INTEGRITY OF WELDED JOINTS BETWEEN PIPES FOR PRESSURE VESSELS MADE OF HOT ROLLED FINE-GRAINED STEEL P460NL1

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Abstract:

This paper contains results of tests performed in order to determine mechanical properties of steel P460NL1, used as filler material during the execution of welded joints. Arc welding of samples from which the specimens were taken was carried out through the application of welding process 111, because it is one of the processes for the execution of pipelines for the transport of oil or gas. Microspecimens with diameter of 1,5 mm were tested in order to determine tensile properties of material taken from the heat-affected zone and weld metal, while specimens with diameter of 6 mm were tested in order to determine tensile properties of parent material. Standard Charpy V-notch specimens were used in order to determine impact energy. Results of metallographic tests which refer to the structure of a pipe welded joint are also presented.

On the basis of results of tensile tests carried out on specimens taken from parent material, heat-affected zone and weld metal it was determined that mean values of yield strength and tensile strength of parent material and weld metal are practically equal, while these values for heat-affected zone are more than 20% lower. The situation is similar regarding the value of elongation.Mean values of overall impact energy for parent material and weld metal are practically equal, while in comparison with results obtained for material taken from the heat-affected zone they are more than 2 times lower. Through the analysis of energy necessary for initiation and propagation of cracks it was determined that the ratio of those energies is very good when it comes to parent material and weld metal, while it was also determined that the critical location for crack initiation is the heat-affected zone.

Integrity evaluation of the air tank during exploitation was carried out through the analytical calculation of strength of the shell and upper bottom based on their technical properties after the completion of reparatory welding/surface welding.

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1 INTRODUCTION

Hot rolled fine-grained steels with improved strength for pressure equipment are defined in standards EN 10027-4 [1] and EN 10028-3 [2]. Longitudinally welded pipes are being produced through the application of high frequency welding, while spirally welded pipes are being produced through the application of flux-cored arc welding. Samples of 8 mm thick sheet metal were joined through the application of arc welding.

2 EXPERIMENTAL PROCEDURE

Chemical composition of parent material is presented in table 1, while mechanical properties are shown in table 2. Chemical composition of the applied electrode EVB 50Ni is presented in table 3, while mechanical properties of pure weld metal are shown in table 4.

Table 1. Chemical composition of steel P460NL1, in accordance with standard [2]

Steel	C	Si	Mn	Cr	P	S	Cu	Ni	Mo	Al	Ti	V
P460NL1	0.20	0.60	1.10-1.70	0.30	0.025	0.015	0.70	0.80	0.10	0.020	0.030	0.20

Table 2. Mechanical properties of steel P460NL1, in accordance with standard [2]

Steel	Yield strength *YS / MPa*	Tensile strength *TS / MPa*	Elongation *A / %*	Impact energy *KV / J*
P460NL1	min. 470	570-730	min 17	min 63 (+ 20 ^{0}C)

Table 3. Chemical composition of electrode EVB 50Ni, mass percentage

Electrode	C	Si	Mn	Ni
EVB 50Ni	0,13	0,20	1,40	0,90

Table 4. Mechanical properties of weld metal

Electrode	Yield strength *YS / MPa*	Tensile strength *TS / MPa*	Elongation *A5 / %*	Impact energy *KV / J*
EVB 50Ni	min. 460	580-620	Min. 27	min. 120

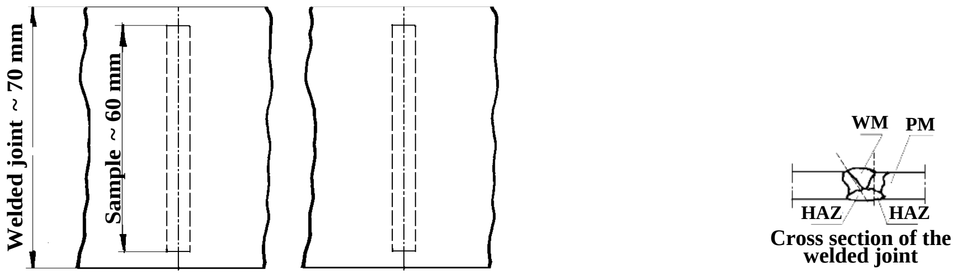
2.1 Sampling and manufacturing of specimens for tensile testing

Microspecimens were extracted from weld metal and heat-affected zone, as presented in figure 1. Appearance of the specimen is shown in figure 2. Microspecimens are being made as follows: samples taken from weld metal and heat-affected zone are being machined in order to obtain 3 mm diameter and afterwards create an M3 mm thread, while test sections of specimens are being machined with a displacement at 1.5 mm. Standard shape of a specimen with a 6 mm diameter, taken from parent material, is presented in figure 3. Tensile tests [3] were carried out at an electromechanical tensile testing machine SCHENCK-TREBEL RM 100.

2.2 Sampling and production of specimens for impact energy tests

In order to determine the impact energy specimens were extracted from samples of parent material, weld metal and heat-affected zone (three specimens from each sample), in accordance with figure 4. Dimensions of specimens are shown in figure 5 [4]. Tests were carried out through the use of SCHENCK TREBELL 150/300 Charpy pendulum, which enables division of overall impact energy into 2 components: crack initiation energy and crack propagation energy.

a) Samples taken from heat-affected zone *b) Samples taken from weld metal*



c) Length of required samples *d) Welded joint*

Figure 1. Appearance of samples from which the microspecimens were extracted

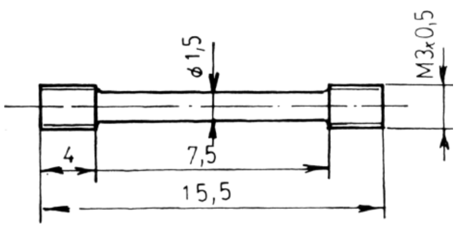


Figure 2. Dimensions of microspecimens taken from HAZ and WM samples

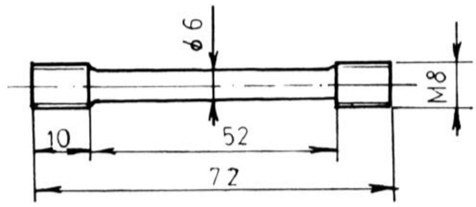


Figure 3. Dimensions of microspecimens taken from parent material sample

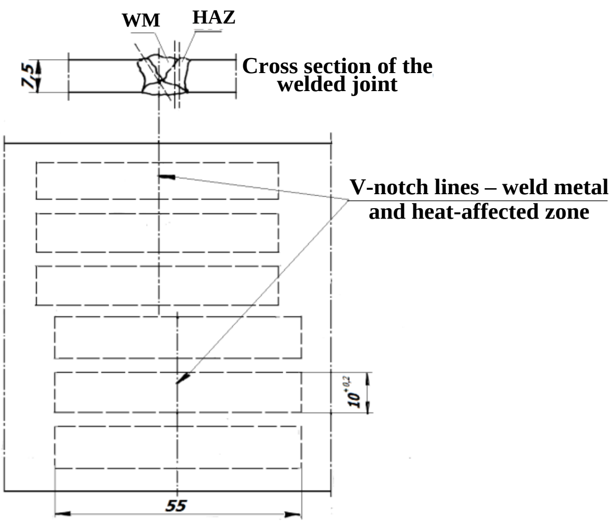


Figure 4. Position of specimens within the sample

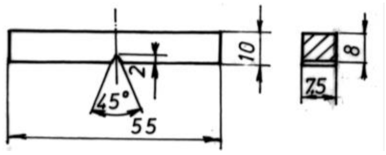


Figure 5. V-notch specimen

2.3 Sampling and Microstructural Testing

Locations where samples in the area of welded joints at pipes Ø139.8 x 8 mm which are supposed to operate under pressure of p = 160 bar (p = 16 MPa) were taken in order to perform structural tests are presented in figure 6.

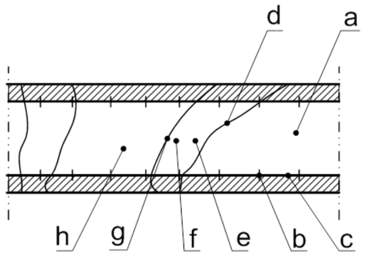


Figure 6. Arrangement of pipe samples taken for microstructural tests

3 ANALYSIS OF TEST RESULTS

3.1 Analysis of Chemical Composition

Results of quantometric analysis that refer to the chemical composition of steel P460NL1, which was used during these researches, are given in Table 5. The analysis showed that this steel has significantly lower content of carbon than the maximum value defined in the standard [2] and that it is, according to the value of carbon equivalent C_{ek}, prone to cold cracking.

Table 5. Chemical composition of steel P460NL1, mass percentage

Steel	C	Si	Mn	P	S	Cr	Ni	Nb	Cu	Al	Cek
P460NL1	0.123	0.266	1.334	0.015	0.007	0.026	0.019	0.004	0.140	0.030	0.398

3.2 Tensile testing

Basic mechanical properties of material (stress – strain curve) are being determined by tensile testing [3]. Results that refer to tensile properties of parent material, weld metal and heat-affected zone of steel P460NL1 are presented in tables 6, 7 and 8. Mean values of yield strength for parent material and weld metal are almost equal and 22% lower than mean value of yield strength for heat-affected zone (HAZ). Situation’s practically the same when it comes to elongations. A curve obtained during the testing is shown in figure 7.

Table 6. Tensile properties of parent material

Specimen designation	Yield strength, YS / MPa	Tensile strength, TS / MPa	Elongation, A5 / %
Epr-1	444	551	25.2
Epr-2	435	540	23.4
Epr-3	446	556	24.8

Table 7. Tensile properties of material in heat-affected zone

Specimen designation	Yield strength, YS / MPa	Tensile strength, TS / MPa	Elongation, A5 / %
Epr-1	524	583	18.7
Epr-2	614	657	18.4
Epr-3	603	648	15.1

Table 8. Tensile properties of weld metal

Specimen designation	Yield strength, YS / MPa	Tensile strength, TS / MPa	Elongation, A5 / %
Epr-1	433	583	25.3
Epr-2	442	596	21.7
Epr-3	444	618	23.7

On the basis of results of tensile tests it was determined that mean values of yield strength and tensile strength of parent material and weld metal are almost equal, while mean values of yield strength and tensile strength of material in heat-affected zone are more than 20% lower. The situation is similar regarding the value of elongation.

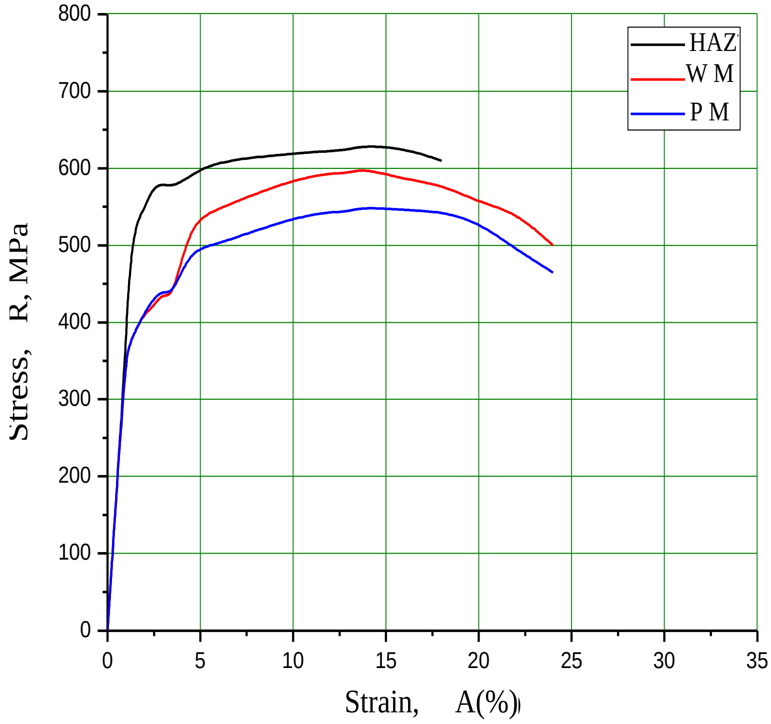


Figure 7. Stress – strain curve for HAZ, WM, PM at 20 °C

3.3 Determination of Impact Energy

Testing of notched specimens enables the determination of impact energy required in order to cause the fracture of the specimen [4]. It is most commonly used in order to check the quality and homogeneity of material. This kind of testing is useful when it comes to determination of proneness toward brittle cracking, or proneness toward ductility reduction during service. Test results are presented in table 9.

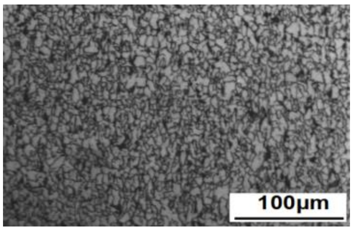
Table 9. Results of impact energy testing

Sample designation	Specimen designation	Overall impact Energy, E_I [J]	Crack initiation Energy, E_{ci} (J)	Crack propagation energy, E_{cp} (J)
PM	1	115,3	28,2	87,1
	2	104,4	23,4	81,0
	3	112,3	27,6	84,7
WM	1	118,7	35,3	83,4
	2	130.4	40,9	89,5
	3	89,9	25,7	64,2
HAZ	1	52,7	22,6	30,1
	2	50,2	21,5	28,7
	3	46,4	20,4	26,0

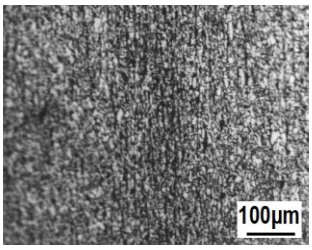
Mean values of overall impact energy for parent material and weld metal are practically equal, while in comparison with results obtained for material taken from the heat-affected zone they are more than 2 times higher. Through the analysis of energy necessary for initiation and propagation of cracks it was determined that the ratio of those energies is very good when it comes to parent material and weld metal, while it was also determined that the critical location for crack initiation is the heat-affected zone.

3.4 Metallographic Tests

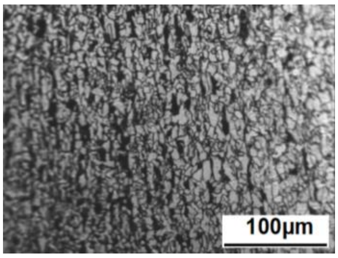
Structures of parent material, heat-affected zone and weld metal of pipe samples obtained by metallographic testing are shown in figures 9 and 10.



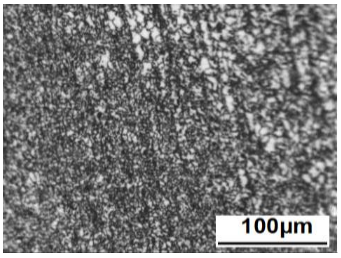
a) Parent metal



b) Parent metal

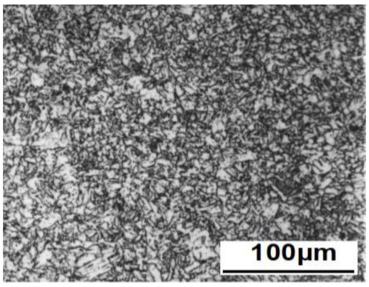


c) Parent metal

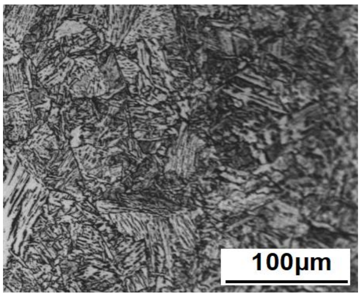


d) Parent metal and heat –affected zone

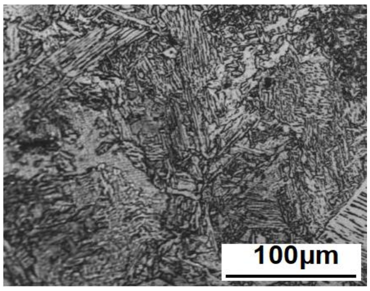
Figure 8. Microstructure of parent metal and transition area between the parent metal and HAZ



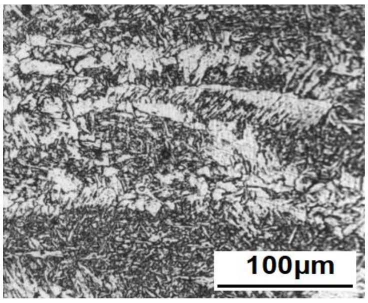
a) Fine-grained section of the HAZ



b) Coarse-grained section of the HAZ



c) Fusion line between the HAZ and weld metal



d) Weld metal

Figure 9. Microstructure of transition areas between HAZ and weld metal

Basic properties of obtained microstructures are as follows;

- Parent metal has a typical ferrite-pearlite structure, figure 8 (a-c).
- Section of the HAZ next to PM is being characterized by fine grains with structure similar as parent metal, figures 8 (d) and 9 (a);
- Coarse-grained section of HAZ possesses complex microstructure which consists of bainite, small amount of proeutectoid ferrite and secondary ferrite, figure 9 (b);
- Transition area between HAZ and WM possesses a similar mixed structure - predominant bainite, a bit of coarse proeutoctoid ferrite and secondary ferrite, figure 9 (c);
- Weld metal possesses complex microstructure which consists of secondary bainite, coarse proeutoctoid ferrite, acicular ferrite and bainite, figure 9 (d).

Parent metal has a typical ferrite-pearlite structure. It should be noted that the volumetric share of ferrite and pearlite in various areas differs, figure 8 (a-c). In the local areas of PM microstructure bandiness is detectable, or in other words clusters of secondary phase particles and inclusions fractured during the process of rolling in oriented formation, figure 8 (b-c). Differing volumetric share of ferrite and pearlite in tested areas, as well as presence of bands in local areas indicate that the structure of parent metal is non-homogeneous. Strongly expressed inhomogeneity of microstructure in the area of heat-affected zone, figures 8 (d) and 9 (a-b), is a consequence of microstructural transformations that occurred due to various rates of heating and cooling of particular zones in this area during the welding process. In the transition area between parent metal and HAZ the structure is similar to the structure of parent metal but significantly finer grained, figures 8 (d) and 9 (a). As can be detected on photographs presented in figures 8 (d) and 9 (a-c), fine-grained structure characteristic for the transition area between HAZ and parent metal is getting coarser towards the fusion line between HAZ and WM. In the middle section of the heat-affected zone, figure 9 (b), as well as in the fusion area between the heat-affected zone and weld metal, figure 9 (c), microstructure consists of upper and lower bainite, ferrite and secondary phases. In figure 9 (d) the microstructure that consists mostly of ferrite and bainite, with a small volumetric share of secondary phases, is shown.

4 INTEGRITY EVALUATION

According to the pressure equipment directive [5], for design and evaluation integrity during exploitation it is necessary to use calculation methods based on empirical formulas, analytical procedures and fracture mechanics. Integrity evaluation of the air tank during exploitation was carried out through the analytical calculation of strength of the shell and upper bottom based on their technical properties after the completion of reparatory welding/surface welding.

4.1 Calculation of shell strength with respect to internal pressure

Calculation of shell strength with respect to internal pressure has been carried out through the use of standard [6]. This proved that thickness of the cylindrical section of the shell is sufficient.

$$s_o = \frac{D_o \cdot p}{2 \cdot f \cdot v + p} + \delta_e + c = \frac{139.8 \cdot 16}{2 \cdot 241.25 \cdot 0.8 + 16} + 0.8 + 1 = 8.01 mm \leq 8 \qquad (1)$$

where f is the nominal design stress [6]:

$$f = \min\left\{\frac{R_{p0.2/t}}{1.5}; \frac{R_{m/20^\circ}}{2.4}\right\} = \min\left\{\frac{442}{1.5}; \frac{579}{2.4}\right\} = 241.25 MPa$$

5 CONCLUSION

On the basis of results of executed tests and earlier researches it can be concluded that the procedure and welding technology for steels with improved strength have critical influence on mechanical properties of welded joint, as well as on the reliability of pipelines for the transport of oil and gas. Welding of welded pipes should be carried out with as little heat input as possible.

ACKNOWLEDGEMENT

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6 REFERENCES

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