Development of rolling procedures for pipes of K55 strength class at the laboratorial mill

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Experimental results of physical simulation of the manufacturing technology of coiled rolled strip for pipes of K55 strength class (API SCT) at the laboratorial mill are presented. This manufacturing process includes hot rolling with accelerated cooling and coiling at high temperature. Melting of 4 laboratorial melts of K55 steel was conducted. Mechanical properties of pilot strips were examined. Investigation of microstructure via the methods of optical and scanning electronic microscopy was conducted. All samples have ferrite-pearlite microstructure which corresponded to the aimed microstructure. It was noted that molten metal without vanadium is more susceptible to forming of undesirable products of intermediate transformation stage. Recommendations on chemical composition and manufacturing technology of K55 steel on 2000 rolling mill are developed. Steel has the following aimed chemical composition for the main elements: 0.32 % C; 0.5 % Si; 1.05 % Mn; 0.05 % V. The following main technological parameters were recommended: heating up to 1240-1260 ºC; temperature after 5th stand 1060-1100 ºC; thickness of rolled semiproduct 30-40 mm; temperature before 6th stand 950-970 ºC; finishing rolling temperature 830-870 ºC; temperature in the 1st coiling group 650-680 ºC; coiling temperature 620-640 ºC.
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Introduction

Steels with rather high carbon content are used for casing pipes and tubings (in comparison with gas and oil line pipes), what is explained by high requirements to their strength parameters as well as necessity to obtain rather low $\sigma_т/\sigma_в$ relationship. It is very important to provide small axial segregation and high steel cleanness for non-metallic inclusions in manufacture of rolled products for casing pipes and tubings [1-7].

Rolled products for casing pipes and tubings are manufactured mainly in wide hot strip mills using controlled rolling technology, with finishing of deformation in the γ-area with consequent accelerated cooling (for pipes without volume heat treatment), and via usual hot rolling procedures (for pipes which are subjected to heat treatment) [8-15].

Welded pipes are manufactured via strip forming in a forming mill with consequent welding of edges by high-frequency current (usually between 100 and 400 Hz). Preparation of strip edges includes their shearing (at the distance 15-20 mm from the edge of coiled strip) for elimination of defects which are widely presented on the edges. Shearing was carried out under 2º angle, and surface after shearing should remain clean. High-frequency current initiates heating of edges up to the temperature of forge welding (about 1400 ºC) and then reducing rolls connect strip edges together under sufficient pressure, what finalizes in welding. Welded joint is then subjected to high-speed cooling to provide integrity of welded seam structure. After such cooling, the seam structure contains martensite, and it is subjected to local seam heat treatment (usually normalization at the temperature about 900 ºC or tempering at the temperatures below ferrite → austenite transformation, within the temperature range 540-700 ºC) in order to provide equal strength of seam metal and main pipe metal [16-21].

The researches for prediction of the level of mechanical properties of steels with 75 variants of chemical composition were carried out earlier using the formulas of regression models. Calculation of predicted level of mechanical properties and type of microstructure was conducted for 18 most prospective chemical compositions using physical-mathematical model developed by "Severstal" JSC. The required type of microstructure to provide high level of tensile strength in combination with low value of yield strength was determined for pipes of K55 grade according to API 5CT. Based on these calculations, it was concluded about good prospects of 4 variants of steel chemical compositions for conduction of laboratorial experiments.

Previous researches [22] allowed to determine the aimed microstructure, the most suitable chemical compositions and theoretical substantiation of technological conditions for pipe production. Thereby necessity of development and pilot testing of rolling procedures for pipes of K55 grade at the laboratorial rolling mill was required.

T. S. Varkhaleva, Leading Expert of Severstal Management JSC also participated in this research.

Materials and methods

Development of the plan for laboratorial experiments

The experimental scheme for manufacture of pilot steel samples in laboratorial conditions was developed for checking of possibility of obtaining the required level of mechanical properties for the selected variants of chemical composition and for determination of the optimal K55 steel structure, which provides the most favourable combination of strength properties, toughness, ductility and cold resistance. The experiment includes melting in the laboratorial induction vacuum furnace of melts with 40 kg mass and with chemical composition in correspondence with the **Table 1** and rolling of obtained ingots in the laboratorial mill using the controlled rolling procedure via one deformation route, with varying the finishing rolling temperature and consequent air cooling. Coiling simulation was conducted via placing of rolled strips in the thermal furnace (which is pre-heated up to the coiling temperature) and retarded cooling of samples together with the furnace during at least 24 hours. The initial ingot thickness makes 80 mm and thickness of rolled strips – 8.5 mm.

To obtain the aimed ferrite-pearlite structure and to prevent forming of the intermediate transformation structures, it is necessary to finish rolling at the temperatures above A_{r3}, to provide air cooling of rolled strips and to simulate coiling above the temperature of bainite transformation. The developed deformation procedures and the preset temperature conditions of rolling are presented in the **Table 2** and **Table 3**. The experimental scheme on the laboratorial mill is shown on the **Fig. 1** and **Fig. 2**.

Table 1. **Steel chemical composition for conducting of laboratorial experiments**

Variants of chemical composition	C	Mn	Si	Nb	V	Cr	Ni	Cu	Mo	Ti	N	Al	Ceq
1	0.29	1.2	0.45	0.002	0.002	0.04	0,04	0.06	0.002	0.005	0.008	0.03	0.51
2	0.29	1.0	0.45	0.002	0.05	0.04	0,04	0.06	0.002	0.005	0.008	0.03	0.48
3	0.27	1.2	0.45	0.002	0.05	0.04	0,04	0.06	0.002	0.005	0.008	0.03	0.50
4	0.27	1.2	0.45	0.002	0.002	0.04	0,04	0.06	0.002	0.005	0.008	0.03	0.47

Calculated values of A_{r3} are equal to 720 °C, 736 °C, 726 °C and 726 °C, while initial temperature of bainite transformation B_s is equal to 639 °C, 657 °C, 645 °C and 645 °C (both parameters for the variants 1-4 respectively).

Table 2. **The developed deformation procedures of pilot K55 steel samples**

No. of pass	1	2	3	4	5	6	7	8	9	10
Initial thickness, mm	80	77	60	47	37	29	23	18	14	11
Final thickness, mm	77	60	47	37	29	23	18	14	11	8.5
Reduction, %	~0.038	22.1	21.7	21.3	21.6	20.7	21.7	22.2	21.4	22.7

Table 3. **Preset temperature conditions of rolling of pilot K55 steel samples**

No. of melt	No. of rolling procedure	$T_{heating}$, °C	Roughing rolling stage		Finishing rolling stage		Accelerated cooling		Cooling rate, °C/s
			T_s, °C	T_f, °C	T_s, °C	T_f, °C	T_s, °C	T_f, °C	
1-4	1	1200	≥1000	actual	actual	910	900	600	5

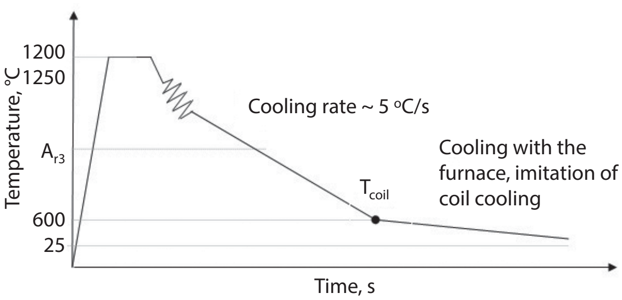


Fig. 1. Scheme of the experiment conduction at the laboratorial mill: hot rolling imitation

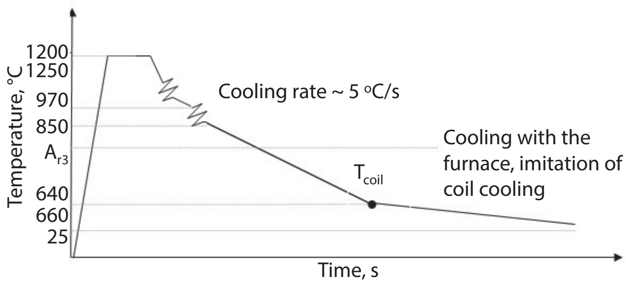


Fig. 2. Scheme of the experiment conduction at the laboratorial mill: controlled rolling imitation

The technique of conduction of pilot rolling at the laboratorial mill

The first pilot rolling was conducted in correspondence with the suggested schemes (Fig. 1 and 2). The temperature during rolling and cooling was measured by hand pyrometer.

The billets were heated in a chamber resistance furnace up to the temperature 1240 ºC and then they were gels at the preset temperature during at least 1 hour.

The billets which were heated to the preset temperature, were at first rolled at the laboratorial mill for the square section 80x80 mm and then for the strip with thickness 31 mm; afterwards intermediate cooling and final rolling for the strip with final thickness 8.5 mm were carried out.

3 billets from each melt were rolled according to the procedure of controlled rolling, with the starting temperature of the 2nd stage 950 ºC. The finishing rolling temperature made about 800 ºC.

All strips were subjected to accelerated cooling after rolling. It was realized via periodical (with 2-5 s interval) dipping of the billets in a water tank, which was previously heated to 70-75 ºC. The finishing cooling temperature for strips with coiling temperature 650 ºC and 600 ºC was 650 ºC and 600 ºC respectively. The cooling rate was varied via variation of the period of strip location in water between periodical temperature measurements.

After rolling and cooling to the preset temperature, rolled strips were put in a preliminarily heated (up to 650 ºC or 600 ºC) chamber resistance furnace (according to the plan of experiments) for imitation of coiling process. After rolling the strips were subjected to retarded cooling in the furnace down to the room temperature during 24 hours.

Deformation procedure during rolling at the laboratorial mill is presented in the **Table 4**, while actual temperature conditions of rolling and cooling are presented in the **Table 5**.

The samples for extension testing along rolling direction and for impact bending testing across rolling direction were taken from rolled strips, and the specimens for mechanical testing were manufactured. They include the specimens of III No. 7 type for extension testing (GOST 1497-84) and the specimens of 12 type, with sharp notch of 10x7.5 cross section for impact bending testing (GOST 9454-85).

Results and discussion

The hot rolling technology for strips with accelerated cooling and coiling temperature 600 °C is tested. After conduction of pilot rolling operations, the samples for extension testing (along rolling direction) and for serial testing on impact bending for cold resistance examination were taken

Table 4. **Deformation procedure during 2nd rolling of K55 steel at the laboratorial mill**

No. of pass	1	2	3	4	5	6	7	8	9	10	11
Initial thickness, mm	Ingot	Ingot	80	63	50	40	31	24	19	15	11
Final thickness, mm	80	80	63	50	40	31	24	19	15	11	8.5
Reduction, %	-	-	21.3	20.6	20.0	22.5	22.6	20.8	21.1	26.7	22.7
Force, MN	0.17	0.21	0.28	0.27	0.27	0.30	0.45	0.47	0.48	0.66	0.44

Table 5. **Actual temperature conditions of rolling and cooling of pilot K55 steel samples**

No. of melt	Procedure	Roughing rolling stage (80 mm→31mm)		Pause time, s	Finishing rolling stage (31 mm→8,5 mm)		Accelerated cooling				Coiling temperature, ºC
		T_s, ºC	T_f, ºC		T_s, ºC	T_f, ºC	T_s, ºC	T_f, ºC	Cooling time, s	$V_{cool.}$, ºC/c	
1	4 (CR+AC)	1175	1050	71	950	800	790	647	30	4.8	650
2	4 (CR+AC)	1200	104 5	63	950	795	785	660	35	3.6	650
3	4 (CR+AC)	1200	1040	62	950	800	790	650	37	3.8	650
1	5 (CR+AC)	1220	1075	76	950	795	785	592	55	3.5	600
2	5 (CR+AC)	1190	1070	76	950	790	780	645	22	6.1	650
3	5 (CR+AC)	1215	1060	76	955	800	790	650	25	5.6	650
1	6 (CR+AC)	1185	1095	78	950	810	800	595	30	6.8	600
2	6 (CR+AC)	1200	1080	81	955	805	790	590	43	4.7	600
3	6 (CR+AC)	1200	1090	80	950	810	780	595	47	3.9	600
4	1 (CR+AC)	1205	1070	76	950	805	10	2	600	40	600
4	2 (CR+AC)	1200	1080	86	950	800	12	4	610	23	600
4	3 (CR+AC)	1200	1095	88	950	805	15	2	620	21	600
4	4 (CR+AC)	1200	1090	85	950	810	17	3	620	24	600

Table 6. **Mechanical properties of pilot K55 steel samples**

Strip processing procedure	No. of strip	Orientation	σ_T	σ_B	σ_T/σ_B	δ_5	KV+21 (sample 7.5x10 mm)		
							1	2	3
1-1 (coiling at 650 °C)	10	across					70	69	68
		along	377	563	0.67	33.4			
1-2 (coiling at 600 °C)	13	across					65	70	68
		along	414	599	0.69	36.4			
1-3 (coiling at 600 °C)	16	across					61	64	60
		along	437	634	0.69	32.6			
2-1 (coiling at 650 °C)	11	across					64	59	61
		along	441	619	0.71	32.2			
2-2 (coiling at 650 °C)	14	across					68	62	63
		along	466	645	0.72	30.6			
2-3 (coiling at 600 °C)	17	across					60	69	66
		along	454	644	0 .70	30.0			
3-1 (coiling at 650 °C)	12	across					60	59	67
		along	441	635	0.69	31.4			
3-2 (coiling at 650 °C)	15	across					61	64	60
		along	470	647	0.73	30.4			
3-3 (coiling at 600 °C)	18	across					70	73	69
		along	479	661	0.72	30.8			
4-1 (coiling at 600 °C)	2	across					59	60	60
		along	483	674	0.72	28.2			
4-2 (coiling at 600 °C)	3	across					55	57	56
		along	487	680	0.72	29.6			
4-3 (coiling at 600 °C)	4	across					85	74	78
		along	506	690	0.73	30.8			
4-4 (coiling at 600 °C)	5	across					64	64	63
		along	498	686	0.73	30.6			
Requirements of API 5CT			379-552	≥655		≥17			

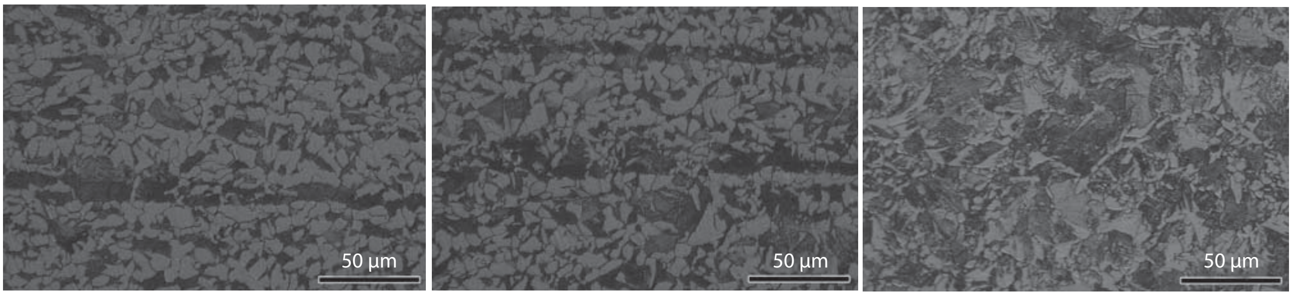


Fig. 3. Typical image of strip microstructure, x300:
a - 1-1 ½ of thickness, CR+AC, T_{coil} = 650 °C; *b* - 1-2, ½ of thickness, CR+AC, T_{coil} = 600 °C; *c* - 1-3, ½ of thickness, CR+AC, T_{coil} = 600 °C

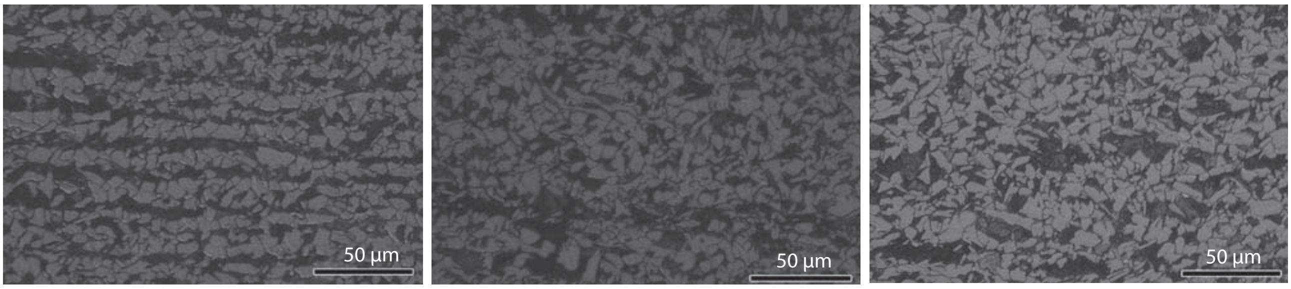
from each strip. Microstructure and kinetics of phase transformation in steel were examined as well.

The results of conducted mechanical testing are presented in the **Table 6**.

Study of microstructure of samples

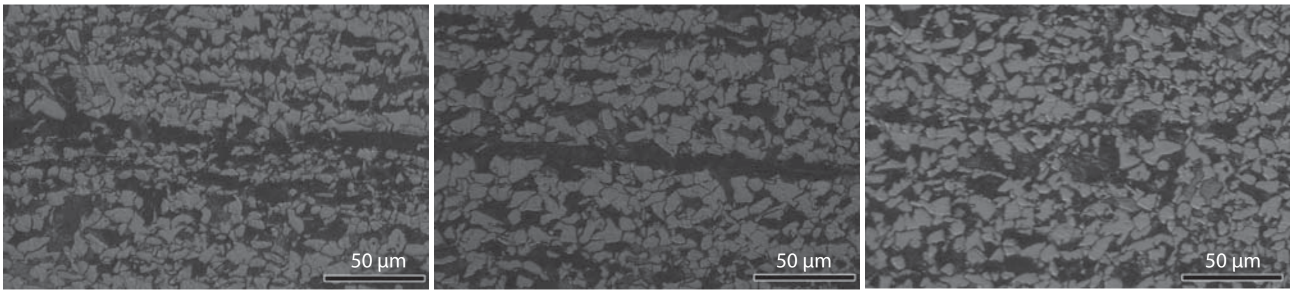
Microstructure of strips was examined on the samples taken from strip central part. The specimens were manufactured in longitudinal direction. 2-4 % HNO_3 alcohol solution was used for pickling. Microstructure components were examined with x300 magnification. Images of microstructure obtained on ½ and ¼ strip thickness differ slightly; they are presented in the **Fig. 3-6**.

Examination of microstructure displayed that increase of cooling rate leads (at other equal conditions) to ferrite grain refining; lowering of coiling temperature also leads to ferrite grain refining and increase of the part of quasi-polygonal ferrite. It should also noted that structure of the sample taken



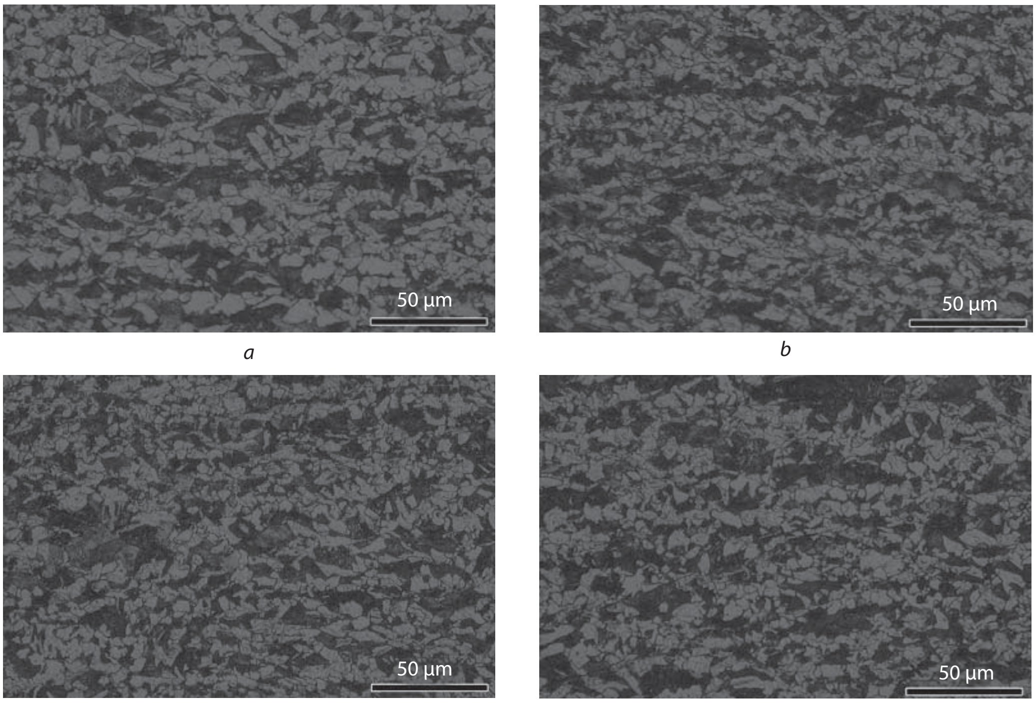
a *b* *c*

Fig. 4. Typical image of strip microstructure, x300:
a - 2-1 ½ of thickness, CR+AC, T_{coil} = 650 °C; *b* - 2-2, ½ of thickness, CR+AC, T_{coil} = 650 °C; *c* - 2-3, ½ of thickness, CR+AC, T_{coil} = 600 °C



a *b* *c*

Fig. 5. Typical image of strip microstructure, x300:
a - 3-1 ½ of thickness, CR+AC, T_{coil} = 650 °C; *b* - 3-2, ½ of thickness, CR+AC, T_{coil} = 650 °C; *c* - 3-3, ½ of thickness, CR+AC, T_{coil} = 600 °C



c *d*

Fig. 6. Typical image of strip microstructure, x300:
a - 4-1, ½ of thickness; *b* - 4-2, ½ of thickness; *c* - 4-3, ½ of thickness; *d* - 4-4, ½ of thickness

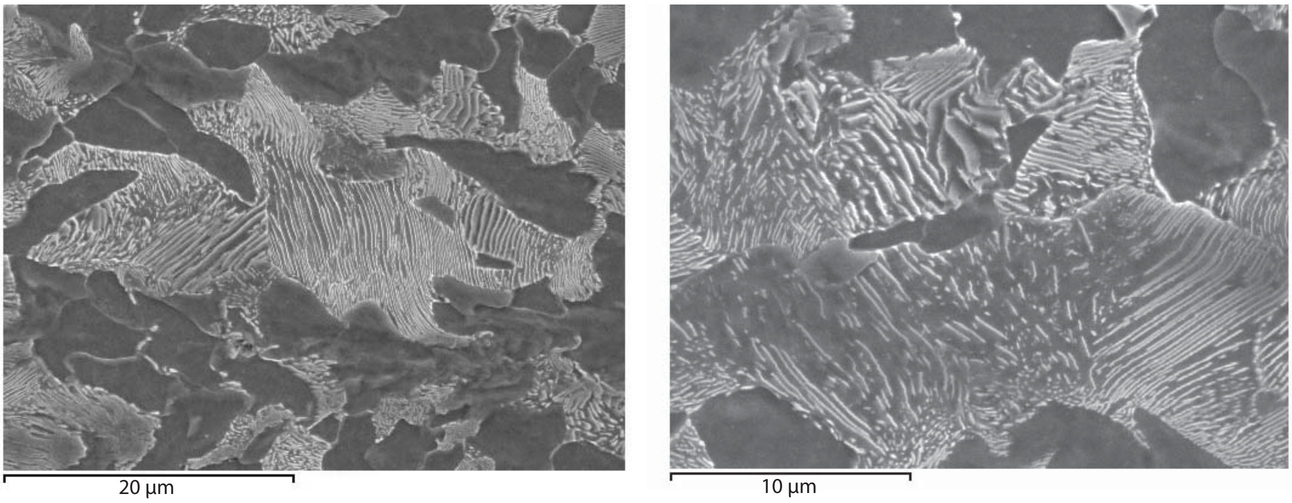


Fig. 7. Typical image of strip microstructure, SEM:
a – strips No. 4-1, x3000; *b* – strips No. 4-1, x5000

from the strip 3-3 is characterized by more coarse grain size in comparison with structure of the sample taken from the strip 2-3; it is connected with lower cooling rate.

It was noted that microstructure of melts, which are micro-alloyed by vanadium (melts 2 and 3) differs by smaller grain size and absence of shift transformation products in the structure, what can be connected with smaller size of austenite grain in these melts and, respectively, with smaller austenite stability that led to its decomposition during accelerated cooling and holding via diffusion mechanism.

Study of mechanical properties of pilot strips displayed thatbthe samples taken from the melts No. 1-3, containing 0.28-0.31 % C and 1-1.2 % Mn, don't provide the required level of tensile strength for K55 steel for the heating temperature before rolling 1240 ºC, temperature of controlled rolling and coiling 600-650 ºC. In this connection it was recommended to conduct melting of No. 4 melt, containing 0.32 % C and 1.1 % Mn, with vanadium addition and correction of cooling procedures.

Rolling of strips was carried out via the controlled rolling and accelerated cooling procedures. Deformation conditions were the same as were used in tolling the melts No. 1-3. The aimed finishing cooling temperature made 600 ºC; strip cooling rate at the 1st cooling stage (to 650 ºC) was varied, while cooling rate until the finishing cooling temperature (~600 ºC) was approximately the same.

After rolling and cooling to the preset temperature the rolled strips were placed (in correspondence with the experimental plan) in a chamber resistance furnace, which was preliminarily heated to 600 ºC for imitation of coiling process. Then strips we subjected to retarding cooling together with furnaces to the room temperature during 24 hours.

All samples taken from the melt No. 4 meet the requirements of API 5CT to mechanical properties of K55 steel. The required level of strength parameters was achieved sue to increase of carbon content in steel as well as to increase of strip cooling rate before the temperature ~650 ºC (imitation of dual-stage accelerated cooling in real production conditions of 2000 rolling mill at "Severstal" JSC).

As a result, it was revealed in this study that increase of cooling rate before the intermediate temperature 650 ºC led to substantial structure refining in comparison with structure of the samples taken from the melts No. 1-3.

In order to determine morphology of carbon-containing phase, microstructure was examined via the method of scanning electron microscopy (SEM) (Fig. 7) on the samples taken from strips No. 4-1 (with minimal values of strength parameters among strips from the melt No. 4) and from the strips No. 4-3 (with maximal values of strength parameters among strips from the melt No. 4).

The research displayed that morphology of carbon-containing phase differs slightly, despite difference of cooling rate for strips before the temperature 650 ºC. The second phase for two researched samples is presented by pearlite or mixture of pearlite and degenerated pearlite (see **Fig. 7**).

Conclusion

The experiment plan at the laboratorial mill is prepared; it includes testing of two variants of the technology of rolled coils manufacture of pipes of K55 strength class (API SCT). This manufacturing process includes controlled rolling with accelerated cooling or hot rolling without accelerated cooling, and coiling at high temperature as well. Melting of 4 laboratorial melts of K55 steel was conducted. Mechanical properties of pilot strips were examined.

The research displayed that the samples taken from the melts No. 1-3, which contain 0.28-0.31 % C and 1-1.2 % Mn, don't provide the required level of tensile strength for K55 steel in the conditions of heating before rolling up to 1240 ºC, controlled rolling and coiling at the temperature 600-650 ºC. The melt No. 4, containing 0.32 % C and 1,1 %

Mn as well as vanadium additive, on the contrary provides the required level of mechanical properties, which meets the requirements for K55 steel ($\sigma_{0.2}$ = 483-506 N/mm², $\sigma_в$ = 674-690 N/mm², δ_5 = 28-31 %, KV^{+21} = 55-74 J) after correction of cooling conditions. Microstructure was examined by the methods of optical and scanning electron microscopy. All samples were characterized by ferrite-pearlite microstructure, which corresponded to the aimed microstructure. It was noted that metal of the melt No. 1 (without vanadium) is mostly susceptible to forming of undesirable products of intermediate transformation (for the same cooling conditions).

The results of laboratorial experiment were analyzed. Recommendations for chemical composition and production technology of K55 steel at 2000 mill were developed. This steel has the following aimed composition (for the main elements): 0.32 % C; 0.5 % Si; 1.05 % Mn; 0.05 % V. The following technological parameters were recommended: heating up to 1240-1260 ºC, temperature after the 5th stand 1060-1100 ºC, thickness of a billet for rolling 30-40 mm, temperature before the 6th stand 950-970 ºC, finishing rolling temperature 830-870 ºC, temperature at the 1st coiling group 650-680 ºC, coiling temperature 620-640 ºC.

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