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Assessment of the integrity of welded pipes

The subject of the paper is analysis of the integrity of welded pipes made of API J55 steel by high frequency contact welding (HF). Experimental research on the mechanical properties of the base material was conducted on pipes withdrawn from exploatation after 70 000 hours at service. Defect influence of the surface crack on the integrity of pipes was tested using hydrostatic pressure of pipes with axial surface crack in the base material. Fracture behaviour was tested using modified compact specimen (CT), with the initial crack in the base material, welded joint and heat affected zone (HAZ). Critical value of the tensile strength factors K_{Ic} was determined based on the critical value J of the integral J_{Ic}.

Apart from the experimental research, based on the derived values of K_r and S_r and by applying fracture analysis diagram (FAD) an assessment of the integrity of welded pipes with axial surface crack on the outer surface area was conducted.

Keywords: *seam casing pipes, axial surface crack, high frequency contact welding, fracture analysis diagram (FAD).*

INTRODUCTION

Reliability of the pipeline system is important not only for the reasons of exploatation but also for the sake of perserving the environment. For the above reasons, research was conducted in order to assess fracture resistence of welded pipes and analysis of the integrity of pipeline system using fracture analysis diagram (FAD)was conducted. Pipelines used in the process of exploatation can be made out of welded and seamless pipes respectively [1,2]. Specification of the pipeline system, according to the API 5CT standard, for the most part includes the properties of the pipeline system, such as are the dimensions of the pipes and joints, resistance of the pipeline system to internal and external pressure, as well as mechanical characteristics and chemical components.

Some of the developed standards and recommendations that were taken into consideration deal with the influence of large cracks on the integrity of pipes loaded with internal pressure and bending [3]. However, welded pipes can have axial surface cracks on the internal or external surface area, and can be subjected to diverse loading, including internal and external pressure, as well as axial loading (for example, due to the wight of the structure).

Methods for the assessment of the defect of pipes under pressure are important for maintaining safety and retaining stability of pipes in the plant [4-9]. The core part of the analysis of the integrity of pipes is how to efficiently and precisely make an estimate of maximum allowed pressure and determine parameters of mechanical fracture, such as tensile strength factors (K_{Ic}) and J-integral of defect pipes. As opposed to internal circular and axial semi-elliptic surface cracks [4-15,17], a very limited number of studies is in the area which deals with the determination of K_{Ic} and J-integral for pipes with external axial semi-elliptic surface cracks [13]. So far, no detailed 3D finite element analysis (FEA) exist for a wide range of surface cracks on the external area of pipes. Conducted analysis mostly regard the application of 3D elasto-plastic finite element analysis for the determination of J integral for circular [16] and axial surface cracks on the external area of pipes[17].

In certain fracture analysis diagrams (FAD), limited loading of pipes with a crack is used to define Lr parameter which represents the value of plastic collapse [18]. In addition to this, when an assessment of the integrity of structures is conducted using R6 method [19], referential stress is defined by loading. In such cases loading is usually assessed for defects of high toughness(strength) steel [20, 21]. Vast number of existing solutions for the pressure of pipes containing defects are developed analytically or empirically, based on the data derived from research [20]. These solutions were usually regarded as being too conservative, but the degree of conservatism can`t be quantified. Recently, based on the finite element analysis, equations for determining pressure for cylinders with external axial semi-elliptic surface crack were developed [21]. However, suggested equations relate to a very limited number of defect dimensions as shown in [22], and in accordance with that, extended research with the aim of finding new solutions, is desirable.

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In this paper,analysis of the integrity of welded pipes with axial surface crack made of API-J55 was conducted. The pipe subjected to analysis was in the process of exploatation and was withdrawn during reparation procedure, after the period of service of approximately 70 000 hours (8 years). This period is significantly shorter in comparison to projected work life of up to 30 years.

By CT testing using modified specimen, indirectly (using critical values *J* of J_{Ic} integral) critical values of tensile strength factor K_{Ic} were determined. Based on the critical value of tensile strength factor K_{Ic} for the base material, heat affected zone (HAZ) and seam metal, critical lengths of cracks were calculated.

For the assessment of the integrity of the pipeline system fracture analysis diagram(FAD) was applied. Based on the derived K_r i S_r a point was drawn into the fracture analysis diagram (FAD) , and is located in the safe zone of the diagram. Having in mind the conservatism of FAD analysis in all its aspects, a conclusion can be made that welded pipes are safe not only from brittle fracture but plastic collapse as well.

1. EXPERIMENTAL PROCEDURE

Research shown in this paper was conducted with the aim of making an assessment of the integrity of pipes after a period of approximately 70 000 hours at service (8 years).

Properties of API J55 steel were determined on the samples collected from pipes made by HF welding. Diameter of analysed pipes was Ø139,7 mm and nominal wall thickness 6,98 mm. Chemical components of API-J55 steel are shown in table 1.

Table 1 - Chemical components of API J55 steel [mas. %]

C	Si	Mn	P	S	Cr	Ni	Mo	V	Cu	Al
0.2924	0.233	0.963	0.013	0.0216	0.0995	0.0579	0.0123	0.003	0.131	0.025

*Ceq=[C+Mn/6+(Cr+Mo+V)/5+(Ni+Cu)/15]= 0.2924+0.963/6+ (0.0995+0.0123+0.003)/5+ +(0.0579+0.131)/15]=0.49

1.1 Mechanical characteristics

Positions of sample extraction for determination of mechanical characteristics of the base material and welded joint of cross welded pipes are defined by a standard [23].

Shape and dimensions of the samples used for the analysis of tensile properties are defined by a standard [24]. Measurement procedure for controlling defects is conducted using electromechanical testing device SCHENCK-TREBEL RM 100, the speed of introducing load tension is 5 mm/min.

Results derived by analysing tensile properties of the base material of the samples parallel to the direction of rolling, are shown in table 2 Test diagram is shown in figure 1.

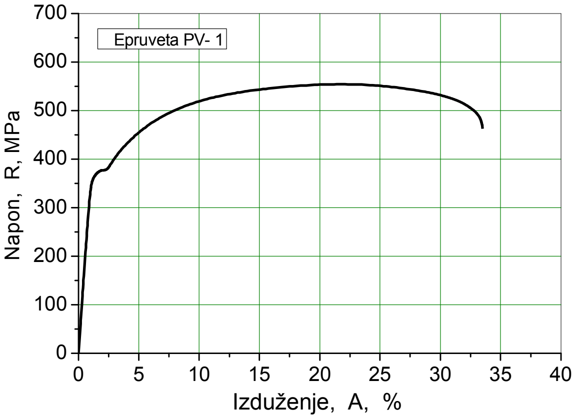

Figure 1 - Strain-stress diagram - elongation procentage, specimen PV– 1, pipe withdrawn from exploatation, 20 °C

Table 2 - Tensile properties of the base material parallel to the direction of rolling

Material	**Specimen**	**Temperature [°C]**	**R_e [MPa]**	**R_m [MPa]**	***A* [%]**
Exploited	PV	20	380	562	33
Standard API 5CT			379-552	> 517	

1.2. Fracture resistance

Welded pipes under pressure can be extremly sensitive to cracks and their stable or unstable growth. Accordingly, it is of immense importance to determine reliable criteria for estimating the remaining life cycle of pipes under pressure with cracks in the base material and in welded joint. For the sake of better understanding of crack initiation and growth in welded pipes, exposed to high pressure and chemically agressive work environment, parameters used for controlling the behavior of materials at the tip of the crack and fracture resistance must be quantitatively expressed. Hence, critical value of the stress intensity factor K_{IC}, crack growth resistance curves (J-Δ*a*), are experimentally investigated [25].

1.2.1. Analysis of modified (CT) specimens

Analysis using modified CT specimen, were conducted at room temperature using SCHENCK-TREBEL RM 100 device. Thickness of modified CT specimen is d = 6,98 mm (equals the thickness of pipe walls) [25]. Indirectly (using a critical value *J* of

J_{Ic} integral) the critical value of stess intensity factor K_{Ic} is derived, and calculated using equation 1 and shown in table 3:

$$K_{Ic} = \sqrt{\frac{J_{Ic}\cdot E}{1-\nu^2}} \qquad (1)$$

By applying equation:

$$K_{Ic} = 1{,}12\,\sigma_c\cdot\sqrt{\pi\cdot a_c} \qquad (2)$$

And taking into consideration stress values, $\sigma = \sigma_c$, (where σ_c represents stress at fracture), approximative values of critical lengths of cracks are calculated (a_c), za OM,HAZ i MŠ.

Table 3 - K_{Ic} values– pipe withdrawn from exploitation

Specimen mark	Temperature, [°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

Based on the derived K_{Ic} values for the base material, heat affected zone and welded joint, base material is proven to be least resistent according to the parameters of initiation and crack drowth.

2. ASSESSMENT OF THE INTEGRITY OF PIPES WITH AXIAL SURFACE CRACK

Analysis were conducted on the canister under pressure, with axial surface crack in the base material, figure 2. Canister is made out of a piece of the welded pipe withdrawn from exploitation. On the external surface area ot the pipe, axial surface crack in the base material dimensions: *a*=3,5 mm i 2c=200 mm is made by electroerosion.

The pipe prepared for hydrostatic pressure analysis is shown in figure. 3.

Figure 2 - Canister with axial surface crack in the external area

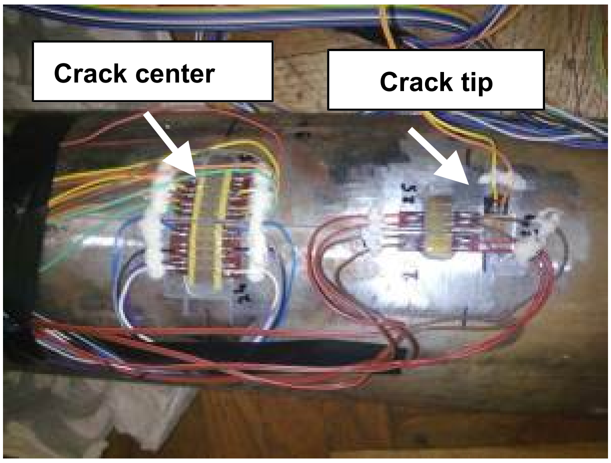

Figure 3 - Preview of the pipe prepared for analysis

Testing pressure is increased successively in steps from 1 MPa to the pressure of 8 MPa, and then by 0,5 MPa until reaching the pressure of 22 MPa, whereat defects were registered using a linear strain gage LY 11-6/120, produced by HBM [26].

Diagrams od defect dependability on test pressure *p* are shown in figures 4 do 7.

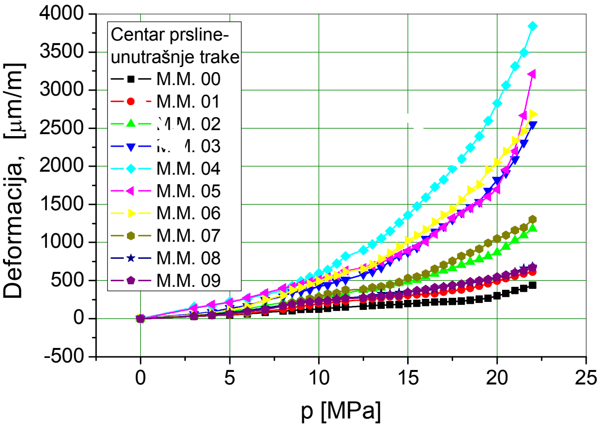

Figure 4 - Defects depending on pressure, inside strain gage - crack middle

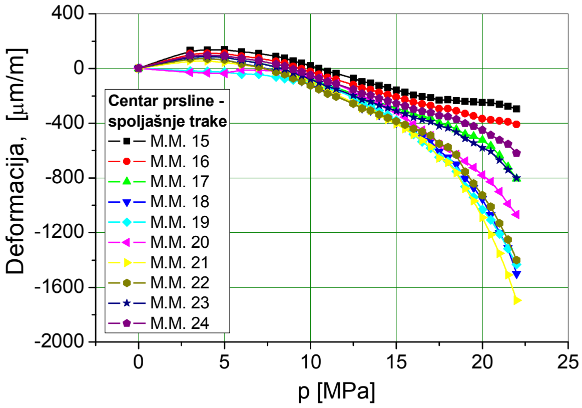

Figure 5 - Defects depending on pressure, outer strain gage - crack middle

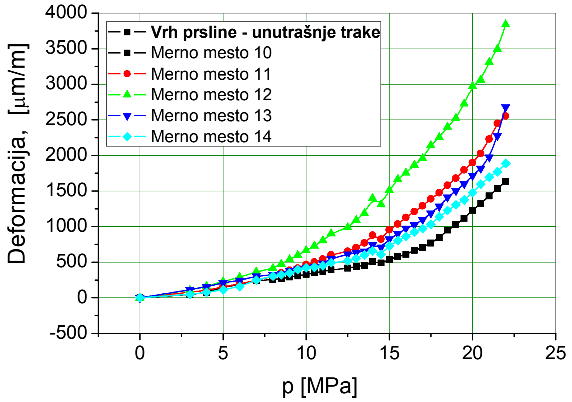

Figure 6 - Defects depending on pressure, inside strain gage – crack tip

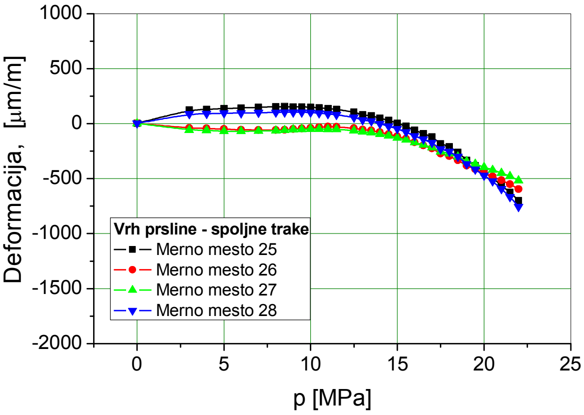

Figure 7 - Defects depending on pressure, outside strain gage – crack tip

2.1. Fracture analysis diagram- FAD

Structures made of tough materials are not susceptible to brittle fracture, but can fail by plastic collapse if they are overloaded. Plastic collapse mechanism is not encompassed by a CTOD (crack tip opening displacement) design curve, so its analysis requires a broader approach. Therefor, a concept with two fracture criteria was introduced in order to describe a mutual effect of a brittle fracture and a plastic collapse, realized using a Failure Assessment Diagram - FAD) [27]. The base point of this diagram is a modified strip yield model for a temporary crack in an infinite plate, which connects effective stress intensity factor K_{eff} to a non effective stress [28]:

$$K_{eff} = \sigma_Y \sqrt{\pi a}\left[\frac{8}{\pi^2}\ln\sec\frac{\pi}{2}\frac{\sigma}{\sigma_c}\right]^{1/2} \qquad (3)$$

In real structures, flow stress σ_Y should be substituted by collapse stress σ_C, which apart from materials also depends upon geometry of structures, including a crack. The next step in modifying FAD is expressing effective stress intensity factor in a non-dimensional form as K_{eff}/K_I:

$$\frac{K_{eff}}{K_I} = \frac{\sigma_c}{\sigma}\left[\frac{8}{\pi^2}\ln\sec\frac{\pi}{2}\frac{\sigma}{\sigma_c}\right]^{1/2} \qquad (4)$$

As a final step, non-dimensional variables, $S_r=\sigma/\sigma_c$ i $K_r=K_I/K_{Ic}$ are defined and they represent X-axis and Y-axis in a modified FAD, figure 5, and equation is transformed into:

$$K_r = S_r\left[\frac{8}{\pi^2}\ln\sec\left(\frac{\pi}{2}S_r\right)\right]^{-1/2} \qquad (5)$$

If a material is completely tough, structures fail by plastic collapse at S_r=1, whereas structure fracture for completely brittle materials requires K_r=1. In all of the remaining cases there is an interaction between plastic collapse and brittle fracture, so K_r i S_r are less then 1, and pairs of corresponding values form a border curve, shown in figure 8. Thereat K_{eff} is taken to be equal to toughness of material fracture ,K_{Ic}, so K_r, is determined based on equation:

$$K_r = \frac{K_I}{K_{Ic}}$$

For calculating S_r only primary stresses are taken into consideration, as secondary stresses do not influence structure collapse.

Using a handbook ,for geometry shown in figure 2 K_I-factor, is expressed using a following equation:

$$K_I = \sqrt{\frac{\pi a}{Q}}\frac{pR_i^2}{R_o^2 - R_i^2}\cdot$$

$$\cdot\left[2G_0 + 2\left(\frac{a}{R_i}\right)G_1 + 3\left(\frac{a}{R_i}\right)^2 G_2 + 4\left(\frac{a}{R_i}\right)^3 G_3\right] \quad (6$$

a constant Q is calculated based on:

$$Q = 1 + 1{,}464\left(\frac{a}{c}\right)^{1{,}65}$$

where G_j values depend upon a/c, a/t and t/R_i and are shown in a reference list [13]. Relevant G_j values for the purpose of this research are derived by interpolation and extrapolation are:

$$G_0 = 1{,}584 \qquad G_1 = 0{,}839$$

$$G_2 = 0{,}600 \qquad G_3 = 0{,}480$$

At initial depth *a* = 3,5 mm and crack length 2c=200 mm the derived equation is

$$Q = 1{,}0058 \ \text{ i } \ K_I = 32{,}067\left[MPa\sqrt{m}\right]$$

$$K_r = \frac{K_I}{K_{Ic}} = \frac{32{,}067}{91{,}4} = 0{,}35$$

Stress at net intersection equals $\sigma_n=2pR/t$, whereat factor 2 was taken due to weakened intersection by a crack of 3,5 mm length and 6,98 mm thickness (50%), to get

$$S_r = \frac{2\left(\frac{2pR}{t}\right)}{\left(R_{eH}+R_m\right)} = \frac{2\left(\frac{2\cdot 22\cdot 69{,}85}{6{,}98}\right)}{\left(380+562\right)} = 0{,}93$$

Based on the derived values of K_r i S_r a point with coordinates (0,93; 0,35) located in the unaffected zone of a diagram was drawn into a fracture analysis diagram FAD, figure 8.

Table 4 - K_r i S_r parameter values depending on a pressure change

A [mm]	t [mm]	p [MPa]	K_r	S_r
3,5	6,98	22	0,35085	0,93485
3,5	6,98	20	0,31895	0,84987
3,5	6,98	18	0,28706	0,76488
3,5	6,98	16	0,25516	0,67989
3,5	6,98	14	0,22327	0,59491
3,5	6,98	12	0,19137	0,50992
3,5	6,98	10	0,15948	0,42493
3,5	6,98	8	0,12758	0,33995

Table 4 shows K_r and S_r parameter values depending on the pressure change. Derived K_r and S_r values are drawn into a fracture analysis diagram(FAD), figure 9.

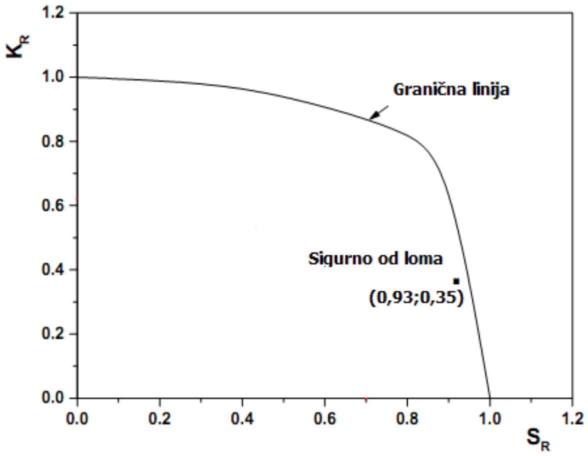

Figure 8 - Fracture analysis diagram (FAD) for a pipe with axial surface crack on the outer surface

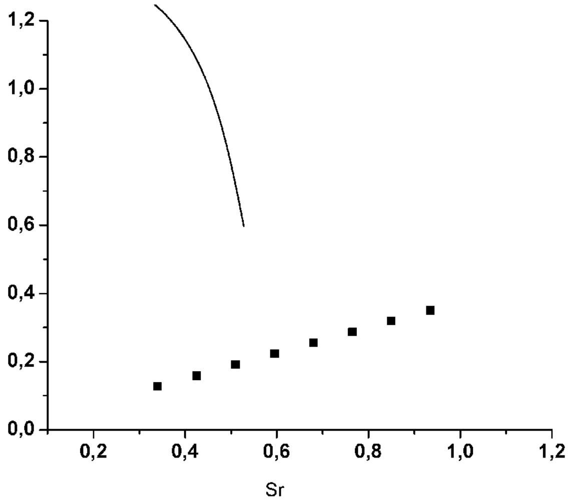

Figure 9 - Fracture analysis diagram (FAD) for a pipe with axial surface crack on the outer surface area at different pressures

CONCLUSION

In this paper, assessment of the integrity of welded pipes with axial surface crack on the outer surface of pipes made of API-J55 steel is conducted using fracture mechanics.

Based on the critical values of stress intensity factor K_{Ic} of the base material, heat affected zone HAZ and weld metal critical lengths of cracks are calculated. Based on the derived results, base material is proven to be least resistant according to crack initiation and growth.

Having in mind conservativeness of FAD analysis in all its aspects, a conclusion can be made that welded pipes are safe not only from brittle fracture, but also from plastic collapse. It is important to note that FAD enables a simple assessment of the integrity, which can ascertain with reliability weather a welded pipe is safe from fracture, under the condition that geometry and loading are represented in a conservative way. On the other hand, if integrity can not be proven, this does not mean that a welded pipe is useless, but that additional, more complex analysis are required.

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IZVOD

PROCENA INTEGRITETA ZAVARENIH CEVI

Predmet rada je analiza integriteta zavarenih cevi izrađenih od čelika API J55 visokofrekventnim kontaktnim zavarivanjem (VF). Eksperimentalna ispitivanja mehaničkih osobina osnovnog materijala su izvršena na cevima povučenim iz ekspolatacije posle 70 000 sati rada. Uticaj oštećenja tipa površinske prsline na integritet cevi ispitan je hidrostatičkim pritiskom cevi sa aksijalnom površinskom prslinom u osnovnom materijalu. Ponašanje pri lomu je ispitivano korištenjem modifikovanih kompaktnih epruveta za zatezanje (CT), s početnom prslinom u *osnovnom materijalu, zavarenom spoju i zoni uticaja toplote (ZUT). Kritična vrednost faktora intenziteta napona K_{Ic} određena je na osnovu kritične vrednosti J integrala J_{Ic}.*

Osim eksperimentalnog istraživanja, na osnovu dobijenih vrednosti za K_r i S_r primenom dijagrama analize loma (FAD) izvršena je procena integriteta zavarenih cevi sa aksijalnom površinskom prslinom na spoljašnjoj površini.

Keywords: *aksijalna površinska prslina, visokofrekventno kontaktno zavarivanje, dijagram analize loma (FAD).*

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