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# Risk based analysis of temperature and time effects on brittle fracture of A-387 Gr. B welded joint

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**Abstract**

Risk based analysis of temperature and time effects on fracture toughness values is applied to different regions of a welded joint made of low-alloyed Cr-Mo steel A-387 Gr. B, designed for high temperature applications. Heterogeneity of microstructure and properties of welded joint is evaluated by testing standard 3BP specimens with crack tip located at different regions of a joint, including the base metal (BM), weld metal (WM) and heat-affected-zone (HAZ). Experiments were performed both at the room temperature and at design working temperature, 540C. Based on these results, fracture toughness values are determined and used for risk based analysis, including risk matrix presentation as the basis for decision making process.


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*Keywords:* low-alloyed steel; welded joint; crack; plane strain fracture toughness

## 1. Introduction

Risk based approach is usually explained by the risk matrix, Fig. 1, using the simple definition of risk (product of probability and consequence). Nevertheless, neither probability, defined as the number of events in certain period of time, divided by the total number of pressure vessels operating in the same period of time, nor API procedure, [1, 2], or its European competitor, RIMAP, [3], both based on empirical rules, lead to reliable and simple procedure. In the first approach, definition of probability is simple mathematical term with no relevance to real problem, whereas the second approach tends to be too complex, and somewhat artificial, [4,5]. Therefore, another approach is used here, based on simple and reliable procedure, with sound physical meaning, applying fracture mechanics principles and structural

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integrity assessment, as explained in [4-7]. To illustrate this approach, previously conducted investigation of welded joint behavior is used, as explained in details in [8-10], and here just briefly.

| Probability | | Consequence category | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| | ≤0.2 | Low risk | Low risk | Low risk | Medium | High risk |
| | 0.2-0.4 | Low risk | Low risk | Medium | Medium | High risk |
| | 0.4-0.6 | Low risk | Medium | Medium | High risk | Very high |
| | 0.6-0.8 | Medium | Medium | High risk | Very high | **Very high** |
| | 0.8-1.0 | High risk | High risk | Very high | **Very high** | **Extreme** |

Figure 1. Risk matrix, [1-3]

One should notice that the risk matrix, as presented in Fig. 1, is somewhat arbitrary divided into 5 areas of risk: Low, Medium, High, Very high and Extreme. There is no general rule about the risk matrix, so this is just one of options, as used in this paper.

## 2. Experiment – Fracture toughness of welded joint

The parent material was steel A-387 Gr. B with thickness of 102 mm. Chemical composition and mechanical properties of the PM are given in tables 1-2, [8].

Table 1. Chemical composition of PM specimens

| Specimen mark | % mas. | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | C | Si | Mn | P | S | Cr | Mo | Cu |
| N | 0,13 | 0,23 | 0,46 | 0,009 | 0,006 | 0,85 | 0,51 | 0,035 |

Table 2. Mechanical properties of PM specimens

| Specimen mark | Yield stress, $R_{p0,2}$, MPa | Tensile strength, $R_m$, MPa | Elongation, A, % | Impact energy, J |
|---|---|---|---|---|
| N | 325 | 495 | 35,0 | 165 |

Welding of steel sheets made of this parent material was performed in two stages, according to the requirements given in the welding procedure provided by a welding specialist, and these stages include:

- Root weld by E procedure, using a coated LINCOLN S1 19G electrode (AWS: E8018-B2), and
- Filling by submerged arc welding (SAW), wherein wire denoted as LINCOLN LNS 150 and powder denoted as LINCOLN P230 were used as additional materials.

Chemical composition of the coated electrode LINCOLN S1 19G, and the wire LINCOLN LNS 150 is given in tab. 3, whereas their mechanical properties are given in tab. 4, [8].

Table 3. Chemical composition of additional welding materials

| Filler material | % mas. | | | | | | |
|---|---|---|---|---|---|---|---|
| | C | Si | Mn | P | S | Cr | Mo |
| LINCOLN Sl 19G | 0,07 | 0,31 | 0,62 | 0,009 | 0,010 | 1,17 | 0,54 |
| LINCOLN LNS 150 | 0,10 | 0,14 | 0,71 | 0,010 | 0,010 | 1,12 | 0,48 |

Table 4. Mechanical properties of additional materials

| Additional material | Yield stress, $R_{p0,2}$, MPa | Tensile strength, $R_m$, MPa | Elongation, A, % | Impact energy, J at 20°C |
|---|---|---|---|---|
| LINCOLN Sl 19G | 515 | 610 | 20 | > 60 |
| LINCOLN LNS 150 | 495 | 605 | 21 | > 80 |

Butt welded joint was made with U groove, chosen based on thickness, in accordance with standards SRPS EN ISO 9692-1:2012, [11], and SRPS EN ISO 9692-2:2008, [12]. The effect of temperature on the parent material and welded joint components tendency towards brittle fracture was assessed by determining fracture toughness in plain strain conditions, i.e. by determining the critical value of stress intensity factor, $K_{Ic}$. Tests were performed at room temperature of 20°C, as well as at the elevated temperature of 540°C. The effect of exploitation time is evaluated by testing specimens taken from new samples and from 40 years exploited samples.

For the purpose of determining $K_{Ic}$, three point bending specimens (3PB) were used for room temperature testing, with geometry defined in accordance with standards ASTM E399, [13] and ASTM E1820, [14]. For determining $K_{Ic}$ at the temperature of 540°C, modified CT specimens, with geometry defined in accordance with standard BS 7448 Part 1, [15], were used.

Experiments were performed by testing a single specimen by successive partial unloading, i.e. by single specimen method, as defined by standard E813, [16]. The testing was performed with fatigue cracks in PM, WM and HAZ, at room temperature of 20°C and the elevated temperature of 540°C, using electro-mechanical tensile test machine.

For room temperature testing, the specimens was equipped with a COD extensometer to measure crack tip opening. Since no extensometer that can work at high temperatures was available, crack tip opening during testing at 540°C was registered using an inductive sensor, with previously established calibration curve, showing the ratio between values obtained using the extensometer and those obtained from the sensor.

Based on the obtained data, a $J$-$\Delta a$ curve is drawn, and the regression line is then constructed, according to standard ASTM E1152, [17], providing the critical value of J-integral, $J_{Ic}$, as well as the fracture toughness, $K_{Ic}$, by using the following relation:

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

Typical $F$-$\delta$ and $J$-$\Delta a$ diagrams for specimens taken out of PM, WM and HAZ, tested at room and elevated temperature 540°C, are shown elsewhere, [15]. It is important to note that the elasticity module values (160 GPa) corresponding to elevated temperature (540°C) were used for calculation of fracture toughness. The effect of test temperature and exploitation time on critical stress intensity factor values, $K_{Ic}$, is visible from results given in tables 5-9, for PM, HAZ and WM cracked specimens, respectively.

Table 5. Mean values of $K_{Ic}$ for new PM

| point | Temperature, °C | $J_{Ic}$, kJ/m$^2$ | $K_{Ic}$, MPa m$^{1/2}$ |
|---|---|---|---|
| 1 | 20 | 60,9 | 118,5 |
| 2 | 540 | 44,4 | 88,4 |

Table 6. Mean values of $K_{Ic}$ for exploited PM

| point | Temperature, °C | $J_{Ic}$, kJ/m$^2$ | $K_{Ic}$, MPa m$^{1/2}$ |
|---|---|---|---|
| 3 | 20 | 43,5 | 100,2 |
| 4 | 540 | 23,0 | 63,6 |

Table 7. Mean values of $K_{Ic}$ for new HAZ

| point | Temperature, °C | $J_{Ic}$, kJ/m$^2$ | $K_{Ic}$, MPa m$^{1/2}$ |
|---|---|---|---|
| 5 | 20 | 52,7 | 101,2 |
| 6 | 540 | 34,6 | 78,0 |

Table 8. Mean values of $K_{Ic}$ for exploited HAZ

| point | Temperature, °C | $J_{Ic}$, kJ/m$^2$ | $K_{Ic}$, MPa m$^{1/2}$ |
|---|---|---|---|
| 7 | 20 | 38,0 | 92,7 |
| 8 | 540 | 21,5 | 61,4 |

Table 9. Mean values of $K_{Ic}$ for new WM

| point | Temperature, °C | $J_{Ic}$, kJ/m$^2$ | $K_{Ic}$, MPa m$^{1/2}$ |
|---|---|---|---|
| 9 | 20 | 72,7 | 129,8 |
| 10 | 540 | 50,4 | 94,1 |

## 3. Risk based analysis

Temperature and time effects on $K_{Ic}$ are discussed in more details in [10] from engineering point of view. In this paper focus is more on presentation of results in appropriate form to the top management in the scope of decision making process after 40 years of exploitation. Namely, the main purpose of the investigation was to determine temperature and time effects on welded joint behavior, as being critical point in pressure vessels. Anyhow, there is often a gap between engineering way of thinking and interpretation of results obtained by investigation as presented here, and decision making process in which top managers have to decide what to do with the equipment. The authors of this paper believe that the approach presented here can serve as a bridge between engineering and managerial way of thinking.

Toward this end, simple engineering reasoning and analysis is used to evaluate consequence and probability. Consequence can be estimated considering data given in table 10 and explained in more details in [5]. In the case considered here, consequence is estimated as category 3 since it can cause serious injuries to people.

Table 10. Consequence categories

| | Potential consequences | | | |
|---|---|---|---|---|
| | People | Property | Environment | Reputation |
| 0 | No injuries | No losses | No damage | No harm |
| 1 | Insigni ficant injuries | Loss up to 10 K€ | Minor damage to environment | Insignificant consequences. Employees and population awareness. |
| 2 | Minor injuries | Loss from 180 K€ to 540 K€ | Minor consequ-ence and damage to environment. Small costs.. | Mild consequences. There is a concern at the local level. |
| 3 | Serious injuries | Loss from540 K€ to 1,8 M€ | Moderate consequence. Short-term damage to environment.. | Minor consequences. There is a concern at the regional level |
| 4 | Permanent incapabilit y | Loss from 1,8 K€ to 50 M€ | Major conse-quences. Big damage to en-vironment. Large costs. | Moderate consequenes. There is a concern at the national level. |
| 5 | Death | Loss over 50 M€ | Dire consequ-ences. Lomg-term and big damage. Huge costs. | Dire consequ-ence..Concern and reaction at the international level. |

Probability can be taken as the ratio between the distance of the calculated point in FAD from the zero point, and the distance of the point on the limit line, defined at the cross section of the line drawn from the zero point through the calculated point, also from the zero point, as explained in more details in [5,6]. Data needed for this calculation is the crack length (a=41 mm), corresponding stress intensity factor ($K=Y\sigma\sqrt{a}=52.5$ MPa$\sqrt{m}$), to provide "y" coordinate as the ratio $K/K_{Ic}$, and $S_r=\sigma/\sigma_y=462/211=0.36$ to provide "x" coordinate, being the same for all points in this case, since both the stress $\sigma$ and yield strength $\sigma_y$ are the same for all points. Coordinates for 6 chosen point are shown in Fig. 2.

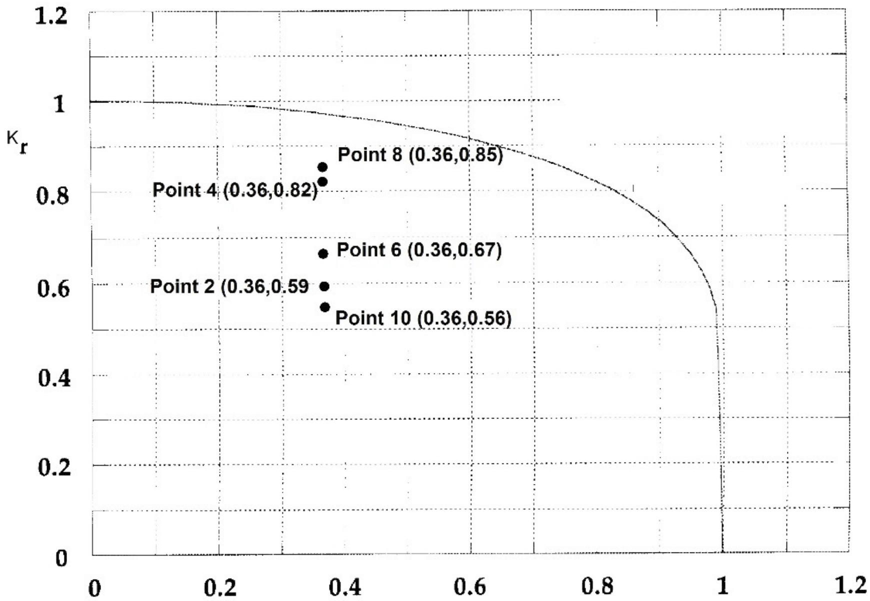


Figure 2. Six points of interest positioned in FAD

Taking into account that consequence category can be taken as 3, and an analysis based on FAD, presented in Fig. 2, indicating 5 points of interest (PM and HAZ new and exploited, WM new, all tested 540°C), risk matrix has been made and presented in Fig. 3. Just as an example, let us consider new HAZ (point 6), which has medium risk, whereas 40 years exploited HAZ (point 8) indicates high risk. In other words, instead of looking at numbers (e.g. reduction from 78 MPa $m^{1/2}$ for new HAZ to 61.4 MPa $m^{1/2}$ for exploited HAZ), which is important fact for engineers, but definitely not for managers, they can see data provided in a simple way to make a decision, which in this case probably lead to some action to reduce the risk.

| Probability category | Consequence category | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| ≤0.2 | | | | | |
| 0.2-0.4 | | | | | |
| 0.4-0.6 | | | **2, 10** | | |
| 0.6-0.8 | | | **6** | | |
| 0.8-1.0 | | | **4, 8** | | |

Figure 3. Risk matrix for the case study with 6 points

## 4. Conclusions

Based on the results and approach presented here one can conclude the following:

- Engineers/scientists typically provide research results which are not meaningful for managers when they have to decide what to do with damaged/old equipment.
- Relatively simple approach can bridge the gap between engineering and managerial way of thinking, as shown here in the case of 40 years of exploitation of pressure vessel.
- Long exploitation period lead to high risk level of welded joints in pressure vessel considered in this analysis.

## 5. Acknowledgements

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