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INVESTIGATION OF S960QL TYPE HIGH STRENGTH STEEL AND ITS WELDED JOINTS APPLYING ABSORBED SPECIFIC FRACTURE ENERGY AND NOTCH OPENING DISPLACEMENT

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Abstract: Classical techniques of fracture toughness evaluation, such as determination of the plain-strain fracture toughness, or the critical value of the crack-tip opening displacement are complex methods. The determination of the absorbed specific fracture energy and the notch opening displacement is basically simpler; notched cylindrical tensile specimens characterized by different notch radii can be applied. S960QL type high strength steel and its welded joints without and with preheating were examined; notch opening displacement and absorbed specific fracture energy values were determined. Conclusions belong to the effect of the preheating and the sensitivity of the high strength steel, as well as the reliability of the applied material characteristics were drawn.

Keywords: *high strength steel, cold cracking, notch opening displacement, absorbed specific fracture energy*

1. INTRODUCTION

The most commonly used structural material for the construction of engineering structures is (structural or low alloyed) steel, and the most widely used manufacturing technology is welding. Nowadays, steel producers develop modern versions of high strength base materials and filler metals with yield strength start from 690 MPa and up. However, high strength lightweight structures with low cost of steel weldments lead to apply in many practical aspects (e.g. mobile cranes, hydropower plants, offshore structures, trucks, earthmoving machines, and drums), because of an extensive reduction in weight [1].

The welded joints are sensitive parts of structures because the welded regions are in complex metallurgical state and stress condition. Before the Second World War, the design of all engineering structures was based on yield/tensile strength and ductility. Mild steel was used as the structural material and the minimum yield strength of the weld metal was found to be around 340 MPa. The yield strength to tensile strength ratio (Y/T) of the weld metals that were used for welding the mild steel in early designs was very high and the designers did not pay much attention to the yield strength of the weld metals. It has been reported that the maximum yield strength of the filler metal that has been used for joining the mild steel plates was about 59% higher than the base material [2].

During the welding process, the joining parts are affected by heat and force, which cause inhomogeneous microstructure and mechanical properties, and furthermore, stress concentrator places can form. Both the inhomogeneity of the welded joints and the weld imperfections play important role in case of different loading conditions. High cycle fatigue and fatigue crack growth phenomena are a very common problem in welded structures [3], together cold cracking sensitivity, especially in high strength steels.

Classical techniques of fracture toughness evaluation, such as determination of the plain-strain fracture toughness (K_{Ic}), or the critical value of the crack(-tip) opening displacement (C(T)OD) are complex methods [4, 5]. The necessity of fracture mechanical test is inevitable, applying notched and precracked specimens [6]. The determination of the notch opening displacement (NOD) and/or the absorbed specific fracture energy (ASPEF = W_c) is basically simpler; notched cylindrical tensile specimens can be applied, characterized by different notch radii.

The aims of our article are to introduce the notch opening displacement and the absorbed specific fracture energy quantities, and their application possibility at welding of high strength steel and its welded joints.

2. Background

It can be assumed that the ASPEF is the work of all external forces in an infinitesimal element in the crack point which is necessary for the propagation of crack. Thus the total energy is equal to the sum of energy of elastic deformation, energy of plastic deformation, and energy of crack propagation (formation of new fracture surface). The energy of elastic deformation will be released after the rupture; furthermore, the surface energy is negligible compared to the energy of plastic deformation. If we refer the energy of plastic deformation to the absorbing volume (V), we get a physically correct value. The ASPEF defined by the previous way can be determined applying tensile tests [7–9] (see *Figure 1* [10]), and can be calculated using *Equation (1)*:

$$W_c = \int_{l_0}^{l_u} \frac{Fdl}{V} = \int_0^{\varphi_u} \sigma d\varphi \,. \tag{1}$$

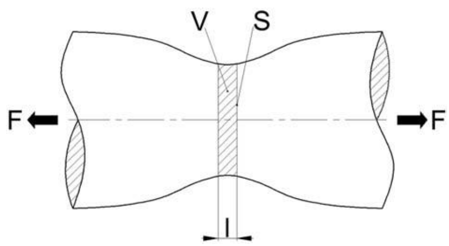

Figure 1. *Characteristics of the un-notched and notched specimens* [10]

Figure 2 [10] shows a stress concentration place, in other words a notch, which can be considered a crack, if the notch radius is sufficiently small. Applying tensile stress, a plastic zone will formed in the root of the notch, in which considerable energy can be absorbed. The length (L) of the fictive tensile specimen is equal to the width of the plastic zone, and this length depends on the material characteristics and the sharpness of the notch. If we have crack the length value will be minimum, furthermore, the absorbed energy will be minimum, too. Regarding to the strain, the elongation (ΔL) depends on the material characteristics and the length (L), accordingly if we have crack the elongation will be minimum. This minimum value should be equal to the COD value. Both minimum values can be determined by indirect methods [11, 12].

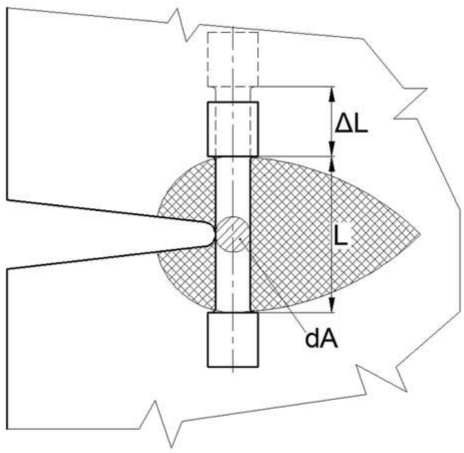

Figure 2

Stress concentration place with its plastic zone and fictive tensile specimen [10]

3. INVESTIGATIONS AND THEIR RESULTS

3.1. Preparation of welded joints

S960QL type, quenched and tempered high strength steel (produced by Thyssen Stahl AG and designated as XABO 960) was applied for our experiments. The chemical composition and the mechanical properties of the 15 mm thick base material plate can be found in *Table 1* and *Table 2*, respectively.

Table 1

Chemical composition of the used base material based on manufacturer certification (in weight%)

C	Si	Mn	P	S	Al	Cr	Mo	Ni	V
0.17	0.28	0.7	0.01	0.001	0.031	0.62	0.37	1.69	0.05

Table 2
Basic mechanical properties of the used base material based on manufacturer certification

Yield strength, R_{eH}, MPa	**Tensile strength, R_m, MPa**	**Elon-gation, A, %**	**Charpy impact energy, KV, J**				
			Testing temperature, °C	**No1**	**No2**	**No3**	**Aver-age**
1,003	1,077	15	–40°C	29	27	31	29
			–60°C	22	20	19	20

The dimensions of the welded workpieces were 600 mm x 125 mm. V joint shape was used, with 60° opening angle, with 2 mm gap between the two plates (root opening), and with 1 mm root face. The welding equipment was a MIG/MAG power source; 1.2 mm diameter solid wires in Union X96 (Böhler) types, and 18% CO_2 + 82% Ar gas mixture (M21) were applied. The welding position was flat position (PA).

Two welded joints were prepared, the first one without preheating, and the second one with preheating. Based on the chemical composition of the base material, the type of butt welded joint, and the applied welding process, the calculated preheating temperature was T_{pre} = 106 °C. Accordingly to the recommendation of the base material manufacturer, higher preheating temperature was selected, which was T_{pre} = 150 °C. It should be noted that during the preparation of the welded joint without preheating, the interpass temperature was less than T_{ip} = 50 °C. The welding technological parameters are summarized in *Table 3*. The table shows the welding current (I), the voltage (U), the wire-feed speed (v_{wire}) and the welding speed (v_w) values, with the heat input (Q). The parameters of the root and the filler layers were shown separately.

Table 3
The applied welding parameters during our experiments

Layer(s)	**I, A**	**U, V**	**v_{wire}, m/min**	**v_w, mm/s**	**Q, kJ/mm**
1 root	100–120	21–22	3.1–3.5	3.6–4.1	0.49–0.54
2–5 filler	240–275	29–31	10	9.2–13.0	0.49–0.72
6–10 filler	275–280	30–31	10	7.7–9.7	0.72–0.93

3.2. Basic investigation of welded joints

Welding procedure tests were accomplished on both welded joints; the detailed results of the non-destructive and mechanical tests can be found in *Table 4*.

Table 4

Detailed results of the executed non-destructive and mechanical tests

Testing method	**Welded joint without preheating**	**Welded joint with preheating (150 °C)**
Visual testing (VT)	sufficient	sufficient
Magnetic particle testing (MT)	sufficient	sufficient
Ultrasonic testing (UT)	sufficient	sufficient
Tensile strength, R_m, MPa	1,011–1,037	1,013–1,047
Bending strain using non-standardized method with more rigorous criteria, %	38.1–38.3	38.2–38.4
Charpy impact energy in the weld metal at –40 °C, KV, J	48 (45–53)	51 (45–57)
Charpy impact energy in the heat affected zone at –40 °C, KV, J	54 (46–60)	63 (51–79)
Hardness, HV10	383–421	383–464

Comparing the results of the welded joints without preheating and with preheating, as well as the comparable results of the base material and the welded joints, it can be drawn that there are no significant differences between the results.

3.3. NOD and ASPEF investigations

Cylindrical notched specimens with different notch radii (R) were prepared to perform tensile tests. The different notch radii represent different stress concentration factors (K_t). *Figure 3* shows the characteristics of the un-notched and the notched specimens, where the diameter of the tested length of the un-notched specimens (d_0) and the minimum diameter of the notched specimens at the notches (d_0) were the same. The larger diameter (D_0) of the notched specimens was the same, too.

Figure 3

Characteristics of the un-notched and notched specimens

Stress concentration factor (K_t) values were specified using a web calculator [13] developed based on formulas for stress and strain [14] and were controlled based on the well-known classical handbook [15]. The data belong to the specimens are summarized in *Table 5*.

Table 5

Characteristic data of the applied specimens

D_0, mm	d_0, mm	R, mm	d_0/D_0, –	R/D_0. –	K_t, –
N/A	4	∞	N/A	N/A	1
6	4	1	0.667	0.167	1.67
		0.5		0.083	2.12
		0.3		0.050	2.60
		0.2		0.033	3.07
		0.1		0.017	4.15

Notch Opening Displacement (NOD) investigations

Specimens cut from base material and welded joints without preheating and with preheating (150 °C) were investigated. The notch locations of the specimens cut from welded joints were different, namely located in the weld metal, or in the heat affected zone, or in the boundary of the joint parts. These different positions allowed a statistical evaluation of the properties of the welded joints.

To determine the notch opening displacement (NOD) values of the specimens, the contour lines of all different notch radii were projected before the tensile tests. After the tests, in other words after the rupture, the two broken parts of all specimens were fitted carefully and the changed contour lines were projected again. Using the differences between the two contour lines, the NOD values were determined. *Table 6* summarizes the results, the determined NOD values.

Table 6

The determined notch opening displacement (NOD) values (in mm)

R, mm	Base material	Welded joint without preheating	Welded joint with preheating (150 °C)
1	0.35	0.72	N/A
	0.50	0.66	N/A
	0.35	0.52	N/A
0.5	N/A	N/A	0.57
	N/A	N/A	0.42
	N/A	N/A	0.42
0.3	N/A	N/A	0.29
0.2	0.29	0.25	0.25
	0.28	0.31	0.28
	0.36	0.31	N/A
0.1	0.29	0.22	0.18
	0.22	0.36	0.17
	0.15	0.26	0.13

Based on the previously summarized theoretical background, there is a connection between the notch opening displacement (NOD) and the notch radius (R) values; and the value of the function at R = 0 (at crack) is equal to the crack opening displacement (COD), as follows:

$$NOD = kR + NOD_{R=0} = kR + COD \,. \tag{2}$$

Figure 4 shows the measured values and the regression lines using the Least Squares Fitting (LSF) method, taking into account all measured data can be found in *Table 6*.

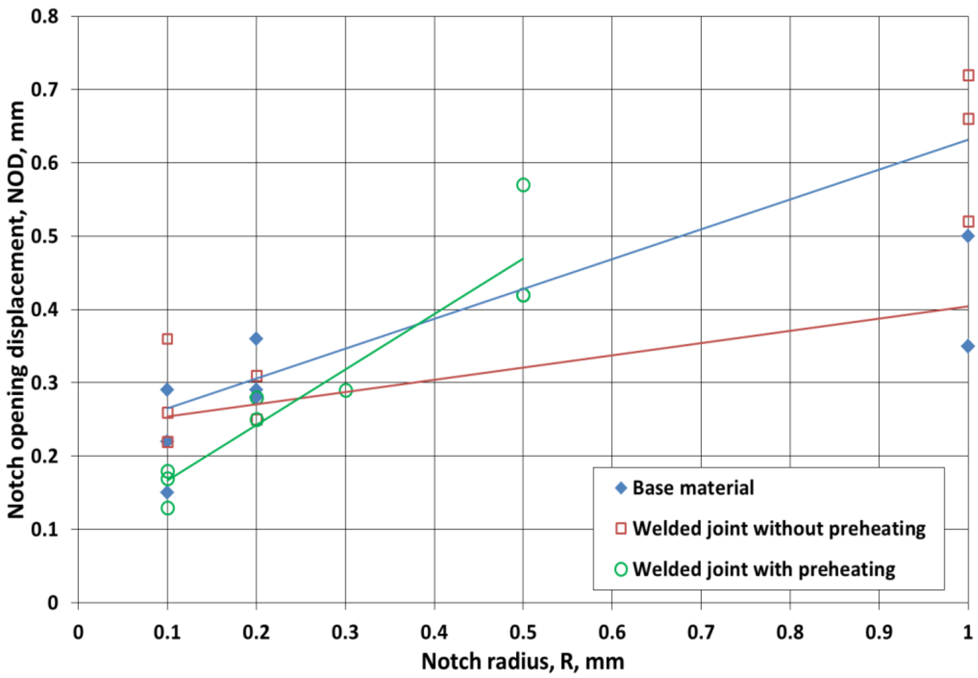

Figure 4
The NOD – R functions taking into account all measured data

Because the measured notch opening displacement (NOD) values belong to different notch radii (R) in the three main groups (base material and welded joints), and there are different number of specimens at notch radii, mathematical-statistical values of the samples (NOD values at notch radius) were calculated. Using the average NOD values, NOD – R functions were imaged. The calculated average, standard deviation (STD) and standard deviation coefficient values can be found in *Table 7*, and the NOD – R functions taking into account the average values of the measured data can be seen in *Figure 5*.

Table 7

The main statistical parameters of the investigated NOD samples

R, mm	Statistical parameter	Base material	Welded joint without preheating	Welded joint with preheating (150 °C)
1	Average	0.400	0.633	N/A
	STD	0.087	0.103	N/A
	STD coefficient	0.217	0.162	N/A
0.5	Average	N/A	N/A	0.470
	STD	N/A	N/A	0.087
	STD coefficient	N/A	N/A	0.184
0.3	N/A	N/A	N/A	N/A
0.2	Average	0.310	0.290	0.265
	STD	0.044	0.035	N/A
	STD coefficient	0.141	0.119	N/A
0.1	Average	0.220	0.280	0.160
	STD	0.070	0.072	0.026
	STD coefficient	0.318	0.258	0.165

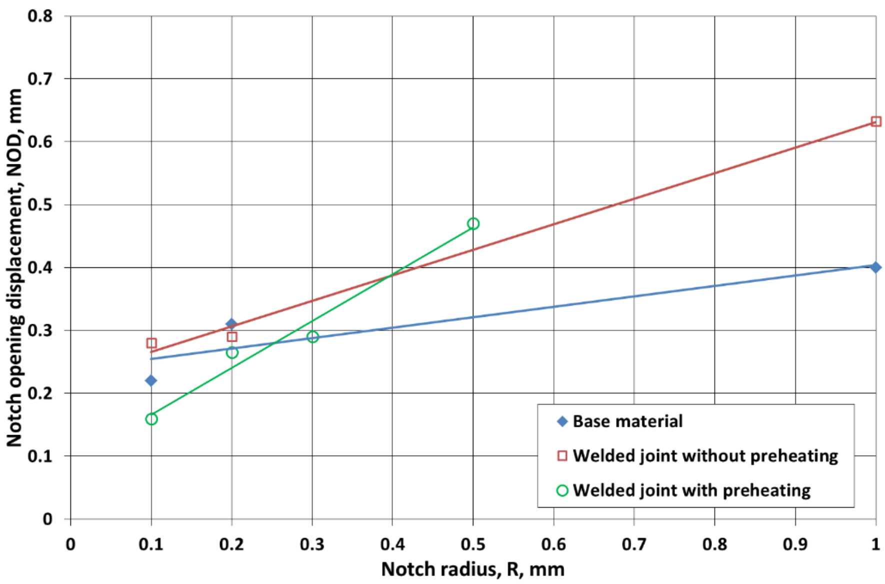

Figure 5

The NOD – R functions taking into account the average values of the measured data

Table 8 summarizes the calculated slope (k), COD ($NOD_{R=0}$) and correlation coefficient values of the approximated straight lines of the three groups, belonging to both all data and average values.

Table 8

The regression parameters of the NOD – R functions and the correlation coefficient values

Group	Material / welded joint	k	$NOD_{R=0}$ = COD, mm	Correlation coefficient
All data	Base material	0.407	0.225	0.9354
	Welded joint without preheating	0.166	0.238	0.7238
	Welded joint with preheating (150 °C)	0.756	0.091	0.9413
Average value	Base material	0.166	0.238	0.9122
	Welded joint without preheating	0.406	0.225	0.9970
	Welded joint with preheating (150 °C)	0.744	0.092	0.9869

Correlation coefficient values demonstrate clearly that using the average values the results are more reliable than using all data.

Absorbed Specific Fracture Energy (ASPEF) investigations

The absorbed specific fracture energy values (W_c) were calculated using the load – extension diagrams and the geometrical features of the specimens. Tensile strength (R_m) and fracture strength (R'_u) values were calculated based on the appropriate loads (F_m and F_u, respectively) and specimen diameters (d_0 and d_u, respectively), where the following equation was applied:

$$W_c = \left(\frac{R_m + R'_u}{2}\right) 2ln\left(\frac{d_0}{d_u}\right). \quad (3)$$

Table 9 summarizes the results, the determined W_c values, furthermore, the calculated statistical parameters can be found in *Table 10*.

Table 9

The determined absorbed specific fracture energy (W_c) values (in MJ/m^3)

R, mm	K_t, –	Base material	Welded joint without preheating	Welded joint with preheating (150 °C)
∞	1	2,210	871	1,598
		2,243	1,513	1,573
		2,232	1,352	1,636
1	1.67	505	673	N/A
		753	747	N/A

R, mm	K_t, –	Base material	Welded joint without preheating	Welded joint with preheating (150 °C)
		450	586	N/A
0.5	2.12	N/A	N/A	681
		N/A	N/A	621
		N/A	N/A	636
0.3	2.60	N/A	N/A	467
0.2	3.07	462	293	281
		396	253	346
		338	281	N/A
0.1	4.15	319	269	158
		319	216	246
		241	325	124

Table 10

The main statistical parameters of the investigated W_c samples

R, mm	Statistical parameter	Base material	Welded joint without preheating	Welded joint with preheating (150 °C)
∞	Average	2,228	1,245	1,602
	STD	16.8	334.0	31.7
	STD coefficient	0.0075	0.2682	0.0198
1	Average	569	669	N/A
	STD	161.4	80.6	N/A
	STD coefficient	0.2835	0.1205	N/A
0.5	Average	N/A	N/A	646
	STD	N/A	N/A	31.2
	STD coefficient	N/A	N/A	0.0483
0.3	N/A	N/A	N/A	N/A
0.2	Average	399	276	314
	STD	62.0	20.5	N/A
	STD coefficient	0.1556	0.0745	N/A
0.1	Average	293	270	176
	STD	45.0	54.5	63.0
	STD coefficient	0.1537	0.2019	0.3577

For analogous reasons to those described under the NOD investigations, both all W_c data and average W_c data were illustrated in *Figure 6* and *Figure 7*, respectively.

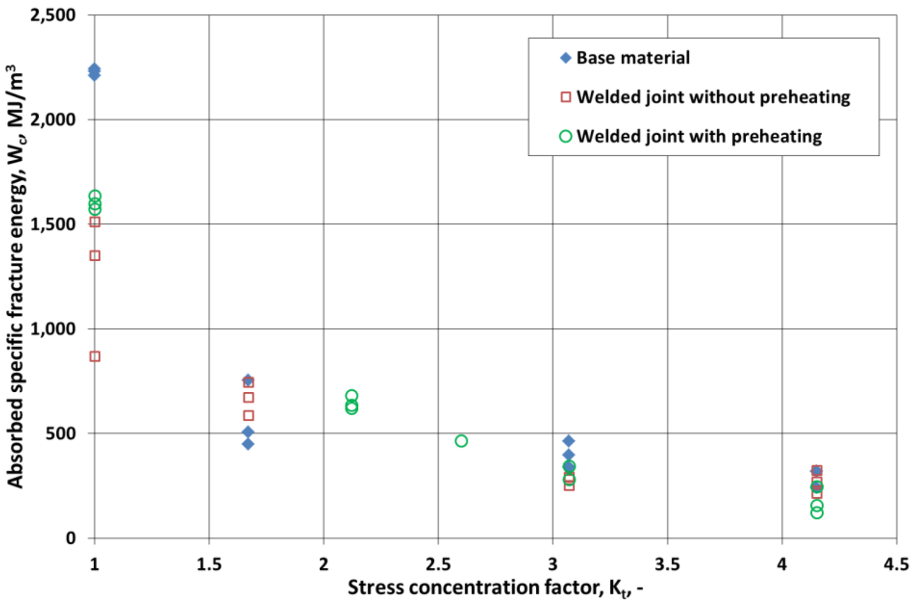

Figure 6

The $W_c - K_t$ functions taking into account all measured data

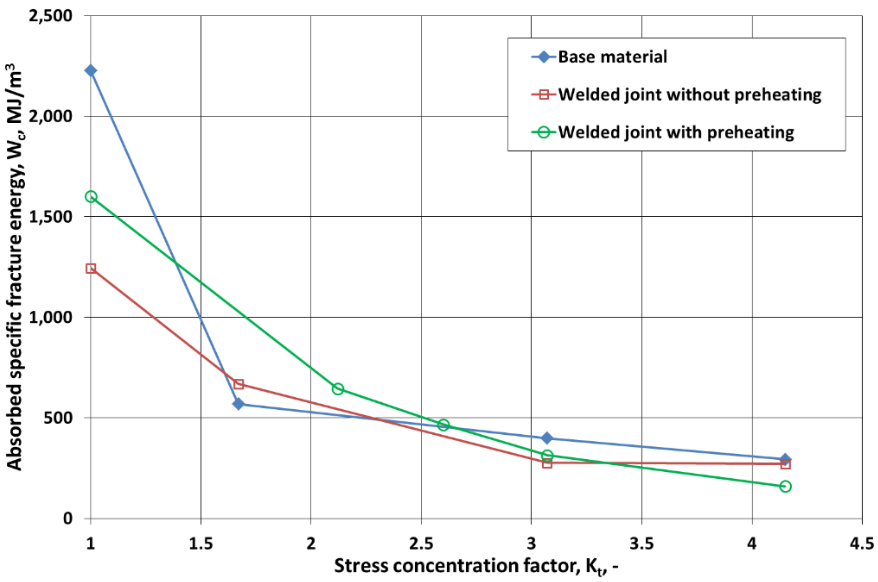

Figure 7

The $W_c - K_t$ functions taking into account the average values of the measured data

4. Summary and conclusions

Based on our investigations and the calculated results, the following findings and conclusions can be drawn.

The applied gas metal arc welding process and technological parameters are suitable for production welded joints of the investigated high strength steel with eligible quality.

Based on the executed welding procedure tests and their results, the applied preheating temperature has no significant effect on the main characteristics (imperfections and mechanical properties) of the welded joint.

Applying the notch opening displacement (NOD) and the absorbed specific fracture energy (W_c) values, both the base material and the welded joints without and with preheating can be characterised from other point of view (in our case cold cracking sensitivity), too.

Because of different notch radii (R) were applied in the three main groups (base material and welded joints), and different number of specimens were investigated at different notch radii, it was necessary analysing both all measured data and calculated average data. Both the notch opening displacement (NOD) and the absorbed specific fracture energy (W_c) samples consists of relatively small number of data (in other words specimens), in several cases have high standard deviation coefficients. (See grey coloured cells in *Table 7* and *Table 10*.) During the further investigations, the element number of samples (in other words the number of the tested specimens) should be increased.

Based on notch opening displacement (NOD) and absorbed specific fracture energy (W_c) investigations, and based on both all data and average data, the applied preheating temperature has no significant effect on NOD and W_c values, in other approach on cold crack sensitivity of the welded joints. Only COD ($NOD_{R=0}$) value of the preheated welded joint is an exception, however that is a consequence of the applied notch radii. It should be noted that the investigated welded joints were prepared without constraints; the deformations of the welded plates were free during the welding process. In that case when the welded structure can be produced without constraints, further investigations should be accomplished to study the welding technology without preheating temperature. In that case when the welded structure can be only produced with constraints, further investigations should be accomplished to study the determination of the efficient preheating temperature. These investigations can be built upon notch opening displacement (NOD) and absorbed specific fracture energy (W_c).

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