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Effect of Temperature and Chromium Content on Tensile and Fracture Mechanics Properties of Cr-Mo Steel Welded Joints †

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Abstract

Temperature and Cr content on the tensile and fracture mechanics properties of welded joints made of two Cr-Mo steels (A387 Gr. B and SA387 Gr. 91) are presented and analyzed. Tensile strength, yield stress and elongation, as well as the stress–strain curves are obtained by standard tensile tests using specimens extracted from welded joints. Fracture toughness testing was carried out to determine the critical stress intensity factor, K_{Ic}, and the critical crack length, a_c, for all three zones of the welded joint, parent metal (PM), heat-affected zone (HAZ) and weld metal (WM). Based on these results, the tensile and fracture mechanics properties of welded joints made of A387 Gr. B and SA387 Gr. 91 steels are compared and analyzed.

Keywords: welded joint; crack; tensile properties; fracture toughness; critical crack length

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1. Introduction

Two different Cr-Mo steels, A-387 Gr. B and SA-387 Gr. 91, are commonly used for components which operate at high temperatures and in corrosive environments. Due to their excellent mechanical properties, including welded joints, use of these steels enables significant material savings compared to conventional steels, especially in the case of SA-387 Gr. 91 [1]. However, the influence of the heterogeneity of the structure and the mechanical properties of their welded joints is still an issue, and has been addressed by many researchers [2–6], including recent contributions by the authors [7–9]. With respect to steel SA-387 Gr. 91 and its welded joints, most of the focus has been on strength and creep properties in relation to the steel's microstructure, especially in HAZ [2–6], including detailed study of the simulated heat-affected zone with an emphasis on microstructure and mechanical properties, as well as the effect of cracks. With respect to the previous research of the authors, the effect of temperature and time on tensile properties and fracture toughness was analyzed in [7,8] for welded joints made of A387 Gr. B, while the effects of material heterogeneity and temperature on impact toughness and fracture resistance of SA-387 Gr. 91 welded joints were analyzed in [9,10].

In this paper, the effects of temperature and Cr content on the tensile and fracture mechanics properties of PM, WM and HAZ were evaluated by testing at room and elevated temperature (540 °C for A-387 Gr. B and 575 °C for SA-387 Gr. 91).

2. Parent Material and Welded Joints

The two Cr-Mo steels used in this research were different in chemical composition, as shown in Tables 1 and 2.

Table 1. Chemical composition: A-387 Gr. B steel, weight %, [7].

Element	C	Si	Mn	P	S	Cr	Mo	Cu
Weight %	0.13	0.23	0.46	0.009	0.006	0.85	0.51	0.035

Table 2. Chemical composition: SA-387 Gr. 91 steel, weight %, [9].

Element	C	Si	Mn	P	S	Cr	Mo	Ni	V	Nb	Cu
Weight %	0.129	0.277	0.443	0.001	0.001	8.25	0.874	0.01	0.198	0.056	0.068

Welding of steel A-387 Gr. B was undertaken according to the following welding procedure:

- Root weld—manual metal-arc welding (MMAW) with coated electrode LINCOLN Sl 19G from Lincoln electric, Ohio, USA;
- Filler weld—submerged arc welding (SAW), with LINCOLN LNS 150 wire and LINCOLN P230 powder.

The U groove was used for a butt-welded joint, 15 mm thick, in accordance with the corresponding standard SRPS EN ISO 9692-2:2023 [11].

Welding of steel SA-387 Gr. 91 was undertaken according to the following welding procedure:

- Root weld—gas tungsten arc welding (GTAW) with BOEHLER C 9 MV-IG wire from Voestalpine Bohler welding, Pötschach, Austria, diameter 2.4 mm;
- Filler weld—MMAW, with BOEHLER FOX C9 MV electrode, diameter 2.5 and 3.2 mm.

All other welding details are given in [7] for A387 Gr. B and in [9] for SA387 Gr. 91.

3. Tensile Properties

Tensile testing of butt-welded joints is defined by the standard SRPS EN ISO 4136:2013, "Destructive testing of welded joints of metallic materials—Transverse tension testing" [12]. Tests were performed on specimens in Figure 1, using an electromechanical tensile testing machine in load control with a loading speed of 5 mm/min.

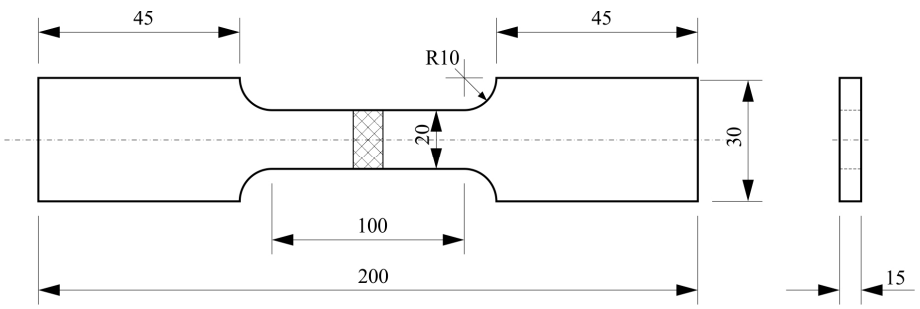


Figure 1. Specimen for tensile testing of welded joints.

Results for the steel A-387 Gr. B welded joint, tested by transverse tension at 20 °C and 540 °C, are shown in Table 3, whereas typical stress–strain curves are shown in Figures 2 and 3, respectively.

Table 3. Results of tensile tests of the welded joint with A-387 Gr. B.

Specimen Designation	Testing Temperature, °C	Yield Stress, $R_{p0.2}$, MPa	Tensile Strength, R_m, MPa	Elongation [1], A, %	Fracture Location
WJ-1-1	20	295	451	19.2	PM
WJ-1-2		285	448	20.4	PM
WJ-1-3		291	454	19.7	PM
WJ-2-1	540	217	293	26.3	PM
WJ-2-2		205	285	25.6	PM
WJ-2-3		211	287	26.9	PM

[1] measured at L_0 = 100 mm, as comparative value (not as a material property).

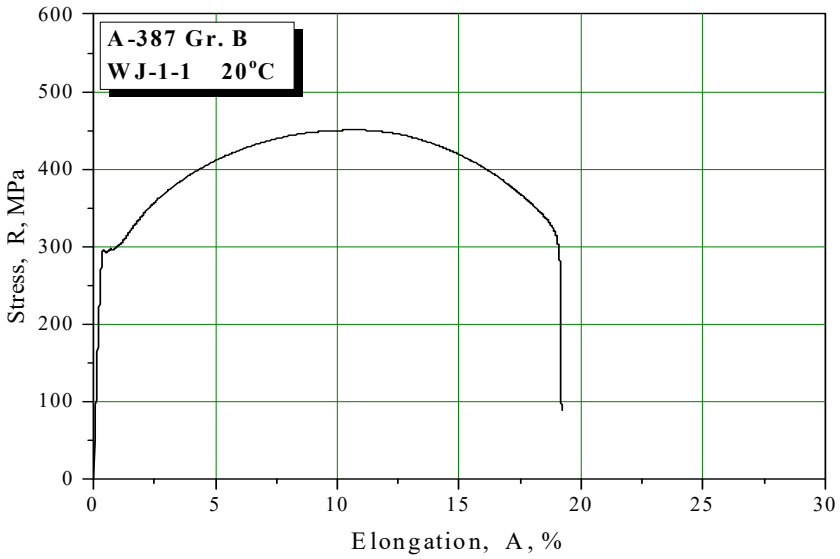


Figure 2. Stress–strain curve—specimen WJ-1-1 at 20 °C.

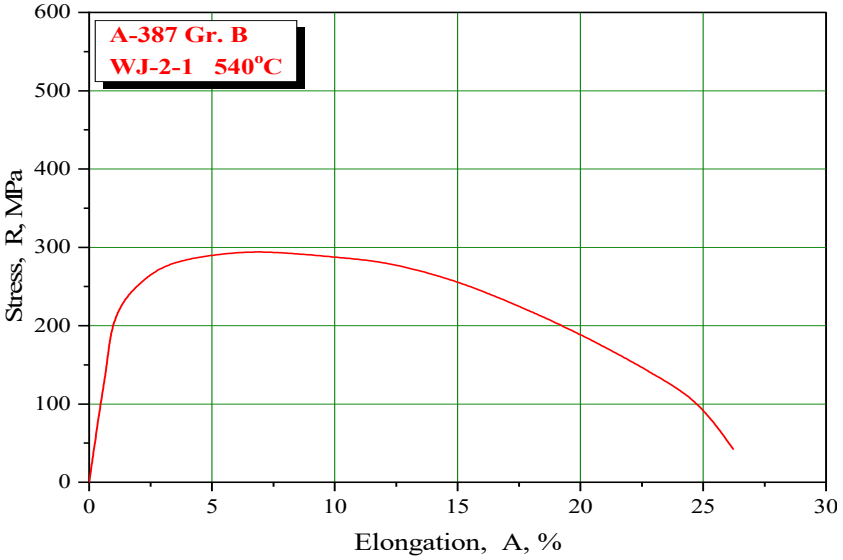


Figure 3. Stress–strain curve—specimen WJ-2-1 at 575 °C.

Results for the steel SA-387 Gr. 91 welded joint, tested by transverse tension at 20 °C and 575 °C, are shown in Table 4, whereas typical stress–strain curves are shown in Figures 4 and 5, respectively.

Table 4. Results of tensile tests of the welded joint with SA-387 Gr. 91.

Specimen Designation	Testing Temperature, °C	Yield Stress, $R_{p0.2}$, MPa	Tensile Strength, R_m, MPa	Elongation [1], A, %	Fracture Location
WJ-3-1	20	592	724	25.3	PM
WJ-3-2		601	725	22.6	PM
WJ-3-3		597	734	24.6	PM
WJ-4-1	575	319	333	18.2	PM
WJ-4-2		331	345	16.1	PM
WJ-4-3		328	338	14.9	PM

[1] measured at L_0 = 100 mm, as comparative value (not as a material property).

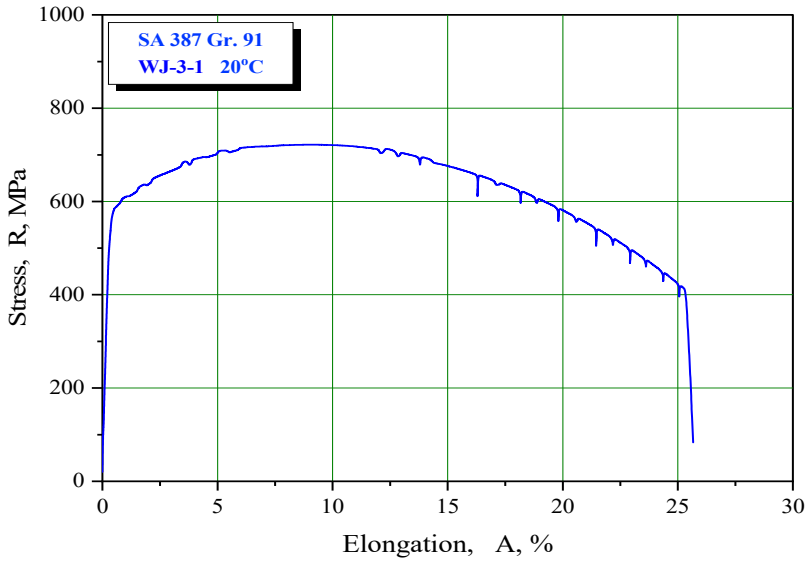


Figure 4. Stress–strain curve—specimen WJ-3-1 at 20 °C.

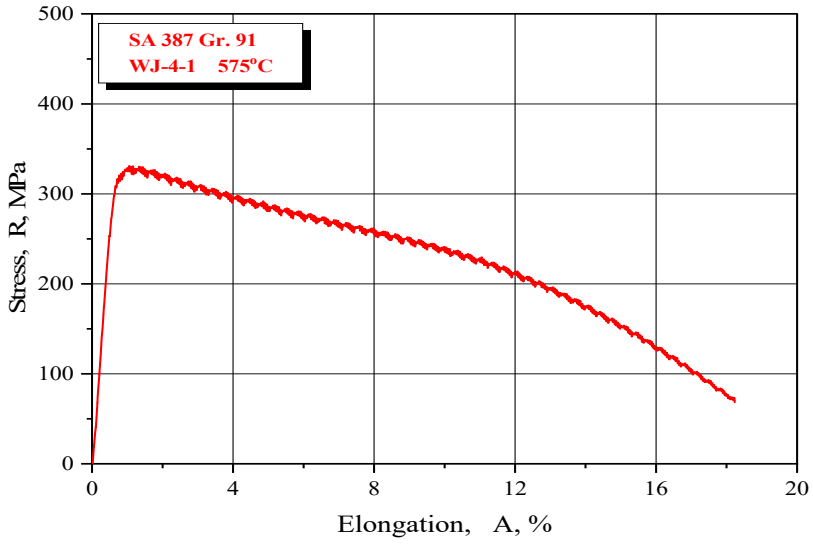


Figure 5. Stress–strain curve—specimen WJ-4-1 at 575 °C.

4. Fracture Mechanics Properties

Fracture toughness, K_{Ic}, was determined via the critical J-integral, J_{Ic}, using the procedure defined by standards ASTM E1820 [13] and BS 7448 Part 1 and 2 [14,15]. Three-point bending specimens (SEB) were used for testing at 20 °C, while modified CT specimens were used for testing at high temperatures; a single specimen technique was used in all cases, as shown in Figure 6a. To determine J_{Ic} values, the regression line was constructed on J-Δa curves as shown in Figure 6b. Knowing J_{Ic} values, the fracture toughness, K_{Ic}, was calculated using:

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

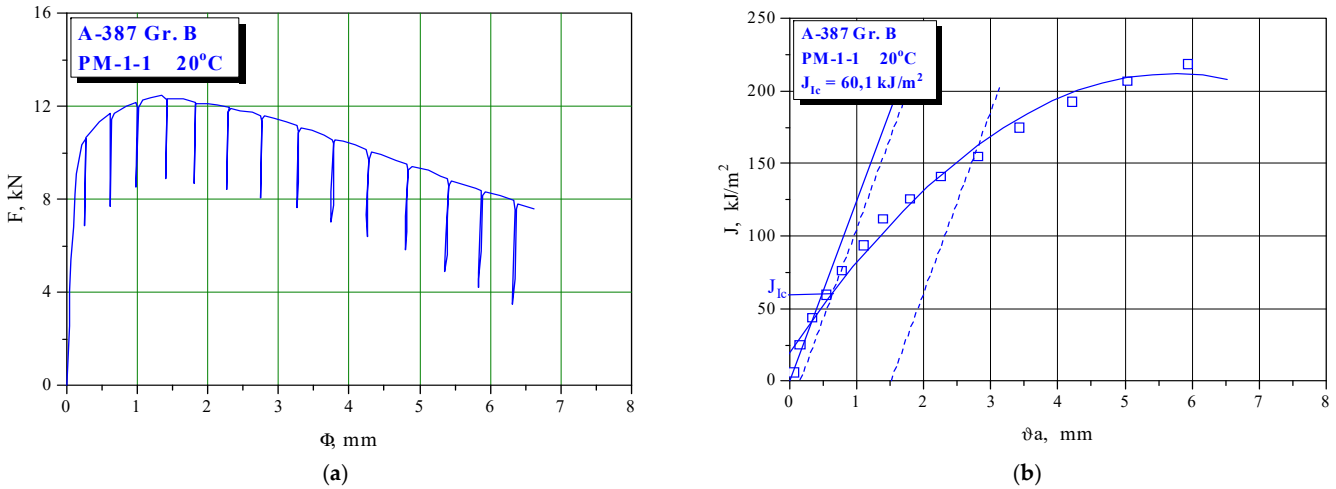


Figure 6. Diagrams of F-δ (**a**) and J-Δa (**b**)—specimen PM-1-1, [7].

Modulus of elasticity at room temperature was 210 GPa, 160 GPa at 540 °C and 175 GPa for 575 °C. The critical crack length, a_c, was calculated using the following formula:

$$K_{Ic} = \sigma \cdot \sqrt{\pi \cdot a_c} \quad (2)$$

where the yield stress, $R_{p0.2}$, was used as the relevant value for the stress σ.

The values of the critical stress intensity factor, K_{Ic}, and the critical crack length, a_c, are given in Tables 5–7 for PM, WM and HAZ, respectively, tested at 20 C and 540 °C (A-387 Gr. B).

Table 5. Values of K_{Ic} and a_c specimens with a notch in PM A-387 Gr. B.

Specimen Mark	Temperature, °C	J_{Ic}, kJ/m^2	K_{Ic}, MPa·m$^{1/2}$	a_c, mm
PM-1-1	20	60.1	117.8	38.5
PM-1-2		63.9	121.4	40.8
PM-1-3		58.6	116.3	37.5
PM-2-1	540	43.2	87.2	40.0
PM-2-2		44.7	88.7	41.4
PM-2-3		45.3	89.2	41.9

Table 6. Values of K_{Ic} and a_c specimens with a notch in WM A-387 Gr. B.

Specimen Mark	Temperature, °C	J_{Ic}, kJ/m^2	K_{Ic}, MPa·m$^{1/2}$	a_c, mm
WM-1-1	20	72.8	129.6	20.2
WM-1-2		74.3	130.9	20.7
WM-1-3		71.1	128.1	19.8
WM-2-1	540	50.2	93.9	17.4
WM-2-2		52.6	96.2	18.2
WM-2-3		48.4	92.2	16.8

Table 7. Values of K_{Ic} and a_c specimens with a notch in HAZ A-387 Gr. B.

Specimen Mark	Temperature, °C	J_{Ic}, kJ/m^2	K_{Ic}, MPa·m$^{1/2}$	a_c, mm
HAZ-1-1	**20**	53.6	111.2	34.3
HAZ-1-2		51.7	109.2	33.0
HAZ-1-3		49.8	107.2	31.8
HAZ-2-1	**540**	33.6	76.9	31.1
HAZ-2-2		34.2	77.5	31.6
HAZ-2-3		36.1	79.7	33.4

The effect of temperature on the critical crack length, a_c, is shown in Figures 7–9 for PM, WM and HAZ, respectively.

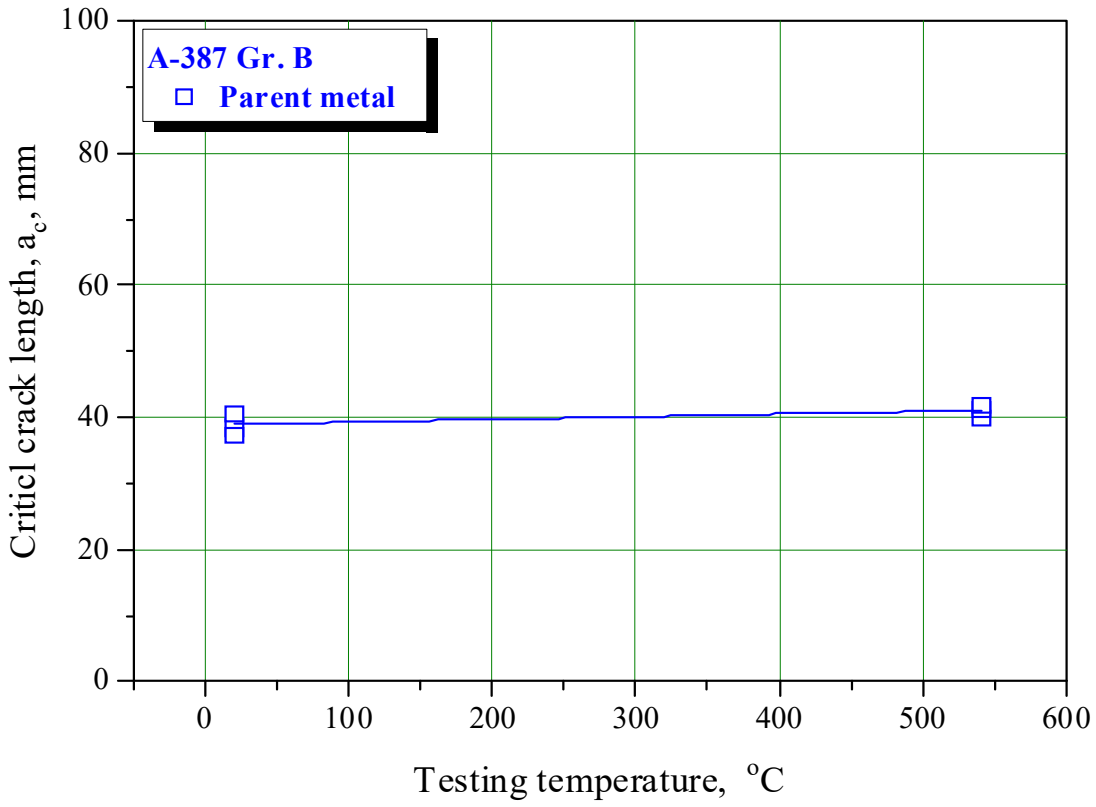


Figure 7. Dependence of the a_c value on the test temperature—PM.

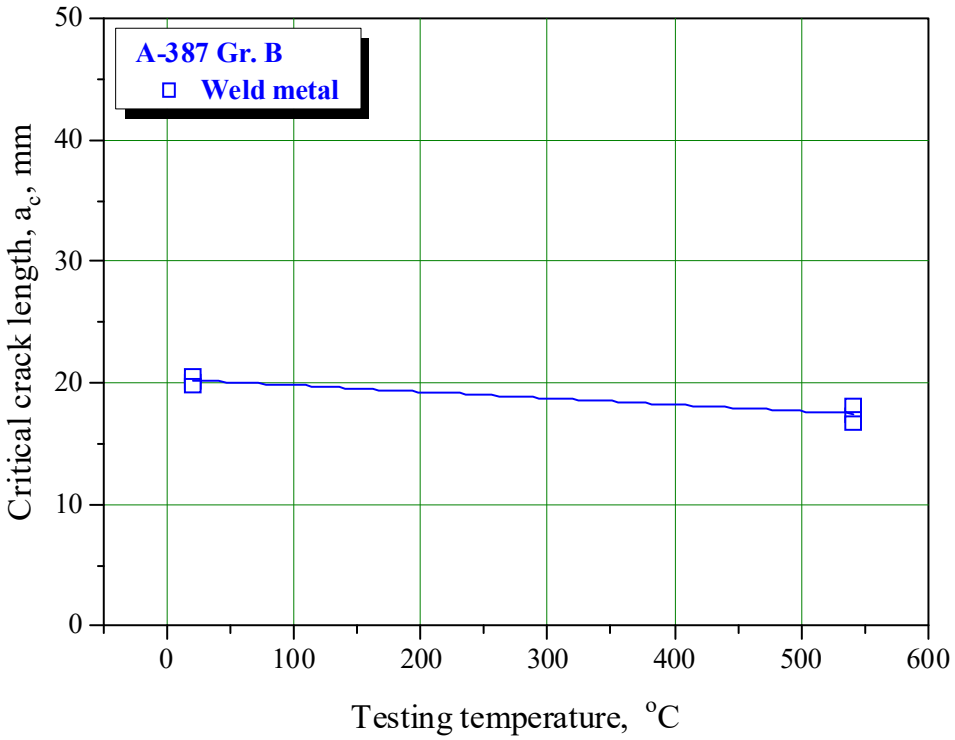


Figure 8. Dependence of the a_c value on the test temperature—WM.

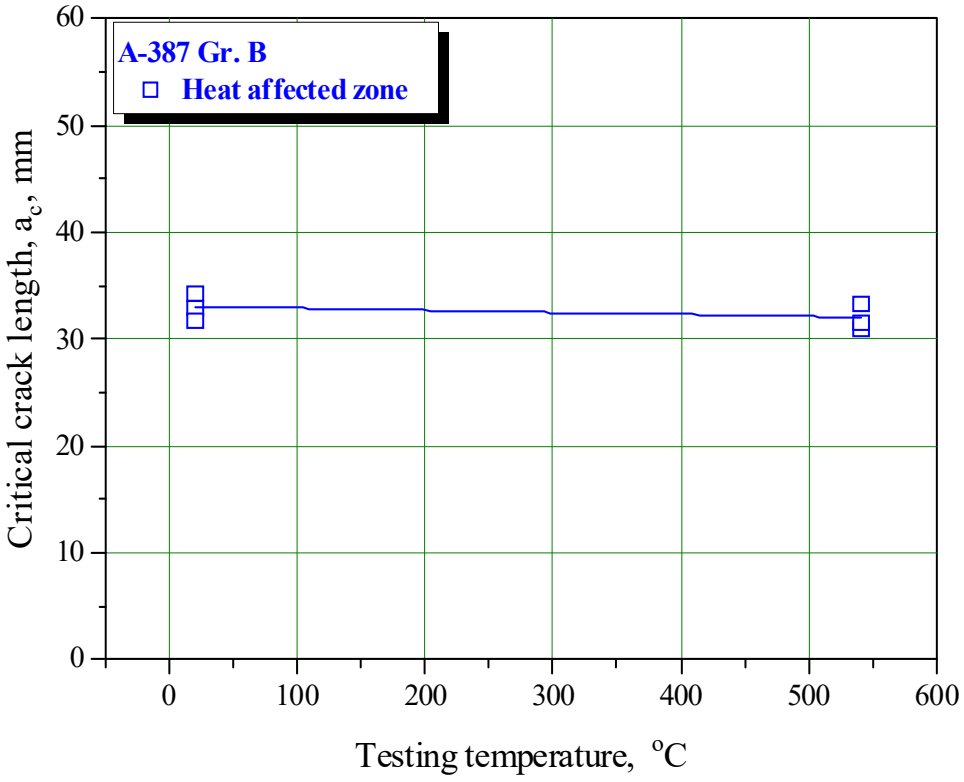


Figure 9. Dependence of the a_c value on the test temperature—HAZ.

The values of the critical stress intensity factor, K_{Ic}, and the critical crack length, a_c, are given in Tables 8–10 for PM, WM and HAZ, respectively, tested at 20 °C and 575 °C (SA-387 Gr. 91).

Table 8. Values of K_{Ic} and a_c specimens with a notch in PM SA-387 Gr. 91.

Specimen Mark	Temperature, °C	J_{Ic}, kJ/m^2	K_{Ic}, MPa·m$^{1/2}$	a_c, mm
PM-3-1	20	131.1	173.9	27.0
PM-3-2		144.2	182.4	29.7
PM-3-3		124.0	169.2	25.6
PM-4-1	575	78.5	122.9	45.3
PM-4-2		80.9	124.7	46.6
PM-4-3		81.9	125.5	47.2

Table 9. Values of K_{Ic} and a_c specimens with a notch in WM SA-387 Gr. 91.

Specimen Mark	Temperature, °C	J_{Ic}, kJ/m^2	K_{Ic}, MPa·m$^{1/2}$	a_c, mm
WM-3-1	20	71.6	128.5	14.8
WM-3-2		64.8	122.3	13.4
WM-3-3		69.2	126.4	14.3
WM-4-1	575	51.2	99.2	29.5
WM-4-2		40.1	87.8	23.1
WM-4-3		38.6	86.2	22.3

Table 10. Values of K_{Ic} and a_c specimens with a notch in HAZ SA-387 Gr. 91.

Specimen Mark	Temperature, °C	J_{Ic}, kJ/m^2	K_{Ic}, MPa·m$^{1/2}$	a_c, mm
HAZ-3-1	20	97.6	150.1	20.1
HAZ-3-2		88.9	143.2	18.3
HAZ-3-3		92.1	145.8	19.0
HAZ-4-1	575	65.3	112.1	37.7
HAZ-4-2		61.6	108.8	35.5
HAZ-4-3		68.5	114.8	39.5

The characteristic diagrams *F-δ* and *J-Δa* for the specimen taken from the WM are shown in Figure 10 for the WM-4-1 specimen tested at a temperature of 575 °C.

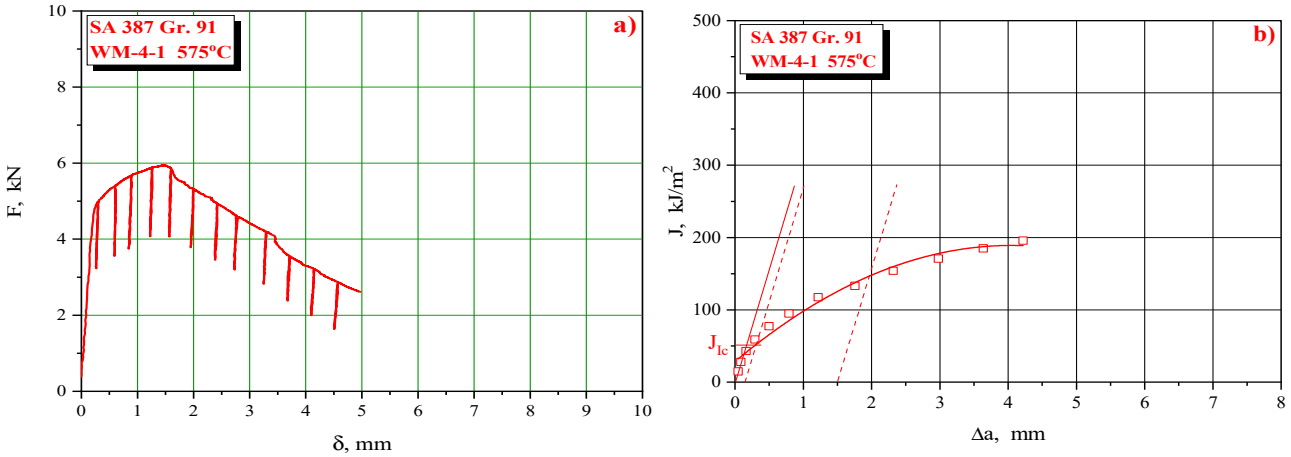


Figure 10. Diagrams of F-δ (**a**) and J-Δa (**b**)—specimen WM-4-1.

The effect of the test temperature on the value of the critical crack length, a_c, is shown graphically in Figures 11–13 for PM, WM and HAZ, respectively.

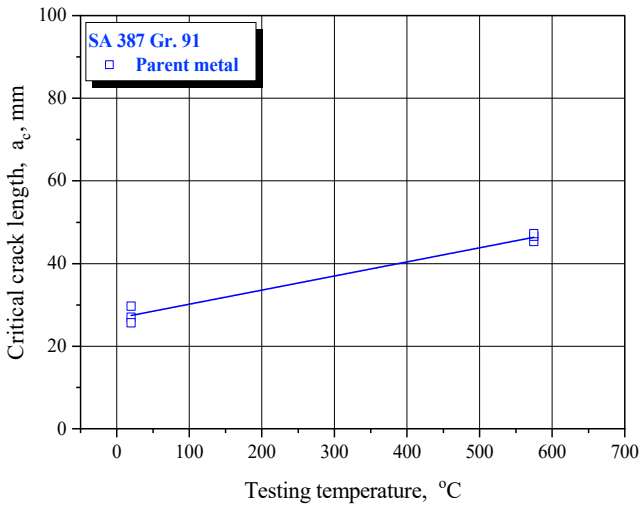


Figure 11. Dependence of the ac value on the test temperature—PM.

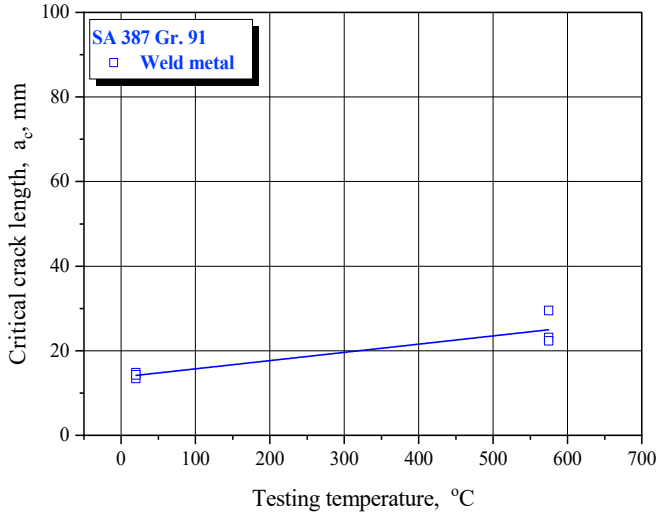


Figure 12. Dependence of the ac value on the test temperature—WM.

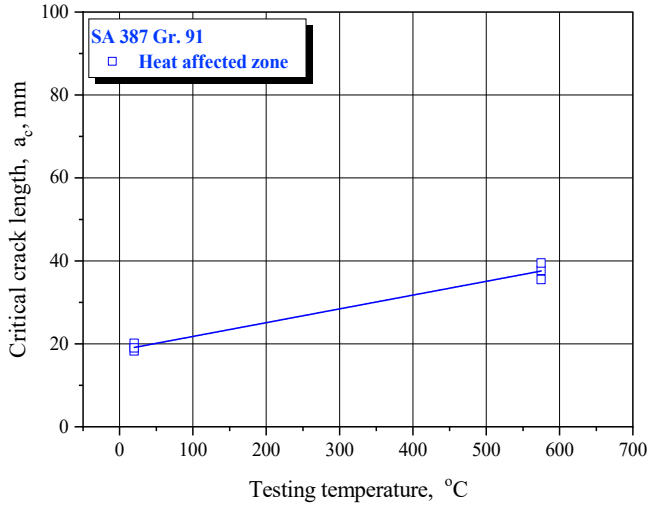


Figure 13. Dependence of the ac value on the test temperature—HAZ.

5. Discussion

5.1. Steel A-387 Gr. B

Yield stress values obtained by transverse tensioning of the butt-welded specimens range from 290 MPa at 20 °C, and decrease to 211 MPa at a temperature of 540 °C, while the tensile strength values also decrease from 451 MPa obtained at 20 °C to 288 MPa obtained by testing at 540 °C. Elongation increases with increasing test temperature, and ranges from 19.8% at 20 °C to approximately 26.3% at 540 °C.

The PM fracture toughness values range from 118 MPa·m$^{1/2}$ at 20 °C to 88 MPa·m$^{1/2}$ at 540 °C [7]. The obtained values of the critical crack length, a_c, in PM are almost the same when compared at room and elevated temperature.

The WM fracture toughness values range from 130 MPa·m$^{1/2}$ at 20 °C to 94 MPa·m$^{1/2}$ at 540 °C [7]. The obtained values of the critical crack length, a_c, in relation to the yield stress level start from 20.2 mm at room temperature and fall to 17.5 mm, at a temperature of 540 °C.

The HAZ fracture toughness values range from 109 MPa·m$^{1/2}$ at 20 °C, to 78 MPa·m$^{1/2}$ at 540 °C [7]. The obtained values of the critical crack length, a_c, at HAZ change slightly from room to elevated temperature.

5.2. Steel SA-387 Gr. 91

Values of the yield stress, obtained by transverse tensioning of the butt-welded specimens, range from 597 MPa at 20 °C, and decrease to 326 MPa at a temperature of 575 °C, while the tensile strength values also decrease from 728 MPa at 20 °C to 339 MPa at 575 °C. Elongation decreases with increasing test temperature, and ranges from 24.2% at 20 °C to approximately 16.4% at 575 °C.

The PM fracture toughness values range from 175 MPa·m$^{1/2}$ at 20 °C to 124 MPa·m$^{1/2}$ at 575 °C [9]. The critical crack length, a_c, increases with increasing temperature. The obtained values of the critical crack length, a_c, for PM range from 27 mm at 20 °C to 46 mm at 575 °C.

The WM fracture toughness ranges from 126 MPa·m$^{1/2}$ at 20 °C to 91 MPa·m$^{1/2}$ at 575 °C [9]. The critical crack length, a_c, as with PM, increases with increasing temperature. The obtained values of the critical crack length, a_c, for WM range from 14 mm at 20 °C to 25 mm at 575 °C.

The HAZ fracture toughness values range from 146 MPa·m$^{1/2}$ at 20 °C to 112 MPa·m$^{1/2}$ at 575 °C [9]. The critical crack length, a_c, as with PM and WM, increases with increasing temperature. The obtained values of the critical crack length, a_c, at HAZ range from 19 mm at 20 °C to 38 mm at 575 °C.

5.3. General

Analyzing the results of the butt-welded specimen tensile testing, it can be seen that with an increase in the test temperature, there is a decrease in the value of yield stress and tensile strength (for both welded joints), an increase in elongation in the welded joint of steel A-387 Gr. B and elongation reduction in the welded joint of steel SA-387 Gr. 91. All the specimens failed in the PM (at both welded joints), which gave us the tensile characteristics of the PM.

The shape of the obtained tensile curves at room temperature corresponds to a ductile material with an approximate share of homogeneous and inhomogeneous elongation in the ratio 1/2:1/2, where homogeneous elongation refers to elongation up to the maximum force, and inhomogeneous elongation is the elongation from the maximum force to failure. When testing the tubes of the welded joint at elevated temperature, we observed that the

ratio of homogeneous and inhomogeneous elongation was less favorable (more pronounced in the welded joint of steel SA-387 Gr. 91) from the perspective of exploitation properties.

6. Conclusions

Based on the obtained test results of the specimens taken from PM, WM and HAZ, it can be seen that, with the increase in test temperature, there is a decrease in the value of the critical J_{Ic} integral, i.e., the fracture toughness K_{Ic}. Likewise, the value of the critical crack length, a_c, also decreases or changes slightly in the welded joint of steel A-387 Gr. B and increases in the welded joint of steel SA-387 Gr. 91. The weakest resistance to crack growth under static force, i.e., the lowest value of K_{Ic}, is for the specimens with a notch in HAZ, and the best resistance to crack development is for the specimens with a notch in WM at the welded joint of steel A-387 Gr. B. At the welded joint of steel SA-387 Gr. 91, the weakest resistance to crack development under static force, i.e., the lowest value of K_{Ic}, is for the specimens with a notch in WM, and the best resistance to crack development is for the specimens with a notch in PM. The highest values of the critical crack length, a_c, were obtained for the specimens with a notch in PM, and the lowest for the specimens with a notch in WM.

The effect of chromium content is beneficial for the tensile properties, except for the elongation at an increased temperature, as well as for the fracture toughness. The latter is significant in the case of the PM and HAZ, whereas almost the same values can be observed for the WM. This indicates potential problems with the use of SA-387 Gr. 91, although the obtained values of K_{Ic} are relatively high.

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