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Original article

Numerical Determination of the Life of Steel Exposed To Low Cycle Fatigue

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ABSTRACT

In the paper, based on the results of the experimental research of high-strength low-alloy steel (HSLA), Nionicral 70 (NN-70), under conditions of low-cycle fatigue (LCF), a numerical analysis of stress and determination of the life of steel samples was performed. Experimental testing of the behavior of the samples were performed with controlled and fully reversible strain ($\Delta\varepsilon/2$ = const, $R_\varepsilon = \varepsilon_{min}/\varepsilon_{max} = -1$), according to the standard ISO 12106:2003 (E). For computational analyses, the following were used: the method of least squares and the method of finite elements (FEM). 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. The analysis justified the effort to numerically solve the estimation of the lifespan of steel under low cycle fatigue (LCF).

Key words: *Steel, LCF, Lifetime, Numerical methods*

1. INTRODUCTION

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 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 development, or more precisely, according to the time of development to the critical length of the crack.

2. TESTED MATERIAL

HSLA steel, NN-70 [1] 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

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have exceptional plasticity, adequate toughness and high resistance to brittle damage, as well as adequate workability and good welding performance [2 - 5]. 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.

Table 1. Chemical composition (%wt) of NN-70 [6 – 29]

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

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

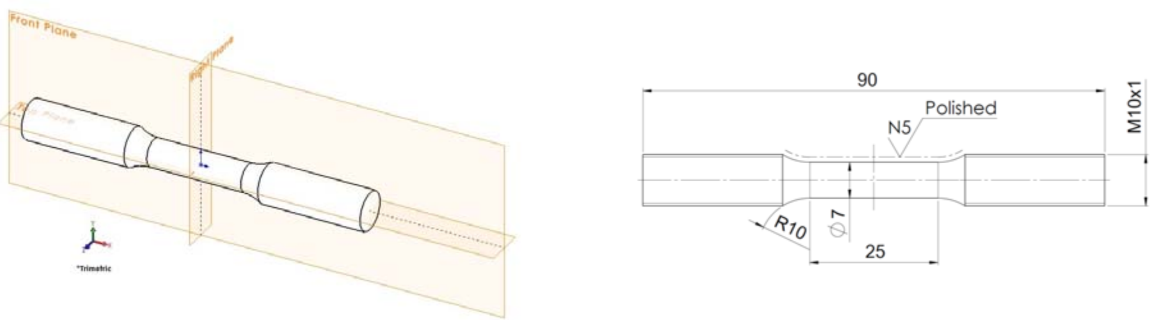
Table 2. Mechanical properties of NN-70 at room temperature, 20 °C, [6 – 29]

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. MATERIAL TESTING

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 samples (RSTS), Fig. 1a, made of sticks, 11x11x95 mm from steel plate NN-70, processed according to the drawing shown in Fig. 1b.

Low cycle fatigue test, in accordance with ISO 12106:2017 (E) [30], was performed on a universal servo-hydraulic MTS machine (rating 500 kN), in the Military Technical Institute in Žarkovo [10, 18]. The test results of 4 samples with controlled strain regimes shown in Table 3 were considered.



a) symmetry in three planes b) geometry of the specimen

Fig. 1 Specimen for LCF test of steel NN-70 [6, 29]

Table 3. Basic data on controlled strain regimes of LCF test NN-70 [18]

RSTS	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]
	test	$\varepsilon[\%] = \varepsilon[V] \cdot 0.2$	1/100	3*25	1*2	test	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

The test results were processed using the EXCEL program [15, 16, 18, 26]. The results of that processing are shown in Tables 4 and 5, as well as Figures 2, 3, and 4.

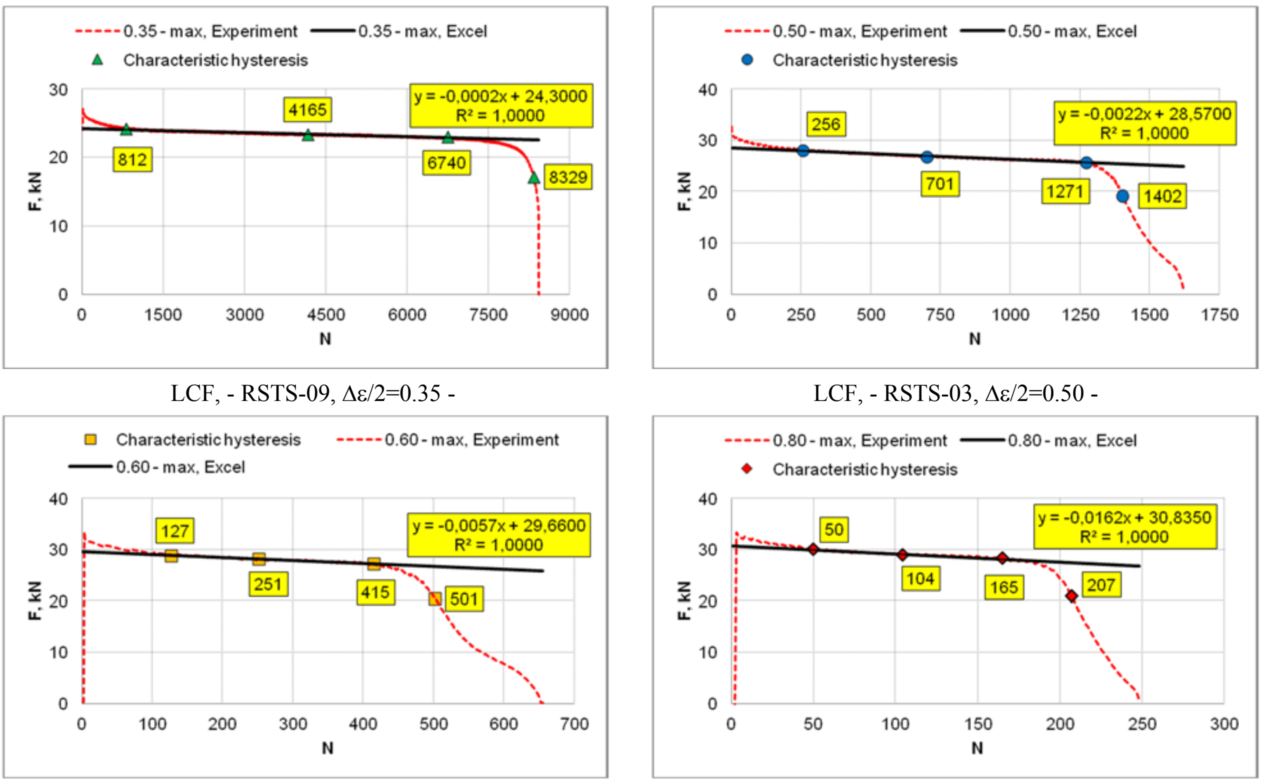
Table. 4 Characteristic processed test data of LCF steel NN-70 [25, 26]

LCF NN-70, ISO 12106 [30]		Stabilization regions		Characteristic cycles of stabilization			
RSTS	$\Delta\varepsilon/2$, %	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. Calculated LCF elastic and plastic strain amplitude components of NN-70 steel at characteristic Ns [25, 26]

RSTS	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



LCF, - RSTS-09, $\Delta\varepsilon/2$=0.35 -

LCF, - RSTS-03, $\Delta\varepsilon/2$=0.50 -

LCF, - RSTS-06, $\Delta\varepsilon/2$=0.60 -

LCF, - RSTS-08, $\Delta\varepsilon/2$=0.80 -

Fig. 2 Graphical results of LCF test of NN-70 steel samples [25, 26]

4. FEM SIMULATION

The data from Table 2 and the data derived from processing the results of the low cycle fatigue (LCF) test using Excel were employed for the static and fatigue calculations of the Finite Element Method (FEM) model of the parent material (PM) specimen within the Cosmos module of the SolidWorks parametric program. These inputs are illustrated in Fig. 5. An illustration of the results of the calculation for a load of 27 kN (RSTS) is shown in Fig. 6 and Table 6. The SolidWorks program provides various analyses for the FEM static calculation, including the evaluation of Mises stress distribution and the assessment of normal stresses, strains, and elongations. Concerning fatigue calculation, it offers information on the minimum and maximum number of iso-sections within the lifecycle and the percentage of damage for a specific section of the test specimen. The methodology delineating the cycle count for reaching the critical point of fracture under a particular load (RSTS) is depicted in Fig. 6, while the results obtained from this methodology are detailed in Table 6. The iso-section, encompassing the complete ligament of the test specimen and lying between the minimum and maximum lifecycle cycles, signifies the cycle at which the fracture occurs.

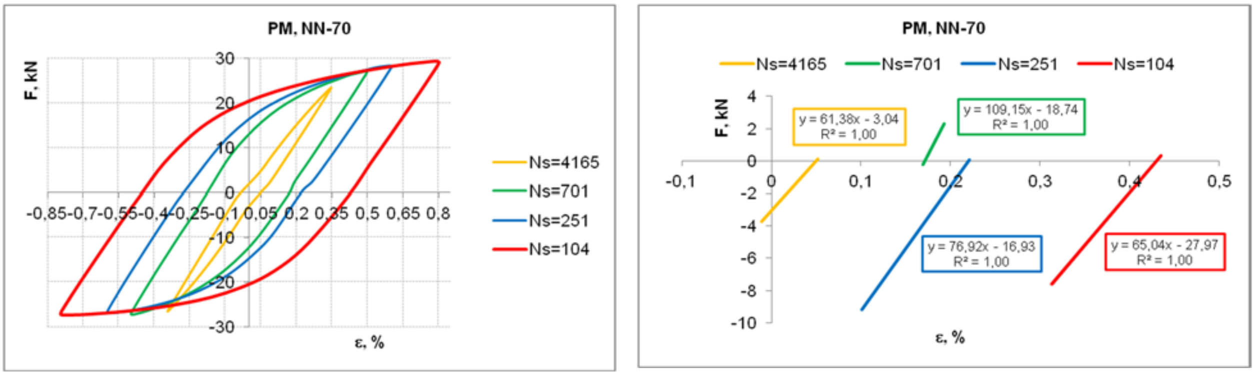


Fig. 3 Graphic view of processed stabilized hysteresis, Ns, LCF testing of HSLA steel NN-70 [25, 26]

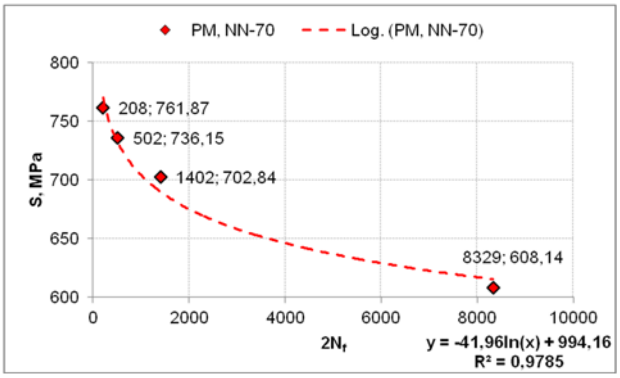
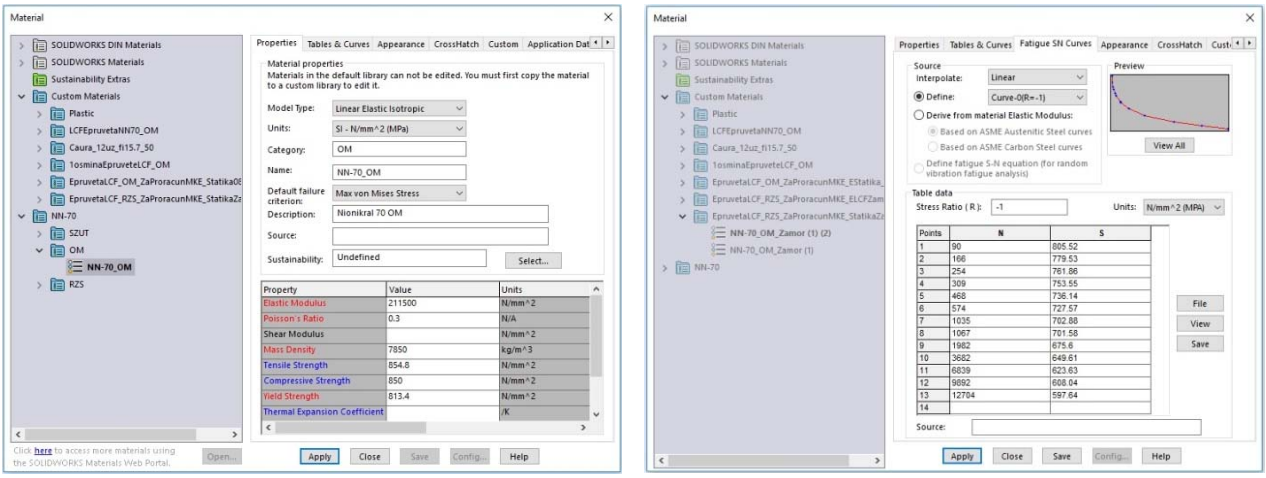


Fig. 4. Dependence S(σ)-2Nf obtained in EXCEL by the method of least squares [25, 26]



a) Input data for static calculation

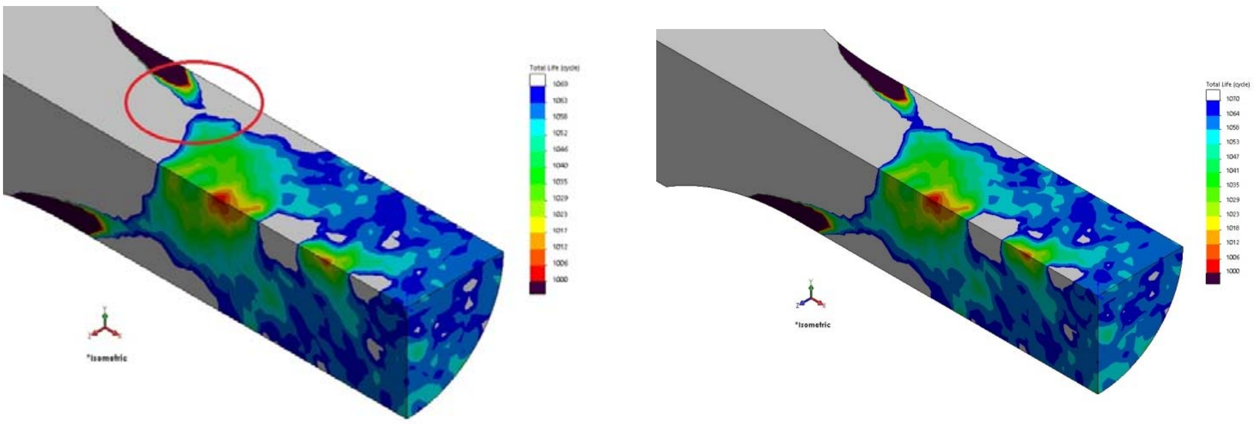
b) Input data for LCF calculation

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

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

Testing specimen, cross section = 38.5 mm^2							FEM		
	LCF, Test		N_{fExcel}		F, kN	S_{Nf}, MPa	N_{fFEM}	S_{NfFEM}, max, MPa	
	Δε/2	N_{fTest}						Mizes	Normal
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} = -41,96ln(N_f) + 994,15 (from formula in Fig. 4)



The cycle preceding the breaking cycle, 1069 Break cycle, 1070

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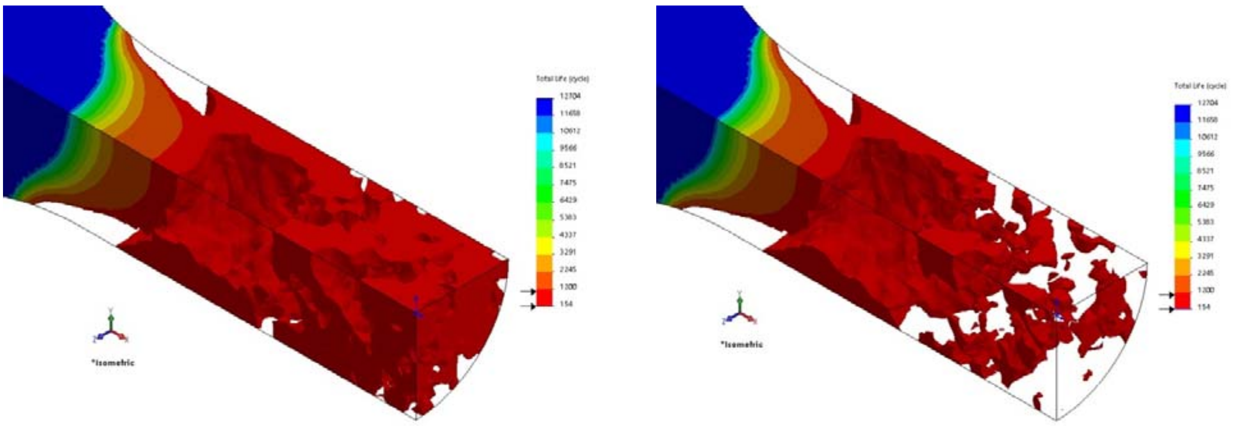

5 cycles before breaking, 1060 Break cycle, 1065

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Fig. 6 Determination of the failure cycle of RSTS HSLA steel NN-70 for a load of 27 kN (see table 6)

5. DISCUSSION OF RESULTS

By utilizing the least squares method in the EXCEL programs and employing the FEM in SolidWorks, we processed the outcomes of the LCF test and calculations. This process provided the essential data required to determine: (a) cyclic stress-strain curve (1), Table 7 and Fig. 7, and (b) fatigue life curve (2) and transition fatigue life (3), N_{fT}, Table 8 and Fig. 8.

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

	Method	n'	K', MPa	E, MPa, (from $N_{1/4}$ cycle)
$\Delta\varepsilon = \frac{\Delta\sigma}{E} + 2\left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}}$ (1)	Standard [30]	0.047	946.2	221378 (221.4 GPa)

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

	Method	elastic part			plastic part		
		E, MPa	σ'f, MPa	b	ε'f	c	***N*_fT**
$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f'}{E} N_f^b + \varepsilon_f' N_f^c$ (2) $N_{fT} = \left(\frac{\varepsilon_f' \cdot E}{\sigma_f'}\right)^{\frac{1}{b-c}}$ (3)	Standard [30]	221378	1153.8	-0.060	0.1045	-0.594	274

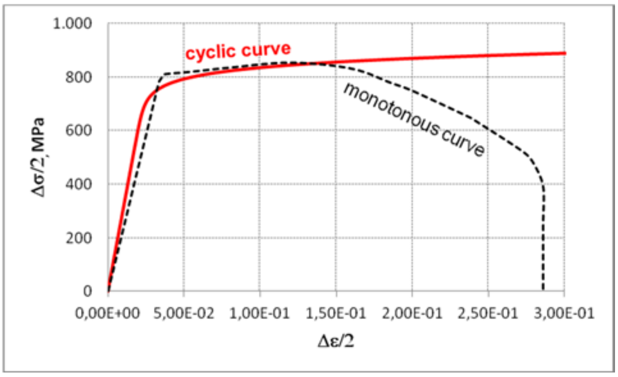

Fig. 7 Cyclic stress-strain curve of HSLA steel NN-70 (1)

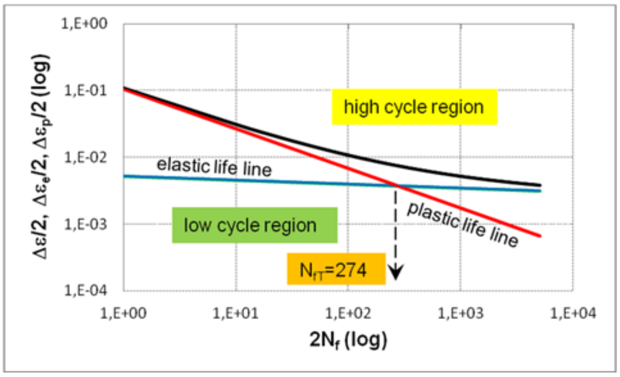

Fig. 8 Fatigue life curve (2) and transition fatigue life of HSLA steel NN-70 (3)

6. CONCLUSION

The paper outlines fatigue test results (LCF) conducted on a smooth, round test specimen using HSLA steel NN-70 as the base metal. These test results served as input data for low-cycle fatigue simulations on these samples, employing Finite Element Method (FEM) calculations in SolidWorks. The primary objective was to obtain comparative results for assessing the lifespan using both testing and FEM calculations. The methodology employed in determining the cycle count for specimen fracture in this study facilitates FEM-based calculations to predict fracture cycles for other components made from the same base metal subjected to low cycle fatigue loads (LCF).

One of the interesting and promising directions for future research involves applying the methodologies presented here to determine the size of fatigue cracks. This parameter stands as a crucial factor for characterizing fatigue existence, particularly under variable loading conditions. This approach aims to determine fatigue life, cycles until failure, and evaluate material resistance concerning crack initiation. Additionally, the progression of these cracks can also be tracked using Non-Destructive Testing (NDT) methods.

The stabilization phase observed during the LCF tests conducted on all samples of the HSLA steel NN-70 base metal exhibits a strong alignment with the general equation of a straight line, y (F or σ) = m x (N) + b. By employing linearization, the coefficients m and b can be derived, providing insight into the weakening trend within the HSLA steel NN-70 base metal.

These findings are valuable as they offer a practical contribution to assessing the behavior of high-strength, low-alloy NN-70 steel under LCF operating conditions.

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NOTE

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