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IMPACT OF COOLING RATE ON THE HARDNESS OF HEAT AFFECTED ZONE OF MICROALLOYED STEEL P460NL1

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ABSTRACT
Cooling time in the temperature interval from 800 °C to 500 °C has a significant impact on the properties of heat affected zone of welded joints on microalloyed steels. Based on the cooling time it is possible to calculate the cooling rate. This paper presents the results of hardness tests of heat affected zone on the microalloyed steel P460NL1 in relation to different values of cooling rate.
Keywords: welding, cooling rate, hardness, heat affected zone, microalloyed steel, P460NL1

1. INTRODUCTION
In order to prevent undesirable microstructural transformations, such as martensitic transformation, in the heat affected zone of microalloyed steels it is necessary to use appropriate parameters of welding process (preheating temperature, welding current, electric arc voltage, travel speed etc.). Cooling rate and cooling time in the temperature interval between 800 °C and 500 °C has a significant impact on the mechanical properties of heat affected zone of welded joints on microalloyed steels. Cooling parameters depend on welding parameters. This paper presents the results of hardness tests of heat affected zone on the microalloyed steel P460NL1 in relation to different values of cooling rate.

2. EXPERIMENTAL PROCEDURE AND RESULTS
The plates of microalloyed steel P460NL1 were used as a base material for welding. This steel is meant to produce pressure vessels designated for work at low temperatures. The chemical composition of the base material is: 0,153% C – 0,38% Si – 1,4% Mn – 0,015% P – 0,0021% S – 0,031% Al – 0,037% Cr – 0,63% Ni – 0,004% Mo – 0,061% Cu – 0,099% V – 0,038% Nb – 0,004% Ti – 0,0003% B – 0,0052% N. Steel plates (14 mm thick) were used for welding. Before welding plates edges were prepared to form Y groove. Two welded joints, each 500 mm long, have been made. Welding was performed using two different types of commercially available filler materials: flux-corred self-shielded electrode wire of diameter Ø1,6 mm, for the first welded joint (WJ-1) and metal-corred electrode wire of diameter Ø1,2 mm, for the second welded joint (WJ-2). The second electrode wire was used in combination with mixture of gases: Ar + 6% CO2 + 1 %O_2.

Multi-pass welding was carried out, with 5 passes in each welded joint. Welding parameters for both welded joints are shown in table 1.

Based on the welding parameters, heat input [1] was calculated for each of the passages, using the formula (1):

$$q = (60 \cdot k \cdot I \cdot U) / (10000 \cdot V_t) \quad (1)$$

q – heat input per unit length of welded joint (kJ/mm),
I – welding current (A),
U – electric arc voltage (V),
V_t – welding travel speed (cm/min) and
k – efficiency coefficient (k = 0,8).

The results of these calculations are also shown in table 1.

Table 1. Welding parameters and heat input per unit length of welded joint

Welded joint	Passages	T_p (°C)	I (A)	U (V)	V_t (cm/min)	q (kJ/mm)
WJ-1	1	130	115	20,2	6,8	1,6
	2	120	199	24,7	13,5	1,7
	3	120	227	26,2	15,9	1,8
	4	120	232	26,3	21,9	1,3
	5	120	228	26,3	17,6	1,6
WJ-2	1	150	225	26,7	27,3	1,1
	2	130	217	26,7	19,2	1,4
	3	120	232	27,7	21,4	1,4
	4	135	232	26,6	22,6	1,3
	5	120	224	26,8	19,6	1,5

Using the data shown in table 1, the calculations of cooling time of the material in the range between 800 °C and 500 °C were conducted for each of the passages in the welded joints. These calculations were performed using the formulas (2), (3) and (4) in accordance with the requirements defined in the European standard EN 1011-2: 2001 / A1: 2003, Welding - Recommendations for welding of metallic materials - Part 2: Arc welding of ferritic steels, Annex C [1].

The transition thickness was calculated for each case, using the formula (2) in order to determine in how many directions the heat is conducted during cooling [1]:

$$d_t = \text{sqrt}((10^5 \cdot F_2 \cdot q^2/d^2 \cdot (4300-4,3 \cdot T_p))/(6700-5 \cdot T_p) \cdot ((1/(500-T_p)^2-1/(800-T_p)^2)/(1/(500-T_p)-1/(800-T_p)))) \quad ...(2)$$

In the case when transition thickness has a smaller value comparing to the nominal thickness of base material, the heat is conducted in two directions and the formula (3) is applicable for calculating cooling time of the material in the temperature rangde from 800 °C to 500 °C [1]:

$$\Delta t_{8/5} = 10^5 \cdot F_2 \cdot q^2 / d^2 \cdot (4300 - 4,3 \cdot T_p) \cdot (1 / (500 - T_p)^2 - 1 / (800 - T_p)^2) \quad ... (3)$$

In the case when transition thickness has a greater value comparing to the nominal thickness of base material, the heat is conducted in three directions and the formula (4) is applicable for calculating cooling time of the material in the temperature rangde from 800 °C to 500 °C [1]:

$$\Delta t_{8/5} = F_3 \cdot q \cdot (6700 - 5 \cdot T_p) \cdot (1 / (500 - T_p) - 1 / (800 - T_p)) \quad \text{... (4)}$$

d – nominal thickness of base material (d = 14 mm),
d_t – transition thickness (mm),
q – heat input per unit length of welded joint (kJ/mm),
T_p – preheating temperature (°C),
$\Delta t_{8/5}$ – cooling time of the material in the temperature range from 800 °C to 500 °C (s),
F_2 – geometry factor (F_2 = 0,9) and
F_3 – geometry factor (F_3 = 0,9).

Considering that the cooling profile is continuous [2], when the cooling time in the temperature range between 800 °C and 500 °C is known, the mean cooling rate can be calculated using the simple formula (5):

$$V_c = (800\ °C - 500\ °C) / \Delta t_{8/5} = 300\ °C / \Delta t_{8/5} \quad \text{... (5)}$$

V_c – cooling rate (°C/s) and
$\Delta t_{8/5}$ – cooling time of the material in the temperature range between 800 °C and 500 °C (s).

The results of all these calculations are shown in table 2.

Table 2. Cooling parameters of welded joints

Welded joint	Passages	d_t (mm)	$\Delta t_{8/5}$ (s)	V_c (°C/s)
WJ-1	1	20,4	22,3	13,5
	2	20,8	23,9	12,6
	3	21,4	26,8	11,2
	4	18,2	14,0	21,4
	5	20,2	21,2	14,2
WJ-2	1	17,2	10,6	28,3
	2	19,1	17,1	17,5
	3	18,9	16,2	18,5
	4	18,4	15,1	19,9
	5	19,5	18,6	16,1

In order to establish a correlation between the cooling rate and values of hardness in the heat affected zones of welded joints, two samples were prepared by cuting the welded plates. Hardness testing of the heat affected zones of both samples were performed using the Vickers method HV_{10}. The results are shown in figure 2.

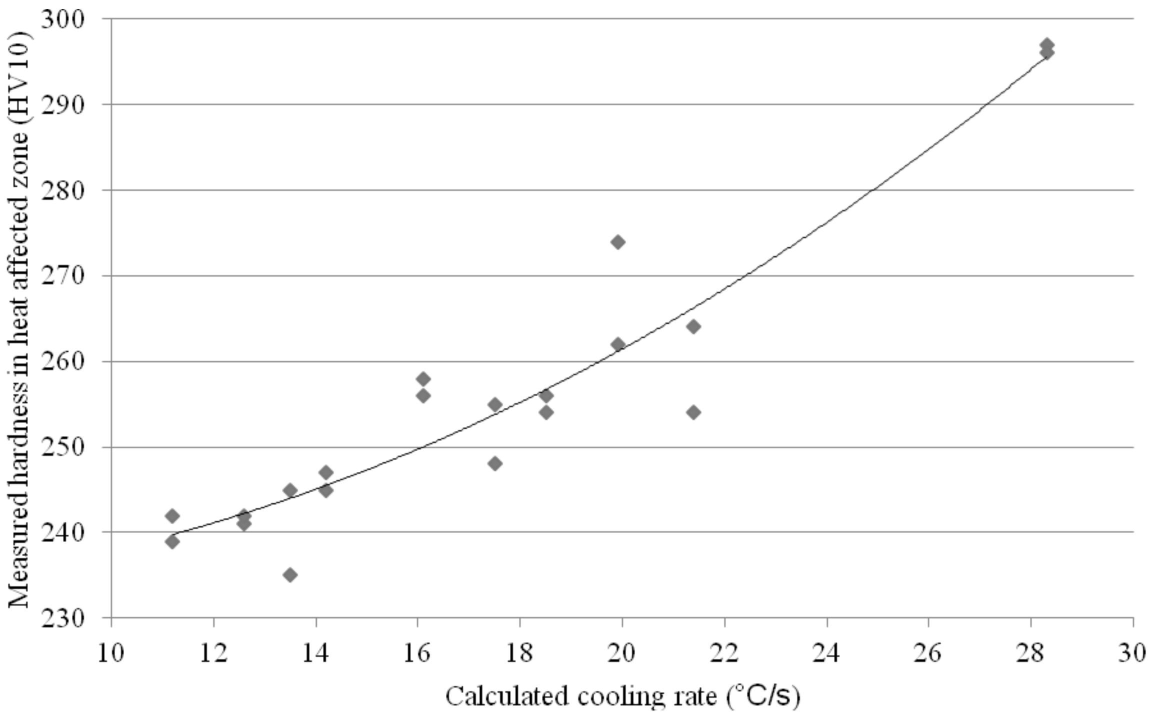

Figure 2. Correlation between the cooling rate and values of hardness in the heat affected zones

3. CONCLUSIONS

Based on the shown results it can be concluded that the trend of increase in hardness of heat affected zone depending on the cooling rate is approximately linear. At a cooling rate of 28 °C/s the hardness of 297HV is achieved in heat affected zone. The high value of hardness in heat affected zone corresponds to martensitic microstructure. Therefore, it is recommended that the cooling rate, during welding of steel P460NL1 should be lower than 20 °C/s. Diagrams like this shown in figure 2 can be used to select suitable welding parameters, which will not lead to the undesirable transformation of the microstructure, such as a martensitic transformation, in heat affected zone.

4. REFERENCES

[1] European standard EN 1011-2: 2001 / A1: 2003, "Welding - Recommendations for welding of metallic materials - Part 2: Arc welding of ferritic steels".,

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