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Tomasz Kozak

Gdansk University of Technology, Faculty of Mechanical Engineering, Department of Materials and Welding Technology, Narutowicza 11/12, 80-233 Gdansk, Poland
tkozak@pg.gda.pl

RESISTANCE TO COLD CRACKING OF WELDED JOINTS MADE OF P460NL1 STEEL

ABSTRACT

The results of investigations of resistance to cold cracking of high strength steel welded joints have been presented. The steel used was P460NL1 which is designed to work under pressure. Welding was carried out with coated electrodes (MMA) and flux cored wire by FCAW method. Parameters changed in the implant test were diffusible hydrogen content and weld heat input. Partial resistance to cold cracking of joints for the studied ranges of welding parameters have been shown. Cold cracking resistance decreases with increasing diffusible hydrogen content in the joint and increasing the cooling rate in the HAZ metal measured by cooling time in the temperature range 800-500^{0}C.

Key words: *arc welding, cold cracking resistivity, implant test, high strength low alloy steel*

INTRODUCTION

Cold cracking occurs during cooling of the welded joint, or after a certain period of time from reaching an ambient temperature by the joint. To avoid or reduce the risk of inducing cold cracks a lot of research works have been carried out [1, 2, 3, 4]. Cold cracking is still a problem that may appear in welded structures manufacturing [5, 6]. This article aims to show the influence of the basic welding conditions on the phenomena of high strength steel used mostly for pressure vessels building. The most common and most ferquently used welding methods and conditions have been taken into account, namely welding with coated electrodes (MMA) and gas-shielded arc welding with flux cored wire (FCAW). Both of these methods can introduce hydrogen into joints causing cold cracking. The amount of hydrogen depends on the welding conditions and the state of welding materials. Another variable parameter characterizing thermal conditions during welding was weld heat input, which was changed within the recommended range for the steel tested. The tendency to cold cracking was determined on the basis of the implant test.

PROPERTIES OF WELDED JOINTS TESTED

P460NL1 steel according to PN-EN 10028-3 is a low alloy, normalized, fine-grained high strength steel, designed to work under pressure. The usual method of welding is manual metal arc welding with coated electrodes. In the method there is an easy possibility to change the electrode type and diameter which controls weld heat input and joint strength. To join this steel semiautomatic gas shielded arc welding methods are used as well. It is very important is to use high purity gases in the method. Automatic submerged arc welding is also frequently applied. During welding the heat input value should be kept in the range of 1,0-3.0 kJ/mm. The use of multilayer welding technique and basic electrode coating or basic or neutral flux is recommended .

Table 1. *The basic properties required for P460NL1 steel and welding consumables for MMA and FCAW welding methods*

Parent material		P460NL1
	Properties	
Re min	MPa	460
Rm min	MPa	570
KV min	J	27
Test temperature	^{0}C	-50
A_5 min	%	17
	Suitable welding materials	
MMA	standard	PN-EN 499
Electrodes	designation	OK48.08
FCAW	standard	PN-EN 758
Flux cored wire	designation	OK15.11

Based on the above information for the selected methods, preliminary welding procedures (pWPS) for butt weld joints for 25mm thickness of the steel have been designed. The welding conditions set up as a result from the characteristics of parent material, ability to meet the requirements by the welded joint and conditions of use of welding consumables specified by the manufacturer and suitable for welding of certain structures. Table 1 summarizes the basic mechanical properties of the steel and selected welding consumables which meet the basic requirements. Table 2 shows the chemical composition of welded joints materials according to the analysis or mill test certificate. In table 3 the mechanical properties of the base metal used in the cold cracking tests have been presented. Table 4 shows the results of hardness measurements in different areas of welded joints. Hardness tests were carried out with the help of portable hardness tester EQUOTIP using the Shore method. Welded joints were also subjected to metallographic examinations. Table 5 presents the macro and microstructures of joints welded by the two welding methods. As the number of samples was quite large, only microstructures of important areas of the joint which were close to the last layer have been shown for the sake of clarity. As can be seen from all the above tables, the resulting welded joints present typical microstructures and have common mechanical properties represented by low level of hardness and as a consequence can meet the operational tasks.

RESULTS OF EXPERIMENTAL TESTS

Tests for resistance to cold cracking were performed by an implant method according to PN-90/M-69760 [7]. The implants were made from 12mm thick steel sheets. As shown above the joints welded by two common methods were tested. The variable parameters of the welding processes were: heat input value and content of diffusible hydrogen in the joint. The detailed terms and conditions of the implant test are shown in Table 6. The tests were conducted on the IMPLANT 02 test machine. Fig. 1 shows a general view of the IMPLANT test machine. Suitable stress in the implant specimen cross section is achieved by controlling oil pressure by adjustable reducing valve, which maintains the oil pressure in the actuator. The relationship between stress at implant specimen and pressure in actuator was linear. The relationship is as follows:

$$\sigma_i = 78{,}204 \cdot p - 11{,}357$$

where:
σ_i - stresses in the plane of the notch for implant specimen, MPa
p - pressure in the actuator, MPa.

Table 2. *Chemical compositions of parent materials and weld metal of welded joints obtained from mill test certificates or chemical analysis*

No	Steel	Standard/place of test	Test no/analysis	Thickness	Chemical composition											
				t	C	Mn	Si	S	P	Al.	Cu	Cr	Ni	V	Nb	Ti
				mm	% wt.											
1	P460NL1	EN10028	362638	12	0,14	1,51	0,34	0,003	0,013	0,021	0,02	0,03	0,6	0,16	0	0,01
2	P460NL1	Weld-electrode OK4808	analysis	25	0,058	1,21	0,29	0,029	0,0027	0,013	0,027	0,012	0,66	0,038	0,016	0,038
3	P460NL1	Weld- wire OK1511	analysis	25	0,13	1,34	0,33	0,021	0,0027	0,036	0,018	0,025	0,49	0,16	0,015	0,031

Table 3*. The mechanical properties of the parent material per mill test certificate*

No	Steel	Standard/test place	Mill test cert. No	t	Re	Rm	A5	T	KV ave.
				mm	MPa	MPa	%	°C	J
1	P460NL1	EN10028	362638	12	519	615	24	-50	58

Table 4*. The hardness test results of welded joints of steel P460NL1*

No	Weld method	Hardness HV											
		Weld metal				HAZ				Parent material			
		1	2	3	ave.	1	2	3	ave.	1	2	3	ave.
1	**MMA**	197	199	196	**197**	182	185	180	**182**	175	183	180	**179**
2	**FCAW**	239	241	234	**238**	181	189	181	**184**	171	178	169	**173**

In order to fulfill the research program it was necessary to obtain certain levels of diffusible hydrogen in the joints. Such levels were obtained by controlling the covered electrodes wetting. Some information on how to humidify the electrodes were taken from the literature [8, 9]. For electrodes OK4808 the following relationship between diffusible hydrogen content H_D [ml/100gFe] and humidification time t_n[h] obtained:

$$H_D = 0{,}6729 \cdot t_n + 2{,}39$$

Determination of diffusible hydrogen was carried out using the glycerol method according to the conditions given in [10, 11]. The hydrogen content determined on the base of the mercury method can be calculated from the following relationship [12]:

$$H_Dg = 0{,}658 \cdot H_Dr$$

or [13]:

$$H_Dr = 1{,}16 \cdot H_Dg + 2{,}4$$

where:

H_Dg – the diffusible hydrogen content measured by the glycerol method, ml/100g,

H_Dr – the diffusible hydrogen content measured by the mercury method, ml/100g,

Table 5. *Photographs of macro and microstructures of welded joints of steel P460NL1. Etched by 4% HNO_3. Magnification x 250*

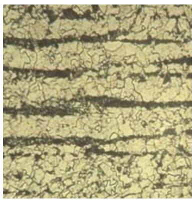
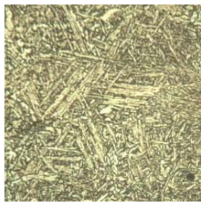
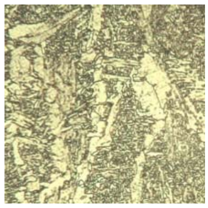
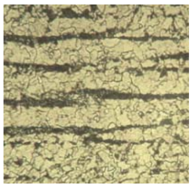
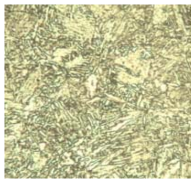
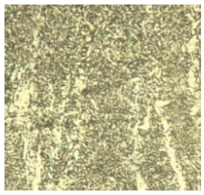
Welding method	Macrostructure	Parent material	Coarsened grain region	Weld metal
MMA				
FCAW				

Table 6. *Conditions for performance of resistance to cold cracking measurements*

Test no	Welding method	H_D ml/100g Fe	e_L kJ/mm
1	**MMA**	2,0	2,6
2		7,0	2,1
3		12,0	1,6
4	**FCAW**	5,0	1,0
5		10,0	2,4

The implant tests were performed according to PN-90/M-69760 standard [7]. Three samples were used for each level of applied stress. As stated above the two parameters (apart from the stress level) changed. They were: the heat input and the diffusible hydrogen level for the two mentioned welding methods, the manual covered electrode (MMA) and semi-automatic shielding gas arc method (FCAW). The example of the test result is shown on Fig. 2 as a graph σ_i versus time to implant sample break t_z.

Fig.1. Photograph of IMPLANT 02 test machine

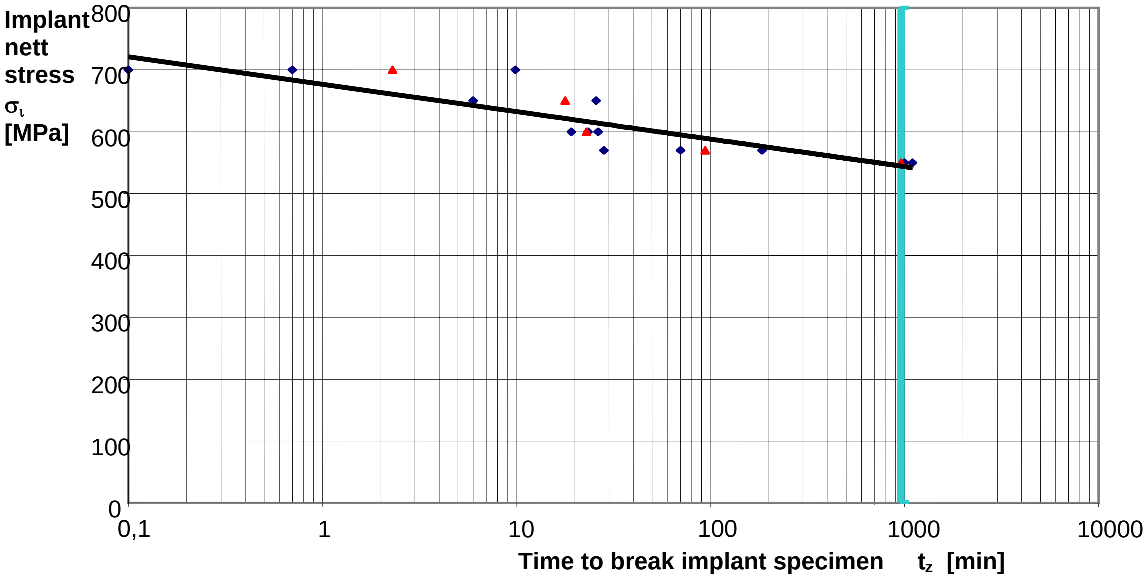


Fig. 2. Implant test results: Steel P460NL1, MMA welding, el = 2.6 kJ/mm, H_D =2ml/100gFe. σ_{kr}=550MPa. Each test result marked squere, average and critical marked as triangle

On the graph the critical stress σ_{kr} is defined for breaking time equal to or greater than16 hours (960 minutes), for at least two out of three samples tested. On the graph all the individual measurements are indicated as squers. The average and critical values are indicated as triangle. The Table 7 summarizes all the results of measurements for the applied conditions. The table also shows value $\alpha=\sigma_{kr}/R_e$ which is an indicator of cold cracking resistivity of welded material. For the used P460NL1 steel the yield stress was Re = 519MPa. It is understood that if the value of $\alpha<0,6$ than the steel is considered as not resistant to cold cracking and when $0,6 < \alpha < 1$, steel is considered partially resistant to cold cracking [14].

***Table 7**. All test results of cold cracking resistance obtained in implant test for welded P460NL1 steel*

Test no	Welding Method	Hd	e_L	σ_{kr}	$t_{8/5}$	α
		ml/100g Fe	kJ/mm	MPa	s	-
1	MMA	2,0	2,6	550	11,7	1,06
2		7,0	2,1	480	9,4	0,93
3		12,0	1,6	430	7,2	0,83
4	FCAW	5,0	1,0	450	4,5	0,87
5		10,0	2,4	420	10,8	0,81

This table also shows cooling time between 800 and 500^{0}C for the metal in HAZ as a result of heating and cooling process resulting from specified implant test conditions (weld heat input, thickness of plate welded, etc.). The cooling time $t_{8/5}$ was determined according to the relation specified in [15] as follows:

$$t_{8/5} = (6700 - 5 \cdot T_0) \cdot f_3 \cdot k \cdot e_L \left(\frac{1}{500 - T_0} - \frac{1}{800 - T_0} \right)$$

where:
$t_{8/5}$ - cooling time in the temperature range 800 ÷ 500ºC, s
f_3 - the aspect ratio of three direction heat flow, f_3 = 1.0
k- heat efficiency, for MMA and FCAW welding k=0,85
T_0 - initial temperature of the work piece, 20ºC
d - thickness of the auxiliary plate d = 20mm - does not affect the $t_{8/5}$
e_l - welding heat input, kJ/mm
The heat input was determined on the basis of the relationship:

$$e_L = 0{,}001 \cdot U \cdot I / v$$

where:
U-arc voltage, V
I - welding current, A
v - welding speed, mm/s

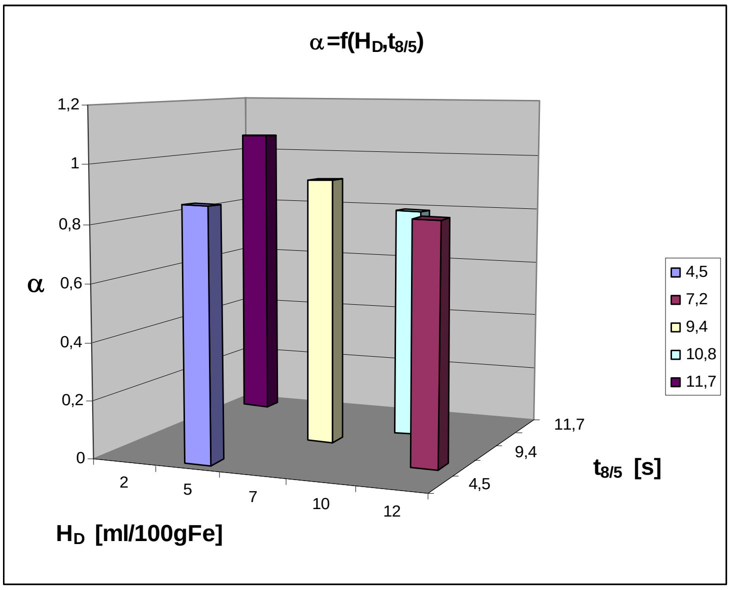


Fig. 3. The influence of the diffusible hydrogen H_D and the cooling time $t_{8/5}$ on resistance to cold cracking indicator α for joints made by MMA and FCAW methods on P460NL1 steel

As shown above, the parameters influencing the resistance to cold cracking changed to quite a large extent. The welding heat input was changed in the range of 1,6-2,6kJ/mm. Obviously the heat input is in relation to HAZ metal cooling time between temperature 800-500^{0}C, which was in the range $t_{8/5}$=4,5-11,7s. The second changed parameter, the diffusible hydrogen content varied in the range H_D=2-12ml/100gFe. Table 7 shows that with increasing diffusible hydrogen content and decreasing the welding heat input and thus shortening the cooling time in the 800-500^{0}C, a decrease of resistance to cold cracking is visible. The resistance to cold cracking can be expressed by the value of the critical stress, or cold cracking resistivity of welded material indicator α. The same relationship can be seen from Fig. 3 showing three dimensional graph α=f(H_D, $t_{8/5}$). It shows that α decreases with increasing diffusible hydrogen content of H_D and with decreasing cooling time $t_{8/5}$ value, and thus increasing the cooling rate in the HAZ. The graph shows that during the welding of P460NL1 steel, partial resistance to cold cracking is observed regardless of the value of $t_{8/5}$ and H_D ($0,6<\alpha<1$). Only for low cooling rate ($t_{8/5}$=11,7s) and low diffusible hydrogen content, H_D=2ml/100gFe cold cracking resistivity indicator is $\alpha>1$.

CONCLUSIONS

The study of resistance to cold cracking of welds made by coated electrodes and flux cored wire on P460NL1 steel can allow to formulate the following conclusions:

1. The investigation of resistance to cold cracking was carried out by implant test for standard, recommended conditions of MMA and FCAW welding and two variables: heat input in the range e_l=6-2,6kJ/mm and diffusible hydrogen range H_D=2-12ml/100gFe.
2. Planed levels of diffusible hydrogen in welded joints were obtained after a controlled humidification of coated electrodes.
3. Conditions of welding during implant tests for different heat input resulted in changes of the cooling time in the HAZ metal in the range $t_{8/5}$=4,5-11,7s.
4. Critical implant stress σ_{kr} and cold cracking resistance indicator $\alpha=\sigma_{kr}/R_e$ measured during the implant tests for the P460NL1 steel are dependent on diffusible hydrogen content H_D and cooling time $t_{8/5}$.
5. Relationship between cold cracking indicator α versus H_D and $t_{8/5}$ is show in Table VII and the graph on the Fig. 3. The higher diffusible hydrogen H_D and lower cooling time $t_{8/5}$ the lower the resistance to cold cracking of the P460NL1 steel during welding.
6. Steel P460NL1 during welding by both methods (MMA and FCAW) for standard conditions shows partial resistance to cold cracking (cold crack resistance indicator $0.6<\alpha<1$).

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