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VARIABLE AND IMPACT LOAD TESTING OF HSLA STEEL WELDS

ISPITIVANJE PROMENLJIVIM I UDARNIM OPTEREĆENJEM ZAVARA HSLA ČELIKA

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- zarez
- prslina

Abstract

Welded joint as a complex and heterogeneous structure presents a critical point in the welded structure. Therefore, welded joint structural safety is estimated based on properties of the whole welded joint and all of its components. The most common way to evaluate welded joint behaviour is by comparing the properties of base metal (BM), heat affected zone (HAZ) and weld metal (WM), but in a number of cases the behaviour of the whole welded joint differs from the behaviour of weld metal, heat affected zone and base metal.

Izvod

Zavareni spoj kao kompleksna i heterogena struktura predstavlja kritično mesto u zavarenoj konstrukciji. Stoga, sigurnost zavarene konstrukcije se procenjuje na osnovu osobina zavarenog spoja kao celine, i osobina svih njegovih sastavnih delova. Najčešće se za ocenu ponašanja zavarenog spoja porede osobine osnovnog metala (BM), zone uticaja toplote (HAZ) i metala šava (WM), ali se u brojnim slučajevima ponašanje zavarenog spoja kao celine razlikuje od ponašanja metala šava, zone uticaja toplote i osnovnog metala.

INTRODUCTION

Properties that describe crack initiation and propagation, under variable load, are the most important for the exploitation safety of welded structures. Fatigue is described as cumulative damage due to variable load, which is shown with fatigue crack initiation and propagation. Fatigue crack initiation on smooth and homogenous shapes, due to local stress concentration on inevitable constructional crossings and cross-section changes, cannot be described with simple dependences of load, stress, material properties and cross-section dimension. Therefore, the empirically derived dependencies are used, based on massive experimental and laboratory testing. Fatigue strength, which determines the stress level with no crack, is a generally accepted property in that case. Accordingly, the welded structural parts design based on possible material fatigue is conducted using fatigue strength and recommendations, derived from failure analysis of parts during exploitation and massive testing.

Additional data on material behaviour is obtained from impact testing (fracture energy of pre-cracked specimen). It represents the local behaviour of material, conditioned with stress concentration in form of the notch. The possibility to separate the total energy, as the initiating energy and propagation energy of a crack, introduces the new approach to estimate material behaviour during impact testing. This is the most common testing procedure, whether it is regarded to the weld metal when specimens are taken from the additional material applied by special process, or it is regarded to the testing when the so-called associated tubes are welded to simulate load conditions within the structure.

PROPERTIES OF INVESTIGATED STEEL AND WELDED JOINT

The Nionikral-70 (NN70) steel is chosen for investigation of welding technology influence on the behaviour of welded joint and its constituents exposed to variable and impact loads. This steel belongs to the group of low-alloyed high strength (HSLA) steels. Investigated samples are produced by Akroni - Slovenian Steel Jesenice, in electric furnace, casted into blooms and flat rolled to slabs 18 mm thick. Specified strength, ductility and toughness properties are obtained by quenching and tempering, followed by grain refinement due to adequate chemical composition, micro alloying and precipitation. Chemical composition of the delivered plates is given in Table 1, and mechanical properties in Table 2, /1/.

Welded joint is designed as butt 2/3 X-weld. Groove preparation is done according to the SRPS C.T3.030.

Basic coated, low hydrogen electrode Tenacito-75 is selected for plate welding, in diameters of 3.25 mm and 4.0 mm, as defined in Acroni Jesenice manual, according to base material properties and thickness and chosen welding procedure.

Chemical composition of the used electrode is given in Table 3, and its mechanical properties in Table 4, /1/.

Table 1. Chemical composition of the Nionicral 70 steel.
Tabela 1. Hemijski sastav čelika Nionikral 70

Batch	% mass									
	C	Si	Mn	P	S	Cr	Ni	Mo	V	Al
180079	0.10	0.20	0.23	0.009	0.018	1.24	3.10	0.29	0.05	0.08

Table 2. Mechanical properties of Nionikral-70.
Tabela 2. Mehaničke osobine čelika Nionikral 70

Batch	Testing direction	Yield strength $R_{p0,2}$, MPa, min.	Tensile strength R_m, MPa, min.	Elongation δ, %
180079	L - T	710	770	14

Table 3. Chemical composition of electrode Tenacito-75.
Tabela 3. Hemijski sastav elektrode Tenacito-75

% mass					
C	Mn	Si	Cr	Ni	Mo
0.06	1.45	0.25	0.55	2.0	0.35

Table 4. Mechanical properties of electrode Tenacito-75.
Tabela 4. Mehaničke osobine elektrode Tenacito-75

Yield strength $R_{p0.2}$, MPa	Tensile strength R_m, MPa	Elongation %	Impact energy, J		
			–20°C	–40°C	–60°C
725	780	12	110–140	65–95	50–80

FATIGUE TESTING

Welded joint strength under variable load, frequently met in non-stationary service conditions, governs welded structural integrity and life. Welded joint fatigue strength is determined by specimen or model testing under variable load until crack or fracture appears. It should be taken into consideration that damage in form of a crack appears after a large number of load changes with a stress level lower than the yield stress (high-cycle fatigue), or after a relatively small number of load change (up to 50 000 cycles) with stress level close to yield stress (low-cycle fatigue). High-cycle fatigue is experimentally analysed in this research.

A large number of factors influence the testing results. Therefore, the selection of type and mode of load (load or displacement control, bending or tension), cycle parameters (amplitude, range, frequency and load change diagramme in the cycle), specimen shape (rectangular or round cross-section, smooth or notched), cycle number, evaluation criteria (macro-crack detection, load reduction, fracture) is of special significance.

With load level lower than yield stress, typically for high-cycle fatigue, testing is commonly performed under displacement control, when stress amplitude, S_a, is given. It is best to simulate structural service conditions with load cycle, but simplified forms of load cycles are used in practice (usually alternating cyclic, Fig. 1).

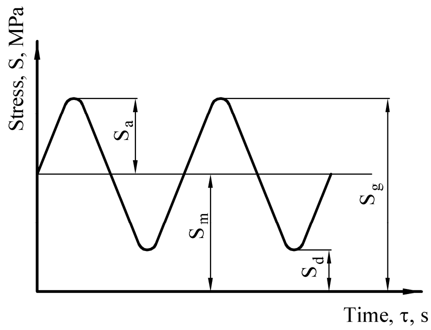

Figure 1. Alternating load scheme for stress ratio $R = -1$.
Slika 1. Naizmenično promenljivo opterećenje, odnos napona $R = -1$

The fatigue behaviour of NN70 steel exposed to variable load is tested on specimens (Fig. 2) taken from base metal and from welded joint, transversal to load direction.

Testing is performed on the Amsler high frequency pulsator, at room temperature and 70% air humidity. The high frequency pulsator can perform sinusoidal alternating load in range of –100 to 100 kN. Mean load and load amplitude are registered with 50 N precision. Achieved frequency is 140–150 Hz, depending on load value. The test is performed with alternating load ratio $R = S_d/S_g = -1$ (tension-compression in Fig. 1).

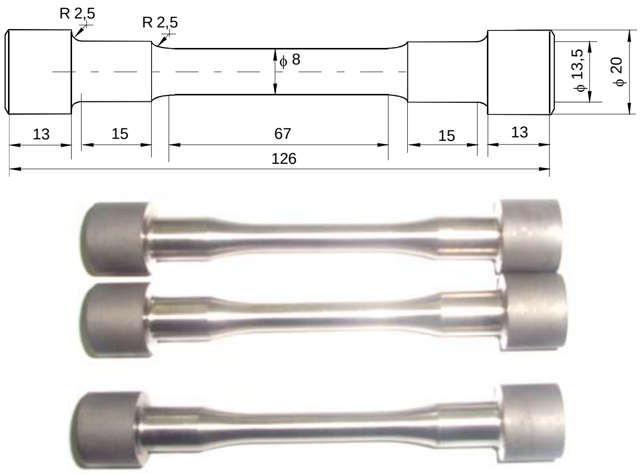

Figure 2. Fatigue test specimen design and view.
Slika 2. Epruveta za ispitivanje zamora – crtež i izgled

The testing procedure is performed according to ASTM E466. Variable load testing results are shown in the form of stress *S* vs. number of cycles *N* (Wöhler curve) in Fig. 3 for welded joint, and in Fig. 4 for base metal, /1/. Obtained *S-N* diagramme enabled to determine endurance limit S_f. The number of load cycles before fracture and the level of stress under which there is no crack initiation or fracture after a certain number of cycles (usually 10^6 to 10^8 cycles) are determined in this test with constant load range, according to the standard. The endurance limit, S_f, is defined after 10^7 cycles for steel, according to ASTM E 468-82. This very expensive testing is justifiable when data are needed for design of parts submitted to long-term variable load using the fatigue and fracture mechanics aspect.

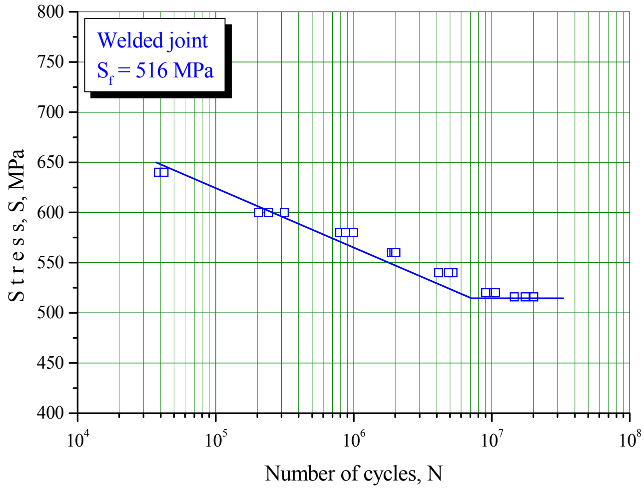

Figure 3. S-N diagramme for welded joint specimens.
Slika 3. S-N dijagram za epruvete iz zavarenog spoja

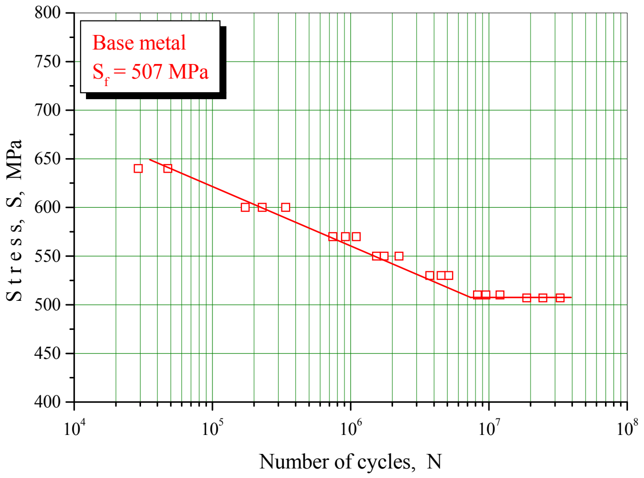

Figure 4. S-N diagramme for base metal specimens.
Slika 4. S-N dijagram za epruvete iz osnovnog metala

IMPACT TESTING

A large number of machine parts and structural parts are submitted to variable loads during exploitation. Properties of base material and especially welded joint that are submitted to impact load differ from the properties obtained in case of static force effect. Therefore, the need to determine them is understandable. Pre-cracked specimen testing by bending, performed by impact effect of force, can offer an explanation on the material behaviour in case of obstructed deformation, or three-dimensional stress state. Determination of the work needed for fracture, under certain test conditions, is most commonly used for the ongoing quality, material homogeneity and treatment control. Brittle fracture tendency and accordingly the brittleness increase (ageing) during exploitation can be determined by this procedure.

Impact tests of the specimen with a notch in the base metal, weld metal, and heat affected zone, are performed in order to determine the impact total energy, as well as its components, crack initiation and crack propagation energy. The testing procedure and specimen dimensions and shape, as shown in Fig. 5, are defined according to SRPS EN 10045-1 EN and SRPS EN 10045-2, or ASTM E23-02.

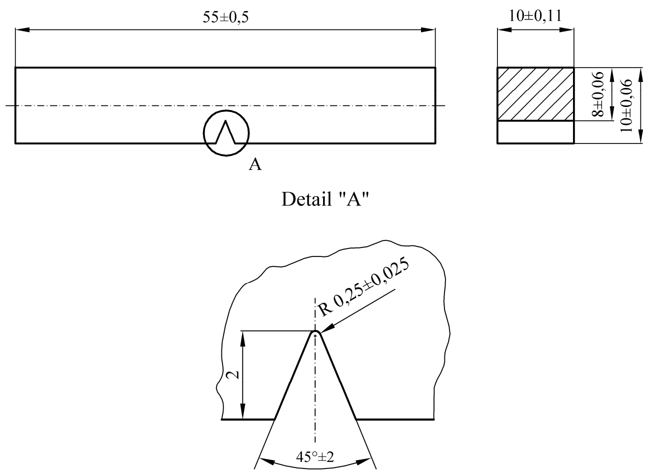

Figure 5. Specimen for impact energy determination.
Slika 5. Epruveta za ispitivanje žilavosti

The notch position in relation to welded joint is defined according to EN 875, Fig. 6. The notch is fabricated by milling in such a way that there are no changes made in to the material condition. There must not be visible traces of machining in the notch root.

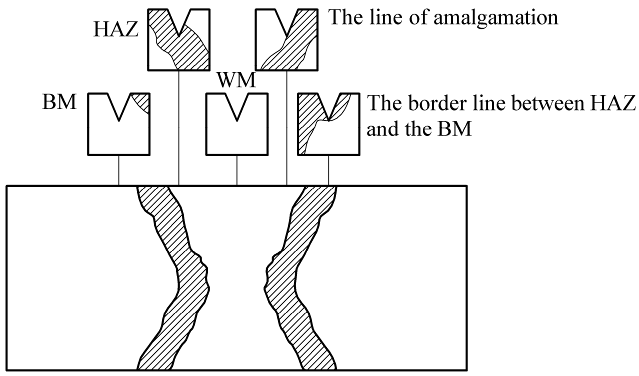

Figure 6. Notch position in relation to the welded joint.
Slika 6. Položaj zareza u odnosu na zavareni spoj

Testing is performed on the SCHENCK TREBEL 150 J, instrumented Charpy pendulum, at room temperature.

Three groups of specimens were fabricated with different V2 notch position:

- I group - specimens with V2 notch in base metal (BM)
- II group - specimens with V2 notch in weld metal (WM)
- III group - specimens with V2 notch in heat affected zone (HAZ)

It is possible to calculate the energy needed for specimen fracture from the force-time diagramme, Fig. 7, as:

$$A=\int_0^{t_1} F(t)v(t)dt$$

where: *F(t)*– force in function of time; *v(t)* – pendulum speed during fracture in function of time; *t* – fracture duration.

Since testing is performed on instrumented Charpy pendulum with oscilloscope it is possible to grade notch positioning effect on crack initiation energy A_I, and crack propagation energy A_P, as integral components of impact total energy. Areas A_I and A_P, marked on the force-time diagramme, Fig. 8, are proportional to crack initiation and propagation energies, /7/.

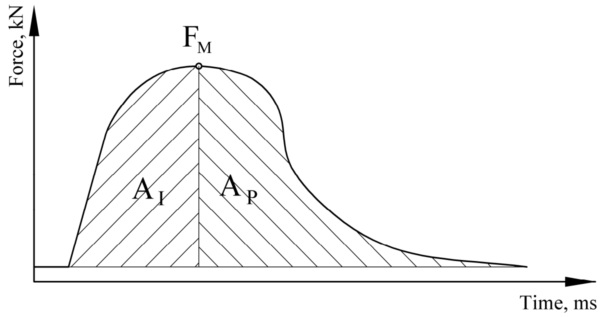

Figure 7. Typical force-time diagramme.
Slika 7. Tipičan dijagram sila-vreme

Impact test results are given in Table 5 for specimen with notch in BM, in Table 6 for specimen with notch in WM and in Table 7 for specimen with notch in HAZ, /1/.

Table 5. Impact test results for specimen with notch in BM.
Tabela 5. Rezultati ispitivanja udarom za epruvetu sa zarezom u BM

Specimen	Test temperature °C	Energy total, A_T, J	for initiation A_I, J	for propagation A_P, J
BM-1a	20	118	43	75
BM-2a		126	49	77
BM-3a		131	50	81

Table 6. Impact test results for specimen with notch in WM.
Tabela 6. Rezultati ispitivanja udarom za epruvetu sa zarezom u WM

Specimen	Test temperature °C	Energy total, A_T, J	for initiation A_I, J	for propagation A_P, J
WM - 1a	20	47	17	30
WM - 2a		40	12	28
WM - 3a		43	19	24

Table 7. Impact test results for specimen with notch in HAZ.
Tabela 7. Rezultati ispitivanja udarom za epruvetu sa zarezom u HAZ

Specimen	Test temperature °C	Energy total, A_T, J	for initiation A_I, J	for propagation A_P, J
HAZ - 1a	20	129	45	84
HAZ - 2a		124	41	83
HAZ – 3a		119	39	80

CONCLUSION

Endurance limit values S_f, after approximately 10^7 cycles, obtained as results of weld joint and base metal specimen tests, are very similar. Obtained endurance limit of welded joint is 516 MPa, and for base metal it is 507 MPa. This can be seen as well based on the crack initiation position and specimen fracture afterwards. The fact that in both cases, initiation and fracture appeared in the base metal, which explains the obtained results that represent the base metal endurance limit, indicates that the base metal is the worst component of welded joint in variable load conditions, /1/.

The location where specimens were taken has influence on the impact total energy value A_T, as well as the V-notch position. Welded joint structure heterogeneity, followed by different mechanical properties of some areas in the welded joint (base metal, weld metal and heat affected zone), has a crucial effect on impact properties, more precisely on the impact total energy value. Specimens with V-notch in base metal have the highest value of impact total energy, about 125 J, /1/, for testing at room temperature. Specimens with V-notch in WM have the lowest value of impact total energy and it is around 43 J, /1/, for testing at room temperature. Impact total energy is around 124 J, /1/ when the V-notch is positioned in HAZ. Specimens with V-notch in HAZ have the most optimal ratio between crack initiation energy A_I and crack propagation energy of 1:1.98, /1/, for testing at room temperature. Specimens with notch in BM have crack initiation and propagation energy ratio of 1:1.64 at room temperature, and specimens with notch in WM have crack initiation and propagation energy ratio of 1:1.71 at room temperature, /1/.

Specimens with V-notch in base metal and heat affected zone have the highest value of impact total energy, or the best ductility. Specimens with notch in weld metal have the lowest value of impact total energy, or the worst ductility. Thus, welded joint structure heterogeneity has caused that the weld metal has the worst ductility properties.

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