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Damage Level Estimate of API J55 Steel for Welded Seam Casing Pipes

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Original scientific paper

The subject of this paper is investigation of the damage level of API J55 steel, used for manufacturing casing pipes by high frequency (HF) contact welding. The analysed pipe was withdrawn after about 70 000 hours of service in an oil drilling rig. Experimental analysis included determining the mechanical properties of the base material and welded joint, in particular the tensile and impact toughness testing. Fracture behaviour is examined by testing the modified compact tension (CT) specimens machined with a pre-crack in the base metal, weld metal and heat affected zone (HAZ). The critical value of the stress intensity factor K_{Ic} is determined using the critical value of the J integral J_{Ic}. Fatigue crack growth rate and fatigue threshold stress intensity factor range are determined by three point bending tests of the Charpy specimens with a V-notch. The investigation conducted on specimens cut from the exploited pipe and the new pipe of the same grade revealed that material properties were not seriously altered during the analysed period of service.

Keywords

Casing pipe
Damage level
High frequency contact welding
Pipe integrity

Ključne riječi

Integritet cijevi
Razina oštećenja
Visokofrekventno kontaktno zavarivanje
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Procjena razine oštećenja API J55 čelika za izradu šavnih zaštitnih cijevi

Izvornoznanstveni članak

U radu su prikazani rezultati ispitivanja razine oštećenja čelika API J55, korištenog za izradu zaštitnih cijevi visokofrekventnim kontaktnim postupkom zavarivanja (VF). Ispitivana cijev povučena je iz eksploatacije nakon približno 70 000 radnih sati u naftnoj bušotini. Izvršena su eksperimentalna ispitivanja mehaničkih svojstava osnovnog materijala i zavarenog spoja - određivanje rasteznih svojstava i udarne žilavosti. Ponašanje pri lomu je ispitivano korištenjem modificiranih kompaktnih epruveta za zatezanje (CT), s početnom pukotinom u osnovnom materijalu, metalu šava i zoni utjecaja topline (ZUT). Kritična vrijednost koeficijenta intenzivnosti naprezanja K_{Ic} određena je na osnovi kritične vrijednosti J integrala J_{Ic}. Ispitivanje brzine rasta zamorne pukotine i praga zamora izvedeno je na standardnim Charpy epruvetama sa zarezom. Na osnovi rezultata eksperimentalnih ispitivanja na epruvetama izrađenim od rabljenog i novog materijala iste klase, zaključeno je da svojstva materijala nisu u velikoj mjeri izmijenjena tijekom analiziranog perioda.

Symbols/Oznake

A	- percentage elongation at fracture, % - postotno izduženje pri lomu
a_c	- critical crack length, mm - kritična duljina pukotine
b	- width of the ligament in front of the crack tip, mm - širina ligamenta ispred vrška pukotine
C	- coefficient in equation (4) - koeficijent u jednadžbi (4)
CTOD	- crack tip opening displacement, mm - otvaranje vrška pukotine
da/dN	- fatigue crack growth rate, m/cycle - brzina rasta zamorne pukotine
E	-Young's modulus, GPa - Youngov modul
E_{tot}	- total impact energy, J - ukupna energija udara
E_i	- crack initiation energy, J - energija nastanka pukotine
E_p	- crack propagation energy, J - energija rasta pukotine
J_{Ic}	- critical value of the J integral, kN/m - kritična vrijednost J integrala
K_I	- stress intensity factor, MPa·m$^{1/2}$ - koeficijent intenzivnosti naprezanja
K_{Ic}	- critical value of the stress intensity factor, MPa·m$^{1/2}$ - kritična vrijednost koeficijenta intenzivnosti naprezanja
m	- exponent in equation (4) - eksponent u jednadžbi (4)
R_e	- yield strength, MPa - granica tečenja
R_m	- ultimate tensile strength, MPa - rastezna čvrstoća
$1/C_i$	- slope of the unloading line on the force - load line diplacement diagram - nagib linije rasterećenja na dijagramu sila - pomak na liniji djelovanja sile
Δa	- crack growth increment, mm - prirast duljine pukotine
ΔK	- stress intensity factor range, MPa·m$^{1/2}$ - opseg koeficijenta intenzivnosti naprezanja
ΔK_{th}	- fatigue threshold stress intensity factor range, MPa·m$^{1/2}$ - prag zamora
η	- coefficient in equation (2) - koeficijent u jednadžbi (2)
ν	- Poisson's ratio - Poissonov faktor
σ_c	- stress at fracture, MPa - naprezanje pri lomu

1. Introduction

Reliability of the oil and gas drilling rig systems is very important for continuous exploitation, but also for environment protection. Pipelines are the most economical and safest way for oil and gas exploitation and transport. They can consist of seam or seamless pipes. Pipeline specifications defined by the standard [1] mainly include the dimensions of the pipes and their joints, resistance of a pipe to the pressure at the inner or outer surface and mechanical properties. However, reasons that very often lead to the failures of the pipelines built from seam pipes are insufficient crack initiation and propagation resistance as well as poor quality of the welded joint.

Modern technologies for welded pipes manufacturing enable a continuous production process, with the main aim of achieving the welding rate equal to the pipe forming rate. The machines for automatic and semi-automatic manufacturing of the longitudinally welded pipes are mainly constructed for high frequency welding, which does not require the use of a filler material. The choice of the welding parameters is very important for obtaining the appropriate quality of a welded joint, as shown in [2].

Many investigations of the oil industry pipes worldwide are conducted on the oil and gas transport pipes, which are defined by the standard [3]. For the drilling rig pipes, investigations are mainly concerned with the influence of alloying elements on the corrosion resistance of non-alloyed and low-alloyed steels [4-5] and on the pipe joints [6], while their resistance to crack initiation and propagation is more rarely examined [2].

Detected defects, classified as 'acceptable' during the control procedures according to standards, can sometimes develop to the level that poses a threat to the safe service of the structure. Fracture mechanics estimate the influence of the cracks, taking the loading conditions and geometric factors (e.g. the size and position of a crack) into account. To accomplish this, numerous standards have been developed, defining the testing procedures and specimen types with various crack shapes and positions. The analysis is often conducted using the linear-elastic fracture mechanics (LEFM), but more recently developed procedures extend the use of LEFM. The document [7] defines a combined procedure based on the crack tip opening displacement (CTOD). Other examples of methods for defect influence assessment are defined in [8] and [9]. Many recent investigations (e.g.

[10-12]) deal with analysis of the pipes' behaviour and failure, integrity assessment and remaining service life estimate.

2. Applied procedure

The investigation presented in this paper is conducted with the aim to assess the level of material properties degradation after a period of service life of approx. 70 000 hours (8 years) in an oil drilling rig. The pipe was withdrawn during a reparation procedure, and the analysed period is much shorter in comparison with the projected service life, which is approx. 20-30 years. However, it should be noted that the pipe was subjected to a combination of mechanical loading, elevated temperature and a chemically aggressive environment during its service life in the rig.

Properties of API J55 steel are determined on specimens taken from the casing pipe manufactured by HF welding. Nominal dimensions of the pipe are: diameter 139,7 mm, wall thickness 6,98 mm. Chemical composition of API J55 steel is given in Table 1.

Besides the pipe withdrawn from the pipeline, experimental investigations are also conducted on a pipe made from new, same grade material. This procedure enabled a comparison to be made between the two materials, and determining the influence of the environment / working conditions on the material properties and behaviour under external loading.

2.1. Mechanical properties

The positions of the specimens and testing procedures for determining properties of the base material and welded joint of the longitudinally welded pipes are defined by the standard [1], see Figure 1 and Table 2.

The shape and dimensions of the specimens for tensile properties determination are defined by the standard [13]. The measurement procedure is performed using the electromechanical testing machine SCHENCK-TREBEL RM 100, in deformation (displacement) control, with the loading rate 5 mm/min.

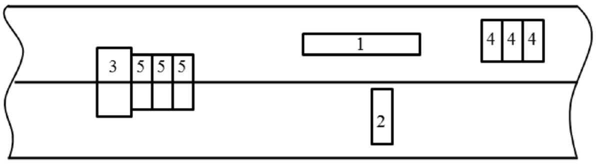

Figure 1. Positions of the specimens cut from the welded pipes

Slika 1. Raspored uzorkovanja epruveta iz zavarenih cijevi

Impact toughness is tested using V-notched Charpy specimens. Testing procedure, shape and dimensions of the specimens were in accordance with the standard [14]. Testing of the new pipe included the base material and the welded joint specimens (positions 4 and 5 in Figure 1), while in the case of the exploited pipe the base material is tested (position 4 in Figure 1). Experimental investigations on instrumented pendulum with oscilloscope SCHENCK TREBELL 150/300 J, conducted on the specimens cut from the exploited pipe, enabled the total impact energy E_{tot} components - crack initiation energy E_i and crack propagation energy E_p to be determined.

2.2. Fracture resistance

Welded joints in the pressurized pipes can be very sensitive to the cracks and their stable and unstable growth. Therefore, it is very important to determine the reliable criteria for remaining service life assessment of a

Table 1. Chemical composition of API J55 steel, mass. %

Tablica 1. Kemijski sastav čelika API J55, mas. %

C	Si	Mn	P	S	Cr	Ni	Mo	V	Cu	Al
0,292	0,233	0,963	0,013	0,022	0,099	0,058	0,012	0,003	0,131	0,025

Table 2. Testing procedures

Tablica 2. Postupci ispitivanja

Position / Pozicija	Testing / Ispitivanje	Specimen position / Položaj epruvete	Specimen designation / Oznaka epruvete
1	Tensile / Rastezanje	Parallel to the rolling direction / Paralelno pravcu valjanja	PR
2	Tensile / Rastezanje	Normal to the rolling direction / Okomito na pravac valjanja	NR
3	Tensile / Rastezanje	Normal to the welded joint / Okomito na zavareni spoj	NW
4	Impact toughness / Udarna žilavost	Normal to the rolling direction / Okomito na pravac valjanja	NR
5	Impact toughness / Udarna žilavost	Normal to the welded joint / Okomito na zavareni spoj	NW

pressurized pipe with a crack in the welded joint or the base material. For better understanding of the crack initiation and growth in the casing pipes, used for the drilling rigs and subjected to high pressure, elevated temperature and chemically aggressive working environment, parameters controlling the material behaviour around the crack tip and fracture resistance should be quantitatively expressed. Therefore, the critical values of the stress intensity factor K_{Ic}, crack growth resistance (J-Δa) curves, fatigue crack growth rate and fatigue threshold stress intensity factor range ΔK_{th} are experimentally investigated.

2.2.1. Compact tension (CT) specimen testing

The modified compact tension (CT) specimens were cut from each pipe (Figure 2), with a fatigue pre-crack in the base metal, weld metal and heat affected zone.

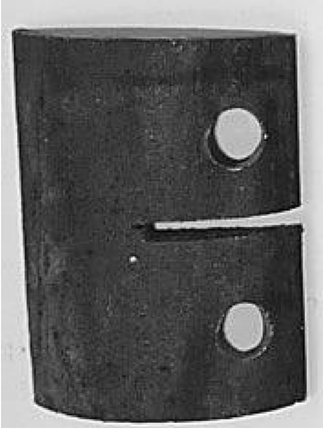

Figure 2. Modified CT specimen

Slika 2. Modificirana CT epruveta

The testing is performed at room temperature, using the electromechanical testing machine SCHENCK-TREBEL RM 100. The thickness of the modified CT specimens is d = 6,98 mm (equal to the pipe wall thickness), and their dimensions are given in Figure 3.

2.2.2. Fatigue crack growth

The standard [15] defines the procedure for fatigue crack growth rate da/dN measurement and stress intensity factor range ΔK calculation. Standard Charpy specimens are used, with fatigue crack in the base material, equipped with the measuring foil RUMUL RMF A-5 for continuous crack length monitoring. Investigations are conducted at room temperature, with three point bending force-controlled load. A high frequency resonant pulsator CRACKTRONIC is used.

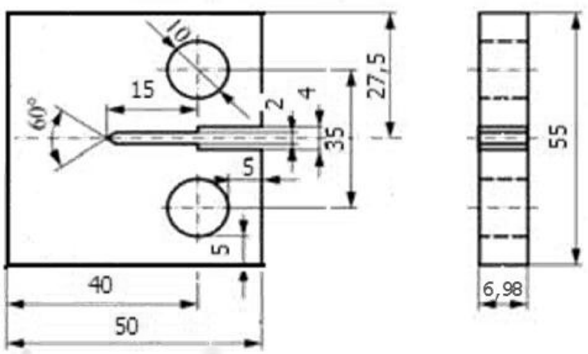

Figure 3. Dimensions of a modified CT specimen

Slika 3. Dimenzije modificirane CT epruvete

3. Results and discussion

The results obtained on specimens cut from the longitudinal direction (PR) of the exploited and new pipe are given in Table 3a. Although the differences exist, especially for yield strength, the requirements of the standard [1], also given in the Table 3a, are satisfied for both materials. One of the reasons for this degradation of the yield strength is period of service in the drilling rig, but one should also have in mind that these two materials have been produced at different times. Therefore, it is

Table 3a. Tensile properties of the base material, parallel to the rolling direction

Tablica 3a. Rastezna svojstva osnovnog materijala, paralelno pravcu valjanja

Material / Materijal	Specimen / Epruveta	Temperature / Temperatura, °C	R_e, MPa	R_m, MPa	A, %
Exploited / Rabljeni	PR	20	380	562	33
New / Novi	PR		537	585	27,4
Standard API 5CT			379-552	> 517	> 22,5

Table 3b. Tensile properties of the base material - new pipe, normal to the rolling direction and welded joint

Tablica 3b. Rastezna svojstva osnovnog materijala - nova cijev, okomito na pravac valjanja i zavareni spoj

Material / Materijal	Specimen / Epruveta	Temperature / Temperatura, °C	R_e, MPa	R_m, MPa	A, %
New / Novi	NR	20	552	595	28,3
New / Novi	NW		554	580	30,5

possible that their initial properties after manufacturing might have been different.

The values obtained by testing the specimens normal to the rolling direction (NR) are not significantly different from those shown in Table 3a, corresponding to the longitudinal axis of the pipe, i.e. parallel to the rolling direction. Also, the values obtained for the specimens cut from the welded joint (NW) are similar to those obtained by the testing of the base material, which can be explained by the fact that the HF welds are produced without a filler material. These results, given in Table 3b, are obtained by testing the new material.

The base material has a pearlite-ferrite microstructure. Although it is partially oriented, this fact apparently does not influence the tensile properties, i.e. they do not exhibit significant dependence on the testing direction.

The hardness properties of the two pipes do not differ significantly. When comparing the zones of the welded joint, the smallest hardness is obtained in the HAZ, as shown in [2].

The impact toughness testing of the exploited pipe included specimens cut from the base material, as shown in Figures 4 and 5. The results obtained by testing the specimens cut from the new pipe are shown in Figures 4 and 6, and include data related to the base material and welded joint (i.e. specimens machined with a notch in each of these two zones). Obviously, certain differences between the two materials exist, but they are not significant. The material from exploitation has slightly higher values of impact toughness in comparison with the new material, which can be attributed to the higher yield stress value of the latter.

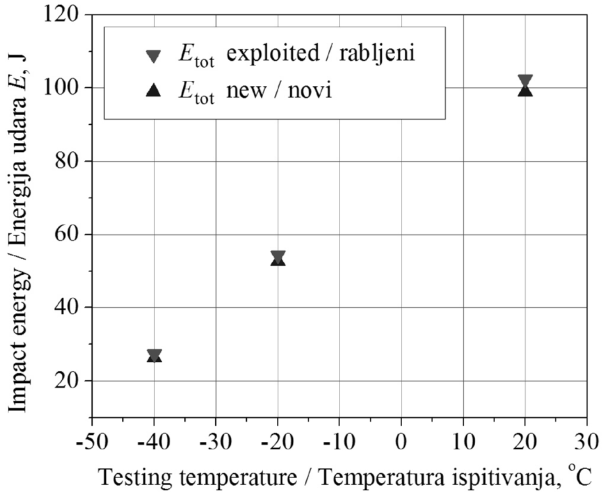

Figure 4. Dependence of the total impact energy on testing temperature - notch in the base material (NR)

Slika 4. Ovisnost ukupne energije udara od temperature ispitivanja - zarez u osnovnom materijalu (NR)

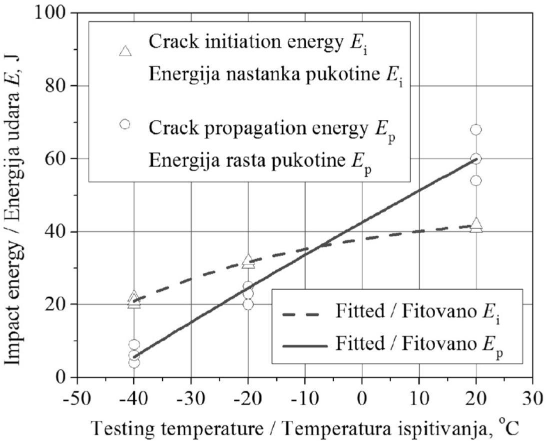

Figure 5. Dependence of the energy of crack initiation and propagation on testing temperature - notch in the base material (NR), exploited pipe

Slika 5. Ovisnost energije nastanka i rasta pukotine od temperature ispitivanja - zarez u osnovnom materijalu (NR), rabljena cijev

Total impact energy increases with the increase of temperature, which can be seen in Figures 4 and 6. At – 40 °C, it approaches the minimum impact energy, which is 27 J for API J55 steel, according to the standard [1]. However, this temperature is much lower than the operating temperature of the oil drilling rig pipelines, which is about 100 °C. Figure 5 presents the dependence of crack initiation and crack propagation energy on testing temperature, for the exploited material. Crack initiation energy grows slower in comparison with the component corresponding to the crack propagation, i.e. ductile component of fracture increases with the increase of temperature. The welded joints exhibit slower increase of total energy with the increase of temperature in comparison with the base material, as shown in Figures 4 and 6.

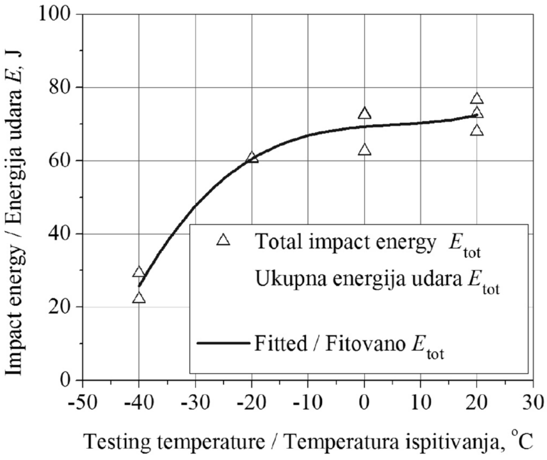

Figure 6. Dependence of the total impact energy on testing temperature - notch in the welded joint (NW), new pipe

Slika 6. Ovisnost ukupne energije udara od temperature ispitivanja - zarez u zavarenom spoju (NW), nova cijev

Due to the thin walls of the pipe, requirements for fracture toughness measurement could not be satisfied. Therefore, the critical value of the stress intensity factor K_{Ic} is determined using the critical value of the J integral J_{Ic}, in accordance with the standard [16].

$$K_{\mathrm{Ic}} = \sqrt{\frac{J_{\mathrm{Ic}} \cdot E}{1-\nu^2}}\,, \tag{1}$$

where E is the Young's modulus and ν is Poisson's ratio.

The values of the J integral are determined by the single specimen method, using the technique of partial unloading. The procedure for determining the critical value of the J integral J_{Ic} includes forming the fracture resistance curve (J-Δa curve), in accordance with the standard [17]. The crack growth increment Δa is determined based on the change of compliance. The basic procedure defined by [16] is the multi specimen method, but it is more complex to undertake.

During testing by the single specimen method, the specimen is partially unloaded in intervals, to approximately 30 % of the current load value. This level of unloading is determined based on the experience for the analysed material type. The increment of the crack growth between two consecutive unloading operations, Δa, can be determined based on the change of the compliance during the crack growth. This increment is calculated for the current force value, using the expression:

$$\Delta a_i = \Delta a_{i-1} + \left(\frac{b_{i-1}}{\eta_{i-1}}\right) \cdot \left(\frac{C_i - C_{i-1}}{C_{i-1}}\right), \tag{2}$$

where b is remaining ligament length, and η is constant defined by [16].

Obtained diagrams J-Δa, for specimens cut from the exploited and new pipe, are shown in Figures 7 - 12.

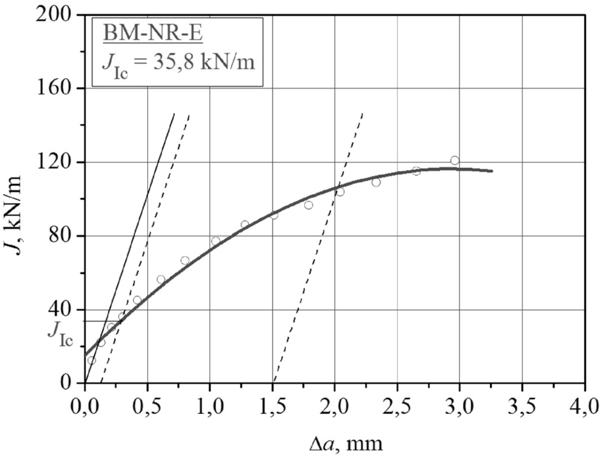

Figure 7. Curve J-Δa - pre-crack in the base material, exploited pipe

Slika 7. J-Δa krivulja - početna pukotina u osnovnom materijalu, rabljena cijev

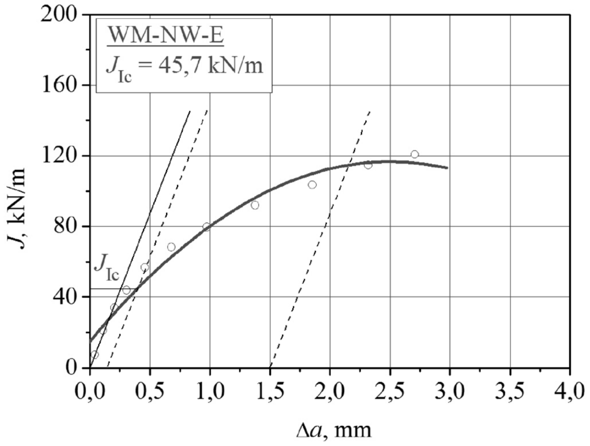

Figure 8. Curve J-Δa - pre-crack in the weld metal, exploited pipe

Slika 8. J-Δa krivulja - početna pukotina u metalu šava, rabljena cijev

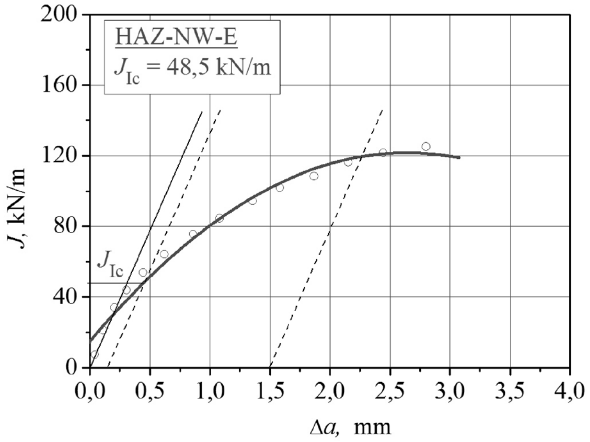

Figure 9. Curve J-Δa - pre-crack in the HAZ, exploited pipe

Slika 9. J-Δa krivulja - početna pukotina u ZUT, rabljena cijev

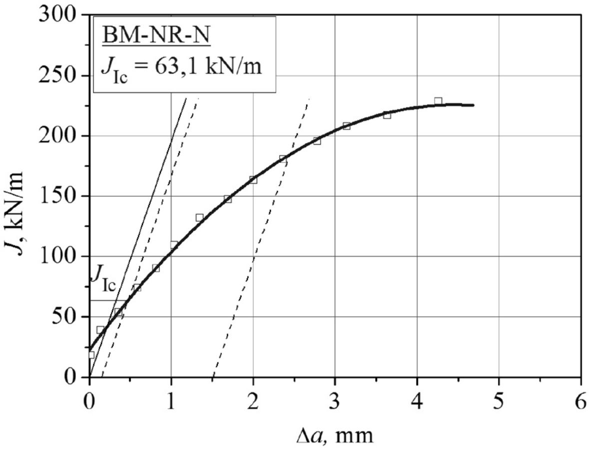

Figure 10. Curve J-Δa - pre-crack in the base material, new pipe

Slika 10. J-Δa krivulja - početna pukotina u osnovnom materijalu, nova cijev

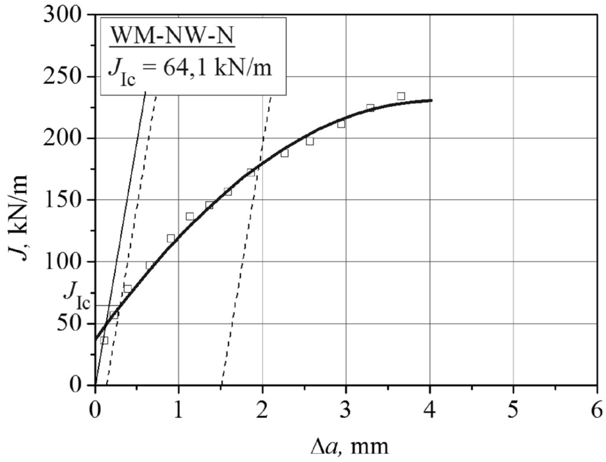

Figure 11. Curve *J*-Δ*a* - pre-crack in the weld metal, new pipe

Slika 11. *J*-Δ*a* krivulja - početna pukotina u metalu šava, nova cijev

The calculated values of K_{Ic} are given in Tables 4 and 5. Approximate values for the critical crack length a_c are obtained using the expression:

$$K_{Ic} = 1,12 \cdot \sigma_c \cdot \sqrt{\pi \cdot a_c}\ , \qquad (3)$$

where σ_c is the stress at fracture.

Based on the critical values of the stress intensity factor and *J* integral given in Tables 4 and 5, as well as *J*-Δ*a* curves for both materials, it can be seen that the period of exploitation does reduce the fracture resistance of the analysed steel. However, in addition to the effect of operating conditions, the differences in fracture resistances of the two materials can also be affected by the differences in yield strength values of the exploited and new material, shown in the beginning of this section.

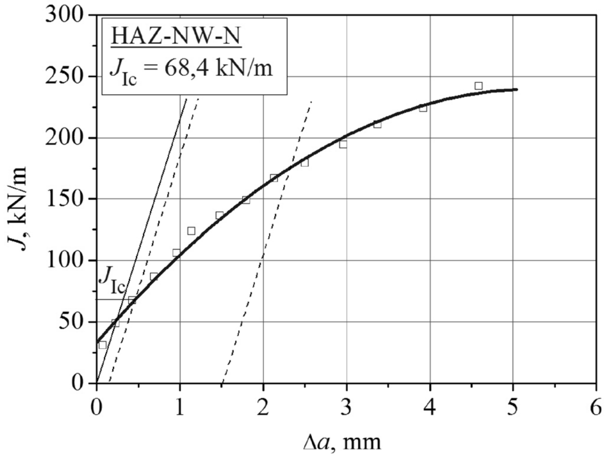

Figure 12. Curve *J*-Δ*a* - pre-crack in the HAZ, new pipe

Slika 12. *J*-Δ*a* krivulja - početna pukotina u ZUT, nova cijev

Paris equation for metals and alloys establishes a relation between the fatigue crack growth rate d*a*/d*N* and stress intensity factor range Δ*K*, using the coefficient *C* and exponent *m*:

Table 4. K_{Ic} values - exploited pipe

Tablica 4. Vrijednosti K_{Ic} - rabljena cijev

Specimen designation / Oznaka epruvete	Temperature / Temperatura, °C	J_{Ic}, kN/m	K_{Ic}, MPa·m$^{1/2}$	a_c, mm
BM-NR-E	20	35,8	91,4	14,4
HAZ-NW-E		48,5	106,4	19,6
WM-NW-E		45,7	103,3	18,5

Table 5. K_{Ic} values - new pipe

Tablica 5. Vrijednosti K_{Ic} - nova cijev

Specimen designation / Oznaka epruvete	Temperature / Temperatura, °C	J_{Ic}, kN/m	K_{Ic}, MPa·m$^{1/2}$	a_c, mm
BM-NR-N	20	63,1	121,4	25,5
HAZ-NW-N		68,4	126,4	27,5
WM-NW-N		64,1	122,3	25,9

Table 6. Parameters of the fatigue crack growth

Tablica 6. Parametri rasta zamorne pukotine

Material / Materijal	Temperature / Temperatura, °C	ΔK_{th}, MPa·m$^{1/2}$	*C*	*m*	d*a*/d*N*, for Δ*K*=15 MPa·m$^{1/2}$, m/cycle
Exploited / Rabljeni	20	9,2	$2,11 \times 10^{-15}$	6,166	$3,75 \times 10^{-8}$
New / Novi		9,5	$1,23 \times 10^{-13}$	3,931	$5,17 \times 10^{-9}$

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C\left(\Delta K\right)^{m}. \tag{4}$$

The fatigue crack growth rates da/dN are determined as a function of the variable loading (expressed through the stress intensity factor range), and diagrams log(da/dN) - log(ΔK) are formed, see Figures 13 and 14.

The investigation is conducted using the specimens with a crack in the base material, because the results obtained by testing the modified CT specimens exhibited the smallest critical crack lengths for the crack in this zone. The values of the coefficient C, exponent m, fatigue threshold stress intensity factor range ΔK_{th} and fatigue crack growth rate da/dN for ΔK=15 MPa·m$^{1/2}$ are given in Table 6.

The influence of exploitation time on the fatigue crack growth rate can be related to the values of the parameters of the Paris equation (C and m). The value of the stress intensity factor range ΔK=15 MPa·m$^{1/2}$ is adopted for the analysis because it is within the stable crack growth area in the diagram da/dN-ΔK, where Paris law can be applied.

The fatigue crack growth rate is larger for the exploited material, i.e. the resistance to fatigue crack growth decreases during the service life of the part, which does not stand for the fatigue threshold stress intensity factor range ΔK_{th}.

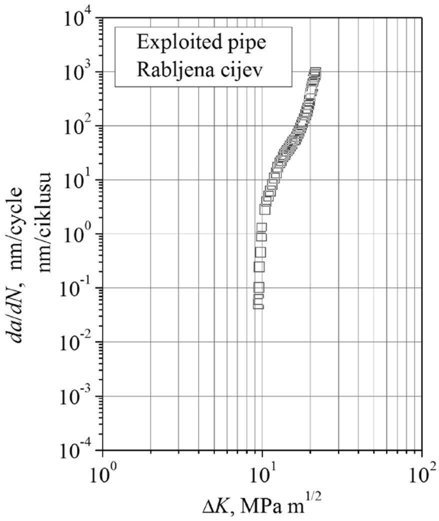

Figure 13. da/dN-ΔK curve - crack in the base material, exploited pipe

Slika 13. Krivulja da/dN-ΔK - pukotina u osnovnom materijalu, rabljena cijev

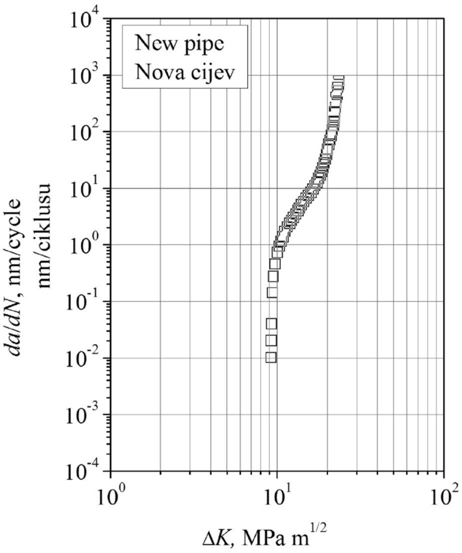

Figure 14. da/dN-ΔK curve - crack in the base material, new pipe

Slika 14. Krivulja da/dN-ΔK - pukotina u osnovnom materijalu, nova cijev

4. Conclusions

In this paper, detailed investigation is conducted on API J55 steel specimens, cut from the longitudinally welded casing pipes, manufactured by high frequency contact welding. The analysis included testing of the specimens from the exploited pipe (withdrawn from a pipeline) and a new pipe made of the same grade material, with the aim of determining degradation of the material properties after a period of service which was much shorter then the projected service life.

The following can be concluded:

- The mechanical properties obtained by testing the specimens cut from the new pipe and exploited pipe exhibit certain differences, which are the most pronounced for yield strength. However, the requirements of API 5CT standard are satisfied for both materials. It should be noted that the two analysed materials, although of the same grade, were not produced at the same time, which means that their as-delivered properties might have been different. Therefore, the differences in mechanical properties are not entirely caused by working conditions and aggressive environment during the service life.
- Impact toughness measurement is conducted on the base material and welded joint specimens. It is shown that the exploited material has somewhat higher impact toughness in comparison with the new one. With the increase of temperature, slower increase of total impact energy is obtained for the welded joint in comparison with the base material.

- Testing of the modified compact tension specimens led to the conclusion that the base material has the lowest critical value of the stress intensity factor when compared with the weld metal and HAZ. Also, the values obtained for the material from exploitation are lower, which is also the case for the crack growth resistance, expressed through J-Δa curves. Such behaviour may be partially attributed to the difference in yield strength values of the materials.
- Fatigue crack growth rate $\mathrm{d}a/\mathrm{d}N$ increases with exploitation time, i.e. the resistance to crack growth is reduced. On the other hand, the fatigue threshold stress intensity factor range ΔK_{th} does not change significantly.

The final conclusion of the presented investigation is that the material properties were degraded during the analysed period (cca 70 000 hours, i.e. 8 years), but the integrity of the exploited pipes is not significantly endangered. However, it should be noted that, besides the crack-like defects, corrosion damages occur very often on casing pipes in oil and gas drilling rigs. This will be the subject of a separate paper [18], which is currently in the preparation phase.

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