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USE OF STRUCTURAL STEELS IN STORAGE TANK CONSTRUCTION AFTER NORMALIZED ROLLING

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ABSTRACT

The work investigates the structure and ductility of sheet rolled steels of the strength class 355 and 420 in the plane *X–Y*. It is shown that the use of normalized rolling does not provide sheet rolled steel S355+N the state, which is equivalent to the state after normalization. As a result of carrying out normalized rolling, due to the additional compression of the sheet in the temperature region near the temperature A_{c3}, a banded structure is formed in steel, which has a high anisotropy of mechanical properties. The formation of such a fibrous structure leads to a brittle state of the metal in the plane *X–Y* at a calculation temperature. To prevent brittle layered fracture, it is necessary to use structural steels of the strength class S355 and S420, produced in accordance with the standard DSTU EN 10025-3:2007 in a state after normalization and limit the content of sulphur $S \leq 0.10$ %. In the case of using the mentioned steels in the state after normalized rolling, it is recommended to use a metal with a thickness of not more than 15 mm, which will provide a safe service of a metal in welded assemblies over the direction of thickness. An additional criterion for stability of sheet rolled steels S355 and S420 to the brittle layered fracture, in addition to the rolled metal Z quality group, it is proposed to use such an indice as impact work, which is determined on the specimens with a V-shaped notch in the rolling plane *X–Y* (along the sheet axis).

KEYWORDS: structural steels of strength class 355 and 420, normalized rolling, brittle layered fracture, vertical cylindrical steel tanks

INTRODUCTION

Due to the transition of the construction industry on using structural steels, which are manufactured in accordance with the standards DSTU EN 10025, the problem of compliance of the mechanical properties of these steels and their welded joints with the requirements of the current regulatory framework of Ukraine is relevant. Traditionally, in Ukraine for welded metal structures, a carbon steel St3sp5-zv [1] (strength class S255) and a low-alloy steel 09G2S-12 [2] (strength class S325 at a thickness $10 \leq t \leq 20$ mm) were used, which were delivered in a hot-rolled state or after normalization. The mentioned steels have a high ductility, a sufficient level of cold resistance and a good weldability, which led to their widespread use in critical structures [3], in particular, for vertical cylindrical tanks [4]. Structural steels, according to DSTU EN 10025-2-S355J2+N [5], DSTU EN 10025-S-355N(NL)) [6] and DSTU EN 10025-3-S420N(NL) [6], refer to a higher strength class and quite often are delivered after normalized rolling. The peculiarity of the mentioned steels is their production by metallurgical plants with a low content of sulphur: $S \leq 0.010$ % and phosphorus: $P \leq 0.015$ %, which should provide their high cold resistance [3].

The standards [5, 6] indicate that the state of steel after normalized rolling is equivalent to the state after normalization. At the same time, the works [7–9] note that unlike normalization, in the process of normalized rolling at the final stage, an additional metal deformation is performed in the austenitic zone at values of temperature close to the point A_{c3}, which at sufficient compression allows obtaining a fine-grained structure due to a multiple full recrystallization [9]. In this case, additional deformation should lead to greater structural heterogeneity compared to the normalized state and, accordingly, to greater anisotropy of mechanical properties of the metal [10]. From this point of view, it is appropriate to carry out additional studies of the properties of sheet rolled steels made in accordance with DSTU EN [5, 6] in a state of normalized rolling, which are widely used in construction in order to take into account their features. In the case of vertical cylindrical tanks, it is necessary to take into account the work of the metal in the direction of thickness (Z-direction), which occurs in welding-in branch-pipes (overlapped welded joint, which reinforces the sheet-wall; T-joint by welding-on the wall to the branch-pipe) and in the assembly of the joint “wall-contour sheets of the bottom”. In order to prevent the emergence of a layered metal fracture, postweld heat treatment (PWHT) is carried out to remove welding residual stresses in places of welding-in branch-pipes and hatches into the wall in order to offset their influence during the metal work in the direction of thickness [11–13]. The conditions under which it is necessary to carry out PWHT of places of welding-in branch-

Table 1. Standard requirements for carrying out postweld heat treatment (PWHT) of places of cutting-in of branch-pipes and hatches into the wall of vertical cylindrical tanks

Design standard	Grade of steel	Thickness of the girth, mm	Diameter of the branch-pipe, mm
API 650-13 [11]	S235	$t > 25$	≥ 300
	S275J0; S355J0; S355(J2 або K2); A841M, grade A, class 1, 2 (ReH ≥ 461 MPa)	$t > 13$	≥ 50
EN 14015 [12]	S275; S355	$t > 25$	≥ 300
	S420	$t > 20$	All diameters
DSTU B V.2.6-183:2011 [13]	ReH ≥ 345 MPa	$t > 25$	≥ 300

Notes. 1. In table the requirements for an incomplete list of steel grades are provided. 2. ReH is the minimum guaranteed yield strength.

pipes in the wall differ significantly depending on the design standard (Table 1).

The data analysis given in Table 1 shows that there is no single approach to solving the prblem of selecting the conditions, under which it is necessary to carry out PWHT. The main factors affecting the need for its conducting are the strength class of steel and the hole diameter. The most rigid requirements are specified in the standard API 650-13 [11]: for the steel of strength class S275J0 and more than the thickness of the sheet $t \geq 13$ mm, PWHT is already required. In the standard EN 14015 [12]: for the steels S275 and S355 at a thickness $t \geq 25$ mm, and for the steel of strength class S420 at a thickness $t \geq 20$ mm. The least rigid requirements are contained in the domestic standard DSTU B V.2.6-183:2011 [13], which requires carrying out additional studies for the conditions of PWHT treatment.

One of the criteria for the quality of sheet rolled metal and its resistance to layered fracture, which has become widespread in practice, is its guaranteed compliance with the quality class Z15, Z25, Z35 based on the results of tensile tests of the specimens in the direction of sheet thickness [14, 15]. However, it should be noted that the size of reduction in area ψ_z is mainly affected by the presence of nonmetallic inclusions in steel [3, 16, 17]. In our case, it is possible to expect an increased structural banding of metal and a low content of globular nonmetallic inclusions. Taking into account that propagation of cracks is determined by the toughness of metal matrix [16], the use of the specified criterion may be insufficient. In addition, the determination of reduction in area ψ_z occurs at a positive temperature that does not correspond to the calculated operation temperature, which also cannot fully guarantee the absence of brittle layered fracture of welded metal structure during its further operation.

Considering the abovementioned, the evaluation of the resistance to brittle layered fracture of the sheet rolled steels S355 and S420 in the rolling plane *X*–*Y*

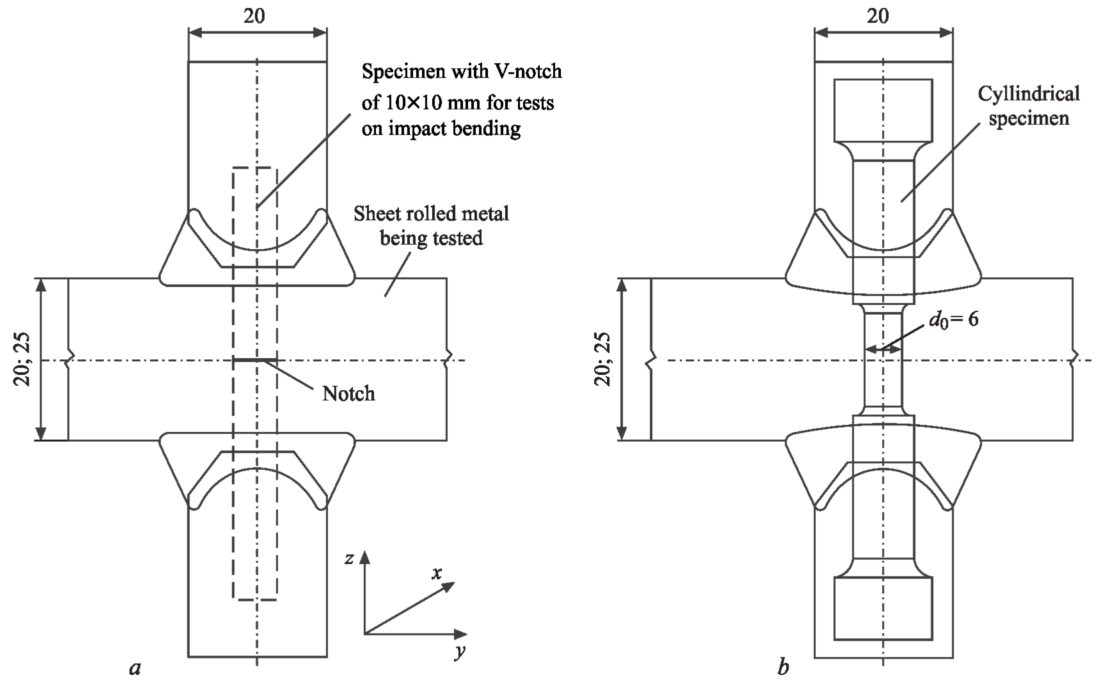

Figure 1. Scheme of cutting out specimens from cruciform welded joints: *a* — on impact bending with notches in the plane *X*–*Y*; *b* — on tension to determine the quality class of steel

Table 2. Chemical composition of sheet rolled steels S355J2+N, P3555NL2 and S420NL

Data source	Mass fraction, %											
	C	Mn	Si	P	S	Cr	Ni	Cu	Al	V	Nb	Ti
S355J2+N, *t* = 25 mm, normalized rolling												
Control analysis of PWI	0.14	1.34	0.18	0.022	0.016	0.036	0.03	0.05	0.028	<0.005	0.023	0.015
S355J2+N, *t* = 20 mm, normalized rolling												
Control analysis of PWI	0.15	1.37	0.20	0.017	0.009	Was not determined			0.028	–	0.023	0.017
DSTU EN10025-2:2007, Table 4	≤0.23	≤1.70	≤0.60	≤0.35	≤0.35	–			–	≤0.55	–	≤0.13
P355NL2, *t* = 20 mm, normalization												
Control analysis of PWI	0.17	1.33	0.33	0.009	0.002	0.036	0.045	0.010	0.033	0.006	0.033	0.003
DSTU EN10028-3:2018, Table 1	≤0.18	1.10–1.70	≤0.50	≤0.020	≤0.005	≤0.30	≤0.50	≤0.70	0.025	≤0.10	≤0.05	≤0.03
S420NL, *t* = 25 mm, normalization												
Control analysis of PWI	0.13	1.50	0.26	0.015	≤0.002	0.07	0.07	0.05	0.041	0.054	0.035	<0.005
DSTU EN 10025-3:2007, Table 3	≤0.22	0.95–1.80	≤0.65	≤0.030	≤0.025	≤0.35*	≤0.85	≤0.60	–	V+Nb+Ni ≤ 0.26 %		
*Mo+Cr ≤ 0,38 %.												

Table 3. Mechanical properties of base metal of tested specimens of steels S355J2+N, P355NL2 and S420NL

Data source	σ_y, MPa	σ_m, MPa	σ_y/σ_t	δ_5, %	ψ, %	Impact toughness $KCV_{X\text{–}Y}$, J/cm^2, at a temperature					
						–20 °C		–30 °C		–50 °C	
						L	T	L	T	L	T
S355J2+N, *t* = 25 mm											
Tests of PWI	345.1	495.3	0.69	35.9	72.9	265; 352; 214 277	168; 192; 185 182	163; 170; 171; 179 171	63; 60; 58; 57 59,5	–	–
	346.8	492.8	0.70	35.0	73.9						
S355J2+N, *t* = 20 mm											
Tests of PWI	410	530	0.77	33	67	282; 275; 291 283	131; 163; 127 140	306; 287; 304 299	141; 134; 140 138	–	–
	402	526	0.76	37	71						
DSTU EN 10025-2:2007	≥345	470–630	–	≥22	–	≥ 34	Is not normalized	–	–	–	–
P355NL2, *t* = 20 mm											
Tests of PWI	414	544	0.76	31	–	–	–	–	–	241; 282; 329 284	73; 104; 113 97
	410	549	0.75	33	–	–	–	–	–	–	–
DSTU EN 10028-3:2018	≥345	490–630	–	≥22	–	–	–	–	–	–	≥34
S420NL, *t* = 25 mm											
Tests of PWI	430	583	0.73	33	66.2	–	–	327; 344; 338 336	246.4–333.6 294,1	160; 120; 138; 139 139	–
	433	589	0.74	33	67.3						
DSTU EN 10025-3:2007	≥400	520–680	–	≥19	–	–	–	–	≥29	≥34	–
Note. L — tests on longitudinal specimens, T — tests on transverse specimens.											

Table 4. Investigations for the Z quality group of sheet rolled steels S355J2+N, P3555NL2 and S420NL

Specimen number	Grade of steel, thickness of the sheet	As-delivered steel	ψ_z, %	Z quality group	Mass fraction of sulphur, %
1	S355J2+N, t = 25 mm	Normalized rolling	22.0	Z15	0.016
2					
3					
1	S355J2+N, t = 20 mm	Normalized rolling	41	> Z35	0.009
2			42		
1	P355NL2, t = 20 mm	Normalization	69.1	> Z35	0.002
2			73.2		
1	S420 NL, t = 25 mm	Normalization	66.2	> Z35	0.002
2			67.3		

was carried out on the basis of evaluating the value of impact toughness according to the results of testing standard Charpy specimens with a V-notch.

CHARACTERISTICS OF SOURCE MATERIALS AND RESEARCH PROCEDURE

To study the resistance of the sheet rolled steels S355 and S420 to brittle layered fracture, cruciform billets were made [18] (Figure 1), from which the specimens were cut out to determine the impact toughness $KCV_{X\text{–}Y}$ with a notch in the plane X–Y and the specimens to determine the size of transverse reduction in area during tension in the direction of metal thickness [15].

The specimens of the sheet rolled steels S355J2+N [5], P355NL2 [19] and S420NL [6] with a thickness t = 20 mm and t = 25 mm were investigated. The chemical composition and type of heat treatment of the steels are given in Table 2. The mentioned steels are microalloyed with niobium Nb and aluminum Al, and the steel S420NL is additionally alloyed with vanadium V. The actual sulphur content for the steels P3555NL2 and S420NL is S = 0.003 wt.%. For the steel S355J2+N, the sulphur content S = 0.016 wt.% at t = 25 mm and S = 0.009 wt.% at t = 20 mm. The mechanical properties of the mentioned steels are given in Table 3.

The microsections for metallographic examinations were cut out along the rolling direction and polished to the purity class 14 using diamond pastes. To reveal microstructure, the specimens were etched in a 4 % alcohol solution of nitric acid. The microstructure was examined with the use of the NEOPHOT-32 microscope. The Vickers hardness was measured by the M-400 LECO hardness meter at 98 mN and 9.8 N. The content of nonmetallic inclusions in the studied specimens was determined on polished unetched microsections [21].

The analysis of experimental data of Tables 2, 3 shows that the chemical composition and mechanical properties of the steels S355J2+N, PS3555NL2 and S420NL meet the requirements [5, 6, 19]. The value of the ratio of yield/ultimate strength $\sigma_y/\sigma_m \leq 0.75$ is close to the requirements [13]. Moreover, at a temperature T = –30 °C, the value of impact toughness KCV_{-30} for the steel S355J2+N of 25 mm thick, which is determined with the use of transverse specimens, meets the requirements [6] for the steel S355NL. According to the results of reference tests, the steels PS355NL2 and S420NL can be attributed to the same strength class S420.

RESEARCH RESULTS AND DISCUSSION

The results of studies of the quality of the rolled steels S3555J2+N, P3555NL2 and S420NL in the direction of thickness [15] are presented in Table 4. Analysis of these data shows that to the lowest quality group Z15, the steel S355J2+N with a thickness t = 25 mm belongs, which is delivered in a state of normalized rolling with a high sulphur content of 0.016 %. The structural steel S355J2+N (t = 20 mm) after normalized rolling and the normalized steels P3555NL2 and S420NL belong to a high-quality group Z35, which is associated with a lower sulphur content: S ≤ 0.010 % [3]. From the given data it can be concluded that the main factor that affects the quality of the abovementioned rolled steels (Z group) is the content of sulphur in steel, not the type of heat treatment [3].

At the second stage of investigations, the impact toughness of the mentioned steels in the rolling plane $KCV_{X\text{–}Y}$ (Tables 5, 6) and the impact of high-temperature tempering T = 650 °C (PWHT simulation) on it for the steel S355J2+N were determined (Table 6).

The analysis of the results given in Tables 5, 6 indicates that in the case of sulphur content S ≤ 0.010 %, the main factor affecting the toughness of the rolled metal in the plane X–Y is the type of heat treatment of steel. Thus, based on the results of impact bending tests, the steel S355J2+N, t = 20 mm after normalized rolling has a low impact toughness in the plane X–Y: KCV_{-20} = 9.7 J/cm^2 (Table 6), which is less than required by the standard — $KCV_{-20} \geq 35$ J/cm^2 [13]. Here, sheet rolled metal belongs to the quality class Z35: ψ_z = 41 %, with a low sulphur content: S = 0.009 %.

Table 5. Impact of the type of heat treatment (state of delivery) on impact toughness KCV_{X-Y} of sheet rolled steels S355J2+N, P3555NL2 and S420NL2 when the notch is placed in the plane *X–Y*

Standard, grade of steel, sheet thickness	Mass fraction of sulphur, %	Type of heat treatment	Impact toughness KCV_{X-Y}, J/cm^2, at a temperature	
			–30 °C	–50 °C
DSTU EN 10025-2 S355J2+N. $t = 25$ mm	0.016	Normalized rolling	11.4; 9.6; 8.1 9.7	–
DSTU EN10028-3 P355NL2. $t = 20$ mm	0.002	Normalization	58.9; 51.6; 67.4 59.3	26.9; 13.4; 27.7 22.7
DSTU EN 10025-3 S420NL. $t = 25$ mm	0.002	Normalization	19.9; 18.2; 16.3 18.1	21.0; 21.7; 19.9 20.9
DSTU Б В.2.6-183:2011	≤ 0.010	Any	≥ 35.0; at Ry ≤ 360 MPa; ≥ 50.0; at Ry > 360 MPa transverse specimens*	
DSTU EN 10025-2:2007	≤ 0.035	Normalized rolling	≥ 34.00 (27 J) longitudinal specimens*	–
DSTU EN 10025-3:2007	≤ 0.025	Normalization/ Normalized rolling	≥ 29.00 (23 J) transverse specimens*	≥ 20.00 (16 J) transverse specimens*
DSTU EN10028-3:2018	≤ 0.005	Normalized rolling	≥ 37.50 (30 J) transverse specimens*	≥ 34.00 (27 J) transverse specimens*

*Impact toughness (impact work) in the plane *X–Y* is not normalized.

Table 6. Impact toughness KCV_{X-Y} of sheet rolled steel S3555J2+N with a thickness $t = 20$ mm after different types of heat treatment

Standard, grade of steel	Type of heat treatment	Impact toughness KCV_{X-Y}, J/cm^2, at a temperature		
		–20 °C	0 °C	+20 °C
DSTU EN 10025-2:2007 S355J2+N	Normalized rolling	28; 5; 5.5 9.7	5.5; 26; 24 18.5	26; 37; 15 26
	Normalized rolling + high-temperature tempering ($T = 650$ °C, 1 h)	11; 13; 7 10.3	7; 27; 23 19	–
Requirements of the standard DSTU B V.2.6-183:2011 [13] to the value of *KCV*	For all types of heat treatment	≥ 35.0 transverse specimens*	–	–
Requirements of the standard DSTU EN 10025-2:2007 [5] to the value of *KCV* (*KV*)	Normalized rolling	≥ 34.75 (27 J) longitudinal specimens*	–	–

*Impact toughness (impact work) in the plane *X–Y* is not normalized.

Table 7. Impact toughness KCV_{X-Y} in the plane *X–Y* of sheet rolled steel S420NL with a thickness $t = 25$ mm after normalization and high-temperature tempering

Temperature of testing specimens, °C	Impact toughness *KCV*, J/cm^2	
	AS-delivered (normalization)	After high-temperature tempering ($T = 650$ °C, 1 h)
0	104; 105; 95 101	33; 81; 39 51
–10	51; 74; 48 58	82; 91; 62 78
–20	51; 97; 45 64	48; 61; 38 49
–30	20; 16; 29; 31 24	65; 37; 38 47
–50	21; 22; 20 21	20; 11; 9 13

A high level of toughness in the plane *X–Y* that meets the requirements [19] is inherent to the normalized steel P3555NL2, $t = 20$ mm, the content of sulphur S = 0.002 %: $KCV_{-30} = 59.3$ J/cm^2 (Table 5), which is also confirmed by tensile tests in the direction of thickness: $\psi_z = 69$ %. For the steel S420NL2, $t = 25$ mm, in the normalization state at a sulphur content: S = 0.002 % and a high ductility in the direction of the plane $\psi_z = 66$ % (Tables 4, 7), impact toughness in the plane *X–Y* is equal to $KCV_{-30} = 18–24$ J/cm^2 (Tables 5, 7), which does not meet the requirements of $KCV_{-30} \geq 29.75$ J/cm^2 [6]. However, unlike the steel S355J2+N, the metal of the the axial zone after normalization maintains a sufficient toughness [6, 13] to a temperature $T = –20$ °C, and in the case of carrying out high-temperature tempering, the critical temperature drops to $T = –30$ °C (Table 7).

The studies of the dependences of impact toughness KCV_{X-Y} in the axial zone of the steel S355J2+N, t = 20 mm, the sulphur content S = 0.009 % (Table 6) on the temperature showed that even at a temperature T = +20 °C, it is located in the lower zone of the S-shaped curve, respectively, and the risk of forming lamellar cracks even during welding in factory conditions at a positive temperature can be sufficiently high. A high-temperature tempering does not affect the toughness of the steel S355J2+N in the plane X–Y.

Based on the results of metallographic examinations, it was established, that microstructure of the steels S355J2+N, P355NL2 and S420NL is ferritic-pearlitic (Figure 2). The evaluation of banding [20]

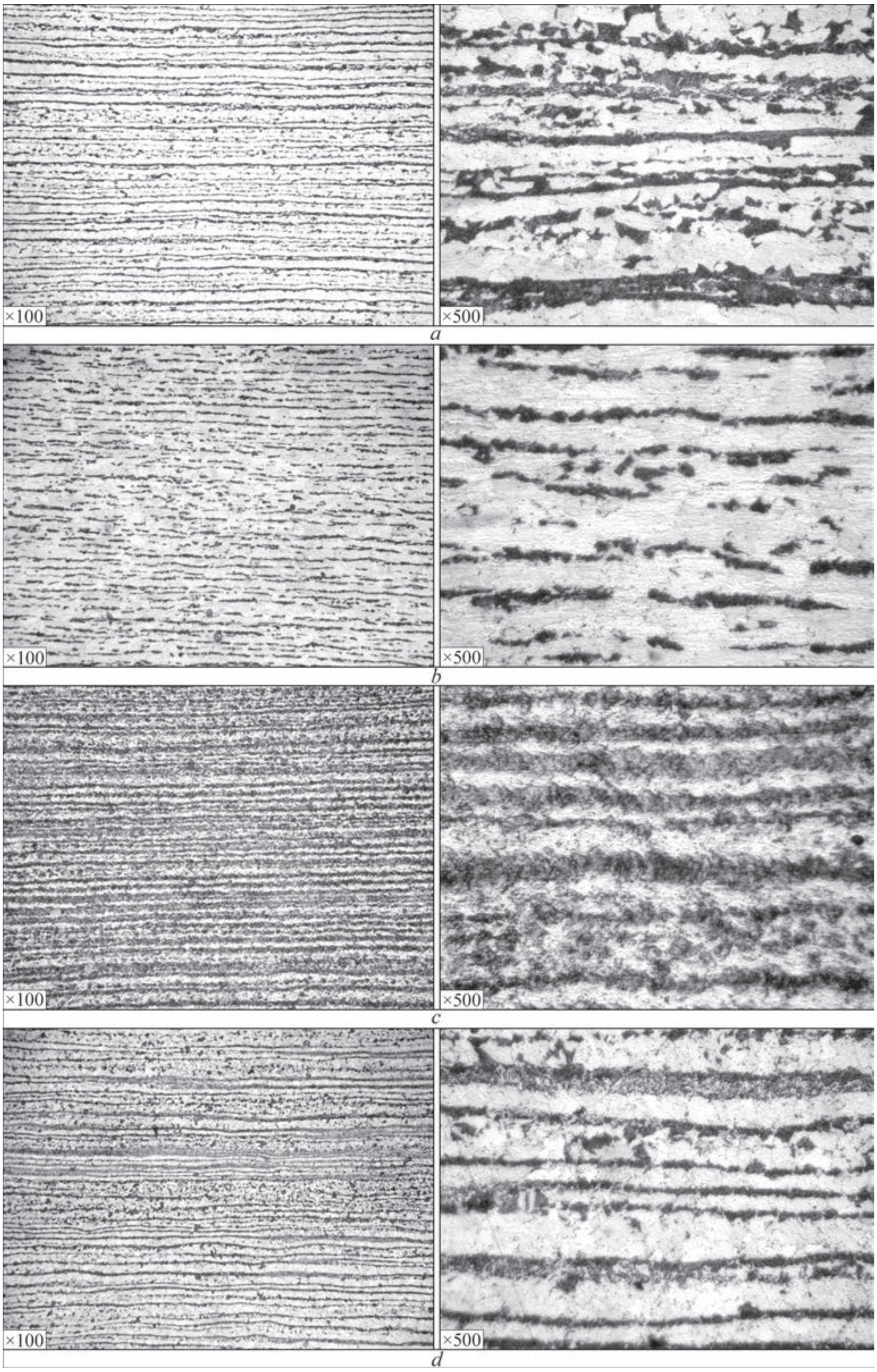

Figure 2. Microstructure of axial zone of investigated steels: *a* — steel B3555J2+N, 20 mm thickness; *b* — steel B355J2+N, 25 mm thickness; *c* — steel P355J2+N, 20 mm thickness; *d* — steel S420NL2, 25 mm thickness

Table 8. Banding of structure of sheet rolled steels S355J2+N, P355Zh2 and S420NL according to DSTU 8974:2019 [20]

Standard, grade of steel, thickness	Banding evaluation
DSTU EN 10025-2 S355J2+N, $t = 20$ mm	Figure 8(4), scale 3, row B (×100)
DSTU EN 10025-2 S355J2+N, $t = 25$ mm	Figure 8(4), scale 3, row B (×100)
DSTU EN 10028-3 P355NL2, $t = 20$ mm	Figure 8(3), scale 3, row B (×100)
DSTU EN 10025-3 S420NL, $t = 25$ mm	Figure 9(5), scale 3, row C (×100)

of these steels (Table 8) shows that S355J2+N after normalized rolling has a much larger banding degree, than P355NL2 and S420NL.

Based on the analysis of the microstructure of the steels (Figure 2), it is seen that unlike S355J2+N, where pearlite is lamellar (Figure 2, *a*, *b*), in the steel P3555NL2 after normalization, sorbite-like pearlite with disoriented grains is formed (Figure 2, *c*). In ferrite, a large amount of carbide precipitates is observed, which transforms the ferrite component into a ferrite-carbide mixture. This leads to an increase in the hardness of ferrite of the steel P355NL2 compared to S355J2+N (Table 9) and a reduction in the mechanical heterogeneity of the structure. In the steel S355J2+N ($t = 20$ mm, 25 mm), a larger difference between the values of hardness of ferritic and pearlitic components is observed, the content of carbides in ferrite is low (Table 9, Figure 2, *a, b*).

The steel S420NL occupies an intermediate position: in it both lamellar as well as sorbite-like pearlite

Table 9. Results of measurements of hardness of metal of sheet rolled steels S355J2+N, P355NL2 and S420NL

Standard, grade of steel, thickness, place of measurement	Hardness of microstructural components *HV* (0.098 N)		Difference in ferrite and pearlite hardness, MPa	Integral hardness *HV* (9.8 N), MPa
	Structural component	Hardness, MPa		
DSTU EN 10025-2 S355J2+N, $t = 20$ mm axial part	Ferrite	1088; 1088; 1264; 1176 1154	720	1548; 1548; 1450; 1470 1504
	Pearlite	1813; 1784; 1813; 1686 1874		
DSTU EN 10025-2 S355J2+N, $t = 20$ mm surface part	Ferrite	1284; 1245; 1264; 1274 1266	713	1450; 1499; 1499; 1480 1482
	Pearlite	1931; 1931; 1813; 1764 1979		
DSTU EN 10025-2 S355J2+N $t = 25$ mm axial part	Ferrite	1587; 1587; 1587; 1587 1587	392	1597; 1637; 1558; 1558 1587
	Pearlite	1891; 2009; 2009; 2009 1979		
DSTU EN 10025-2 S355J2+N $t = 25$ mm surface part	Ferrite	1528; 1646; 1646; 1528 1587	304	1529; 1539; 1666; 1588 1580
	Pearlite	1813; 1813; 1930; 2009 1891		
DSTU EN 10028-3 P355NL2, $t = 20$ mm axial part	Ferrite	1646; 1744; 1617; 1646 1663	294	1646; 1852; 1627; 1752 1719
	Sorbite-like pearlite	1970; 1852; 2009; 1999 1957		
DSTU EN 10028-3 P355NL2, $t = 20$ mm surface part	Ferrite	1499; 1548; 1617; 1499 1540	214	1646; 1646; 1656; 1558 1626
	Sorbite-like pearlite	1617; 1744; 2009; 1646 1754		
DSTU EN 10025-3 S420NL, $t = 25$ mm, axial part	Ferrite	1303; 1480; 1401; 1480 1416	593	1784; 1833; 1612; 1950 1795
	Pearlite	2009; 2009; 2009; 2009 2009		
	Sorbite-like pearlite	2244; 2519; 2254; 2421 2359	943	
DSTU EN 10025-3 S420NL, $t = 25$ mm, surface part	Ferrite	1324; 1480; 1372; 1372 1387	390	1637; 1735; 1735; 1656 1691
	Sorbite-like pearlite	1715; 1784; 1784; 1784 1777		
	Pearlite	2225; 2401; 2450; 2254 2332	945	

Table 10. Evaluation of contamination of sheet rolled steels S355J2+N, P3555NL2 and S420NL [21] with nonmetallic inclusions

Standard, grade of steel, thickness	Contamination					
	By globular oxides			By sulfides		
	Size number	Series	Thickness, μm	Size number	Series	Thickness, μm
DSTU EN 10025-2 S355J2+N, $t = 20$ mm	0.5	Thin	From 3 to 8	0.5	Thin	From 2 to 4
DSTU EN 10025-2 S355J2+N, $t = 25$ mm	1.0					From 13 to 76
DSTU EN 10028-3 P355NL2, $t = 20$ mm	1.5					From 2 to 4
DSTU EN 10025-3 S420NL, $t = 25$ mm	0.5			Not revealed		

is formed (Figure 2, *d*), the precipitation of carbides in ferrite is absent. Mechanical heterogeneity of the structure (difference in hardness of ferrite and lamellar pearlite) *HV* 0.098N is somewhat lower, than for the steel S355J2+N, $t = 20$ mm (Table 9). For sorbite-like pearlite, the difference in hardness with ferrite reaches 943HV, which is much larger than for the steel S355J2+N (Table 9). However, in this case, the negative impact of mechanical heterogeneity is lower due to a smaller banding of the rolled metal and a greater toughness of a sorbite-like pearlite than a lamellar one. For the steel S355J2+N, an increase in the pearlite component in the axial zone [7] is observed, which is associated with carbon diffusion to the center of the sheet. This leads to an increase in the integral hardness *HV* (9.8 N) and the difference in hardness *HV* 0.098N of ferrite and lamellar pearlite (anisotropy of structure) for the axial zone (Table 9). Accordingly, in the axial zone, the minimum toughness of the metal across the thickness of the sheet should be expected.

Considering the fact that the studied steels are characterized by fine-dispersed nonmetallic inclusions that do not significantly affect the toughness of the metal (Table 10), it may be concluded that the main cause for the decrease in toughness in the plane *X–Y* for the sheet rolled steel S355+N, subjected to normalized rolling, is the formation of expressed banded structure with the formation of fibers of ferrite and pearlite as a result of such treatment, which have a high anisotropy of mechanical properties (Figure 2, *a*, *b*, Table 9).

The presence of such anisotropy is the cause of brittle fracture during the test on impact bending in the plane *X–Y* [10] for the steel after normalized rolling, during which its additional deformation in the austenitic area at temperatures close to the point A_{c3} is performed, which causes the formation of expressed fibrous structures. In the steels P355NL2 and S420NL subjected to normalization, as a result of reducing the level of banding and a decrease in mechanical anisotropy between ferrite and pearlite, as well as the formation of fine-grained structure of

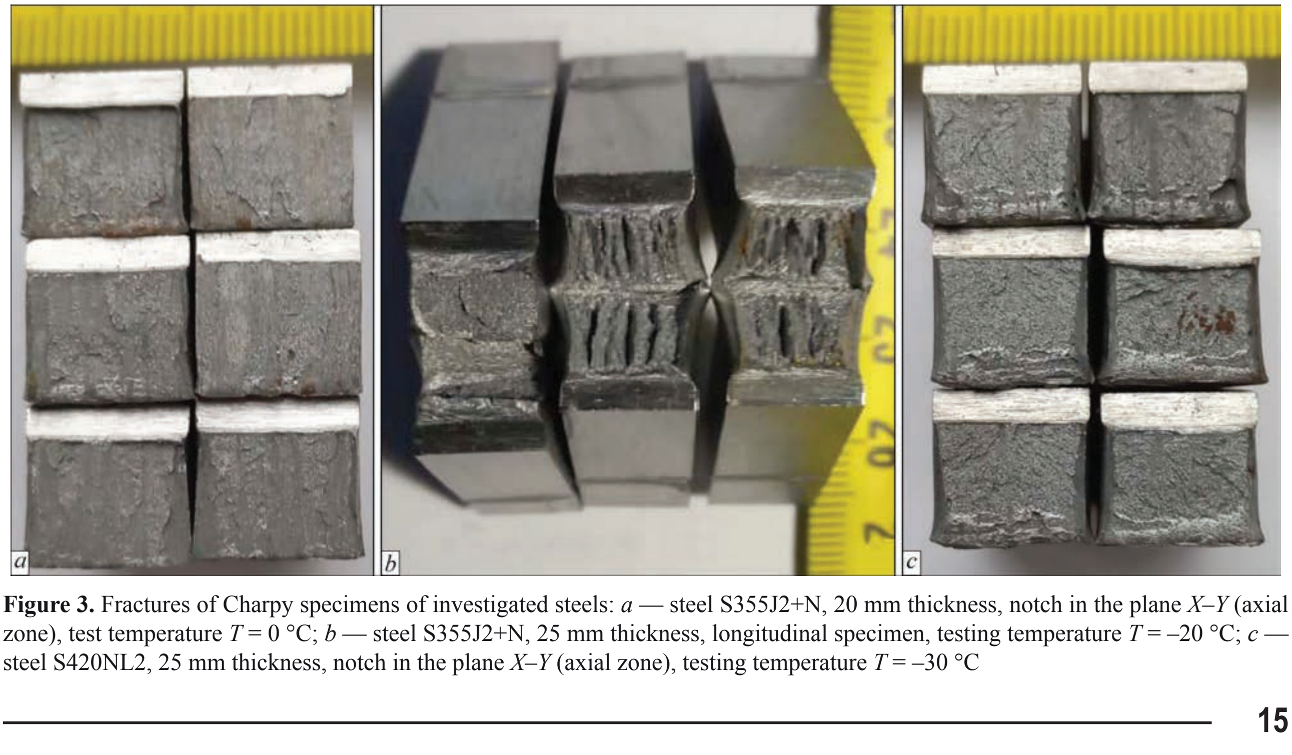

Figure 3. Fractures of Charpy specimens of investigated steels: *a* — steel S355J2+N, 20 mm thickness, notch in the plane *X–Y* (axial zone), test temperature $T = 0$ °C; *b* — steel S355J2+N, 25 mm thickness, longitudinal specimen, testing temperature $T = -20$ °C; *c* — steel S420NL2, 25 mm thickness, notch in the plane *X–Y* (axial zone), testing temperature $T = -30$ °C

sorbite-like pearlite with disoriented boundaries (Figure 2, *c*, *d*, Table 9), the toughness of metal in the plane *X–Y* grows considerably and, respectively, a transition from brittle coarse-crystalline fracture [22] for the steel S355J2+N to a brittle-tough fracture for the steel P355NL2 and S420NL occurs (Figure 3, *a*, *c*). A significant anisotropy of mechanical properties between the fibers of ferrite and pearlite in the steel S3555J2+N is also revealed in the layered metal fracture in the case of testing Charpy specimens, cut out along the rolled metal, on impact bending (Figure 3, *b*) as a result of a bulk stress state before the crack front [16].

It should be expected that due to a low content of nonmetallic inclusions in the steel after normalized rolling, deformation of the axial zone metal during welding will occur in the temperature range, where the material has a sufficient ductility, respectively, the layered fracture will be absent. Manifestation of brittle or quasi-brittle layered fracture may occur during the further operation of the welded structure at low temperatures in the presence of crack-like defects in the axial zone of the rolled metal in the case of action of tensile tests in the direction of thickness. Such initiating defects may be available delaminations of metal or separate elongated clusters of nonmetallic inclusions in steel. In this case, to prevent such layered delaminations, it is important to use a sheet rolled metal with the control of continuity and limit the content of sulphur $S \leq 0.010$ % and phosphorous: $P \leq 0.015$ %.

Thus, the structure of the steel S355J2+N [5] after normalized rolling is fibrous, with an expressed anisotropy, which is different from the structure obtained after normalization. Accordingly, this also applies to mechanical properties [10], such as toughness of metal in the rolling plane *X–Y*. This means that to use the steels [5, 6] after normalized rolling for tanks or other critical structures (bridges, platforms, etc.) in assemblies, where the operation of metal in the direction of thickness should be taken into account, additional conditions must be applied [23, 24]. For cylindrical steel tanks, it is rational to limit the thickness of the sheet steel delivered after normalized rolling with the size $t \leq 15$ mm, for which the standard [15] does not envisage the requirements for the Z quality group.

A high-temperature tempering, which simulated PWHT for the steel S355J2+N after normalized rolling does not significantly reduce banding and mechanical heterogeneity between ferrite and pearlite. Therefore after its end, an increase in impact toughness KCV_{X-Y} in the plane *X–Y* is absent (Table 6). For the normalized steel S420NL, high-temperature tempering promotes further coagulation of carbides, which increases the volumetric fraction of sorbite-like pearlite and, accordingly, reduces the mechanical heterogeneity between pearlite and ferrite. As a result, the transition temperature shifts into the region of lower temperatures: from $T = -20$ °C to $T = -30$ °C (Table 7).

CONCLUSIONS

1. The use of normalized rolling does not provide the sheet rolled steel S355+N the state, equivalent to the normalization state. As a result of normalized rolling, due to the additional compression of the sheet in the temperature region near the temperature A_{c3}, a microstructure is formed in the steel, which has an expressed banding and in which the fibers of ferrite and pearlite are formed with a high anisotropy of mechanical properties. The formation of such a fibrous structure leads to brittle fracture of the metal in the plane *X–Y* at a calculated temperature.

For the axial zone of the sheet, anisotropy of the structure is maximum. Accordingly, in this zone, the minimum toughness of the metal should be expected across the thickness of the sheet, and it can be considered as a probable location for lamellar crack formation.

2. Providing Z quality to the rolled steel in accordance with DSTU EN 10164:2009, which is determined during tension of the specimens in the direction perpendicular to the surface of the product, may be insufficient to prevent brittle layered fracture of the metal in the welded joints when using the steels after normalized rolling with a low sulphur content: $S \leq 0.010$ %. In this case, as an additional condition for resistance of the sheet rolled steels S355 and S420 to a brittle layered fracture, in addition to the rolled metal of the Z quality group, it is recommended to use such an indice as the minimum impact work, which is determined on the specimens with the notch in the rolling plane *X–Y* (along the axis of the sheet) KCV_{X-Y} and the value of which, before the accumulation of static data, is proposed to be taken according to DSTU-N B EN 1993-1-10:201: $KCV_{X-Y} \geq 27$ (40) J or according to DSTU EN 10025-2:2007 and DSTU EN 10025-3:2007, depending on the operating conditions, type of structure and degree of responsibility of welded assemblies. The temperature of testing specimens is determined taking into account the requirements of the relevant standard for designing metal structures of tanks, bridges, etc.

3. For metal structures of tanks of A group (wall, contour sheets of the bottom) under the condition of necessary providing the metal work in the direction of thickness, it is proposed to use the sheet rolled steels S355 and S420 in a state after normalization or normalization with a high-temperature tempering. In this case, the sulphur content in steel should not exceed

S ≤ 0.010 %, and it is necessary to control the continuity for it. In the case of using steels in a state of normalized rolling for the wall and contour sheets of the bottom of tanks, it is rational to limit the thickness of the sheet with a size $t \leq 15$ mm, for which the requirements to provide special properties in the perpendicular direction to the surface of the sheet are not envisaged.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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