

# EVALUATION OF THE BEHAVIOR OF WELDED STRUCTURES UNDER LOW-CYCLE FATIGUE LOADING

## OVREDNOTENJE OBNAŠANJA VARJENIH KONSTRUKCIJ V POGOJIH MALOCIKLIČNEGA UTRUJANJA

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Welded structures are exposed to constant variable loads during their exploitation in real conditions. A variable load affects the integrity and life of a welded structure; therefore, it is of practical importance to understand fatigue behavior, especially the behavior of welded structures under the impact of low-cycle fatigue. The effect of low-cycle fatigue is very prevalent in structures and an assessment of cyclic loading of a material entails modifications of its properties and characteristics related to the dependence of stress and strain. Since the stress-strain response during low-cycle fatigue is in the form of a hysteresis loop, this paper presents the application of one of the two most common relations for testing resistance to low-cycle fatigue, the Ramberg-Osgood relation, which is used to evaluate the behavior of a material, in this case a high-strength low-alloy steel welded joint.

Keywords: low-cycle fatigue (LCF), stress-strain response, Ramberg-Osgood relation

Varjene strukture oziroma konstrukcije so v realnih pogojih uporabe stalno obremenjene s spremenljivimi obremenitvami. Spreminjajoče se obremenitve vplivajo na integriteto in dobo trajanja varjene konstrukcije. Zato je pomembno razumeti, kako se določena konstrukcija obnaša v pogojih dinamičnega utrujanja. Še posebej občutljive so varjene konstrukcije v pogojih malocikličnega utrujanja. V teh vrstah struktur je vpliv malocikličnega utrujanja prevladujoč in ocena cikličnih obremenitev materiala zahteva modifikacije njegovih lastnosti in karakteristik, ki se nanašajo na odvisnost med napetostjo in deformacijo. Odgovor napetost-deformacija je med malocikličnim utrujanjem v obliki histerezne zanke in v tem članku avtorji predstavljajo uporabo ene od dveh najbolj splošnih enačb za testiranje malocikličnega utrujanja. To je Ramberg-Osgoodova enačba, ki se uporablja za ovrednotenje materiala in sicer v tem primeru za zvarne spoje iz malo legiranega jekla z visoko trdnostjo.

Keywords: malociklično utrujanje, odgovor napetost-deformacija, Ramberg-Osgoodova relacija

## 1 INTRODUCTION

Variable load in welded structures is expressed through the load spectrum, which includes all loads in the adopted time frame and their change in intensity and direction. Thus, the concept of material fatigue was introduced to describe the occurrence of fracture under the impact of variable load.<sup>1</sup> More precisely, it is fatigue that shows that a material under the impact of a variable load over time loses its ability to transfer the load due to the initiation and propagation of cracks.

The main characteristic of fatigue is variable stress, lower than tensile strength, which can lead to a fracture after a sufficient number of load changes. In particular, because of this characteristic, it is necessary to study and clarify the fatigue process as well as all the effects that occur during variable loading of a metal, which changes the characteristics of the metal, depending on stress and strain.

Plastic strain, under variable load, is a significant factor that contributes to the fatigue crack initiation. The ex-

istence of plastic strain is particularly expressed in the region of low-cycle fatigue, where macro plastic strains are observed which, with a decrease in the number of cycles to failure, grow significantly faster than the corresponding elastic strains. Fatigue of a material, in the elastic-plastic region, occurs due to stress concentration in the macro area (transition in the geometric form, e.g., notches) or in the micro area (e.g., inclusions).

A fatigue process comprises the crack initiation, crack propagation and finally fracture. It is important to note that there are visible cracks in realistic welded structures when the initiation is reduced only to the beginning of the propagation of an existing crack. Therefore, it is clear that the phase, during which the crack progresses is important for the structure; so the main task is to prevent or oversee the propagation of the fatigue crack.

The practical significance of the fatigue behavior of structures directs the research regarding the fatigue to the area of experimental testing, in order to reach an immediate answer regarding the safety of a considered structure. Such an approach stipulates an experimental analysis of the dependence of influential factors and acting

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quantities, so numerous tests are performed in which only one variable at a time is changed during an experiment. As this approach cannot provide an adequate answer, it is supplemented by theoretical analyses, based on the knowledge of material properties and load impact in given conditions under different circumstances.<sup>2</sup>

If a design is based on the required stiffness or static load, significantly higher than the variable load, then the calculated lifetime should be higher than the required lifetime. It is considered that such dimensioning of machine parts is satisfactory even without fatigue tests. A few percent failure probability can be accepted with structures where replacement of parts is easily feasible, for example, in the automotive industry. For larger structures, including ship welded structures, in many cases, it is necessary to perform tests based on test specimens, models or the entire structures.<sup>1-3</sup>

Fatigue testing performed in order to check the condition of a structure is essentially a much more complex task than fatigue testing carried out for research purposes. The reason for that is the necessity to represent the operating conditions and workloads as faithfully as possible. The requirement to test a structure for verification purpose is usually limited by time, which does not allow for a full fatigue lifetime testing of the welded structure. Therefore, the load gets increased, which can negatively affect residual stresses. On the other hand, accelerated tests cannot, in all cases, show the impact in real time (e.g., regarding friction or corrosion). Elimination of numerous low load cycles from the load spectrum itself is often applied, but that can create a misleading picture since most of the fatigue lifetime is being realized under crack propagation conditions. In general, the tested structure should correspond, in everything, to the structure that will be exploited.

In many relevant scientific papers, such as papers,<sup>4-7</sup> the behavior of different materials under variable loading is described, using the Ramberg-Osgood relation. The aim of this paper is to fill the gap due to a lack of research on the cyclic behavior of structures and their materials, using the Ramberg-Osgood relation.

## 2 MATERIAL BEHAVIOR UNDER LOW-CYCLE FATIGUE DEFINED IN ORDER TO COMPARE THE CYCLIC STRESS-STRAIN CURVE WITH THE MONOTONIC STRESS-STRAIN CURVE

By testing the behavior of materials under the impact of variable load, parameters that will aid the realization of a welded structure that is safe in relation to fatigue damage should be determined. In general, three parameters are important:

- variable stress that a part of the welded structure can withstand to avoid a fatigue crack initiation
- the number of load changes the loaded part with a growing crack can withstand and

- the stress, at which the growth of an existing crack ceases.

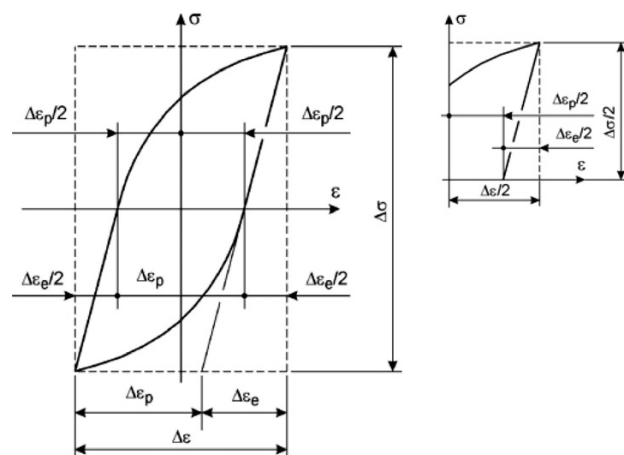
The most important indicator of low-cycle fatigue is the total size of the cyclic plastic strain, based on which it is possible to formulate empirical dependencies between the variable stress, total strain and fatigue life of a material.<sup>2</sup> The stress-strain response at low-cycle fatigue has the form of a hysteresis loop. The strain range,  $\Delta\varepsilon$ , is equal to the total width of the loop, while the stress range,  $\Delta\sigma$ , equals to the total height of the loop. In **Figure 1**, an idealized stabilized loop is separated, showing the total height and width of the loop. The amplitude of the stress corresponds to the half-span of the stress. The total strain,  $\Delta\varepsilon_u$ , corresponds to the sum of the total elastic strain,  $\Delta\varepsilon_e$ , and total plastic strain,  $\Delta\varepsilon_p$ .<sup>8-12</sup> By applying the strain amplitudes over the half-spans, the following is obtained:

$$\frac{\Delta\varepsilon_u}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} \quad (1)$$

In the case of the assessment of the resistance of a structure to material fatigue, the monotonic stress-strain curve is replaced by a hysteresis curve, which defines the stress range,  $\Delta\sigma$ , and strain range,  $\Delta\varepsilon$ .

Nionikral-70 (NN-70) is the material investigated in this low-cycle testing. This steel and its high-strength low-alloyed welded joint is often applicable in ship construction, ship structures and pressure vessels. The basic data regarding its chemical composition, chemical composition of EVB 75 (filler material-basic electrode) and mechanical properties of NN-70 are given in paper.<sup>14</sup>

For this steel and its welded joint, a family of stabilized hysteresis loops for different strain ranges is applied to determine the cyclic stress-strain curve. The area of the hysteresis loop represents the energy per unit of volume, scattered throughout the cycle, mostly in the form of heat. It is important to mention that the variable load changes the properties of the material, which are related to the dependence between stress and strain.



**Figure 1:** Idealized hysteresis loop with separated 1/4 of the hysteresis<sup>13</sup>

The size of the hysteresis loop depends on the strain range,  $\Delta\varepsilon$ , and the stress range,  $\Delta\sigma$ . Hardening or softening under variable load is expressed by measuring  $\Delta\sigma$  at a constant strain amplitude and the number of realized cycles.<sup>15</sup>

Cyclic softening occurs when the cyclic curve is below the monotone (static) curve, while cyclic strengthening occurs if it is above it.

The difference between these two curves varies, sometimes it is small and sometimes significant, indicating a different effect of fatigue. The change in the stress over time shows its increase during hardening and its decrease during softening, which clearly indicates that at a constant stress range, cyclic hardening causes reduced strains, and cyclic softening leads to their increase.<sup>1</sup>

Therefore, within the testing of behavior under LCF, a stabilized state is achieved in the form of a stabilized hysteresis, which is representative of all hystereses. All the necessary parameters for defining the behavior of a material under fatigue load are further determined by means of a stabilized hysteresis.

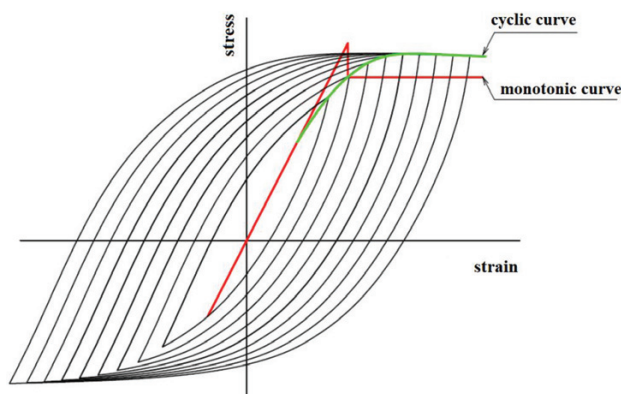
For the purpose of defining and describing of the low-cycle fatigue procedure, it is obligatory to calculate:

- linearized power function of the stress amplitude-plastic strain amplitude,
- cyclic stress-strain curve and
- elastic and plastic components of the strain-life curve and then the strain-life curve.

One of the most important curves for describing the behavior of materials under low-cycle loading is the cyclic stress-strain curve.

Contrary to the monotonic stress-strain curve, which is used in static strength operations, the cyclic stress-strain curve is used in fatigue strength calculations, and these two curves are compared at the end of the calculation due to the assessment of material behavior.<sup>16</sup>

Determination and obtainment of the cyclic stress-strain curve was carried out by means of stabilized hysteresis loops; more precisely, by connecting the family of stabilized hysteresis loops under a fatigue load, with a constant range of strains of different values determined on the test specimens from one series (**Figure 2**).<sup>17–18</sup>



**Figure 2:** Cyclic stress-strain curve and hysteresis loops

The cyclic stress-strain curve represents the connection of the amplitude of the stress,  $\Delta\sigma/2$ , with the amplitude of the total strain,  $\Delta\varepsilon/2$ . The data obtained from the stabilized hysteresis is used to construct the cyclic curve. The amplitude of the total strain (1) consists of the amplitude of the plastic strain and the amplitude of the elastic strain. The elastic component is based on Hooke's law via the relation, where  $E$  is the modulus of elasticity obtained from the stabilized hysteresis:

$$\frac{\Delta\varepsilon_e}{2} = \frac{\sigma}{2E} \quad (2)$$

There is a relationship between the stress amplitude,  $\Delta\sigma/2$ , and the plastic strain amplitude,  $\Delta\varepsilon_p/2$ , defined by the following power function:

$$\frac{\Delta\sigma}{2} = K \left( \frac{\Delta\varepsilon_p}{2} \right)^n \quad (3)$$

where the latter is obtained with an inversion:

$$\frac{\Delta\varepsilon_p}{2} = \left( \frac{\Delta\sigma}{2K} \right)^{\frac{1}{n}} \quad (4)$$

In the previous expression, there are two cyclic characteristics that are used extensively in assessing the fatigue behavior of materials:<sup>19–22</sup>

$K'$  – cyclic strength coefficient and  $n'$  – cyclic strain-hardening exponent. The numerical quantity of the cyclic exponent  $n'$  for metals are in a range between 0.05 and 0.25, where the values above 0.15 correspond to hardening while those below 0.15 correspond to softening of the material.<sup>20</sup>

By logarithmization and linearization of the relation (3) the equation of the straight line  $y = kx + n$  is obtained, which is called the power function of the stress amplitude-plastic strain amplitude:

$$\frac{\Delta\varepsilon_p}{2} = \left( \frac{\Delta\sigma}{2K} \right)^{\frac{1}{n}} \quad (5)$$

In its experimentally determined form, the value of the cyclic strain-hardening exponent,  $n'$ , is observed, while the value of the cyclic strength coefficient,  $K'$ , must be obtained with an inversion. By calculating the value of the exponent,  $n'$ , and the coefficient,  $K'$ , the relation of the cyclic stress-strain curve is obtained by combining expressions (2) and (4) based on (1), thus representing the Ramberg-Osgood relation.<sup>19,23–25</sup>

$$\frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\Delta\sigma}{2E} + \left( \frac{\Delta\sigma}{2K'} \right)^{\frac{1}{n'}} \rightarrow \frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \left( \frac{\Delta\sigma}{2K'} \right)^{\frac{1}{n'}} \quad (6)$$

The difference between the calculations for obtaining the cyclic stress-strain curve and the monotonic stress-strain curve is in the method of calculating the cyclic or monotonic characteristics of the material. Namely, for the cyclic curve, the data obtained from the stabilized hysteresis were used (**Figure 1**), while for the monotonic

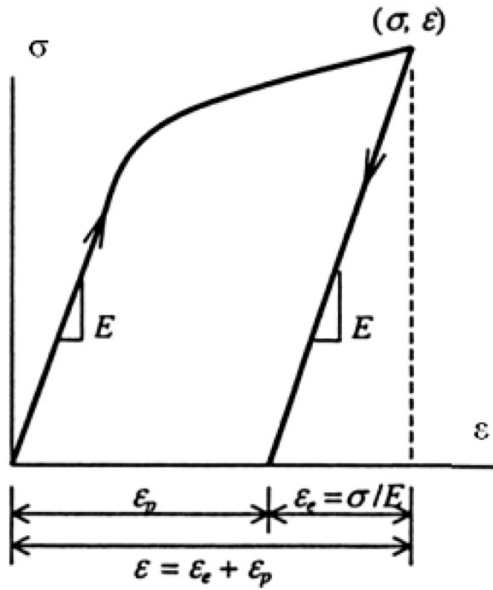


Figure 3: 1/4 of hysteresis loop for N = 1 cycle

curve, the data obtained from the first quarter of the first cycle were used (Figure 3).

As with the cyclic curve, the Ramberg-Osgood relation for 1/4 of the first cycle is used to construct the monotonic stress-strain curve:<sup>26</sup>

$$\varepsilon = \Delta\varepsilon_e + \Delta\varepsilon_p = \frac{\sigma}{E} + \left(\frac{\sigma}{K}\right)^{\frac{1}{n}} \quad (7)$$

The exponent  $n$ , monotonic strain-hardening exponent, and the coefficient  $K$ , monotonic strength coefficient, were obtained by constructing a linearized stress-plastic strain power function, which is based on the following relation:

$$\sigma = K(\varepsilon_p)^n \quad (8)$$

With expression (8) and by linearizing it afterwards, the equation of the straight line  $y = kx + n$  was obtained, called the stress-plastic strain power function, from which the results of the exponent,  $n$ , and the coefficient,  $K$ , were extracted:

$$\lg \sigma = n \lg \varepsilon_p + \lg K \quad (9)$$

At the end, the Ramberg-Osgood relation for the monotonic stress-strain curve (7) is obtained, which serves for the construction of the curve. It is important to note, taking into account the diagram from Figure 3, that plastic and, therefore, elastic strain were obtained by drawing a line parallel to the initial elastic line up to the point  $(\sigma, \varepsilon)$ .<sup>27</sup>

### 3 EXPERIMENTAL PROCEDURE

In Figure 4 the shape of the test specimen is shown. Ten specimens of a circular shape for LCF, on an MTS machine (type servo-hydraulic) connected to a PC were used for controlling the machine and data for testing.

It is important to emphasize that the testing during LCF was done using ISO 12106 and ASTM E 606 standards.<sup>28,29</sup> These standards complement each other very well and provide a credible picture of the behavior of the material, in this case NN-70 steel and its welded joint, under the action of low-cycle fatigue.

Samples with a diameter of 7 mm were obtained from steel plates. They were exposed to a strain control at five levels of the total strain amplitude,  $\Delta\varepsilon/2$ , ranging from 0.4 to 0.8 %.

It was mandatory to determine the curves of extreme values, the number of cycles until crack initiation, the stabilized hysteresis (half-life strain, minimum and maximum stress values) and the modulus of elasticity to obtain the cyclic and monotonous stress-strain curves.

With the obtained data on the controlled strain, the curves of extreme stress values were created with a specified number of cycles to failure (cyclic stress response curves). This was used to determine the cycle of the stabilized hysteresis loop. Hysteresis loops were obtained with an extensometer (a gauge length of 25 mm) with signals acquired from the load cell. Using standard ISO 12106:2003,  $N_f$ , the number of cycles to failure, is defined as the number of cycles matching a decrease by 25 % in the stress value extrapolated over the tensile stress-number of cycles curve when the stress falls

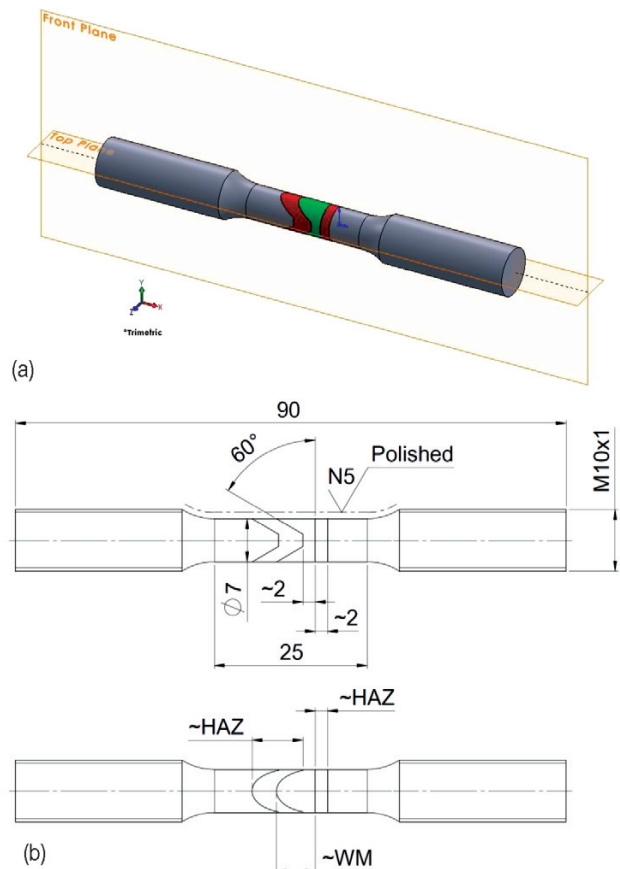


Figure 4: a) Shape of a specimen and b) dimensions of a specimen for LCF testing (HAZ – heat affected zone; WM – weld metal)

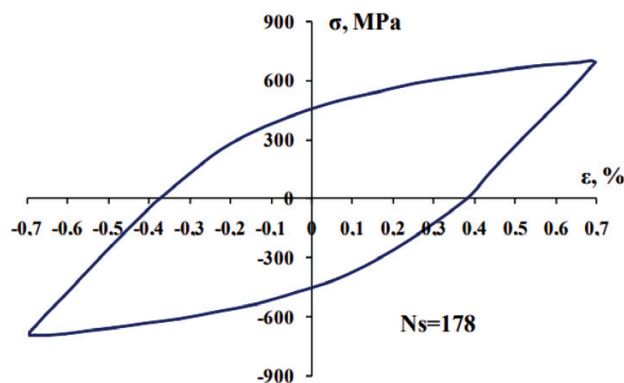


Figure 5: Stabilized hysteresis for a constant strain of 0.7 % ( $N_s = 178$ )

sharply.<sup>28</sup>  $N_s$ , the cycle of the stabilized hysteresis loop, corresponds to half of the number of cycles to failure ( $0.5 N_f$ ). An example of the stabilized hysteresis for a constant strain of 0.7 % is presented in Figure 5.

At each hysteresis, the amplitudes of plastic and elastic strain were isolated, analogously to Figure 1; then the plastic and elastic strains were calculated, as well as other characteristic values for each stabilized hysteresis (the maximum and minimum stress values together with the stress amplitude).

By applying the logarithm to the values of the  $\Delta\epsilon_p/2$  plastic strain amplitude and  $\Delta\sigma/2$  stress amplitude, a linearized power function of stress amplitude-plastic strain amplitude necessary for defining the cyclic characteristics  $n'$  and  $K'$  was obtained, see Figure 6.

The equation of the straight line  $y = kx + n$  corresponds to the form of equation (5), so the linearized power function of stress amplitude-amplitude of plastic strain takes the following form:

$$\lg\left(\frac{\Delta\sigma}{2}\right) = 0.104 \lg\left(\frac{\epsilon_p}{2}\right) + 3.091 \quad (10)$$

where based on equation (5),  $n' = 0.104$  and  $K' = 1233.10$  MPa. In an identical way, the linearized stress-plastic strain power function needed to determine the mono-

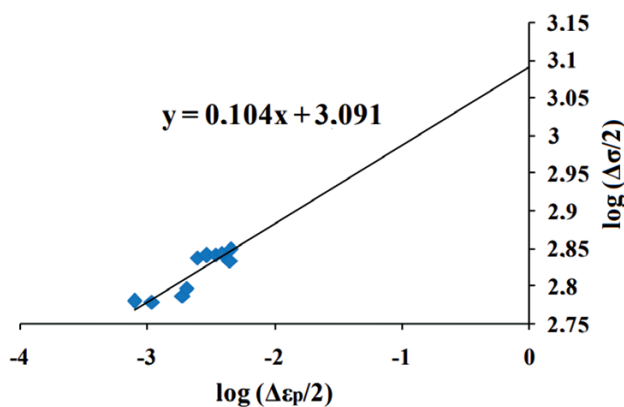


Figure 6: Linearized power function of stress amplitude-plastic strain amplitude

tonic characteristics  $n$  and  $K$ . The exponent  $n$  and coefficient  $K$  were obtained by constructing the linearized stress-plastic strain power function, based on relation (9). By applying the logarithm to the data of stress and plastic strain, the stress-plastic strain power function was obtained (Figure 7), defined by the equation of the strength line  $y = kx + n$ :

$$\lg(\sigma) = 0.075 \lg(\epsilon_p) + 3.027 \quad (11)$$

where based on equation (9),  $n = 0.075$  and  $K = 1064.14$  MPa. Table 1 contains the cyclic and monotonic characteristics obtained through the use of the linearized stress amplitude-plastic strain amplitude power function, in other words, using the linearized stress-plastic strain power function.

Table 1: Cyclic and monotonic characteristics of the HSLA-steel welded joint

cyclic characteristics	cyclic strength coefficient, $K'$ , MPa	cyclic strain-hardening exponent, $n'$
values	1233.10	0.104
monotonic characteristics	monotonic strength coefficient, $K$ , MPa	monotonic strain-hardening exponent, $n$
values	1064.14	0.075

The characteristics from Table 1 were used to form the Ramberg-Osgood relation for constructing the cyclic stress-strain curve (general form of Equation (6)) as well as the Ramberg-Osgood relation for constructing the monotonous stress-strain curve (general form of Equation (7)).

Using the cyclic characteristics from Table 1, the mean value of  $E = 203486$  MPa as well as the values of the stress amplitudes of the stabilized hystereses, the equation of the cyclic stress-strain curve (6) was formed:

$$\left(\frac{\Delta\sigma}{2}\right) = \frac{1}{203486} \frac{\Delta\sigma}{2} \left(\frac{1}{1233.10} + \frac{\Delta\sigma}{2}\right)^{\frac{1}{0.104}} \quad (12)$$

With the monotonic characteristics of the mean value  $E = 203486$  MPa as well as the stress value of 1/4 of the initial cycles, the equation of the monotonic stress-strain curve (7) was formed:

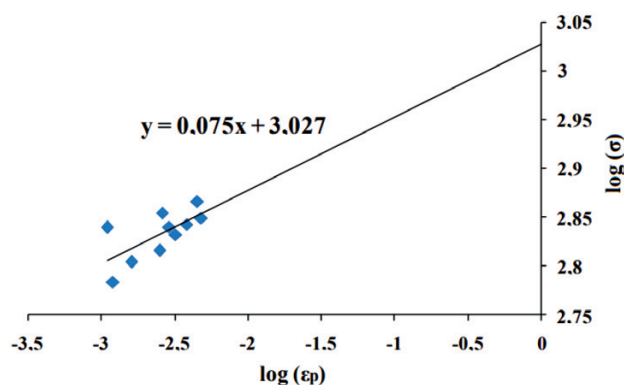
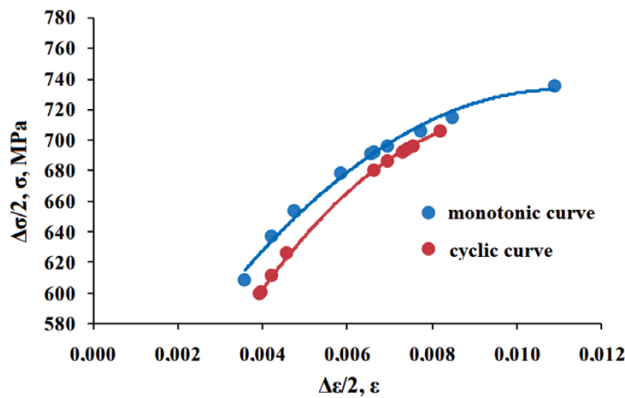


Figure 7: Linearized power function of stress-plastic strain



**Figure 8:** Comparison of the cyclic stress-strain curve with the monotonic stress-strain curve

$$\varepsilon = \frac{1}{203486} \sigma \left( \frac{1}{1064.14} + \sigma \right)^{\frac{1}{0.075}} \quad (13)$$

**Figure 8** shows a comparison of two curves, the cyclic stress-strain curve and monotonic stress-strain curve, and it is clearly noticeable that under LCF steel NN-70 softens.

#### 4 CONCLUSIONS

In this paper, the behavior of steel grade NN-70 under low-cycle fatigue loading at room temperature, under the conditions of given regulated strains at five different amplitude levels, was considered.

As the final test results, cyclic and monotonic stress-strain curves were obtained. Regarding the aim of evaluating the cyclic behavior, cyclic and monotonic stress-strain curves were determined, using the Ramberg-Osgood relation, with accompanying cyclic and monotonic characteristics. Cyclic characteristics were obtained from the linearized stress-amplitude plastic strain power function for stabilization cycles, while monotonic characteristics were obtained from the linearized stress-plastic strain power function for the first quarter of the first cycle. By comparing the cyclic and monotonic curve, it was shown in **Figure 8** that the tested NN-70 steel softens under low-cycle fatigue.

The procedure for testing the resistance of a welded joint of NN-70 steel under low-cycle fatigue at room temperature presented in this paper can serve as the basis for tests at different temperatures; namely, it can be used for an easier determination of cyclic characteristics and parameters of low-cycle fatigue when evaluating the service life of the material. The above conclusion is of vital importance for welded structures because the appearance of fatigue at different external temperatures is a very common occurrence; therefore, the characteristics and parameters of low-cycle fatigue should be calculated during the initial design of welded structures.

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