BEHAVIOUR OF NIONIKRAL-70 IN LOW-CYCLE FATIGUE
NISKOCIKLIČNI ZAMOR UZORAKA ČELIKA NIONIKRAL 70

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Abstract
Experimental research on the behaviour of high-strength low-alloy steel (HSLA) exposed to low-cycle fatigue (LCF) with controlled and fully reversible strain ($\Delta \varepsilon = \varepsilon_{\min}/\varepsilon_{\max} = \pm 1$) has been analysed. LCF tests are performed on a series of smooth bar shaped specimens, $11 \times 11 \times 95 \text{ mm}$, parent metal (PM), welded joint (WJ) and simulated heat affected zone (SHAZ) of steel Nionikral 70 (NN-70) with semi-amplitude of controlled strain, $\Delta \varepsilon/2 = 0.40-0.80$. The results of the experimental investigation have given us important information on the understanding of fatigue behaviour of steel NN-70 and its welded joints. In this work the results of static and dynamic-, that is monotonous and fatigue behaviour of the material, are compared, which is a practical contribution to the assessment of the behaviour of PM and WJ of steel NN-70 exposed to effects of low cycle fatigue, i.e. monotonous and fatigue behaviour of the material.

INTRODUCTION
Most damages on steel structures that lead to catastrophic failures occur due to fatigue loads. Damages of fatigue type represent between 50% and 90% of all damages over the operating life of the structure, thus representing an important structural problem. A large number of machines and plant structures during their operating life have a relatively small number of cycles that last for a long time: various turbojet engines, highly-strained parts of turbines, wave-stricken parts of ship structure, high-pressure vessels, piping, steam lines, gas pipelines, reactor plants and process installations, chemical and food industries, so that one can say that during their exploitation life they are exposed to the effects of variable load of the start-stop-start type, i.e. low-cycle fatigue. For low-cycle fatigue of materials, the values of variable load in critical areas exceed the value of yield stress, $R_{p0.2}$, i.e. after a relatively small number of cycles at these locations, the plastically strained zone start to develop.

The fatigue life of the elements of such steel structures can be assessed by analysing the behaviour that includes processing data on load, geometry and the selected material used for manufacturing the element or structure. Large contributions to this analysis are provided from indicators of material behaviour when affected by LCF, which are determined by LCF tests. The steel NN-70, selected in this study to investigate the experimental behaviour of PM, WJ and SHAZ affected by fatigue loads, among other things, is used in shipbuilding and for the manufacture of pressure vessels. Since these structures are produced mainly by welding, tests are conducted using smooth round specimens from the PM, WJ and SHAZ of steel NN-70 /1-5/, and so it was simulated in this study. When selecting stabilized hysteresis as a representative of all stabilized

Keywords
• high strength low-alloyed steel (HSLA)
• low-cycle fatigue (LCF)
• simulated heat affected zone (SHAZ)
• Nionikral 70 (NN-70)

Izvod
Analizirano je eksperimentalno istraživanje ponašanja uzoraka od niskolegiranog čelika povišene čvrstoće (HSLA) u uslovima niskocikličnog zamora (LCF), sa kontrolisanom i potpornu reverzibilnom deformacijom ($\Delta \varepsilon = \varepsilon_{\min}/\varepsilon_{\max} = \pm 1$). LCF ispitivanja obavljena su na seriji glatkih epruveta paralelopipednog oblika, $11 \times 11 \times 95 \text{ mm}$, osnovnog metala (PM), realno zavarenog spoja (WJ) i simulirane zone uticaja toplote (SHAZ) čelika Nionikral 70 (NN-70), sa poluamplitudom kontrolisane deformacije, $\Delta \varepsilon/2 = 0.40-0.80$. Rezultati eksperimentalnih ispitivanja su nam dali važne podatke o razumevanju zamornog ponašanja čelika NN-70 i zavarenih spojeva izrađenih od ove vrste čelika. U radu je izvršeno i poređenje rezultata statičkog i dinamičkog, odnosno, monotona i zamornog ponašanja materijala, što predstavlja praktični doprinos oceni ponašanja PM i WJ čelika NN-70 u uslovima delovanja niskocikličnog zamora.

Keywords
• niskolegirani čelik povišene čvrstoće (HSLA)
• niskociklični zamor (LCF)
• simulirana zona uticaja toplote (SHAZ)
• Nionikral 70 (NN-70)

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hystereses for one strain level, and for further processing of LCF test results, the recommendations and requirements of standards /6, 7/ are used as well as the methodology based on the linearity of the stabilization regions of LCF, that has been numerically determined, /8/.

CHARACTERISTICS OF NN-70

Steel NN-70 is the Yugoslav version of American steel HY-100 and is intended for manufacture of ship structures, submarines and pressure vessels by welding, where the required toughness, depending on the accumulated strain that ultimately turns into plastic strain /9-11/, is extremely important. The technology of manufacture and thermomechanical processing, /12/, of Nionikral-70 steel is the result of joint research from the Military Technical Institute in Žarkovo (VTI) and ironworks ‘Jesenice’ from Jesenice, /1/, in the early 1990s. Steel is produced in the electric furnace, cast in plates, subsequently rolled into slabs and then into sheets of various thickness. Due to some of its characteristics, it is classified among fine-grained steels. The process of hardening is the combination of classical improvement (quenching and tempering) with grain refinement in accordance with selected chemical composition, by microalloying and appropriate deposition, /9/. In determining the limit values of carbon and other alloying elements for the analysis, bearing in mind the purpose of the steel, care is taken to meet the requirements for a combination of characteristics such as: strength; ductility; resistance to crack initiation and propagation; the stability of these properties at low temperatures; good resistance to fatigue and stress corrosion; good workability and weldability, /13/. 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, /1/.

The starting material used to make test specimens of PM and SHAZ is a plate of dimensions 45 × 205 × 353 mm of low-alloyed high-strength steel NN-70 with properties shown in Fig. 1a and Tables 1 and 2.

To produce WJ, as a starting material, 4 plates from the same batch dimensions 20 × 158 × 208 mm are used. Due to the specific research of HAZ, during welding of WJ plates, the K-shape weld seam is made according to standard SRPS EN ISO 9692-1: 2012, /14/. The mechanical properties of WJ are shown in Table 2 and in Fig.1b, /15-17/. A method of microstructural and mechanical characterization of the heat affected zone (HAZ), /18/, is used to select the regime of simulation, thus establishing the indicator of the most approximate similarity of simulated and real HAZ through surface microstructure (replica) and hardness, HV10, location spot of simulation, and impact tests after the preparation of specimens from simulated samples.

### Table 1. Chemical composition of NN-70 (%wt.), /8/.

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>V</th>
<th>Al</th>
<th>As</th>
<th>Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.106</td>
<td>0.209</td>
<td>0.220</td>
<td>0.005</td>
<td>0.0172</td>
<td>1.2575</td>
<td>2.361</td>
<td>0.305</td>
<td>0.052</td>
<td>0.007</td>
<td>0.017</td>
<td>0.014</td>
</tr>
<tr>
<td>Cu</td>
<td>0.246</td>
<td>0.002</td>
<td>0.007</td>
<td>0.0003</td>
<td>0</td>
<td>0</td>
<td>0.0109</td>
<td>0.007</td>
<td>0.0009</td>
<td>0.0189</td>
<td>0.0096</td>
<td>/</td>
</tr>
</tbody>
</table>

### Table 2. Mechanical properties of parent material NN-70.

<table>
<thead>
<tr>
<th>Properties</th>
<th>PM, /8/</th>
<th>WJ, /15/</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate tensile strength, $R_m$ (MPa)</td>
<td>854.8 (Fig. 1a)</td>
<td>914 (Fig. 1b)</td>
</tr>
<tr>
<td>Yield strength, $R_y$ (MPa)</td>
<td>813.4 (Fig. 1a)</td>
<td>645 (Fig. 1b)</td>
</tr>
<tr>
<td>Elasticity modulus (GPa)</td>
<td>234.7, static (Fig. 1a)</td>
<td>221.4, dynamic, LCF (Fig.2)</td>
</tr>
<tr>
<td>Elongation, $A_5$ (%)</td>
<td>18.4</td>
<td>22.4</td>
</tr>
<tr>
<td>Impact toughness (J)</td>
<td>96.83</td>
<td>81.62</td>
</tr>
<tr>
<td>Crack initiation energy (J)</td>
<td>39.60</td>
<td>25.88</td>
</tr>
<tr>
<td>Crack propagation energy (J)</td>
<td>57.23</td>
<td>55.74</td>
</tr>
<tr>
<td>HV30, plate of PM</td>
<td>245-269</td>
<td>252-262, WJ 288-294, HAZ 269-277</td>
</tr>
</tbody>
</table>
Based on analysis of test results and comparing to results of previous studies, /1-5, 15/, the cooling time $\Delta t = 40$ s is chosen for samples $11 \times 11 \times 95$ mm with HAZ simulation, and from which the LCF SHAZ specimens are made.

There are various methods for determining the modulus of elasticity for calculating the fatigue of structural elements, but the choice of methods does not significantly affect the final result, /19/. The modules of elasticity in this paper are determined analytically for each specimen from tensile testing data or LCF tests from cycle $N_{1/4}$, Fig. 2, and so the mean value is calculated, /8, 15/.

**LOW-CYCLE FATIGUE TESTING**

The behaviour of materials in LCF is tested experimentally in accordance with ISO 12106: 2003 (E), /6/, and/or ASTM E 606-04, /7/. For this purpose, smooth specimens are used at multiple levels of regulated strains with a strain ratio $R_\varepsilon = \varepsilon_{\text{min}}/\varepsilon_{\text{max}} = -1$ at ambient, elevated or reduced temperatures, and are exposed to LCF loading, /20, 21/. Stress-strain response at LCF has the shape of an ideal hysteresis loop /20-23/, shown in Fig. 3. The strain range $\Delta \varepsilon$ corresponds to overall loop width, while the stress range $\Delta \sigma$ corresponds to its overall height. The stress amplitude equals the stress half-range, $\Delta \sigma/2$.

![Graph showing modulus of elasticity from cycle N1/4.](image)

**Figure 2. Modulus of elasticity from cycle N1/4.**

![Graph showing ideal hysteresis loop.](image)

**Figure 3. Ideal hysteresis loop: a) $\sigma$-$\varepsilon$ loop of high stress-amplitude cycle after first application of $\sigma_{\text{max}}$, /22/; b) $\sigma$-$\varepsilon$ response, /20, 21/; c) positive part of loop and determining $\Delta \varepsilon/2$ and $\Delta \sigma/2$, /8/; $y = mx - b$; $F = m e - b$; for $F = 0$; $e = b/m$; $\Delta \varepsilon/2 = \varepsilon$; $\Delta \sigma/2 = \Delta \varepsilon/2 - \Delta \sigma/2$.**
Most of the materials at LCF and at a certain level regulated strain achieve a so-called stabilized condition. It is a condition when the height of the hysteresis loop expressed through a range of force of loading, or stress, slightly changes and we call it region stabilization, Fig. 4. For the analysis at $R_e = -1$, it is sufficient to consider the positive part of the F-N curve, Fig. 4b.

Hysteresis for $N_s$ cycle in the region of stabilization that is close or equal to half the number of cycles to crack initiation $N$ is called stabilized hysteresis /20, 21, 23-25/. The choice of stabilized hysteresis from a wide range of stabilized hystereses that best characterizes material behaviour for a certain level of strain is very important. It represents all hystereses and is used to describe the complete process of low-cycle fatigue, i.e. it provides all necessary data to determine characteristic curves of low-cycle fatigue.

For a full explanation of LCF behaviour of a real material it is necessary to take into account the closure of the crack, /26/, to predict the growth rate of a primary crack and appearance of small secondary damages, /27/, and to foresee a combination of thermal and mechanical loads and local residual stresses that can significantly affect the development of fatigue cracks /28, 29, 30/, using advanced techniques such as scanning and transmission electron microscopy that allow interpretation of measured physical data based on microstructural details, /26, 31/.

The most common methods for determining the number of cycles to crack initiation, $N_f$, are defined by standards /6, 7/. ISO 12106: 2003 (E) /6/ recommends that $N_f(-25\%)$, cycle of crack initiation, should be defined by drop of load tensile force by 25% after the end of stabilization, and $N_f(-25\%) = N_f(-25\%)/2$ to be the cycle of stabilized hysteresis, while the standard ASTM E 606-04, /7/, recommends that $N_f(-50\%)$, cycle of crack initiation, should be defined by the drop of maximum tensile force of load, $F_{\text{max}}$, by 50% and $N_f(-50\%) = N_f(-50\%)/2$ to be the cycle of stabilized hysteresis.

The methodology /8, 32-34/ for determining the start and end of crack initiation and linear establishment of stabilization regions are based on experimental data by arbitrary selection of three cycles, based on which we can establish linearity that we maintain by filtering the data in EXCEL, toward the beginning and the end of the test. In this way we determine the initial, $N_{bs}$, and final, $N_{es}$, cycle of stabilization, i.e. the start and end of crack initiation, Fig. 5.

Stabilized hysteresis, $N_f(50\%)$, is located in the middle of region 3, Fig. 4b, and is determined by $N_f(50\%) = N_{bs} + (N_{es} - N_{bs})/2$. In a similar way, we can establish a cycle of crack appearance of 1 $mm^2$ surface area (threshold NDT), which can be identified by NDT methods, and then the cycle of stabilized hysteresis $N_f(NDT)$, located in the middle of region 3A, Fig. 4b, so that $N_f(NDT) = N_{bs} + (N_{NDT} - N_{bs})/2$, /32/.

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The procedure for determining the stabilized hysteresis is conducted according to standard ISO 12106: 2003 (E), /6/, and the described methods for determining stabilization areas /8, 32, 33, 34/, are applied to all specimens, i.e. all strain levels $\Delta e/2 = 0.40 - 0.80$, and after processing data from all determined stabilized hystereses, obtained using the methods described, the curves of low-cycle fatigue for BM, RWJ and SHAZ of steel NN-70, are defined.
The ultimate goal of the LCF test is to construct characteristic low-cycle fatigue curves that are used in fatigue strength calculations. In order to define and describe the LCF process, it is necessary to determine a linearized step function stress amplitude–plastic-strain amplitude, cyclic stress-strain curve (Ramberg-Osgood), and the elastic and plastic components in the strain-life curve, and finally, the strain-life curve (Manson-Coffin-Basquin).

The cyclic stress-strain curve (CSSC) represents the dependence of stress amplitude $\Delta\sigma/2$ on the total strain amplitude $\Delta\varepsilon/2$, Fig. 6. Experimentally established stabilised hysteresis of multiple-level controlled strains are used to define this curve, Fig. 6a.

The equation of the cyclic stress-strain curve has the form /20, 21, 23, 35/:

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

where: $K'$ – coefficient of cyclic strain hardening; $n$ – exponent of cyclic strain hardening; and $E$ – modulus of elasticity, determined from the cycle $N_{1/4}$, Fig. 6b.

The equation of the basic curve of low-cycle fatigue (BCLCF) /23, 35/ is represented by:

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f}{E} N_f + \varepsilon_f N_f \quad (2)$$

where: $\Delta\varepsilon/2$ – amplitude of total strain; $\Delta\sigma/2$ – stress amplitude at pure alternate variable load; $\sigma_f$ – coefficient of fatigue strength; $N_f$ – number of cycles before crack initiation; $b$ – exponent of fatigue strength, Basquin’s exponent, $\varepsilon_f$ – coefficient of fatigue ductility; and $c$ – exponent of fatigue ductility. Figure 7 shows the basic curve for low-cycle fatigue with parts that relate to the elastic, $\Delta\varepsilon/2$, and plastic, $\Delta\varepsilon_p/2$, component. Figure 7 also illustrates the meaning of the exponents and coefficients necessary for defining the curve of low-cycle fatigue, Eq.(2).

![Figure 6. Construction of a cyclic stress-strain curve using stabilised hysteresis.](image)

![Figure 7. Strain-life curve – determining the transition life for a structure, /20/.](image)

Using the basic curve of low-cycle fatigue, also known as the strain-life curve, Fig. 7, representing the dependence of total-strain amplitude, $\Delta\varepsilon/2$, on the number of cycles up to crack initiation, $N_f$, the portion of plastic and elastic components of material affected by low-cycle variable load can be accurately determined. Intersection of curves of elastic and plastic components, Fig. 7, marks the transition point or transition life, $N_{fT}$.

Due to difficulties in predicting cycle life at extremely low state of LCF, the empirical expression Manson-Coffin-Basquin, Eq.(2), may be replaced by an expression that solves this problem, /36/. Also, due to the assumption of equal plastic and elastic components in Eqs.(1) and (2), which leads to compatibility and establishes a theoretical connection between these equations, a new method for evaluating the Manson-Coffin-Basquin and the Ramberg-Osgood equations is created with respect to compatibility, /37/. Most of the existing methods for assessing $\varepsilon$-N parameters are based on a relatively limited number of experimental data which requires the prediction of crack fatigue life by applying statistical assessment, /38/. Fatigue damage models that ignore the actual fatigue damage, i.e. actual fatigue cracks, should not be used for assessment of the life, /39/. Formulas that describe the fatigue S-N curve from the first cycle to gigacycles with a single function have also
been proposed, and from the parameters of materials’ based monotonous testing, only a Brinell hardness /40/ is required in this formula.

**Programme for testing NN-70 by low-cycle fatigue**

**Defining the test objectives:**

The aim of testing is to compare the behaviour of BM, RWJ and SHAZ of NN-70 exposed to low-cycle fatigue on the basis of: cyclic stress-strain curves (Ramberg-Osgood) and strain-life curves (Manson-Coffin-Basquin).

**Required preliminary tests:**

- testing the chemical composition of steel;
- testing the mechanical properties of steel (determining the modulus of elasticity);
- determining impact energy of BM, RWJ and SHAZ (toughness at different temperatures);
- testing the structural properties (metallography).

**Preparation of the test plan:**

- selecting the testing standard (ISO 12106/03 /6/, ASTM E 606/04 /7/);
- selection of a tearing machine (MTS system, Universal hydraulic dynamic tearing machine of 500 kN, model 641.37A-01, VTI-Žarkovo, Belgrade);
- choice of specimen holders and related equipment during tests (extensometer measuring 25 mm in length);
- selecting the testing regime (controlled strain, room temperature, asymmetry factor –1 defined by sinus function, amplitude levels of strain Δε/2 = 0.40-0.80);
- determining the appearance and sizes of specimens (round smooth specimen, \(\varnothing7/25/90\));
- determining the required number of test specimens (BM-10 pcs, RWJ-10 pcs, SHAZ-10 pcs);
- development of the technological procedure for specimen extraction and machining;
- manufacture of carriers-holders for specimens to be tested;
- determining the dimensions of the required sample;
- determining the direction of roll on a large sample of steel of known chemical composition and mechanical properties

**Sampling**

**Sample sandblasting**

**NDT and hardness testing of a sample**

**Necessary preliminary preparation:**

- choice of device on which simulation will be conducted (SMITHWELD Thermal Cycle Simulator Model 1405 - Department of Mechanical Engineering Faculty, Maribor);
- selection of a simulation regime (frequency, amplitude, water temperature, the clearance between the waveguide and tested sample of material ...);
- determining the appearance and specimen sizes (11 × 11 × 60 mm);
- determining the required number of test specimens (3 × 4 = 12 pcs);
- developing the technological procedure for extraction and machining of specimens (as per diagram);
- simulation of HAZ for different cooling times \(\Delta t_{c5} = 8\), 10, 20 and 40 s, on samples used for preparing specimens for toughness testing;
- measurement of hardness HV10 on a sample of simulated HAZ;
- determining the structure of SHAZ;
- determining the toughness of SHAZ as an approximation of the toughness of real HAZ;
- simulation of HAZ for proper cooling time \(\Delta t_{c5} = 40\) s on samples for preparing specimens for toughness and LCF tests;

**Preparation of the specimens for testing**

**Testing:**

- LCF (VTI-Žarkovo, Belgrade, testing up to rupture of the specimens, photographing and recording results);
- Analysis of fractured surfaces (VTI-Žarkovo).

**Processing of the test results:**

- choice of how to display test results;
- selecting the program for processing results;
- selecting a method to compare the obtained results;
- drawing the curve of extreme stress values (filtering the data obtained from the tearing machine ...);
- determining the number of cycles to crack initiation, \(N_i\), (according to ISO 12106/03, /6/, and literature);
- determining the stabilized hysteresis, its strain half-ranges, minimum and maximum stress values (analytical presentation of strain in EXCEL and that of stress could be taken from the hysteresis);
- determining static and dynamic modules of elasticity (ASTM E 111/04 /41/, ASTM E 606/04 /7/);
- determining cyclic and stress-strain curves (calculating the coefficients and equation, and curve drawing);
- constructing the strain-life curve (linearized elastic and plastic components of the curve and overall curve);
- morphology of fracture (reading the SEM photographs of the surfaces of fractured samples).

**Analysis and conclusions:**

- assessing the cyclic behaviour of steel;
- comparing the cyclic and monotonous stress-strain curves (Ramberg-Osgood relation);
- calculating transient lives (Manson-Coffin-Basquin);
- assessment of the fractured surface.

**Testing of steel NN-70 at low-cycle fatigue**

From the necessity to assess the low-cycle fatigue life, and in order to determine fatigue characteristics BM, RWJ and SHAZ of steel NN-70, the resistance to low-cycle fatigue test is carried out. The preparation of the PM, RWJ and SHAZ in steel NN-70 test of resistance to low-cycle fatigue has consisted of producing smooth cylindrical specimens, Fig. 8: item 1a (PM); item 1b (RWJ); item 1c (SHAZ), and the tool for placing specimens in the tearing-machine jaw, Fig. 8: items 2 and 3, and check of the target static tensile properties BM and RWJ of steel NN -70, Fig. 1 and Table 2.
The procedure for determining low-cycle fatigue characteristics and the geometry of cylindrical smooth specimen, Fig. 8 items 1a, b, and c, are defined by ISO 12106:2003(E) /6/, and ASTM E 606-04e, /7/.

The fatigue test is conducted on a universal MTS system (Material Testing System – Universal hydraulic dynamic tearing machine of 500 kN in VTI-Žarkovo, Belgrade) for material testing, schematically presented in Fig. 9.

Linear characteristics of used MTS force-feeding device, Fig. 9, item 2a, and MTS extensometer with measuring length of $L_0 = 25$ mm, Fig. 9, item 2b, are graphically presented in Fig. 10a and 10b.

Low-cycle fatigue tests are performed on a series of smooth specimens of steel NN-70, with semi-amplitudes of controlled and fully reversible strains, $\Delta\varepsilon/2 = 0.40-0.80$ ($\Delta\varepsilon/2 = \text{const.}, R_\varepsilon = \varepsilon_{\min}/\varepsilon_{\max} = -1$).
Processing and presentation of test results

As a result of low-cycle fatigue test on one specimen (one amplitude level of strain), a record in EXCEL, Fig. 11, can be further processed according to our requirements by using the tools available in EXCEL, /8/.

Before processing the results, it is possible to roughly determine the cycle in which there is a significant drop in force, \( N_{\text{f(estimation)}} \), Fig. 4b, and then establish a relationship between semi-amplitude of controlled strain and estimated cycle of crack initiation, Fig. 12.

To determine the indicators of low-cycle fatigue of the material presented by cyclic stress-strain curve (CSSC) and basic curve of low-cycle fatigue (BCLCF), the following analyses of the results of low-cycle fatigue tests are made:

1. Elastic modules, Figs. 1 and 2, from N\(1/4\) cycle are determined, Fig. 6b.
2. For each amplitude level of strain (each specimen), by filtering data, extreme values of load forces and number of cycles are paired, and thus we eliminated the excess data, Fig. 4a. Both positive and negative values of the load forces are filtered.
3. Diagrams of extreme values of load forces and number of cycles (F-N curves) are drawn for each amplitude level of strain, Fig. 4a.

![Figure 11. Record in EXCEL after the low-cycle fatigue test of a single specimen.](image1)

![Figure 12. Characteristic cycles \( N_f \) and strain half-range for BM and SHAZ specimens, \( N_{\text{f(estimation)}} \) and \( N_{R(25\%)} \).](image2)
4. Diagrams for determining areas of stabilization are drawn (positive part of F-N curves, the area of stabilization is determined by linearization of data on maximum tensile forces of load in low-cycle fatigue tests for each amplitude level of strain, Fig. 4b). Areas of low-cycle fatigue and characteristic hysteresis are defined after the following:

a) determining the maximum force and starting cycle \(N_{\text{start}}\), Fig. 4b,
b) determining the cycle of start of stabilization, \(N_{\text{ps}}\), end of stabilization, \(N_{\text{es}}\), and area of stabilization, Fig. 4b, Table 3,
c) determining the cycles \(N_{f(25\%)}\), \(N_{f(1)}\) for BM, \(N_{f(2)}\) for RWJ, \(N_{f(3)}\) for SHAZ, Fig. 4b, Table 3.

5. The characteristic data of stabilized hysteresis curves for each amplitude level of strain were defined:

a) extreme values of load force \(F_{\text{max}}\) and \(F_{\text{min}}\), Fig. 4b, are read,
b) points of intersection on the hysteresis curve and the positive part of the strain axis are established in EXCEL in order to determine the elastic and plastic components of strain semi-amplitude (coefficients of a straight line, \(m\) and \(b\), intersecting strain axis are determined; in that way, the point of axis intersection, i.e. the values of elastic and plastic components of strain semi-amplitude, Fig. 3c, are determined. For RWJ this is done graphically in AutoCAD /15/, and can be done in another programme for precise drawing, too (Corel, SolidWorks, etc.) or calculated according to various methods of adopted standards that are in effect and commercial software for testing LCF /38, 42/. Comparison of the life curves plotted as a function of plastic-strain amplitude vs. stress amplitude shows the decisive role of plastic-strain amplitudes /43/, so that this should be taken into account,
c) \(\Delta \varepsilon /2\), \(\Delta \sigma /2\), \(A_0 = D^\pi/4, F_n = (|F_{\text{max}}| + |F_{\text{min}}|)/2\) and \(\Delta \sigma /2\) are calculated.

6. Data on all amplitude levels of strain are classified, cyclic stress-strain curves (CSSC) and basic curves of low-cycle fatigue (BCLCF) are constructed and cyclic vs. monotonous stress-strain curves (MSSC) compared:
a) exponents and coefficients are determined using linearized step function, \(n^1\) and \(K^1\), Table 4, Fig. 13a,
b) exponents and coefficients are determined using linearized elastic component, \(b\) and \(\sigma^e_b\), Table 5, Fig. 14a,
c) exponents and coefficients of linearized plastic component, \(c\) and \(\varepsilon^p_c\), are determined, Table 6, Fig. 14b.

7. Data on cyclically stress-strain curves, Fig. 13b, and basic curves of low-cycle fatigue, Fig. 16b, are classified for the group of selected stabilized hystereses, \(N_{s1}\) (PM), \(N_{s2}\) (RWJ), and \(N_{s3}\) (SHAZ), in order to construct them, and finally,

8. Transition life is determined for a group of selected stabilized hystereses, \(N_{s1}\) (PM), \(N_{s2}\) (RWJ), and \(N_{s3}\) (SHAZ), Table 7.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>(\Delta \varepsilon /2) (%)</th>
<th>(y = F\ (kN); x = N)</th>
<th>(R_g)</th>
<th>(N_{s1})</th>
<th>(N_{s2})</th>
<th>(N_{s3})</th>
<th>(N_{s1}^*)</th>
<th>(N_{s2}^*)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PM</strong> (index 1)</td>
<td>10</td>
<td>0.45</td>
<td>(y = 0.001x + 29.01)</td>
<td>0.95</td>
<td>210</td>
<td>1354</td>
<td>1445</td>
<td>723</td>
</tr>
<tr>
<td></td>
<td>06</td>
<td>0.50</td>
<td>(y = 0.005x + 26.57)</td>
<td>0.97</td>
<td>256</td>
<td>1271</td>
<td>1402</td>
<td>701</td>
</tr>
<tr>
<td></td>
<td>05</td>
<td>0.70</td>
<td>(y = 0.004x + 29.04)</td>
<td>0.91</td>
<td>135</td>
<td>333</td>
<td>412</td>
<td>206</td>
</tr>
<tr>
<td></td>
<td>08</td>
<td>0.80</td>
<td>(y = 0.013x + 30.47)</td>
<td>0.85</td>
<td>82</td>
<td>165</td>
<td>207</td>
<td>104</td>
</tr>
<tr>
<td><strong>RWJ</strong> (index 2)</td>
<td>1</td>
<td>0.40</td>
<td></td>
<td></td>
<td>2956</td>
<td>1478</td>
<td>2250</td>
<td>1125</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.40</td>
<td></td>
<td></td>
<td>1701</td>
<td>855</td>
<td>1264</td>
<td>642</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.55</td>
<td></td>
<td></td>
<td>280</td>
<td>290</td>
<td>568</td>
<td>284</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.50</td>
<td></td>
<td></td>
<td>237</td>
<td>207</td>
<td>414</td>
<td>207</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.60</td>
<td></td>
<td></td>
<td>356</td>
<td>178</td>
<td>374</td>
<td>187</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.60</td>
<td></td>
<td></td>
<td>356</td>
<td>178</td>
<td>374</td>
<td>187</td>
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<tr>
<td></td>
<td>7</td>
<td>0.70</td>
<td></td>
<td></td>
<td>356</td>
<td>178</td>
<td>374</td>
<td>187</td>
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<tr>
<td></td>
<td>8</td>
<td>0.70</td>
<td></td>
<td></td>
<td>356</td>
<td>178</td>
<td>374</td>
<td>187</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.80</td>
<td></td>
<td></td>
<td>356</td>
<td>178</td>
<td>374</td>
<td>187</td>
</tr>
<tr>
<td><strong>SHAZ</strong> (index 3)</td>
<td>10</td>
<td>0.40</td>
<td>(y = 0.001x + 28.83)</td>
<td>0.97</td>
<td>719</td>
<td>2218</td>
<td>2736</td>
<td>1368</td>
</tr>
<tr>
<td></td>
<td>01</td>
<td>0.50</td>
<td>(y = 0.001x + 27.72)</td>
<td>0.94</td>
<td>799</td>
<td>1919</td>
<td>2235</td>
<td>1118</td>
</tr>
<tr>
<td></td>
<td>04</td>
<td>0.60</td>
<td>(y = 0.008x + 29.29)</td>
<td>0.86</td>
<td>71</td>
<td>184</td>
<td>248</td>
<td>124</td>
</tr>
<tr>
<td></td>
<td>05</td>
<td>0.60</td>
<td>(y = 0.015x + 31.32)</td>
<td>0.97</td>
<td>53</td>
<td>195</td>
<td>230</td>
<td>115</td>
</tr>
<tr>
<td></td>
<td>02</td>
<td>0.70</td>
<td>(y = 0.013x + 31.32)</td>
<td>0.82</td>
<td>87</td>
<td>155</td>
<td>172</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>03</td>
<td>0.70</td>
<td>(y = 0.020x + 30.85)</td>
<td>0.85</td>
<td>82</td>
<td>165</td>
<td>207</td>
<td>104</td>
</tr>
</tbody>
</table>

**\(N_{s1}\) for PM, \(N_{s2}\) for RWJ, \(N_{s3}\) for SHAZ;**

\(***) \(N_{s1}\) for PM, \(N_{s2}\) for RWJ, \(N_{s3}\) for SHAZ;
Table 4. Exponents $n'$ and coefficients $K'$ of cyclic stress-strain curves (CSSK), NN-70.

<table>
<thead>
<tr>
<th>ISO 12106:2003 (E), /6/</th>
<th>$n'$</th>
<th>log $K'$</th>
<th>$K'$ (MPa)</th>
<th>$E$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NN-70</td>
<td>N$<em>{f1}$, N$</em>{f2}$</td>
<td>N$<em>{s1}$, N$</em>{s2}$</td>
<td>0.047</td>
<td>2.976</td>
</tr>
<tr>
<td>PM /8/</td>
<td>N$_{f1}$</td>
<td>N$_{s1}$</td>
<td>0.104</td>
<td>3.091</td>
</tr>
<tr>
<td>RWJ /15/</td>
<td>N$_{f2}$</td>
<td>N$_{s2}$</td>
<td>0.040</td>
<td>2.967</td>
</tr>
</tbody>
</table>

Linearized step function

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

Cyclic stress-strain curve

Table 5. Exponents $b$ and coefficients $\sigma_f'$ of elastic component of basic LCF curves, steel NN-70.

<table>
<thead>
<tr>
<th>ISO 12106:2003 (E), /6/</th>
<th>$N_f$ (–25%)</th>
<th>$N_s = N_f/2$</th>
<th>$b$</th>
<th>log $\sigma_f'/E$</th>
<th>$E$ (MPa)</th>
<th>$\sigma_f'$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NN-70</td>
<td>$N_f$</td>
<td>$N_s$</td>
<td>–0.060</td>
<td>–2.283</td>
<td>221378</td>
<td>from N$_{f1/4}$</td>
</tr>
<tr>
<td>PM /8/</td>
<td>$N_f$</td>
<td>$N_s$</td>
<td>–0.061</td>
<td>–2.311</td>
<td>216508</td>
<td>from N$_{f1/4}$</td>
</tr>
<tr>
<td>RWJ /15/</td>
<td>$N_f$</td>
<td>$N_s$</td>
<td>–0.030</td>
<td>–2.361</td>
<td>225005</td>
<td>from N$_{f1/4}$</td>
</tr>
</tbody>
</table>

Linearized part of elastic component

\[
\log \frac{\Delta \varepsilon}{2} = b \log N_f + \log \frac{\sigma_f'}{E}
\]

Basic curve of low-cycle fatigue

Figure 13. Construction of CSSC, PM of NN-70, $N_f = N_s$ (force drop 25% /6/):

a) $n' = 0.047$, log $K' = 2.976$ of cyclic stress-strain curve; b) cyclic stress-strain curve.

Figure 14. Comparison of cyclic and monotonous stress-strain curves of NN-70 steel (force drop 25%, /6/):

a) BM, $N_f = N_s$ (PM), and SHAZ, $N_f = N_s$ (SHAZ); b) BM, $N_f = N_s$ (PM), RWJ, $N_f = N_s$ (RWJ), and SHAZ, $N_f = N_s$ (SHAZ).

Analysis and comparison of results

Based on experimental data, linearized step functions, Fig. 13a (for $N_s$ (PM), $N_s$ (RWJ), and $N_s$ (SHAZ)), are determined, and from them the exponents and coefficients necessary for constructing CSSC, Fig. 13b (for $N_s$ (PM), $N_s$ (RWJ), and $N_s$ (SHAZ)). In Fig. 14 (for $N_f$ (PM), $N_s$ (RWJ) and $N_s$ (SHAZ)), a comparison of cyclic and monotonous stress-strain curves is presented, indicating quantitative and qualitative related components of WJ steel NN-70 exposed to static and dynamic loads (low cycle fatigue). In Table 4, classified exponents and coefficients in equation CSSC are shown for all selected stabilized hysteresis of PM, RWJ and SHAZ of steel NN-70. One can observe that for BM and WJ of steel NN-70, the exponent $n'$ ranges from 0.040 to 0.104, and coefficient $K'$ from 926.8 to 1233.1 MPa.
In Fig. 15a (for \(N_{s1}\) (PM), \(N_{s2}\) (RWJ), and \(N_{s3}\) (SHAZ)) the linearized elastic components of total-strain amplitude, and in Fig. 15b (for \(N_{s1}\) (PM), \(N_{s2}\) (RWJ), and \(N_{s3}\) (SHAZ)), linearized plastic components of the total-strain amplitude determined on the basis of experimental data are shown, in order to determine the exponents and coefficients required for constructing BCLCF. Classified exponents and coefficients of the elastic component of total-strain amplitude in BCLCF equation for all selected stabilized hystereses of PM, RWJ and SHAZ of steel NN-70 are shown in Table 5.

One can observe that for PM and WJ of steel NN-70, the exponent \(b\) ranges from –0.030 to 0.061, and coefficient \(\sigma'_{f}\) from 979.9 to 1153.8 MPa.

Classified exponents and coefficients of the plastic component in the total-strain amplitude of BCLCF equation for all selected stabilized hystereses of BM, RWJ, and SHAZ of steel NN-70 are shown in Table 6.

One can observe that for BM and WJ of steel NN-70, the exponent \(c\) ranges from –0.400 to –0.684, and coefficient \(\varepsilon'_{f}\) from 0.0206 to 0.2312.

In Fig. 15 (for NN-70, \(N_f = N_f1\) (force drop 25%, /6/)): a) \(b = –0.060\) and \(\log \sigma'_{f}/E = –2.283\) of the basic curve of low-cycle fatigue; b) \(c = –0.594\) and \(\log \varepsilon'_{f} = –0.981\) of basic curve of low-cycle fatigue.

Table 6. Exponents \(c\) and coefficients \(\varepsilon'_{f}\) of plastic component of basic LCF curves, steel NN-70.

<table>
<thead>
<tr>
<th>ISO 12106:2003 (E), /6/</th>
<th>NN-70</th>
<th>(N_f) (–25%)</th>
<th>(N_s = N_f/2)</th>
<th>(c)</th>
<th>(\log \varepsilon'_{f})</th>
<th>(\varepsilon'_{f})</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM /8/</td>
<td>(N_3)</td>
<td>(N_{s3})</td>
<td>–0.594</td>
<td>–0.981</td>
<td>0.1045</td>
<td></td>
</tr>
<tr>
<td>RWJ /15/</td>
<td>(N_2)</td>
<td>(N_{s2})</td>
<td>–0.684</td>
<td>–0.636</td>
<td>0.2312</td>
<td></td>
</tr>
<tr>
<td>SHAZ /8/</td>
<td>(N_1)</td>
<td>(N_{s1})</td>
<td>–0.400</td>
<td>–1.686</td>
<td>0.0206</td>
<td></td>
</tr>
</tbody>
</table>

Linearized part of plastic component

Basic curve of low-cycle fatigue

\[
\Delta \varepsilon = \frac{\Delta \sigma}{2} = \frac{\sigma_{max}}{E} (N_f^{b} + \varepsilon'_{f} N_f^{c})
\]

\[
\Delta \varepsilon = \frac{\Delta \sigma}{2} = \frac{\sigma_{max}}{E} (N_f^{b} + \varepsilon'_{f} N_f^{c})
\]

Figure 16. Construction of BCLCF, BM of NN-70, \(N_f = N_f1\) (force drop 25%/6/): a) \(\sigma_{max}\) and \(\Delta \sigma/2\) for strain level \(\Delta \varepsilon/2 = 0.40\) to \(0.80\); b) basic curve of low-cycle fatigue.

Table 7. Transition life for a variety of stabilized hystereses.

| ISO 12106:2003 (E), /6/ |  | elastic part | plastic part |
|-------------------------|  |  |  |
| NN-70 | \(N_f(25\%)\) | \(N_s = N_f/2\) | \(b\) | \(\sigma'_{f}(MPa)\) | \(E\) (MPa) | \(c\) | \(\varepsilon'_{f}\) | \(N_{fT}\) |
| PM /8/ | \(N_3\) | \(N_{s3}\) | –0.060 | 1153.8 | 221378 from \(N_{f1/4}\) | –0.594 | 0.1045 | 274 |
| RWJ /15/ | \(N_2\) | \(N_{s2}\) | –0.061 | 1057.97 | 216508 from \(N_{f1/4}\) | –0.684 | 0.2312 | 488 |
| SHAZ /8/ | \(N_1\) | \(N_{s1}\) | –0.030 | 979.9 | 225005 from \(N_{f1/4}\) | –0.400 | 0.0206 | 67 |

Transition life

\[
N_{fT} = \left(\frac{\varepsilon'_{f} E}{\sigma'_{f}}\right)^{-\frac{1}{b-c}}
\]
In Fig. 16a (for Ns₁ (PM), Ns₂ (RWJ) and Ns₃ (SHAZ)) the relationship between $\sigma_{\text{max}}$ and $\Delta\sigma/2$ is shown for all strain levels, and one can observe that the linear dependencies $\sigma_{\text{max}}$–$N_{T}$ and $\Delta\sigma/2$–$N_{T}$ intersect in a certain cycle $N_{T}$. BCLCF defined through appropriate stabilized hysteresis, with finite transition life $N_{T}$, are shown in Fig. 16b (for Ns₁ (PM), Ns₂ (RWJ) and Ns₃ (SHAZ)). In Table 7 the transition life for PM, RWJ and SHAZ of steel NN-70 is calculated based on parameters determined according to the methodology for determining stabilized hysteresis, /8/, and the requirements and recommendation of ISO 12106: 2003 (E), /6/, for determining stabilized hysteresis.

Transition life, $N_{T}$, for PM, RWJ and SHAZ of steel NN-70 ranges in an interval from 67 to 488 cycles, i.e. the biggest transition life has RWJ and is about 2 times higher than transition life PM, and about 7 times higher than transition life SHAZ.

Characteristics of LCF for PM, SHAZ, /8/, and RWJ, /5/, of steel NN-70, are determined according to recommendation from ISO 12106: 2003 (E) /6/ (determination of stabilised hysteresis based on load-force drop by 25% since the end of stabilization), and are shown in Tables 4 to 7.

CONCLUSIONS

Theoretical, experimental and numerical research of the behaviour of low-alloy high-strength steels and their welded joints exposed to loading induced by low-cycle fatigue described in this paper is a very complex research task. Extensive theoretical studies have required synthesis of knowledge in multiple engineering fields and disciplines, and numerical and experimental studies are an important part of this work. Detailed analysis of the historical review of research in this area and analyses of the latest published results as well, have provided the basis for further research in the field of low-cycle fatigue.

One of the goals of the research imposed itself during the processing of the results of experimental investigations, and is expressed through improvement of the methodology and methods of processing low cycle fatigue test results in order to establish a universal methodology for assessment of the behaviour of materials affected by low-cycle load. Through the analysis of the existing results the need arises for further research and the establishment of new universal principles, regarding the accuracy of determination and calculation of parameters, using various computer applications, describing the behaviour of materials, either directly, or indirectly.

From certain characteristic stabilized hystereses, based on criteria from defined standards, the data necessary to determine the equations of characteristic curves of low-cycle fatigue are collected, which are useful for providing mutual quantitative and qualitative comparison.

The new methodology for determining the area of stabilized hystereses and the possibility to select stabilized hystereses for a default criterion opens new perspectives for future research. This applies to the use in low-cycle fatigue tests of other materials with a default criterion for determining stabilized hystereses in different operating conditions.

As one of the most interesting and promising directions for future research, the application of developed methodology imposes itself in order to define the size of a fatigue crack as a major parameter for characterization of the existence of fatigue under conditions of variable load as a quality possible for determining fatigue life and the assessment of material resistance to crack initiation, whose propagation can be traced to its critical size by NDT methods.

The results obtained represent a practical contribution in estimating the behaviour of low-alloy high-strength steel NN-70 and its welded joints exposed to effects of low-cycle fatigue.

ACKNOWLEDGEMENTS

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