






Examination of Absorbed Specific Fracture Energy and Notch Opening Displacement on S960QL Steel and Its Welded Joints

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Abstract. Nowadays, the safety and the economic perspective are given special attention in the production of welded structures made of high-strength steels (HSSs). One of the problems in welding of HSSs is the cold crack sensitivity, which is closely related to the residual welding stresses. These can be controlled by the use of preheating, the correct choice of welding sequence and the post-weld heat treatment (PWHT). Another problem in welding of HSSs is providing adequate toughness and hardness in the heat-affected zone. These can be controlled by heat input, more specifically by limiting the heat input. For these steels, the risk of reduced toughness from a manufacturing point of view is higher than the risk of cold cracking.

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 necessity of fracture mechanical test is inevitable, applying notched and precracked specimens. The determination of the absorbed specific fracture energy (W_c) and/or the notch opening displacement (NOD) is basically simpler. Notched cylindrical tensile specimens can be applied, characterised by different notch radii.

S960QL high strength steel and its welded joints without preheating and with 150 °C preheating temperature were examined; NOD and W_c values were determined and compared. Conclusions belong to the effect of the preheating and the sensitivity of the HSS, as well as the reliability of the applied material characteristics were drawn.

Keywords: High strength steel · Notch opening displacement · Absorbed specific fracture energy

1 Introduction

The most commonly used structural material for the construction of different engineering structures is steel, especially structural or low alloyed steel. The most widely used

manufacturing technology is welding, especially arc welding. In our days, steel manufacturers develop continuously modern versions of high strength steels, both base materials and filler metals for welding. The yield strength values of these modern steels and filler metals are higher than 1000 MPa. Furthermore, high strength steel lightweight structures with low-cost weldments can be applied in many practical cases (e.g. fixed and mobile cranes, hydropower plants, offshore structures, trucks, earthmoving and timber (handling) machines), because of an extensive reduction in weight [1, 2].

The welded joints are sensitive parts of the engineering structures because the welded regions are in complex microstructural states and stress conditions. The yield strength to tensile strength ratio (Y/T) of the base materials and the weld metals are significantly higher than the modern high strength steels and the conventional mild steels. Therefore, both structural designers and welding technologists should attend to toughness and crack sensitivity of welded joints [2, 3].

During the welding process, the joining parts are affected by heat and force, causing inhomogeneous microstructure and mechanical properties in the different parts of the welded joints, as well as stress concentrator points can be formed. Both the inhomogeneity parts and the weld imperfections in the welded joints play an important role in case of different loading conditions. High cycle fatigue (HCF) and fatigue crack growth (FCG) phenomena are very common problems in the welded structures [2, 4–7], together with cold cracking sensitivity, and especially in high strength steels.

Classical methods 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, both for base materials and welded joints [8, 9]. The necessity of fracture mechanical test is essential, applying notched and pre-cracked specimens [10]. The determination of the absorbed specific fracture energy (ASPEF), today W_c , and/or the notch opening displacement (NOD) is basically simpler; notched cylindrical tensile specimens should be applied, characterised by different notch radii.

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

2 Theoretical Backgrounds and Previous Applications

2.1 Specific Fracture Energy (ASPEF)

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 (W_c) is equal to the sum of energy of elastic deformation (W_e), energy of plastic deformation (W_p), and energy of formation of a new fracture surface, in other words for crack propagation (W_s). The energy of elastic deformation (W_e) will be released after the rupture; furthermore, the surface energy (W_s) is negligible compared to the energy of plastic deformation (W_p). If referring the energy of plastic deformation to the absorbing volume (V), then getting a physically correct value, and W_c is equal to W_p . The W_c defined in the previously described way can be determined by applying tensile

tests [11–13]. Figure 1 shows a cylindrical tensile specimen under plastic deformation [14].

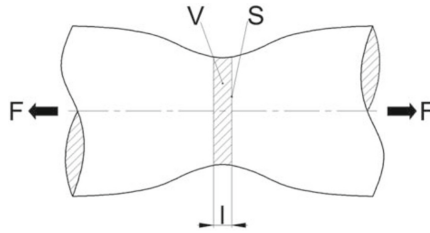


Fig. 1. Characteristics of the tensile specimen under plastic deformation [14]

The W_c value can be calculated using Eq. (1).

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

Several remarkable and interesting applications of W_c (ASPEF) can be found in the literature. Plastic strain and fracture were studied by testing the change in energy referred to as unit volume on unalloyed steel [15]; fracture toughness data measured on brittle materials (PMMA, glass, alumina and graphite) were re-analysed using ASPEF [16]. The relation between low cycle fatigue (LCF) data and ASPEF was studied on different materials, at different temperatures and after different in-service times [17, 18]. The embrittlement tendencies and the effect of neutron irradiation on low and medium strength steels and their weldments were investigated [19, 20]; furthermore, fatigue fracture of band-saw blades was studied by applying W_c values [21].

2.2 Notch Opening Displacement (NOD)

Figure 2 [14] shows a stress concentration place, in other words a notch, which can be considered a crack if the notch radius is sufficiently small.

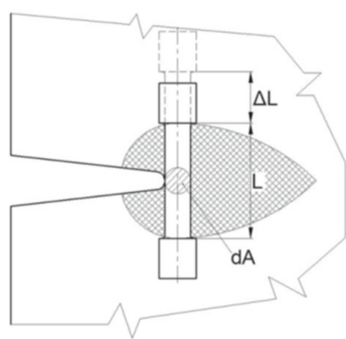


Fig. 2. Stress concentration placed with its plastic zone and fictive tensile specimen [14]

Applying tensile stress, a plastic zone will be formed in the root of the notch, in which considerable energy can be absorbed. The length of the fictive tensile specimen (L) is equal to the width of the plastic zone, and this length depends on the material characteristics and the sharpness of the notch. In the case of having a 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 a 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 [22, 23].

Different applications of NOD can be found in the literature, too. Determination of fracture toughness values on three different types of low-carbon structural steel were compared using conventional (J_{Ic}) and non-conventional (NOD) methods [24]. NOD values of high, medium and low Cr-steels (nominal Cr content 12%, 9% and 2%, respectively) and their welded joints were tested and analysed at high temperature (500 °C) [25]. The measured NOD values and their main statistical characteristics (average, standard deviation (abbreviated as STD), and standard deviation coefficient (abbreviated as STD Coefficient)) were calculated and are summarised in Table 1 [25].

Table 1. Measured NOD values (in mm) and their main statistical characteristics [25]

Notch radius, mm	Identification	High Cr-steel	Medium Cr-steel	Low Cr-steel
0.3	Specimen No1	0.57	1.02	1.15
	Specimen No2	0.67	0.70	1.23
	Specimen No3	0.7	0.72	1.20
	Average	0.647	0.813	1.193
	STD	0.068	0.179	0.040
	STD Coefficient	0.105	0.220	0.034
0.4	Specimen No1	0.73	0.75	1.20
	Specimen No2	0.70	0.60	1.20
	Specimen No3	0.72	0.33	1.27
	Average	0.717	0.560	1.223
	STD	0.015	0.213	0.040
	STD Coefficient	0.021	0.380	0.033
0.6	Specimen No1	0.77	0.67	1.32
	Specimen No2	0.65	1.10	1.35
	Specimen No3	0.92	0.75	1.30
	Average	0.780	0.840	1.323
	STD	0.135	0.229	0.025
	STD Coefficient	0.173	0.272	0.019

The standard deviation coefficient values cover wide range, excessively large values (0.380 and 0.272) can be found among the samples, too.

3 Investigations and Their Results

3.1 Preparation and Basic Investigations of Welded Joints

S960QL type, quenched and tempered high strength steel (produced by Thyssen Stahl AG and designated as XABO 960) was applied for the experiments. The chemical composition and the mechanical properties of the 15 mm thick base material plate are summarised in Table 2 and Table 3, respectively. Table 3 contains the yield strength (R_{eH}), the tensile strength (R_m) and the fracture elongation (A) values.

Table 2. Chemical composition of the used base material (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 3. Basic mechanical properties of the used base material

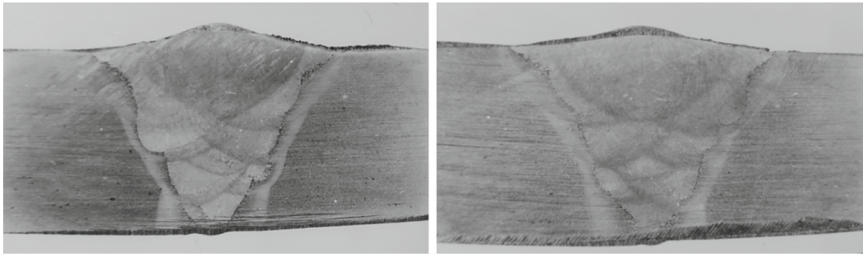
R_{eH} , MPa	R_m , MPa	A, %	Charpy impact energy, CVN, J				
			°C	No1	No2	No3	Average
1003	1077	15,0	-40	29	27	31	29
			-60	22	20	19	20

The dimensions of the welded workpieces were 600 mm x 125 mm, the welding position was flat position (PA). V joint shape was applied, with 60° opening angle, 2 mm gap between the two plates (root opening), and 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% CO₂ + 82% Ar gas mixture (M21) were applied.

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 [26, 27] was $T_{pre} = 106$ °C. Accordingly to the recommendation of the base material manufacturer (Thyssen Stahl AG), a higher preheating temperature was selected, which was $T_{pre} = 150$ °C. During the preparation of the welded joint without preheating, the interpass temperature was less than $T_{ip} = 50$ °C. The welding technological parameters can be found in Table 4, separately for the root and the filler layers. The table introduces the welding current (I), the welding voltage (U), the wire-feed speed (v_{wire}), the welding speed (v_w) values, as well as the heat input (Q) calculated with arc efficiency ($\eta = 0.85$). Figure 3 shows the macrostructure of the welded joints.

Table 4. The applied welding parameters for welded joints preparation

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

**Fig. 3.** The macrostructure of the welded joints: without preheating (left side) and with preheating (right side)

3.2 Basic Investigation of Welded Joints

Welding procedure tests, non-destructive and mechanical investigations were accomplished on both welded joints; the detailed results (individual, average and range values) are summarised in Table 5.

Table 5. Detailed results of the executed non-destructive and mechanical investigations

Testing method	Welded joint without preheating	Welded joint with preheating (150 °C)
Visual testing (VT)	Appropriate	Appropriate
Magnetic particle testing (MT)	Appropriate	Appropriate
Ultrasonic testing (UT)	Appropriate	Appropriate
Tensile strength, R_m , MPa	1011; 1037	1013; 1047
Bending strain using non-standardized method with more rigorous criteria, %	38,25 (38,1; 38,3; 38,3)	38,35 (38,3; 38,3; 38,4)
Charpy impact energy in the weld metal (WM) at -40 °C, CVN, J	48 (47; 53; 45)	51 (45; 57; 51)
Charpy impact energy in the heat affected zone (HAZ) at -40 °C, CVN, J	54 (47; 53; 45)	63 (51; 79; 60)
Hardness, HV10	383–421	383–464

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

3.3 Notch Opening Displacement and Specific Fracture Energy Investigations

Specimen Characteristics. 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 4 shows the characteristics of the un-notched and the notched specimens, where the diameter of the tested length of the un-notched specimens and the minimum diameter of the notched specimens at the notches were the same (d_0). The larger diameter of the notched specimens (D_0) was the same, too.

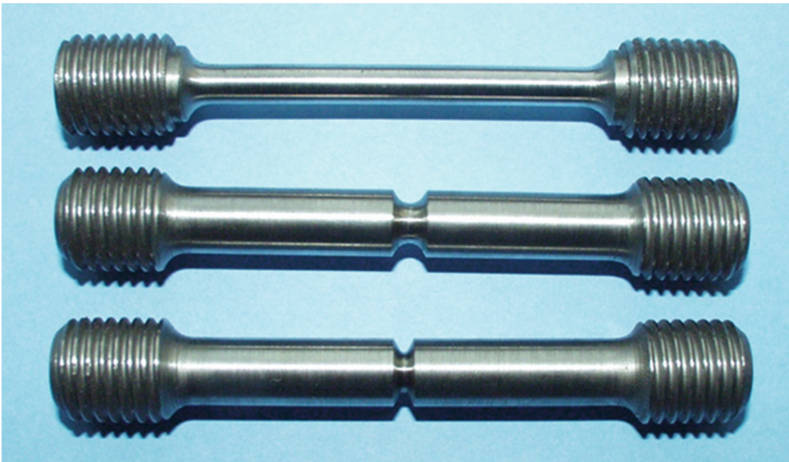


Fig. 4. Shape and geometry of the un-notched and the notched specimens

The stress concentration factor (K_t) values were specified using a web calculator [28] developed based on formulas for stress and strain [29] and were controlled based on the well-known classical handbook [30]. The data belonging to the un-notched and differently notched specimens are summarised in Table 6.

Table 6. Characteristic data of the applied un-notched and notched 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

(continued)

Table 6. (continued)

D_0 , mm	d_0 , mm	R, mm	d_0/D_0 , –	R/D_0 , –	K_t , –
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 the 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 (WM), in the heat-affected zone (HAZ), 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 [19, 24, 25]. Table 7 summarises the results, the determined (also known as measured and calculated) NOD values.

Table 7. 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

(continued)

Table 7. (continued)

R, mm	Base material	Welded joint without preheating	Welded joint with preheating (150 °C)
0.1	0.29	0.22	0.18
	0.22	0.36	0.17
	0.15	0.26	0.13

Based on the shortly summarised theoretical background (see Subsect. 2.2), 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 5 shows the measured values and the regression lines using the Least Squares Fitting (LSF) method, taking into account that all measured data can be found in Table 7.

Because the measured notch opening displacement (NOD) values belong to different notch radii (R) in the three main groups (base material and two welded joints), and there are different numbers of specimens at a 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.

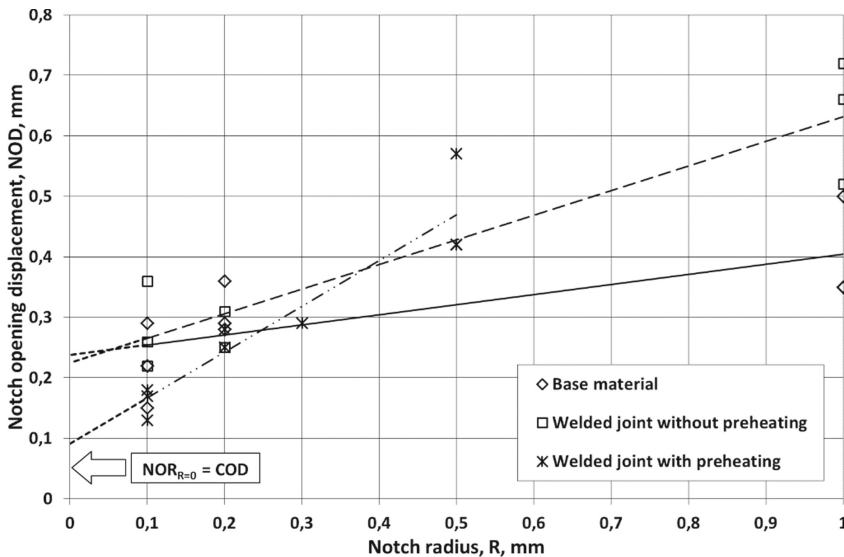


Fig. 5. The NOD – R functions taking into account all measured data

The calculated statistical values are summarised in Table 8, and the NOD – R functions taking into account the average values of the measured data can be seen in Fig. 6.

Table 8. 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

Table 9 summarises the calculated slope (k), COD ($NOD_{R=0}$) and correlation coefficient values of the approximated straight lines of the three material groups, belonging to both all data and average values.

Correlation coefficient values demonstrate clearly that using the average values, the results are more reliable than using all data. It is remarkable that the $NOD_{R=0} = COD$ values of the base material and the welded joint without preheating were essentially the same, however the values belong to the welded joint with preheating were significantly lower.

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

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

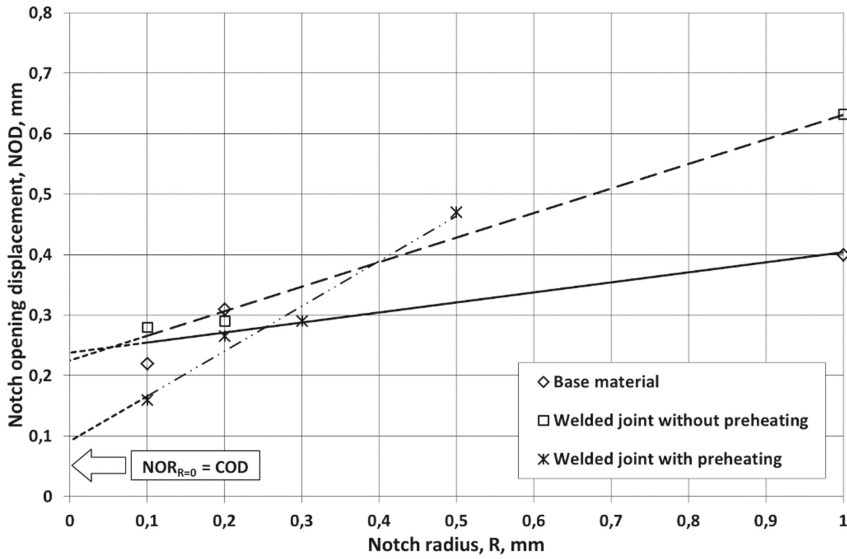


Fig. 6. The NOD – R functions taking into account the average values of the measured data

Table 9. The parameters of the NOD – R functions

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

Table 10 summarises the results, and the determined W_c values, furthermore, the calculated statistical parameters can be found in Table 11.

Table 10. The determined absorbed specific fracture energy (W_c) values (in MJ/m³)

R, mm	K_t , –	Base material	Welded joint without preheating	Welded joint with preheating (150 °C)
∞	1	2210	871	1598
		2243	1513	1573
		2232	1352	1636
1	1.67	505	673	N/A
		753	747	N/A
		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

For analogous reasons to those described under the NOD investigations, both all W_c data and average W_c data were illustrated in Fig. 7 and Fig. 8, respectively.

Table 11. 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	2228	1245	1602
	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

(continued)

Table 11. (continued)

R, mm	Statistical parameter	Base material	Welded joint without preheating	Welded joint with preheating (150 °C)
	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

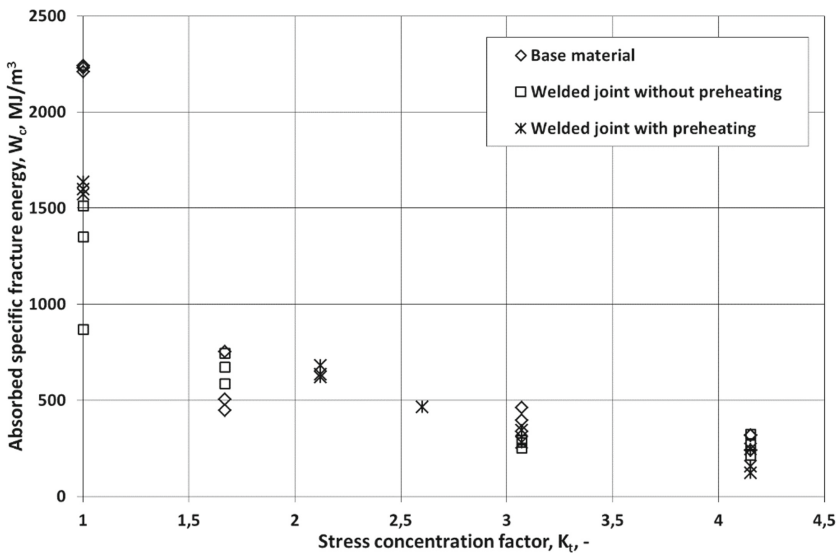


Fig. 7. The $W_c - K_t$ functions taking into account all measured data

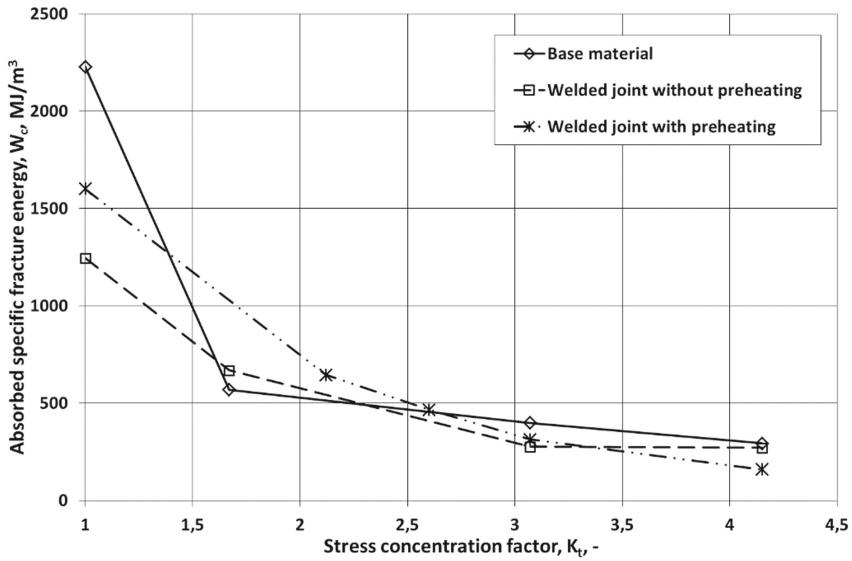


Fig. 8. The $W_c - K_t$ functions taking into account the average values of the measured data

4 Summary and Conclusions

Based on the executed 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 the production of 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 another 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 two welded joints), and a different number of specimens were investigated at a 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 consist of a relatively small number of data (in other words, specimens), in several cases have high standard deviation coefficients. (See 0.318 and 0.258 values in Table 8, and 0.2835, 0.2682 and 0.3577 values in Table 11. These higher standard deviation coefficient values are in harmony with relevant values can be found in the literature [25] (see Table 1)) During the further investigations, both the element number of samples (in other words, the number of the tested specimens) and the number of tested notch radii 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).

Finally, the effect of the preheating temperature should be investigated deeper, analysing the correlations between the mechanical and microstructural characteristics.

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