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Effects of welding technology on the occurrence of fracture in welded joints

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Abstract

Welded joints represent locations where failure is most likely to occur in welded structures. Welded joint failure depends on their vulnerability to crack initiation and growth. These factors are significantly influenced by the welding technology. The effect of welding technology on the frequency of welded joint failure is complex, and has been thoroughly researched in literature. However, there are still numerous factors whose influence is not sufficiently explained. In this paper, the ratio of strength and plasticity of parent materials and weld metals on deformation properties of welded joint zones were analysed, along with the effects of groove edge temperature on cooling time in the heat affected zone and the effect of multiple defects on local stress increase.

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*Keywords:*welding technology, strength and plasticity, cooling time, welded joint defects

1. Introduction

Welded joints represent critical locations in welded structures due to their non-homogeneity, residual stresses and stresses resulting from geometry and weld dimensions. Welding technology affects these factors the most. Its effect of welded joint vulnerability towards fracture is complex and has been thoroughly researched in literature. However, there are still numerous factors whose influence is not sufficiently explained. During the selection of filler materials for welded joint, the ratio

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between strength and plasticity of parent materials and weld metals is not taken into account, between low-carbon and austenitic steels, hence it is impossible to predict the development of strain, location of fracture within the weld and the weld's fracture resistance. In addition, during the development of welding technologies, it is common practice to assume that the cooling time along the weld is constant. However, due to heat generated by the arc, the temperature along the groove edge increases, which extends the cooling time and could result in deteriorated heat affected zone properties. Frequently, multiple defects that occur during the forming of the weld can be found in one location within the joint. Combined effect of defects on fracture occurrence in welded joints is greater than their individual effects. Removing of such defects is often not possible; hence in these cases it is necessary to define a methodology for acceptability evaluation.

2. Strength and plasticity ratio of parent material and the weld metal

Welded joints made of micro-alloyed and high-alloyed austenitic steels are welded using austenitic filler materials (FM), which are chosen based on the Schaeffler diagram [1]. Schaeffler diagram enables the selection of an FM which provides the weld metal (WM) with a structure resistant to cold crack forming, based on the chemical compositions of heterogeneous steels. The Schaeffler diagram does not take into account the characteristic strength and plasticity of the parent material (PM) and WM. Due to this, strain development in the welded joint cannot be predicted, along with the fracture location and resistance.

In order to understand the behaviour of aforementioned welds, two joints were welded and tested. The first welded joint was obtained by welding low-alloyed steel P460NL1, with a thickness of 14 mm (hereinafter referred to as steel M1), with high-alloyed austenitic steel X6CrNiMoTi 17 12 2, with a thickness of 12 mm (hereinafter referred to as steel V). The welded joint was made using the E procedure, and INOX R 29/9 (E 29 9 R 12 - EN ISO 2560 A) electrode was used as filler material. The other welded joint was using the MIG procedure, with MIG 18/8/6 (G 18 8 Mn – EN ISO 24373) as the FM. Chemical compositions of steels mentioned above are given in table 1, whereas their mechanical properties are shown in table 2. Steels M1 and M2 have a ferrite – pearlite structure. Chemical compositions of FM and the mechanical properties of the pure WM are shown in tables 3 and 4.

Table 1.Chemical composition of parent materials (%)

Steel	C	Si	Mn	P	S	Cr	Ni	Cu	Al	Mo	Ti	V	Nb
M 1	0,10	0,49	1,26	0,011	0,014	0,08	0,11	0,21	0,067	0,019	0,002	0,048	0,053
M 2	0,10	0,38	0,64	0,014	0,020	0,76	0,10	0,30	0,015	0,33	-	0,02	0,042
V	0,04	0,35	1,73	0,031	0,004	17,9	11,6	0,18	0,061	2,16	0,38	0,079	0,016

Table 2.Mechanical properties of WM

Steel	Upper yield stress R_{EH} MPa	Lower yield stress R_{EL} MPa	Yield stress $R_{p\,0,2}$ MPa	Tensile strength R_m MPa	Elongation A %	Contraction Z %
M1	453	435	-	565	25	58
M2	-	-	492	620	20	65
V	-	-	324	595	37	53

Table 3. Chemical composition of filler materials (%)

	C	Si	Mn	Cr	Ni
INOX 29/9	0,15	≤ 0,9	0,9	29	9
MIG 18/8/6	0,08	≤ 1,0	7	18,5	9

Macro and micro-structures of the welded joints were tested, along with hardness and tensile properties. Macro-structural tests did not reveal any defects. Micro-structural tests indicated that the heat affected zones (HAZ) of steels M1 and M2 have ferrite-pearlite structure, with a presence of bainite. Both FMs produced a WM with an austenitic structure with partial δ – ferrite, which is more present in welded joint 1. No structural changes were observed within the steel V HAZ, other than grain size growth. Hardness had values typical for these materials.

Table 4.Mechanical properties of pure WM (INOX R 29/9 and MIG 18/8/6)

	Filler material	Yield stress $R_{p0,2\%}$ MPa	Tensile strength R_m MPa	Elongatoin A_5 %	Contraction Z %
Spoj 1.	INOX R 29/9	550	750	42	42
Spoj 2.	MIG 18/8/6	466	682	42	-

Tensile properties of welded joints as a whole, deformation flow in them, as well as the vulnerability of certain weld zones towards fracture were tested using flat specimens with parallel sides, figure 1. Three specimens were tested for each welded joint. Stress-strain dependence obtained using specimens from welded joint 1 is shown in figure 1a. Four characteristic points can be observed, denoted A through D. Shown in table 5 are the values of stresses corresponding to these points. For all three specimens, fracture occurred in steel M1 PM, figure 1c. Specimen fracture was followed by non-uniform deformation of the specimen gauge length. The figure shows that the cross-section contractionwas smallest in the WM centre (2%), whereas the contraction in the WM at the fusion line with steel V was greater (6%) than the contraction at the fusion line with steel M1 (3%).

Stress-strain dependence obtained using specimens from welded joint 2 is shown in figure 1b. Three characteristic points can be observed, denoted A through C. Shown in table 5 are the values of stresses corresponding to these points. In this case, fracture occurred in the PM of steel V, figure 1d, for all three specimens. Specimen fracture was followed by non-uniform deformation of the specimen gauge length. The figure shows that the cross-section contraction was smallest in the fusion line with steel M2 (5%), whereas the contraction in the WM at the fusion line with steel V was the greatest (22%). WM centre contraction was similar to the mean value of the specimen contraction (10%).

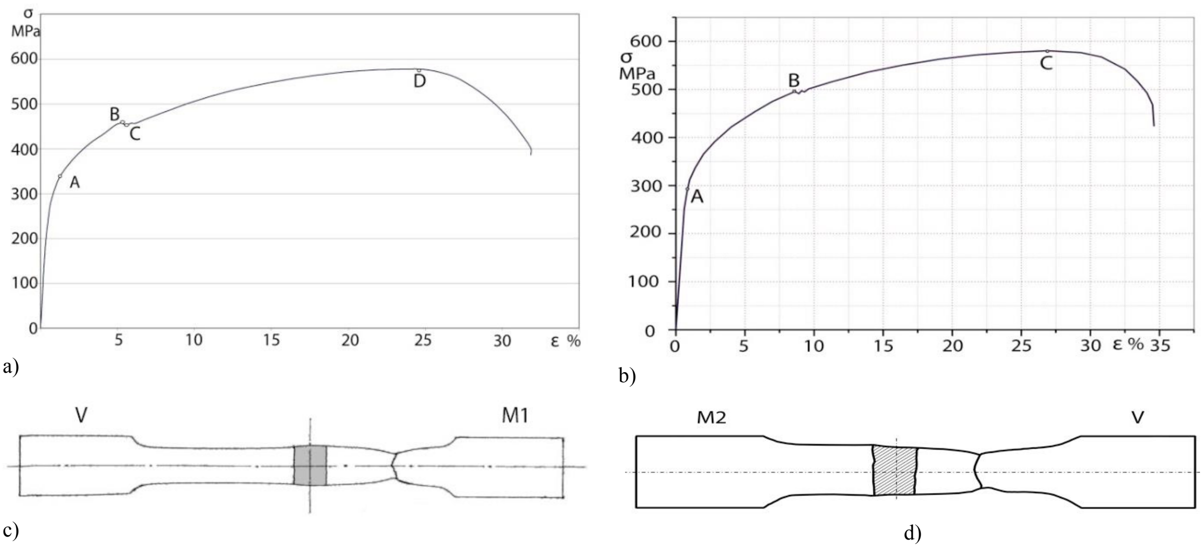

Figure1.Tensile properties of the welded joint as a whole: a) σ – ε diagram, welded joint 1 specimen. b) σ – ε diagram, welded joint 2 specimen. c) Specimen 1.3 after fracture, d) Specimen 2.3 after fracture

Based on figure 1.a and tables 2, 4 and 5, it can be concluded that plastic strain in welded joint 1 initiates in the PM of steel V, since its yield stress is lower than that of M1 and WM. Increase in stress leads to plastic strain in steel V only. Once the stress reaches steel M1 yield levels, plastic strain occurs there, as well. Further increase in stress leads to both PMs deforming plastically. Immediately before reaching steel M1 tensile strength, i.e. stress levels at which fracture occurs, plastic strain initiates in the WM. WM yield stress is slightly lower than the tensile strength of steel M1 and due to this, there isn't enough time for significant plastic strain to developom in the WM. Hence, WM contraction is around 2%. Despite the fact that steel V starts to deform plastically before steel M1, the fracture occurs in the latter since its deformability is lower, and is exhausted first. In welded joint 1, fracture is most likely to occur in steel M1 due to its lowest tensile strength and deformability. On the other hand, fracture is least likely to occur in the WM, even in the presence of cracks, due to its high yield stress, i.e. prominent overmatching effect.

Table 5. Stress values in characteristic points of σ – ε diagrams of welded joint specimens (MPa)

Specimen no.	Stress in pointA		Stress in point B		Stress in point C		Stress in point D		Elongation A %	
	Indivi-dual	Mean value	Indivi-dual	Mean value	Indivi-dual	Mean value	Indivi-dual	Mean value	Individual	Mean value
1.1	337	341	458	462	450	450	579	584	32	31
1.2	337		463		450		579		31	
1.3	350		465		450		595		31	
2.1	321	329	509	506	588	586	-	-	34	32
2.2	334		505		587		-		31	
2.3	331		505		582		-		31	

For welded joint 2, an FM with lower strength and higher plasticity was used. Based on figure 1.b and tables 2, 4 and 5, it can be concluded that the plastic strain in specimens initiates in steel V PM again, since its yields stress is lower than those of steel M2 and the WM. During further increase in stress, plastic strain develops only in steel V, up to a point where stress reaches WM yield level. With additional increase in stress, plastic strain simultaneously develops in steel V and WM, until steel M2 yield stress is reached. Further increase in stress results in simultaneous plastic deforming of all three materials. Under such conditions, steel V yield stress is reached first, hence the specimen fails in its PM. Lowest contraction (5%) in this welded joint is in the fusion line between WM and steel M2. Crack initiation and propagation due to WM defect is unlikely in this case as well, due to significant WM ductility. A large plastic zone forms in front of the crack tip located in a high ductility material, hence very high stresses are necessary for the crack tip to propagate. From the fracture safety aspect, it is favourable that deformation is mostly occurring in materials which can take considerable plastic strain.

It is expected that left and right side of both WMs, outside of PM and FM fusion zones, have similar properties. However, figures 1.c and 1.d indicated that the contraction of the WM is greater on the PM side, due to increased ductility. This suggests that WM behaviour is affected by the properties of the PM it is connected with, in addition to its own properties and stress state. Thus, the mutual influence of welded joint materials is evident. It cannot be observed when testing welded joint parts separately. In order to gain full insight into welded joint properties, it is necessary to investigate the welded joint as a whole.

3. Cooling time in the temperature interval 800–500 ºC

Structures obtained in the HAZ were mostly influenced by the chemical composition, structure and cooling time in the temperature interval of 800 – 500ºC ($t_{8/5}$). Cooling time $t_{8/5}$ in the HAZ is affected by the physical properties of steel (heat conductivity, specific heat), shape and dimensions of the welded joint (thickness, butt or fillet welds) and welding technology parameters (initial temperature and heat input). Too short $t_{8/5}$ contributes to the forming of brittle structures in the HAZ, reduces the release of gases from the WM, which is of particular importance when hydrogen is involved, and increases the temperature gradient which results in higher residual stresses. These factors increase the vulnerability of welded joints to cold cracks. Too long $t_{8/5}$ can also have a negative impact of welded joint properties, since it leads to the expansion of the HAZ, its coarse-grain part, and the increase in HAZ grain size, which leads to diminished mechanical properties and toughness of this part of the weld [2]. In order for welded joints to have properties corresponding to exploitation conditions, cooling time $t_{8/5}$ must be within an optimal range.

Cooling time $t_{8/5}$ is calculated based on preheating temperature (T_p) or interopass temperature (T_{ip}) and the amount of heat input (Q), i.e. amperage, voltage and welding speed [3]. In the case of amperage, voltage and welding speed, it can be assumed that they are constant along the weld. However, PM temperature during welding increases along the joint due to it being heated by the arc [4]. An increase in PM temperature affects the cooling time $t_{8/5}$ in the same way as the increase in T_p. Hence, values of $t_{8/5}$ obtained by calculations based on T_p and T_{mp} apply only to the start of the welded joint. This time increases along individual welds, since the PM temperature increases along the groove edge.

Shown in the following section are the calculated cooling times $t_{8/5}$ along the butt welded joint made by welding of two steel P460NL1 plates, with dimensions of 500 x 200 x 14 mm. MAG welding procedure was used, with ER70S-6 (AWS 5.18) as FM, with a diameter of 1.2 mm and Ar + 5.9% CO_2 + 1.1% O_2 shielding gas. During the welding, amperage and voltage were recorded. These values are given in table 6. During welding, temperatures in the PM were measured along the groove edge, figure 2. Results of this measuring are given in table 7.

Figure 2. Distribution of groove edge temperature measuring points

Table 6. Welding parameters and cooling times $t_{8/5}$

Weld	T_{max} (ºC)	I (A)	U (V)	v_z (mm/sec)	Q (KJ/mm)	d_t (mm)	$t_{8/5}$ (sec)
Root	223	114	17,8	2,36	0,69	> 15	7,3
Filling I	184	171	20,2	3,45	0,80	> 15	7,6
Filling II	302	233	27,0	6,02	0,84	> 15	20,9
Filling III	305	238	26,7	4,90	1,03	> 15	32,3
Filling IV	165	237	26,2	4,24	1,17	> 15	14,5
Filling V	238	238	25,8	4,53	1,08	> 15	20,0

Table7.PM groove edge temperature measuring results during welding (ºC)

Weld	Measuring points							
	1	2	3	4	5	6	7	8
Root	50	57	135	134	158	164	223	207
Filling I	48	50	164	158	163	185	184	181
Filling II	55	54	172	151	173	166	302	241
Filling III	59	50	156	173	222	232	245	305
Filling IV	60	61	-	-	-	-	163	165
Filling V	50	51	-	-	-	-	238	213

The procedure for determining of $t_{8/5}$ is given in literature [3]. The first step in this calculation is the determining of transition thickness, i.e. the thickness of the PM for which heat heat dissipation changes from two-dimensional to three-dimensional. In the case considered here, heat dissipation was two-dimensional. Cooling times $t_{8/5}$, calculated using equations given in [3], are shown in table 6. Limited cooling times $t_{8/5}$ for micro-alloyed steels range from 15 sec [2], 10 – 25 sec [3] and 5 – 20 sec [5]. Cooling times are shortest at the start of the welded joint, ranging from 3 to 8 sec (T_p and T_{ip} of 50 – 60°C). It can be seen from table 6 that cooling times $t_{8/5}$ at the end of the welded joint are significantly longer (groove edge temperature was 165 to 305°C) and that some of these values exceed the ones recommended for this type of steel.

The aforementioned joint was welded with a relatively small energy input. If there is a need for welding with higher energy input (e.g. 1.25 kJ/mm), wherein cooling time $t_{8/5}$ needs to be limited to 20 sec, then the groove edge tempe–rature must not exceed 200°C. In the case of steels for which cooling time $t_{8/5}$ is limited to 15 sec, with welding para–meters including the energy input of 1.25 kJ/mm, the temperature for the same welded joint must not exceed 150°C.

4. Welded joint forming defects

Welded joint forming defects are an integral part of welds. In addition to reducing the load bearing cross-section of the weld, forming defects cause local stress concentrations. Due to this, the probability of crack initiation and growth and the vulnerability to fracture are greater in locations where defects are present. Figures 3 and 4 show the stress states around the defects in the welded joint made of steel S235JRG2, with a thickness of 10 mm. The stress state was deter–mined using the finite element method. Figure 3 shows a 0.5 mm deep undercut, whereas figure 4 shows a 1 mm deep lack of penet–ration. When the welded joint was subjected to a tensile stress of 100 MPa, stresses with a magnitude of 158 MPa occur–red in the undercut root, whereas in the case of lack of penetration, the stress was 214 MPa. The ratios of local stresses around the defects and acting stresses represent the stress concentration factors and were 1.58 and 2.14 in these cases.

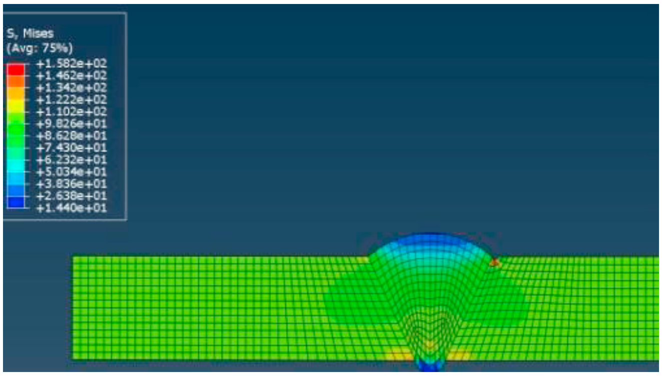

Figure3. Stress state, undercut weld

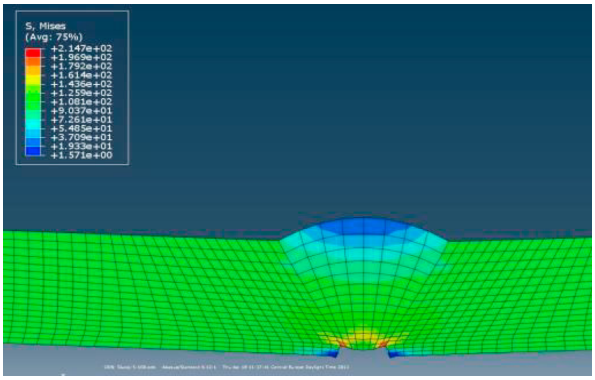

Figure4. Stress state, lack of penetration

During the forming of the welded joint, multiple defects in the same location are often present. It can be expected that defects grouped in such a way will increase stress concentration through their combined effects, thus increasing the probability of crack initiation. In this section of the paper, an example of a welded joint of a liquid carbon-dioxide storage tank was analysed. In this particular weld, three forming defects, including cracks, were detected, figure 5. The tank was made of steel P460NL1, with a thickness of 17 mm. Other data about the tank are as follows: maximum work pressure of 20 bar, test pressure of 26 bar, lowest working temperature of -50°C, outer diameter of 3000 mm.

Figure 5 shows that the crack is located along the weld fusion line. Total crack length is 60 mm, and their maximum depth is 3 mm. Visual dimension control of the location where cracks were detected also revealed welded joint forming defects, including misalignment, excess weld face overhang and a sharp transition from weld face to the PM, whose dimensions were unacceptable for the required quality level B [6]. The storage tank was tested using an internal pressure of 26 bar. The pressure decreases during exploitation, due to the decrease of carbon-dioxide vapor stresses. Internal pressure testing conditions were deemed critical, hence the effect of defects on stress magnitude was analysed with these in mind. Stress caused by the pressure in the tank, P_m, which causes local increase in stresses near the defects, represents stress that acts along the tank axis and is determined according to the following formula: $P_m = pD/4B$, where p is the test pressure of 26 bar, D is the outer tank diameter of 3000 mm, B is wall thickness of 17 mm. For such conditions, P_m = 115 MPa.

Stresses due to presence of defects mentioned above were determined using the finite element method (FEM). The part of the vessel with welded joint defects was modelled using two-dimensional finite elements, based on data from figure 5 and is shown in figure 6. The right end of the model was fixed along the X axis, whereas the load corresponding to a stress of 115 MPa were acting on the left end. Colour variations in figure 6 indicate areas with different stress magnitudes. The highes stress value of 279 MPa (the red area), occurred in the misalignment zone at the transition from weld face to the PM, i.e. in the area where cracks were detected. Stress concentration factor, i.e. the ratio of the highest stress in the area around the defects, and the stress due to internal pressure P_m (115 MPa, in the green area) was 2.43.

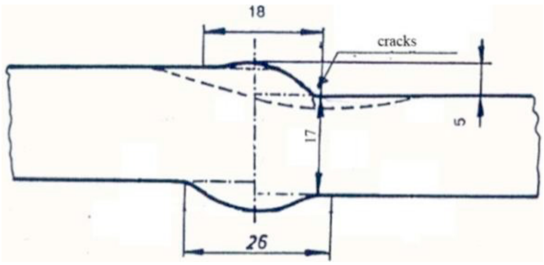

Figure 5. Crack print in the welded joint between lid and mantle

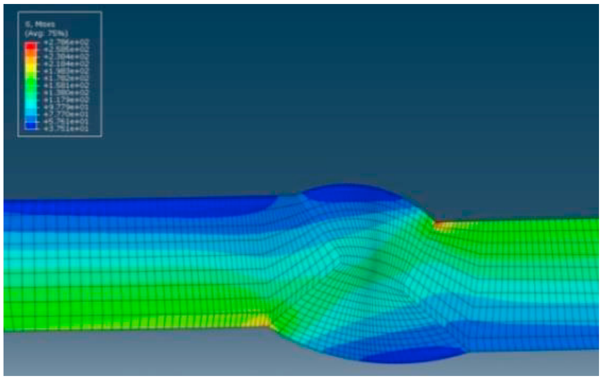
Figure 6.Tank wall cross-section at the crack location

Based on the presented results, it can be concluded that the three defects, which are not considered hazardous on their own, have caused a stress concentration factor (2.43), through their combined effect, which was higher than the stress concentration factor caused by a single unacceptable defect (2.14) – lack of penetration, figure 4. Hence, a greater number of less dangerous defects concentrated at a single location in the welded joint can result in higher local stress concentration, thus leading to increased probability of failure, compared to individual defects which are typically unacceptable, or acceptable for lower quality welded joints.

5. Conclusions

The selection of filler material can affect the distribution of stresses and strain in welded joints. In this way, it is possible to avoid the localisation of strain in welded joint parts with lower deformability, or to localise the strain in welded joint parts with high deformability. By doing so, the probability of crack initiation and growth, i.e. fracture is reduced.

Parent material temperature increases along the groove edge, due to its heating via the arc. This temperature increase affects the cooling time $t_{8/5}$ in the same way as the increasing of preheating or interpass temperatures. Cooling times $t_{8/5}$ are shortest at the start of a welded joint and increase in duration towards their end.

Welded joints typically contain multiple forming defects at the same location. Defects grouped in this way casue a local increase in stresses, thus contributing to crack initiation. Due to this, a larger number of less dangerous defects concentrated at a single location in a welded joint can cause higher local stress concentration, and thus, higher vulnerability to fracture, compared to an individual, also typically unacceptable, defect.

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