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COMPARATIVE ANALYSIS OF HARDNESS IN DIFFERENT ZONES OF WELD

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Abstract: *This paper studies the HV 10 Vickers hardness values measured on the end zones (beginning and end) of the samples taken for approval of welding technologies to analyze the situation less common welding technology without end plates. These values are then compared with those determined by measurements made in areas of welds means to assess the degree of deviation from the recommended values for steel grade analyzed. It was chosen for homologating of a welding process a steel sheet of thickness 20 mm of P355NL1 quality welded by the processes 141 + 111 + 121. The work presents the macroscopic and microscopic analysis of samples and preheats temperature calculation, calculation and estimation of carbon equivalent maximum hardness in the heat affected zone when welding steel P355NL1. In these areas of the beginning and end of the seam, there is a situation similar to welding the weld below 100 mm in length, where the thermal field propagates in welding non-steady state compared to the middle portion of long welded row, where the heat propagates quasi-stationary regime.*

Keywords*: weld, hardness HV 10, homologation, HAZ, WIG welding.*

1. INTRODUCTION

Currently, the approval procedures for welding, welders' authorization or extension of authorization/ certification of welders is performed based on standardized welded samples with lengths of about 500mm, and the end portion with length of 20mm is removed. The ends of the sample welds are not used for the tests, believing that they contain nonconformities due to transient process of welding regime.

In technical literature [1], it is specified that in these beginning and end of line zones, the thermal field propagates in a non-steady state, which is isotherms bend and thicken, which can be proved by the colors appearing on the surface of sheets when cleaned and polished to metallic luster. Thickening of isotherms is explained by the increase of temperature gradients, by the increase of temperature gradients, by the increase of the cooling rate in these critical zones at the beginning and at the end of the line, implicitly by the decrease of the time of cooling $t_{8/5}$.

But there are situations where, in the welding technology, it is not possible to attach some little plates on which to start or finish welded seams.

The present article studies the values of HV 10 Vickers hardness in these beginning and end zones of the welding is made without putting on the technological plates at the beginning and at the end, compared to the values of HV 10 Vickers hardness measured in the middle part of the weld.

In these zones at the beginning and at the end of the weld, a similarity to the case of welding in short lines and multilayer welding, with the weld length less than 100 mm, can be noticed.

We choose for homologating a welding process, a steel sheet of 20 mm thickness, P355NL1 quality, welded by the following processes: 141 + 111 + 121. The added materials are the followings: CORBOROD Mo ø2 + SANBAZ ø3.2 + OS2 ø4 + FLUX OP121TTW.

Symbolizing of welding processes used for homologation*:*

- 141 – inert gas electric arc welding with wolfram electrode (WIG welding);
- 111 – electric arc welding with coated electrode;
- 121 – submerged arc welding with wire electrode.

2. EXPERIMENTAL PROCEDURE DESCRIPTION

2.1. Specific features of P355NL1 base material

P355NL1 steel is steel for pressure vessels, a non-alloyed, quality, fine-grained, with flow limit 355 N/mm^2, normalized, used at low temperatures.

The correspondence of P355NL1 steel to other equivalent steel names is given in Table 1 [2]. P355NL1 steel has the following chemical composition at analysis on liquid steel for flat and long products (Table 2) [2–3]:

2.2. Added material used for welding P355NL1 steel

For homologation of welding probe, three welding processes were used:

The root of weld was welded by 141 process- inert gas electric arc welding with wolfram electrode (WIG welding), using as added material, wire of CARBOROD Mo quality, 2 mm in diameter.

This welding process-electric arc welding in inert gas medium with wolfram electrode is chosen especially for root welding, due first of all to a controlled penetration that allows an excellent control on the formation of the

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Table 1

Correspondence of P355NL1 steel to other equivalent steel names [2]

EN Steel Type	According to EN 10027 – 2	DIN Steel Type	DIN No.	STAS 500/2	United States of America ASTM, AISI	Europe St. EU EN 10025
P355NL1	1.0566	TStE 355	17102	OL52-4kf, normalized	A 36-207, A 510, AP / FP, A299, A516 (70) (485), A573 (70) (485), A618 (II), A633 (D), A678(A), A707(L1), A707 (L2), A714 (II), A724	Fe 510 D1

Table 2

Chemical Composition of P355NL1 steel [2, 3]

Steel	Deoxidation Degree	Subgroup	C %	Si % max	Mn % max	P % max	S % max	Cu % max	Ni % max	Al % max	V % max
P355NL1	FF	QS	0.18	0.50	0.90…1.65	0.025	0.020	0.55	0.50	0.020	0.12

weld root, characterized mainly by protection of liquid bath offered by inert gas that is used.

- Welding parameters for 141 process are as follows:
  I_s = 100 A, U_a = 13 V, Polarity: DC$^+$,
  Welding rate: 8 cm/min,
  Welding energy: 10.50 kJ/cm,

Electrod type: WL 20 ø3.2 mm – Wolfram 20 Lanthanum 2%.

Five lines of filling the gap were welded by 111 process – electric arc welding with coated electrode, using as added material, SANBAZ ø3.2 mm electrodes.

Welding process electric – manual with coated electrodes, is characterized by a versatile quality and thickness of base materials used, as well as welding positions.

- Welding parameters for 111 process are as follows:
  I_s = 129, U_a =23 V, Polarity: DC$^+$,
  Welding rate: 19 cm/min,
  Welding energy: 9.40 kJ/cm.
- Final layers are made by 121 process – submerged arc welding with wire electrode, having as added material OE-S2 4 mm in diameter wire, and as flux OP 121TTW.

The submerged arc welding (SAW) process is suited to make relatively thick welds, with easy access at welding position, with a high facing rate, with a high degree of utilization of added material, with a very high quality of weld no matter operator's skill, as there is a big possibility of alloying the weld by wire and flux.

Welding parameters for 121 process are as follows:

I_s = 575 A, U_a = 29 V, Polarity: DC$^+$,
Welding rate: 55 cm/min,
Welding energy: 17.40 kJ/cm.

3. RESEARCH RESULTS

3.1. HV 10 Vickers hardness tests to the welded sample

We cut the edges of the welded sample without technological plates at the beginning and at the end, using an alternative saw, according to Fig. 1. These have been then cut off for the macro and microscopical analysis, as well for making HV 10 Vickers hardness tests: Fig. 2 corresponding to the macroscopic map for the specimen cut off from the beginning stub of the sample and Fig. 3, corresponding to the macroscopic map for the specimen cut off from the end of the sample (crater area).

Further on, they have been metallographycally polished using abrasive paper (with granulation 400, 600, 800, 1000, 1500), after which abrasive powder (Topol 1, Topol 2 and Topol 3), with granulations from 3 to 0.1 µm.

After that, the polished surfaces were etched with a metallographic etchant specific to low-alloyed steels (Nital 4% for the macrostructure and Nital 2% for the microstructure).

In order to establish HV 10 Vickers hardness values, two test axis have been established on the sample, represented in Fig. 4, on which three sets of HV 10 Vickers hardness were applied for each axis on the two base materials BM1, BM2, on the two heat – affected zones HAZ 1, HAZ 2, as well as in the welded seam WS, with the determined values in Table 3 (illustrated in Fig. 5 for the set of data measured on the upper zone of the welded seam and in Fig. 6 for the set of data measured on the root of weld) for the welded sample applied to the specimen from the beginning of the sample, and Table 4 (illustrated in Fig. 7 for the set of data measured on the upper zone of the welded seam and in Fig. 8 for the set of data measured on the root of weld) applied to the specimen at the end of the sample.

Fig. 1. Image with sampling from the beginning and from the end of the welded plate for homologating the welding process. (1:4 scale).

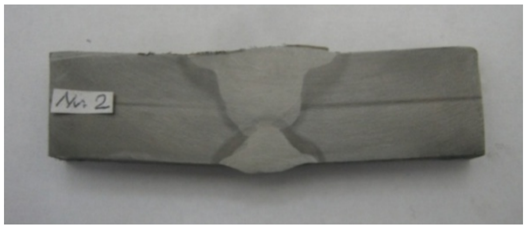

Fig. 2. Macroscopical image for the specimen cut off the beginning edge of the sample. (1:1.3 scale).

Fig. 3. Macroscopical image for the specimen cut off the end of the sample (the crater area). (1:1.3 scale).

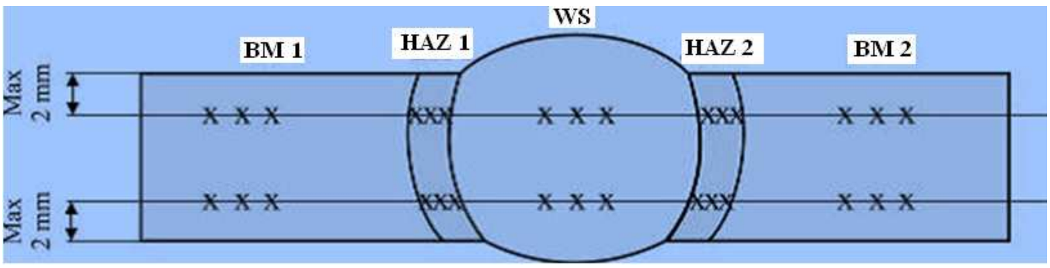

Fig. 4. Graphical representation on two axes of the zones of hardness sampling for P355NL1 steel.

Table 3

HV 10 Vickers hardness values applied to the specimen cut off from the beginning of the sample

Zone / Axis	BM1 Sheet iron 20 mm	HAZ 1 Sheet iron 20 mm	WS	HAZ 2 Sheet iron 20 mm	BM 2 Sheet iron 20 mm
1	289-290-288	302-303-301	319-314-310	299-298-288	275-276-271
2	270-272-271	296-294-297	302-307-305	295-291-289	277-277-275

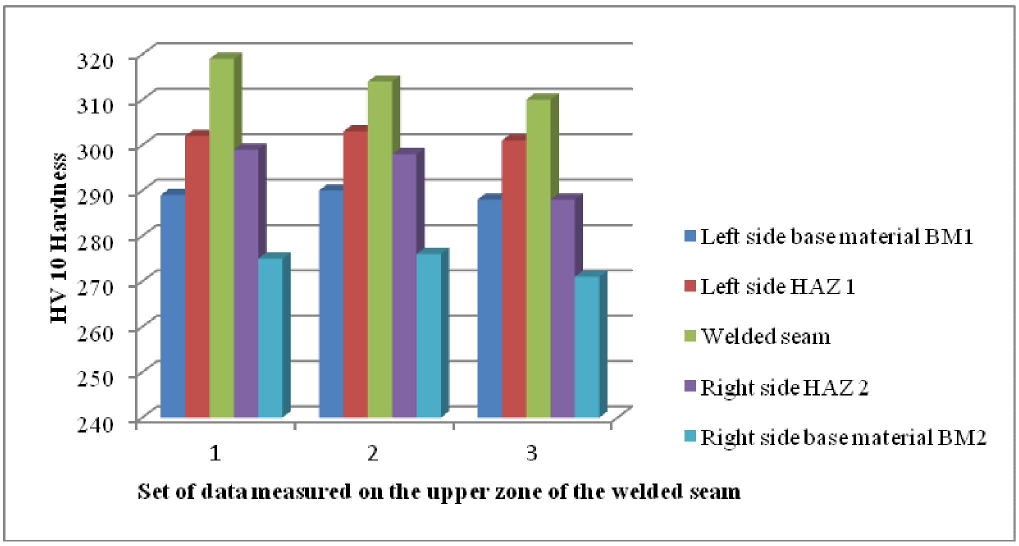

Fig. 5. Graph of the values of HV 10 Vickers hardness measured on the upper zone of the welded seam (axis 1) applied to the specimen from the beginning of the sample for P355NL1 steel.

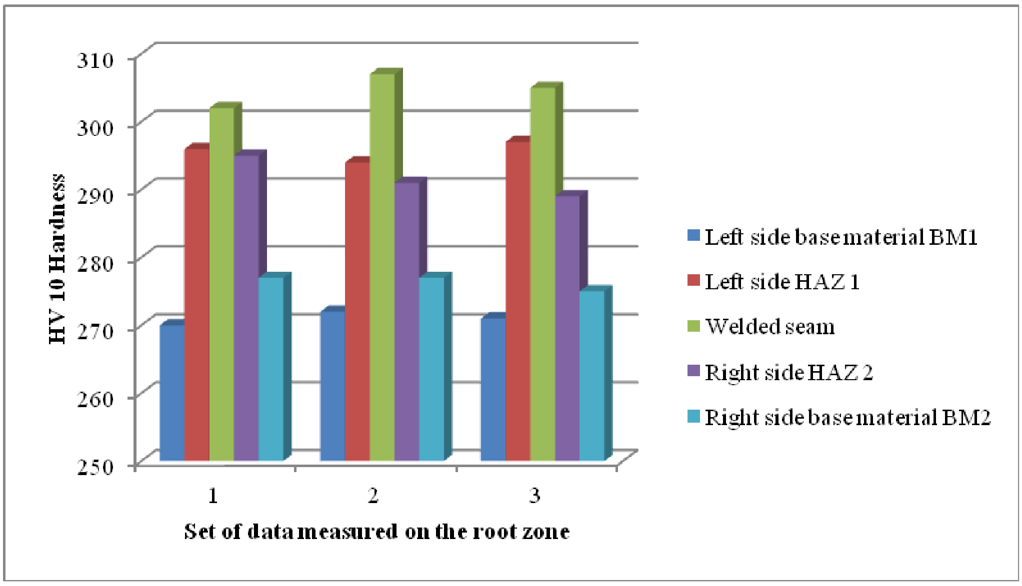

Fig. 6. Graph of the values of HV 10 Vickers hardness measured on the root zone of the welded seam (axis 2) applied to the specimen from the beginning of the sample for P355NL1 steel.

Table 4

HV 10 Vickers hardness values applied to the specimen cut off from the end of the sample

Zone / Axis	BM1 Sheet iron 20 mm	HAZ 1 Sheet iron 20 mm	WS	HAZ 2 Sheet iron 20 mm	BM 2 Sheet iron 20 mm
1	295-298-292	321-322-318	322-324-321	312-317-317	294-293-289
2	279-281-283	307-312-308	319-317-318	306-318-319	293-294-296

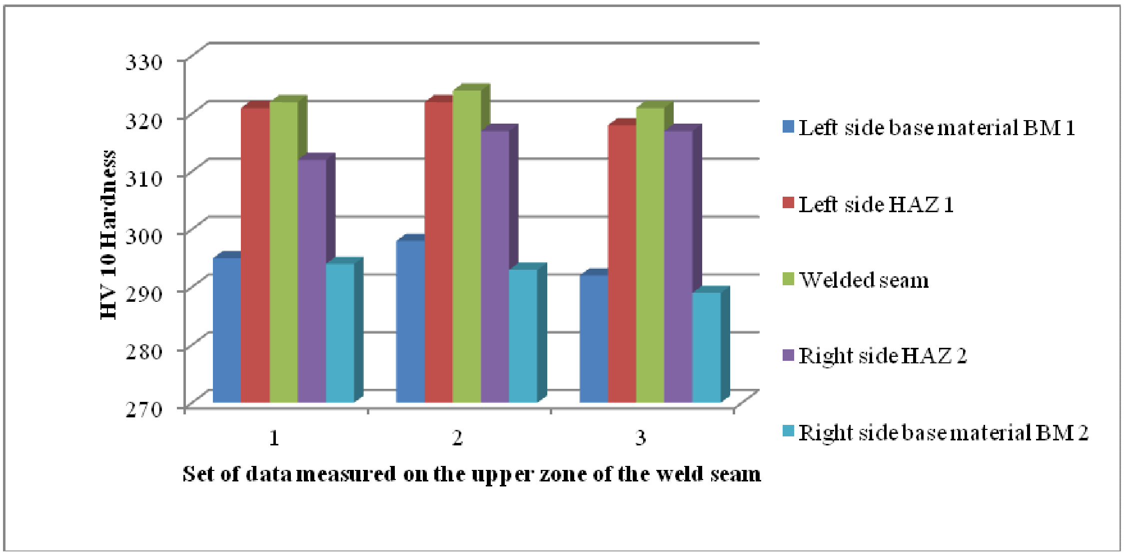

Fig. 7. Graph of the values of HV 10 Vickers hardness measured on the upper zone of the welded seam (axis 1) applied to the specimen at the end of the sample for P355NL1 steel.

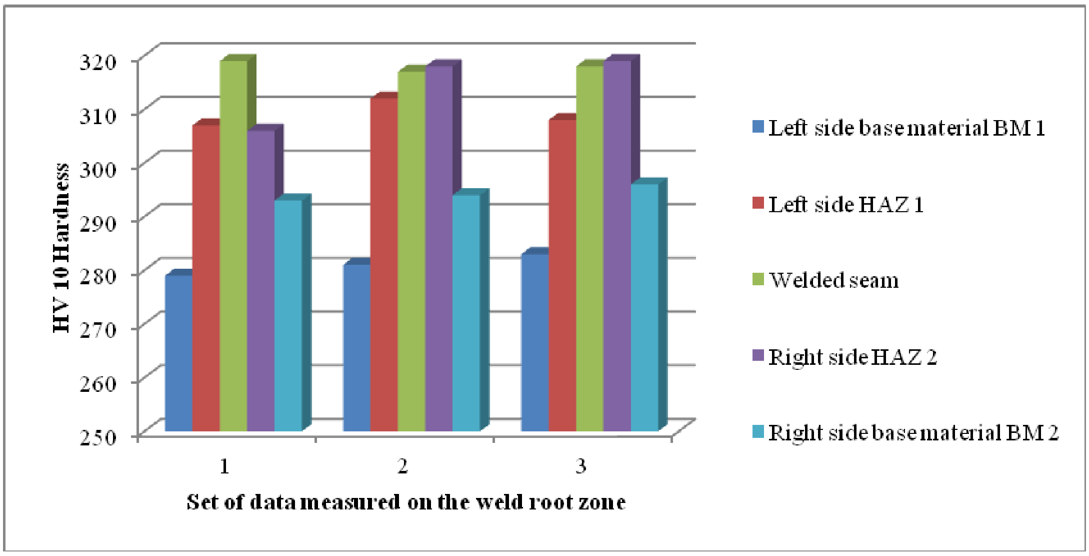

Fig. 8. Graph of the values of HV 10 Vickers hardness measured on the root zone of the welded seam (axis 2) applied to the specimen at the end of the sample for P355NL1 steel.

In order to compare, if we measure the HV 10 Vickers hardness values in the middle part of the weld bead, according to Table 5, illustrated in Fig. 9 for the set of data measured on the upper zone of the welded seam and in Fig. 10 for the set of data measured on the root of weld, we notice an increase of the values of the HV 10 Vickers hardness measured in the beginning and end zones of the weld bead, compared to the values of the HV 10 Vickers hardness values measured in the middle part of the weld bead, as well as an increase of the values of hardness for the end zone of the weld (crater), compared to the values of hardness corresponding to the beginning zone of the weld.

Table 5

Values of the HV 10 Vickers hardness measured in the middle part of the weld bead of P355NL1 steel

Zone / Axis	BM 1 Sheet iron 20 mm	HAZ 1 Sheet iron 20 mm	WS	HAZ 2 Sheet iron 20 mm	BM 2 Sheet iron 20 mm
1	202-205-203	209-208-207	219-224-221	207-207-209	202-201-203
2	201-204-203	210-211-210	218-224-217	205-207-206	201-202-201

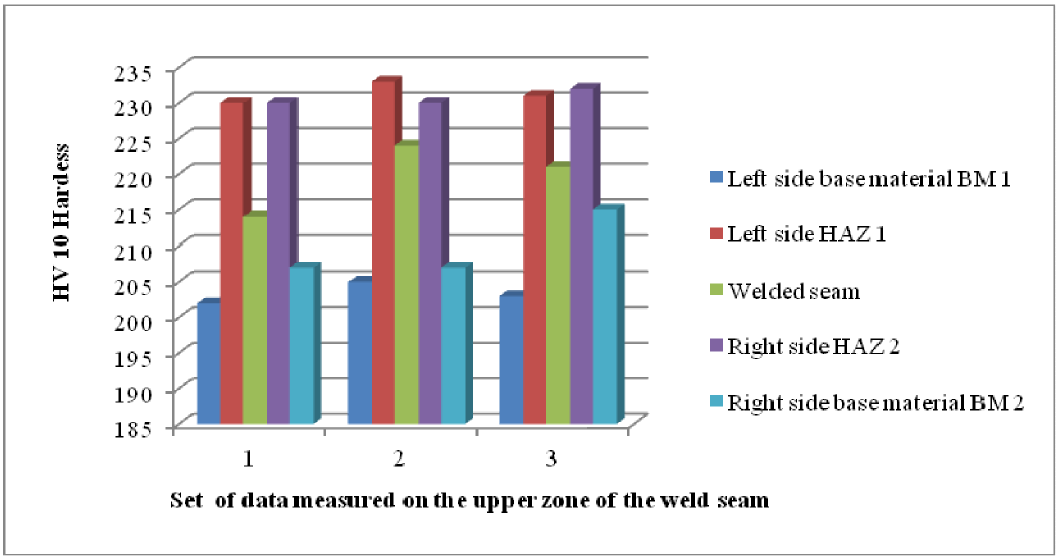

Fig. 9. Graph of the values of HV 10 Vickers hardness measured on the upper zone of the welded seam (axis 1) on a specimen taken off the middle part of the weld, corresponding to P355NL1 steel.

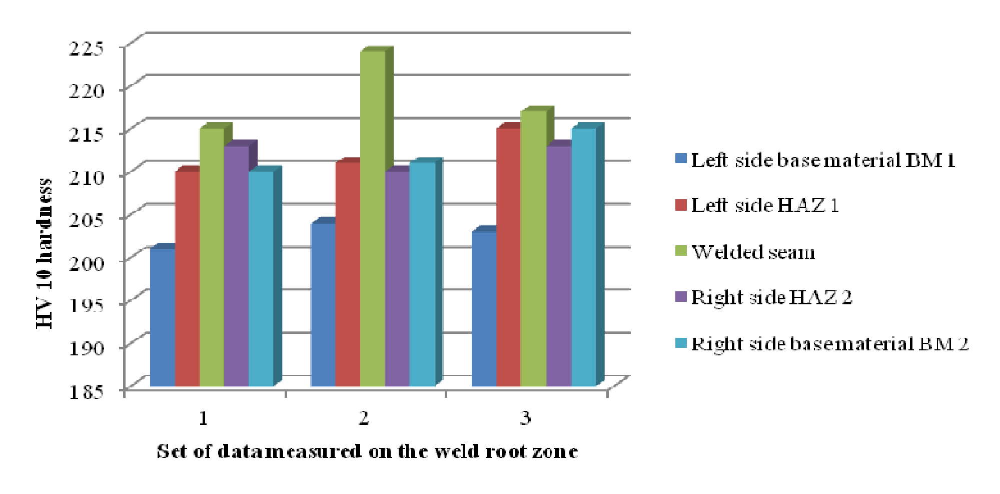

Fig. 10. Graph of the values of HV 10 Vickers hardness measured on the root zone of the welded seam (axis 2) on a specimen taken off the middle part of the weld, corresponding to P355NL1 steel.

3.2. Evaluation of the quality of welded sample of P355NL1 steel taken from the end zones

During the cooling and solidification of the built-up metal, a series of constituents appear in its composition, which give it special properties and special behaviors during service.

Analysis was made by optical microscopy according to SR EN 1321:2000, STAS 7626-79, CR 12361:1996 + AC: 1997 [10–12].

The microscope used was Olympus GX51 equipped with a software specialized in image processing – AnalySis.

Hardness was measured according to EN ISO 6507-1 on surfaces that have been cut off and etched with metallographic etchant. Hardness was measured by Vickers method, using Shimadzu HMV 2T device, under the fallowing conditions: 24 $^{\circ}$C temperature, 60% humidity.

Studying the microstructures in Fig. 11, *a–f*, we notice as follows:

- Fig. 11,*a* – Base material: P355NL1 steel. The microstructure contains ferrite and pearlite situated in lines because of the plastic deformation process (lamination). Magnifying power: 200×. Chemical etching: Nital 2%.
- Fig. 11,*b* – Heat affected zone - HAZ (overheating). An increase of the granulation in the adjacent zone to the fusion line is manifest. Magnifying power: 200 x. Chemical etching: Nital 2%.
- Fig. 11,*c* – Recrystallization zone in the HAZ. Fine ferritic-pearlitic granulation. Magnifying power: 500×. Chemical etching: Nital 2%.
- Fig. 11,*d* – Normalizing zone in the HAZ. Very fine ferritic-pearlitic granulation. Magnifying power: 100×. Chemical etching: Nital 2%.
- Fig. 11,*e* – Overheating zone in the HAZ. Oversize ferritic-pearlitic-martensitic granulation. Islands of martensite, Widmanstatten type acicular and modified pearlite are present. Magnifying power: 200×. Chemical etching: Nital 2%.
- Fig. 11,*f* – Welded seam. The dendritic microstructure oriented in the direction of the heat flow. Magnifying power: 200×. Chemical etching: Nital 2%.

3.3. Establishing the preheating temperature, calculation of the carbon equivalent and evaluation of maximum hardness in heat-affected zone for welding P355NL1 steel.

By calculating equivalent carbon after the method of International Welding Institute for P355NL1 steel [4]:

$$C_e = C + \frac{Mn}{20} + \frac{Ni}{15} + \frac{(Cr + Mo + V)}{10} = 0.308. \qquad (1)$$

Having in view that for welding P355NL1 steel we have chosen SANBAZ electrode, which is a basic coated electrode, and according to the value of carbon equivalent, to the P355NL1 steel is given weldability number I_s – D classification [4]:

$$For \quad C_e = 0.28 \div 0.32 \Rightarrow \quad I_s \Rightarrow D. \qquad (2)$$

For the calculation of preheating temperature the Seferian method was used [4]:

$$T_{pr} = 350 \cdot \sqrt{(Ct - 0.25)} \ \ [°C]. \qquad (3)$$

C_t = total equivalent carbon, calculated depending on the chemical composition of the steel and on the sheet thickness:

$$\mathrm{C_t} = C_e + C_s \ . \qquad (4)$$

C_e represents the equivalent carbon:

$$\mathrm{C_e} = C + \frac{\mathrm{Mn + Cr}}{9} + \frac{\mathrm{Ni}}{18} + \frac{7}{90}\mathrm{Mo} = 0.391, \qquad (5)$$

where C_s represents the carbon introduced based on the thickness of the material:

$$\mathrm{C_s} = 0.005 \cdot s \cdot C_e = 0.0391, \qquad (6)$$

where *s* represents the material thickness, in mm.

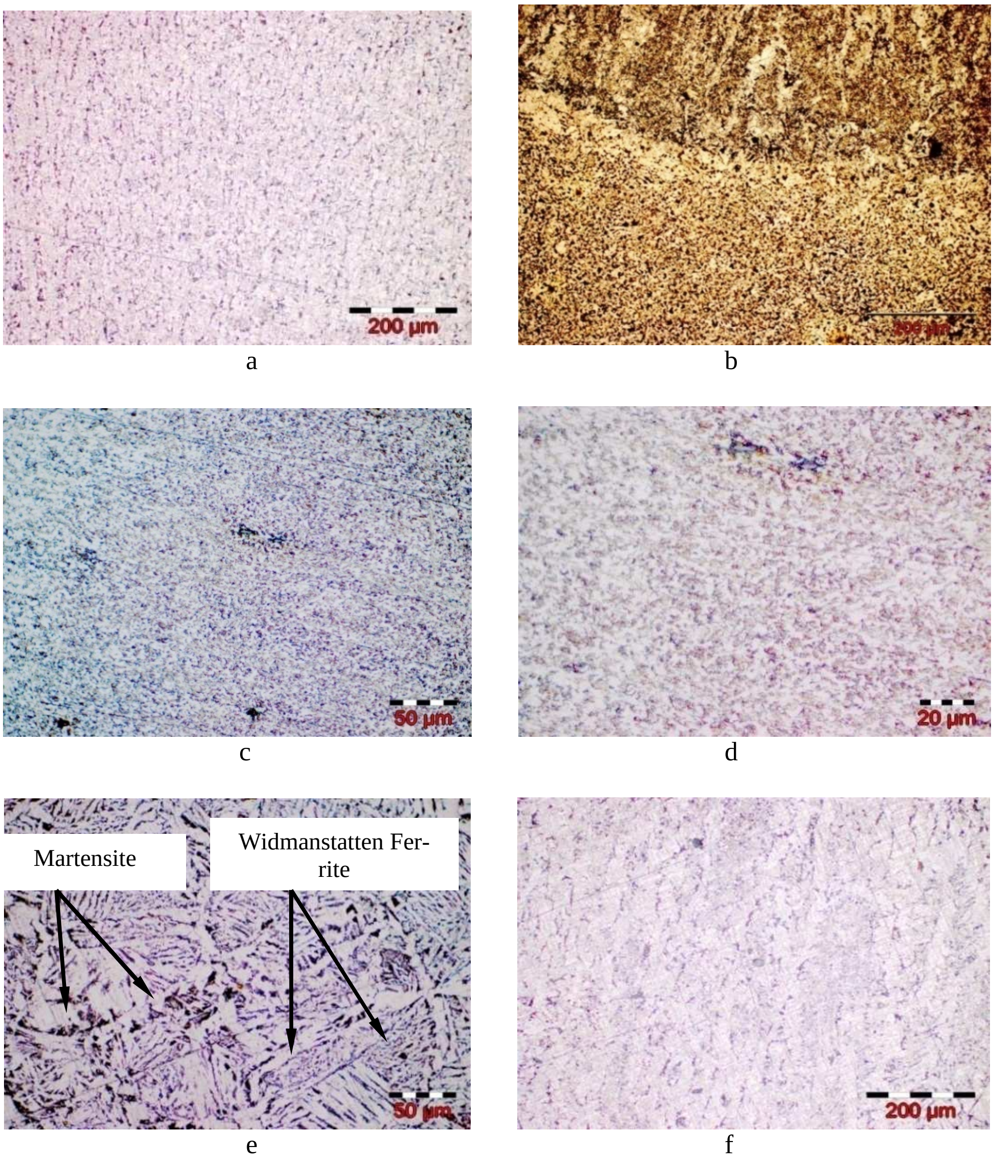

Fig. 11. Microscopical images of the specimen of the welded sample made of P355NL1 steel: *a* – base material: P355NL1 steel; *b* – the heat affected zone – HAZ (overheating); *c* – recrystallization zone in the HAZ; *d* – the normalizing zone in the HAZ; *e* – the overheating zone in the HAZ; *f* – the welded seam.

$$C_t = 0.4301 \quad \Longrightarrow T_{pr} = 230\ °\mathrm{C}. \qquad (7)$$

The behavior of weld joint to cracking is determined by the calculation of maximum hardness from HAZ, using the formula (8) [5–9]:

$$H_{max} = (189 + 67 \cdot C + 507 \cdot P_{cm}) - -(101 + 711 \cdot C - 661 \cdot P_{cm}) \cdot \arctan X \ (\mathrm{HV10}). \qquad (8)$$

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5 \cdot B = 0.327. \qquad (9)$$

X is calculated using the formula:

$$X = \frac{\log\ t_{8/5} + (0.501 + 7.90 \cdot C - 11.01 \cdot P_{cm})}{0.543 + 0.55 \cdot C - 0.76 \cdot P_{cm}}. \qquad (10)$$

$$\log\ t_{8/5} = 3.7 \cdot \left(C + \frac{Mn}{13} + \frac{V}{6} + \frac{Ni}{40} + \frac{Mo}{10} \right) - 0.31 = 0.946. \qquad (11)$$

$$X = -1{,}439 \quad \Longrightarrow \quad H_{max} = 380\ \mathrm{HV}\ 10. \qquad (12)$$

We notice that the value of calculated maximum HV 10 Vickers hardness in the heat-affected zone is superior to the effectively measured values of hardness in the two cases: the beginning and the end parts of welds, as well as the middle parts of welds.

4. CONCLUSIONS

For the steel we studied, P355NL1, by the analysis and the control of HV 10 Vickers hardness applied to the beginning and end of the weld bead, as well as in the middle part of the weld bead, measured on the material, on the heat-affected zone and on the weld seam, we notice higher values of the hardness in the beginning and end zones of the weld bead, compared to the middle part of the weld bead.

These end zones of the welded seam are a centre of non-conformities due to the transitory welding conditions. For this reason, the beginning and the end parts of the welded samples used for homologation of welding processes, for welders' authorization or for prolongation of welders' authorization/certification, are cut off and samples for mechanical tests are not made.

The situation is similar to the case of repair by welding, which is comparable to the case of short lines welding compared to the case of long welds, where the corresponding values of the HV 10 Vickers hardness measured on the beginning and end zones of the weld bead are higher than the values of the hardness measured in the middle of the long welded line, measured in the zones of the base material, on the heat-affected zone and on the welded seam. We understand by long welded line the welded line longer than 100 mm.

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