Beogradu.

[22] Aleksić, V., Milović, Lj., Blačić, I., Vuherer, T., Bulatović, S. (2019). Effect of LCF on behavior and microstructure of microalloyed HSLA steel and its simulated CGHAZ, *Engineering Failure Analysis,* vol. 104, p. 1094–1106.

[23] Bulatović, S., Aleksic, V., Milovic, Lj., Zečević, B. (2021). An analysis of impact testing of high strength low-alloy steels used in ship construction, *Brodogradnja/Shipbuilding/Open Access,* vol. 72, no. 3, p. 1–12.

[25] Bulatović, S., Aleksić, V., Milović, Lj., Zečević, B. (2021). High strength low alloy steels impact toughness assessment at different test temperatures, *Advanced Technologies & Materials*, vol. 46, no. 2, p. 43–46.

[26] Bulatović, S., Aleksić, V., Milović, Lj., Zečević B. (2021). Determination of the coffin-manson equation under low-cycle fatigue conditions, *Structural integrity and life*, vol. 21, no. 3, p. 225–228.

[27] Aleksić, V., Dojčinović, M., Milović, Lj., Zečević, B., Maksimović, A. (2021). Mehanizmi i morfologije kavitacionog oštećenja čelika Nionikral 70, *Zaštita Materijala,* vol. 62, no. 2, p. 95–105.

[29] Aleksić, V., Milović, L., Bulatović, S., Zečević, B., Maksimović, A. (2022). Determination of LCF plastic and elastic strain components of steel, *Machine And Industrial Design In Mechanical Engineering. KOD 2021. Mechanisms And Machine Science, Balaton,* vol. 109. Springer, Cham. p. 341–349.

[30] Aleksić, V., Bulatović, S., Zečević, B., Maksimović, A., Milović, Lj. (2022). Processing of data obtained by the testing of steel under Low cyclic fatigue (part I), *Transactions Of Famena*, vol. XLVI, no. 4, p. 59-72.

[31] Bulatović, S., Aleksić, V., Milović, Lj., Zečević, B. (2022). Determining of the fatigue crack growth rate of HSLA steel at room temperature, *Advanced Technologies & Materials*, vol. 47, no. 1, p. 1–4.

[32] Bulatović, S., Aleksić, V., Milović, Lj., Zečević, B. (2022). Application Of Paris' Law Under Variable Loading, *FME Transactions*, vol. 50, no. 1, p. 72–78.

[33] Bulatović, S., Aleksić, V., Milović, Lj., Zečević, B. (2023). Experimental determination of the critical value of the J-integral that refers to the HSLA steel welded joint, *Tehnički Vjesnik/Technical Gazette,* vol. 30, no. 1, p. 148–152.

[34] ISO 12106. (2017). *Metallic Materials-Fatigue Testing-Axial-Strain-Controlled Method*, Geneva, Switzerland.