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Analysis of SA 387 Gr. 91 welded joints crack resistance under static and impact load

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Abstract

This paper presents the results of experimental testing of crack resistance of specimens taken from a welded plate made of steel SA-387 Gr. 91, while taking into account different filler materials and welding procedures that were used. This type of steels is typically used in pressure vessels, pipelines and gas installations in the chemical and petrochemical industry, as well as in thermal installations. Since it is operating under extreme conditions, which include elevated temperatures and/or corrosion, the mechanical properties of SA-387 Gr. 91 will deteriorate over time, especially its welded joints. For this reason, it is very important to thoroughly analyse the behaviour of welded joints, taking into account the possibility of cracks initiating in any of the three welded joint regions, the parent material (PM), the weld metal (WM) and the heat affected zone (HAZ). This can be achieved by determining the total impact energy of Charpy specimens with V-2 notches in each of the three regions, along with their components, crack initiation and crack propagation energy, as well as by measuring the fracture toughness.

Keywords: SA 387 Gr. 1; welded joint; crack initiation energy; crack propagation energy; fracture toughness

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1. Introduction

Steel SA 387 Gr. 91 is used for high temperature welded component due to its high creep resistance properties in all zones of its welded joints, Milovic et al (2008). Properties of parent material and welded joint significantly differ when subjected to impact load, compared to static load. In both loading cases, crack resistance is of utmost importance, so impact testing on instrumented Charpy pendulum and fracture toughness testing, under plane strain conditions, is crucial to determine welded joint behaviour, as the most critical region of a steel structure, including SA 387 Gr. 91 steel. Such tests are also often used to determine the quality level and homogeneity of the material. Additionally, impact tests can help determine the tendency of materials towards brittle fracture during exploitation (aging), especially in the case of creep resistant steels. Research presented in this paper was focused on determining of crack initiation and propagation, as well as fracture toughness for each individual welded joint region (parent metal - PM, weld metal - WM and heat affected zone - HAZ). All impact tests were performed using an instrumented Charpy pendulum, Čamagić, Jović et al. (2016), in accordance with relevant standards. Fracture toughness, K_{Ic}, was determined via J_{Ic}, also using the standard procedure, as described in Čamagić, Sedmak S. et al. (2019) for similar material, A 387 Gr. B. This approach could prove applicable to a number of other real problems which involve crack initiation, including steels and Al alloys with different applications, SRPS EN ISO 6947:2020 (2020), Milovanović et al. (2019), Baragetti, Borzini et al. (2020). Additionally, other types of failure mechanisms can be investigated using the method presented here, including fatigue, among others, as shown in the works of Baragetti, Božić, Arcieri (2020), Solob et al. (2020) and Pastorčić et al. (2019).

2. Material and methods

Steel SA-387 Gr. 91, with yield stress of 450 MPa and minimum impact energy 41 J at room temperature. Material used in this research was manufactured by "Železarna ACRONI", Jesenice, with chemical composition given in table 1. Welding of the plates needed for testing involved two different procedures and filler materials, Grbović et al. (2020), SRPS EN ISO 21952:2013 (2013), SRPS EN ISO 9692-1:2014 (2014), SRPS EN ISO 3580:2017 (2017):

- Root weld – 4 passes – BOEHLER C9 MV-IG filler metal, gas tungsten arc welding (TIG).
- Filler welds – 10 passes – BOEHLER FOX C9 MV, Ø2.5 mm and Ø3.25 mm electrodes, manual metal arc welding.

To avoid issues with defining notch position in the HAZ, symmetric K-groove was selected for the butt weld joint. Chemical composition of filler metals is shown in table 2 for both welding procedures. Finally, mechanical properties of both filler materials are given in table 3, including both electrode diameter used in the manual arc welding.

Table 1. Base metal chemical composition, steel SA-387 Gr. 91

Chemical composition, weight %										
C	Si	Mn	P	S	Cr	Mo	Ni	V	Nb	Cu
0.129	0.277	0.443	0.001	0.001	8.25	0.874	0.01	0.198	0.056	0.068

Table 2. Filler metal chemical composition (%)

Filler metal	C	Si	Mn	P	S	Cr	Mo	Ni	V	Nb	Cu
C9 MV-IG	0.11	0.23	0.5	0.006	0.003	9.0	0.93	0.5	0.19	0.07	0.0.
FOX C9 MV Ø2.5 mm	0.09	0.19	0.55	0.01	0.006	8.5	1.0	0.5	0.19	0.04	0.1
FOX C9 MV Ø3.25 mm	0.11	0.26	0.66	0.008	0.005	8.5	0.94	0.5	0.20	0.06	0.1

Table 3. Mechanical properties of filler metals

Filler metal	Yield stress, MPa	Tensile strength, MPa	Elongation, %	Impact energy, J
C9 MV-IG	≥ 530	≥ 620	≥ 17	≥ 50
FOX C9 MV Ø2.5 mm	≥ 550	≥ 680	≥ 17	≥ 47
FOX C9 MV Ø3.25 mm	≥ 550	≥ 680	≥ 17	≥ 47

3. Impact test procedure and results

Impact tests were performed using an instrumented Charpy pendulum, enabling separation of the total impact energy into crack initiation and crack propagation energy. The test procedure is defined by standard SRSP EN ISO 9016:2013. Three specimens with V-2 notches in every welded joint region were made for testing, for a total of 9 specimens, in order to obtain more accurate results, Sedmak S. et al. (2020). Testing also included the drawing of force-time and impact energy-time diagrams. Specimen geometry, with a detailed view of the notch position and dimensions, as well as the specimen cutting plan, which includes specimens taken from each individual welded joint region, are shown in figure 1, Čamagić, Jović et al. (2016), SRPS EN ISO 9016:2013 (2013). Results of impact testing of all three groups of V-2 notch specimens are shown in tables 4-6 and corresponding examples of diagrams in figures 2-4, while results for J_{Ic} testing are shown in tables 7-9, and corresponding diagrammes in figures 5-7.

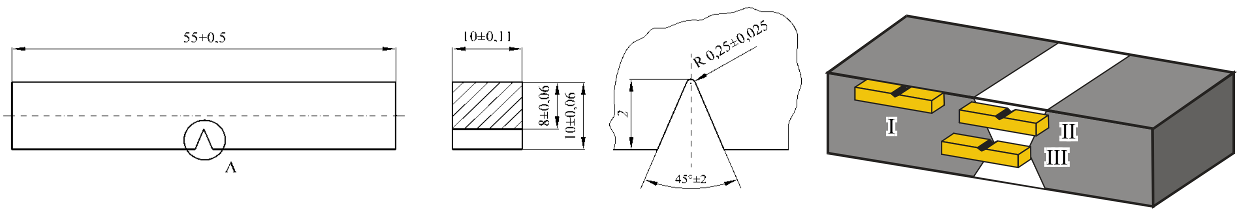

Fig. 1. Specimen geometry (left) and cutting plan (right)

Table 4. Impact test results for specimens with a V-2 notch in the PM

Specimen mark	Impact total energy, AT, J	Crack initiation energy, AI, J	Crack propagation energy, AP, J
PM - 1	251	58	193
PM - 2	268	60	208
PM - 3	275	55	220

Table 5. Impact test results for specimens with V-2 notch in WM

Specimen mark	Impact total energy, AT, J	Crack initiation energy, AI, J	Crack propagation energy, AP, J
WM - 1	144	52	92
WM - 2	168	55	113
WM - 3	157	54	103

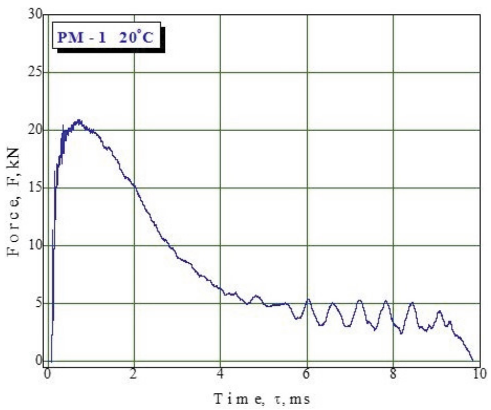

Fig. 2. Impact test diagrams, for specimen PM-1

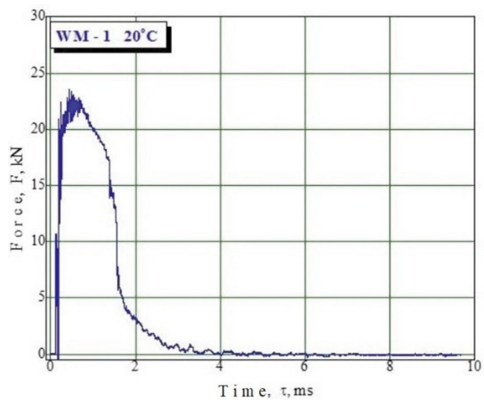

Fig. 3. Impact test diagrams for specimen WM-1

Table 6. Impact test results for specimens with V-2 notch in HAZ

Specimen mark	Impact total energy, AT, J	Crack initiation energy, AI, J	Crack propagation energy, AP, J
HAZ - 1	248	70	178
HAZ - 2	246	59	187
HAZ - 3	249	70	179

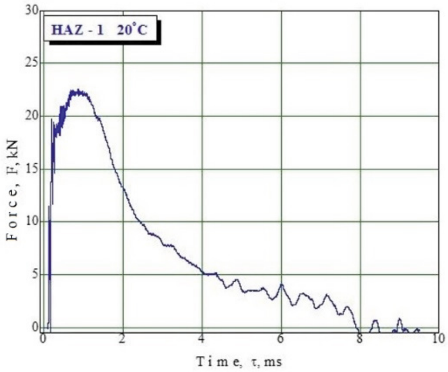

Fig. 4. Impact test diagrams, for specimen HAZ-1

Table 7. Calculated values of K_{Ic} for specimens notched in BM

Specimen mark	Testing temperature, °C	Critical J-integral, J_{Ic}, kJ/m^2	Critical stress intensity factor, K_{Ic}, MPa m$^{1/2}$
PM-1K	20	131.1	173.9
PM-2K		144.2	182.4
PM-3K		124.0	169.2

Table 8. Calculated values of K_{Ic} for specimens notched in WM

Specimen mark	Testing temperature, °C	Critical J-integral, J_{Ic}, kJ/m2	Critical stress intensity factor, K_{Ic}, MPa m1/2
WM-1K	20	71.6	128.5
WM-2K		64.8	122.3
WM-3K		69.2	126.4

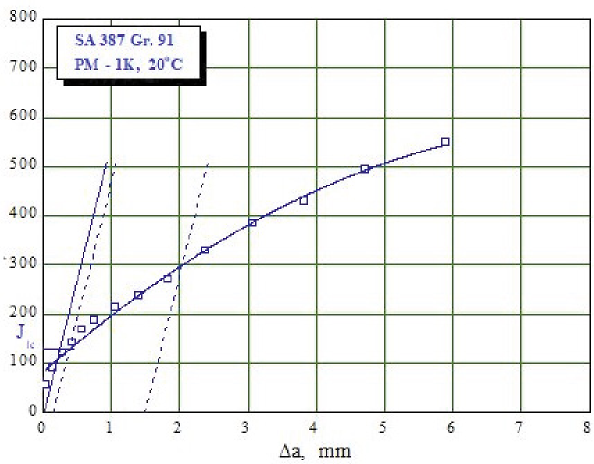

Figure 5. Diagrammes F-δ (a) and J-Δa (b) for the specimen PM – 1K

Table 9. Calculated values of K_{Ic} for specimens notched in HAZ

Specimen mark	Testing temperature, °C	Critical J-integral, J_{Ic}, kJ/m2	Critical stress intensity factor, K_{Ic}, MPa m1/2
HAZ-1K	20	97.6	150.1
HAZ-2K		88.9	143.2
HAZ-3K		92.1	145.8

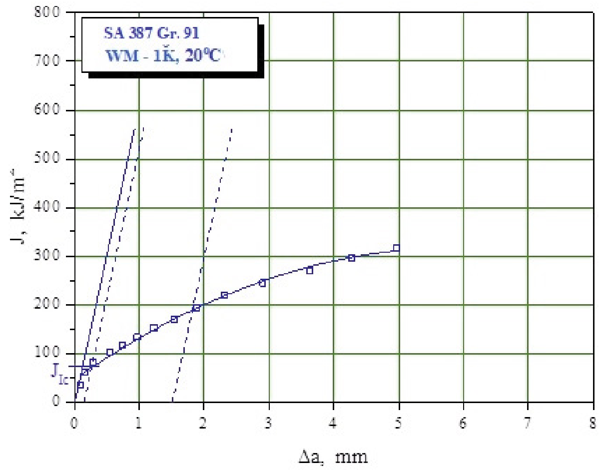

Figure 6. Diagrammes F-δ (a) and J-Δa (b) for the specimen WM-1K

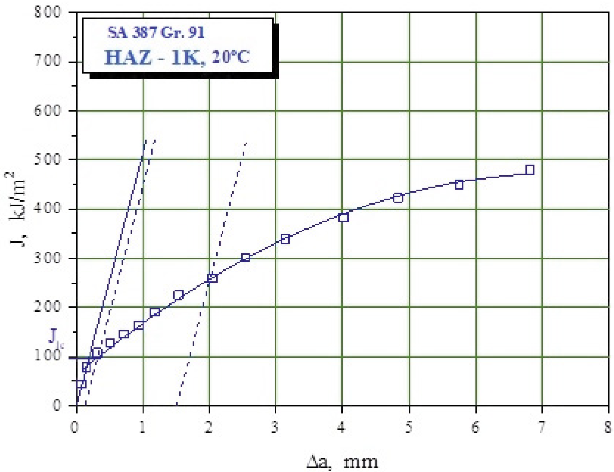

Figure 7. Diagrammes F-δ (a) and J-Δa (b) for the specimen HAZ-1K

4. Discussion and conclusions

The results of impact testing confirmed that the location of the notch in the V-2 specimens has a noticeable effect on its impact properties. Highest impact energy, 265 J, was measured BM, with significantly larger crack propagation energy than crack initiation energy. This ratio, which is also the most favourable from structural integrity point of view, was 3.6:1.

Heat affected zone specimens has slightly lower values of total impact energy, 248 J, with similar distribution of crack initiation and crack propagation energies, while WM has the lowest impact energy values, 156 J, as expected. Crack propagation to crack initiation energy ratios were 1.9:1 for WM and 2.8:1 HAZ.

This suggests that BM has the best ductility (high total energy and much higher crack propagation energy), and that the weld metal has lowest ductility. Additionally, the values for all three specimens in each group had small differences, suggesting good homogeneity of each welded joint region's structures. The detailed approach to experimental testing presented in this paper confirmed the importance of impact tests in determining the predicting the behaviour of welded joint regions in the presence of a crack, depending on its location within the welded joint itself.

Regarding fracture toughness, the highest values are obtained for BM than for HAZ and the lowest for WM, similar with the impact load and corresponding energies, with one significant difference: values for HAZ are now much closer to WM, indicating higher sensitivity of HAZ to static than to impact loading. If compared with separated energies, situation is somewhat different, since HAZ has somewhat better resistance to crack initiation than BM and WM but all values are in the narrow range, whereas BM and HAZ has significantly higher resistance to crack propagation. Therefore, similarity with fracture toughness is clear for crack initiation energy, but for crack propagation energy WM is significantly reduced, making it more sensitive to impact load than the other two zones. Good agreement between different zones for crack initiation energies and fracture toughness can be interpreted as a counteraction of two effects – crack vs notch and crack initiation vs. propagation, as also noticed in previous research with similar steel A 387 Gr. B, Čamagić, Sedmak A. et al. (2019), Čamagić, Marsenić et al. (2018). Finally, one should keep in mind that in all presented cases, both impact and fracture toughness values indicate high resistance to crack propagation, i.e. brittle fracture.

In the future work temperature effects will be analysed, as well as comparison with similar steel A 387 Gr. B, previously tested in the same way, with results presented in Čamagić, Vasić et al. (2106), Čamagić (2017), Čamagić, Arnđelović et al. (2018), Jovanović et al. (2020).

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