

Selection of the optimal parameters of controlled rolling and accelerated cooling of rolled products made of steel with ST80 strength class, which is aimed on manufacturing coiled tubing for Arctic application

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The paper presents the results of examination of the structure and properties of low-alloy steel, which is aimed on manufacturing coiled tubing for Arctic application, depending on different parameters of thermomechanical treatment. Based on the data about structural and phase transformations of overcooled austenite in steel, the temperature and speed processing indicators were selected and realized in the reversed hot rolling mill DUO-500, which is combined with the accelerated cooling system. These indicators meet the requirements of API Specification 5ST for the steel with ST80 strength class within the defined range (from 190 HV / 90 HRB to 240 HV / 99 HRB). The processing parameters, which ensure forming of fine-dispersed ferrite-bainite steel structure and thus achieving the highest level of tough and ductile properties at the preset strength level, were established.

Key words: coiled tubing, low-alloy steel, structural and phase transformations, controlled rolling, accelerated cooling, ferrite-bainite structure, mechanical properties, hardness.

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Introduction

The coiled tubing technology is the most effective tool providing conduction of technological operations without pumping derrick, horizontal drilling and hydraulic fracturing. At present time, a steady trend for increase of well depth and enlargement of length of horizontal sections is observed; together with necessity of mining intensification at the deposits with hard-to-recover reserves, it provides strict requirements to service properties of pipes [1–3].

“Engelsspetstrubmash” JSC is the key coiled tubing manufacturer in Russian Federation. Its technological cycle was based (before introduction of sanction restrictions) on using hot-rolled coils of low-alloy steel, mainly delivered by «ArcelorMittal» company from France. However, recent geopolitical situation made impossible continuation of such collaborating model and revealed sharp demand in development of steel composition and manufacturing procedure for domestic metallurgical product, which will be suitable for further pipe forming via the coiled tubing technology.

According to the requirements of the International standard API Specification 5ST [4], the materials for coiled tubing with ST80 strength class should provide the following complex of properties: tensile strength $\sigma_b \geq 610$ MPa, relative elongation $A_{50} \geq 20$ %, as well as limited hardness level $HRC \leq 22$ or $HRB \leq 99$, what is necessary for prevention of hydrogen cracking and providing fatigue life capability during multiple bending operations.

However, a standard set of parameters is insufficient for operation in the conditions of Far North and Arctic regions. Low climatic temperatures (down to -60 °C) require not only static strength of metal products, but also their high impact strength, low threshold of cold shortness and stability of mechanical properties in the conditions of cyclic loading.

At present time, there are no data in technical literature about the effect of controlled rolling and accelerated cooling parameters on forming of microstructure and complex of properties in domestic low-alloy steels, which are aimed on manufacturing coiled tubing for Arctic application [5–11]. In this connection, the aim of this research was study of the effect of thermomechanical treatment parameters on the structure (size and volumetric part of phase components) and mechanical properties (including impact strength) at the temperatures down to -60 °C, in order to select the optimal rolling technology.

Material and testing methods

The research was carried out at laboratorial samples with thickness 6 mm of steel with ST80 strength class, with the following original chemical composition, % (mass.): ≤ 0.16 C; ≤ 0.50 Si; ≤ 1.00 Mn; ≤ 0.70 Cr; ≤ 0.80 (Ni+Cu+Mo); ≤ 0.05 (Nb+V+Ti). Melting, continuous casting and thermomechanical treatment of steel with this chemical composition was conducted using equipment of the scientific and production complex in the Engineering center of Nosov Magnitogorsk State Technical University.

Dilatometric testing of steel samples were carried out using the Pocket Jaw module of the complex Gleeble 3500. Heating of the samples with diameter 6–10 mm up to austenite state was implemented in vacuum up to the temperature 930 °C with rate 3.3 °C/s via direct current passage. Consequent cooling was conducted at the rates within the range from 1 to 100 °C/s.

Metallographic researches were carried out in the Centre of common use at “Nanosteels” Scientific and research institute of Nosov Magnitogorsk State Technical University. Polished sections for microanalysis were fabricated according to the standard technique in the Buehler sample preparation line. A light microscope Zeiss Axio Observer, using the software Thixomet PRO for processing of metallographic images as well as via scanning electronic microscope JSM 6490 LV were used for microstructure analysis. Quantitative analysis was carried on light and electron microscope microstructure images using the software complex Thixomet PRO.

The complex of mechanical tests was carried out according to the special techniques.

Results and discussion

Achieving the complex of properties, which are regulated by the standard API Specification 5ST for coiled tubing of steel with ST80 strength class ($\sigma_b \geq 610$ MPa, A50 ≥ 20 %, HRC ≤ 22), as well providing cold shortness to -60 °C, are reached due to forming of strictly definite microstructure [10, 12–17]. As for low-alloy steels, which are used in coiled tubing manufacture, fine-grained structure consisting of ferrite and bainite or low-carbon martensite is recognized as the optimal one; it is characterized by high density of dislocations and nano-sized extractions of carbonitrides. Such structure allows to realize their mechanisms of dispersed and sub-structural hardening without significant decrease of ductility and toughness.

The controlled rolling technology combined with accelerated cooling is the most effective method to obtain such structure for coiled rolled products. Varying the temperature parameters at the finished rolling and accelerated cooling stages, as well as cooling rate after rolling, allows managing the forming process for final structure and, respectively, for mechanical properties.

To provide effective management of the properties of coiled rolled products, the features of passing phase and structural transformations during decomposition of overcooled austenite were conducted. Thermo-kinetic diagram for steel with the following original composition, % (mass.): ≤ 0.16 C; ≤ 0.50 Si; ≤ 1.00 Mn; ≤ 0.70 Cr; ≤ 0.80 (Ni+Cu+Mo); ≤ 0.050 (Nb+V+Ti) was built (Fig. 1) [18]. As a result, the temperature and speed conditions of forming the ferrite-bainite structure were determined; this structure provides hardness class within the defined range (from 190 HV / 90 HRB to 240 HV / 99 HRB) for the steel with ST80 strength class.

Based on the obtained data, the experimental procedures of thermal deformation processing of pilot steel for coiled tubing were developed and realized in the reversed hot rolling mill DUO-500, which is combined with the accelerated cooling system. The results of mechanical testing of hot-rolled coiled pilot samples, which were manufactured according to the selected procedures, are presented in the Table.

Metallographic examinations of steel samples with the following composition, % (mass.): ≤ 0.16 C; ≤ 0.50 Si; ≤ 1.00 Mn; ≤ 0.70 Cr; ≤ 0.80 (Ni+Cu+Mo); ≤ 0.050 (Nb+V+Ti), displayed that accelerated post-deformation spraying cooling with rate 10 – 25 °C/s allowed to form mixed ferrite-bainite structure.

It was found after controlled rolling and accelerated cooling according to the procedure No. 1 ($T_{s.a.c.} = 870$ °C and $T_{f.a.c.} = 650$ °C), that ferrite (~ 30 %), bainite (~ 65 %)

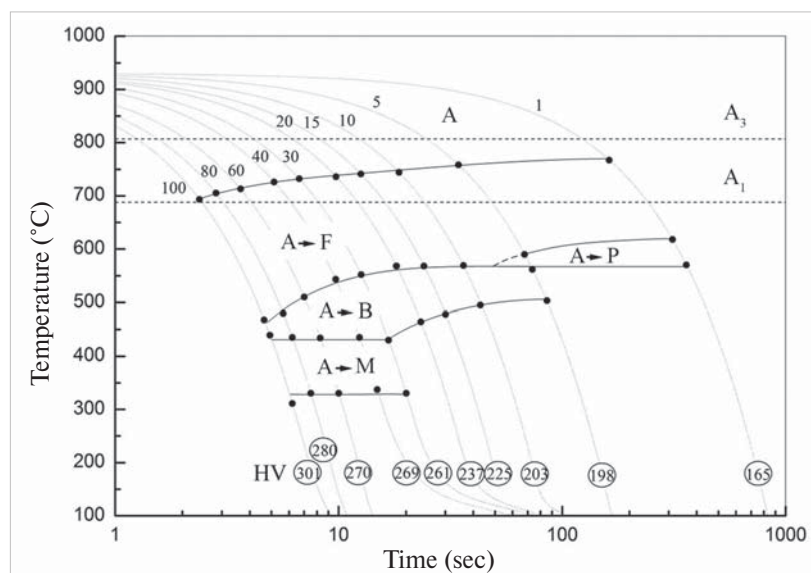


Fig. 1. Thermo-kinetic diagram of overcooled austenite transformation,
% (mass.): ≤ 0.16 C; ≤ 0.50 Si; ≤ 1.00 Mn; ≤ 0.70 Cr; ≤ 0.80 (Ni+Cu+Mo);
 ≤ 0.050 (Nb+V+Ti)
A – austenite; F – ferrite; P – pearlite; B – bainite; M – martensite

Temperature procedure of controlled rolling and accelerated cooling for steel of ST80 class													
No. of rolled piece	Procedures of controlled rolling and accelerated cooling					Mechanical properties							
	Heating before rolling	Finish of roughing rolling	Temperature, °C			Cooling rate, °C/s	For extension testing			HRB	HRC*	KCV, J/cm ²	
			Finish of final rolling	Start of accelerated cooling	Finish of accelerated cooling		$\sigma_{0.2}$, MPa	σ_B , MPa	A50, %			-40	-60
Standard API Specification 5ST							551–620	≥610	≥20	–	<22	–	–
1	1200±10	1000±40	880±10	870±10	650±10	10–25	485	645	26.0	92	<20	78.3	90.7
2			880±10	870±10	600±10		521	667	32.5	89	<20	85.3	101.3
3			880±10	870±10	550±10		584	668	21.5	97	<20	58.7	59.0
4			840±10	830±10	600±10		583	723	22.5	96	<20	122.0	110.0

*According to the GOST 9013-59, the varying range along the «C» scale makes ≥20 hardness units

and small amount (~ 5 %) of pearlite areas are presented in microstructure (Fig. 2, a, b). Presence of ferrite phase in such volume is caused by finishing of accelerated cooling within the ferrite range of temperature transformation.

Bainite is mainly characterized by granular morphology and presented quasi-polygonal ferrite with the islands of the second component, which is distributed between its grains. In this case, the second component in such bainite can have various structure: cementite particles, martensite-austenite (MA) areas, pearlite and degenerated pearlite in the form of small areas.

At the same time, the areas with lath bainite are revealed in the structure. This last one consists of extended α -phase lathes, which are organized in packs with extended MA-areas located along grain boundaries (Fig. 2, c).

It was found that after processing according to the procedure No. 2 ($T_{s.a.c.}=870\text{ }^\circ\text{C}$ and $T_{f.a.c.}=600\text{ }^\circ\text{C}$), that ferrite amount decreases (< 5 %) in comparison with the rolled

piece No. 1, what is explained by lowering of the finishing temperature of accelerated cooling. Bainite consists mainly of granular bainite (~ 80 %) and small amount (~ 5 %) of lath pearlite (~15 %) (Fig. 3, a). MA-areas and pearlite are the second component, both as in granular bainite (Fig. 3, b) as well as in lath bainite (Fig. 3, c); it is connected with relatively high finishing temperature of accelerated cooling.

It was found that after processing according to the procedure No. 3 ($T_{s.a.c.}=870\text{ }^\circ\text{C}$ and $T_{f.a.c.}=550\text{ }^\circ\text{C}$), that small amount (< 5 %) of quasi-polygonal ferrite and bainite, which is divided morphologically to granular and lath ones (approximately in equal parts) are also presented in microstructure (Fig. 4, a). At this processing procedure, only martensite-austenite areas in the form of islands (Fig. 4, b) and lathes (Fig. 4, c) present the second component in bainite, what is stipulated by higher cooling rate in comparison with the procedures No. 1 and No. 2.

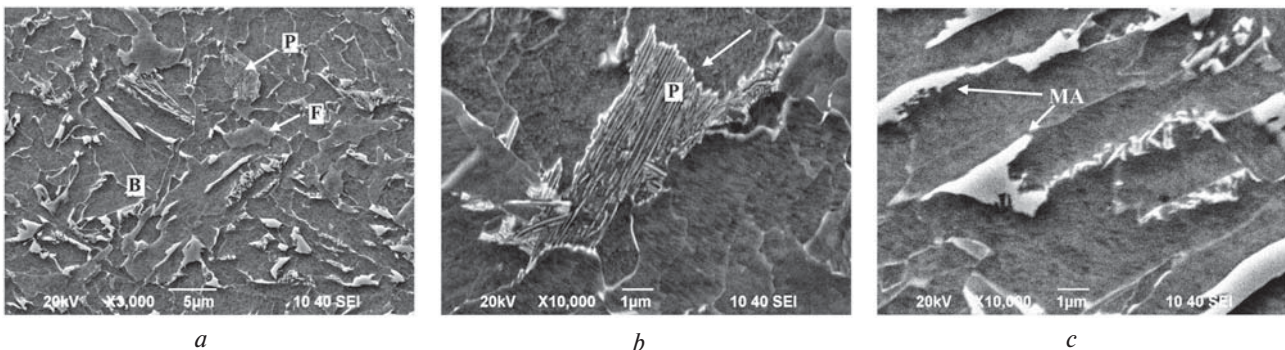


Fig. 2. Microstructure of the examined steel, which was processed via the procedure No. 1 ($T_{s.a.c.}=870\text{ }^\circ\text{C}$ and $T_{f.a.c.}=650\text{ }^\circ\text{C}$): a – ferrite + pearlite + bainite; b – pearlite area; c – MA-areas

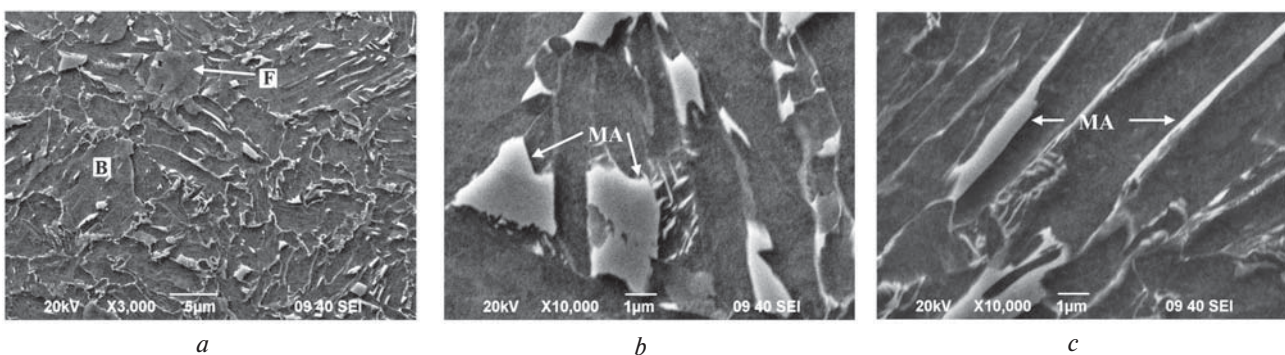


Fig. 3. Microstructure of the examined steel, which was processed via the procedure No. 2 ($T_{s.a.c.}=870\text{ }^\circ\text{C}$ and $T_{f.a.c.}=600\text{ }^\circ\text{C}$): a – bainite + ferrite; b – MA-areas in granular bainite; c – MA-areas in lath bainite

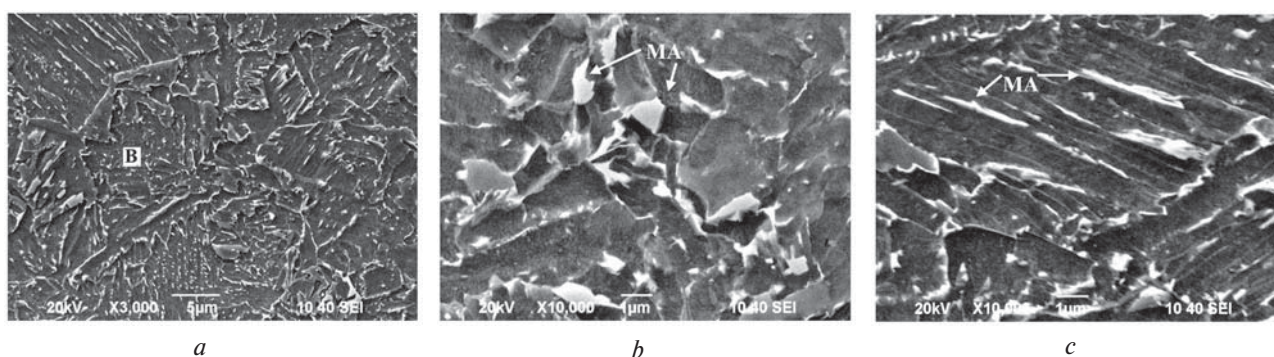


Fig. 4. Microstructure of the examined steel, which was processed via the procedure No. 2 ($T_{s.a.c.}=870^{\circ}\text{C}$ and $T_{f.a.c.}=550^{\circ}\text{C}$): *a* – bainite; *b* – MA-areas in granular bainite; *c* – MA-areas in lath bainite

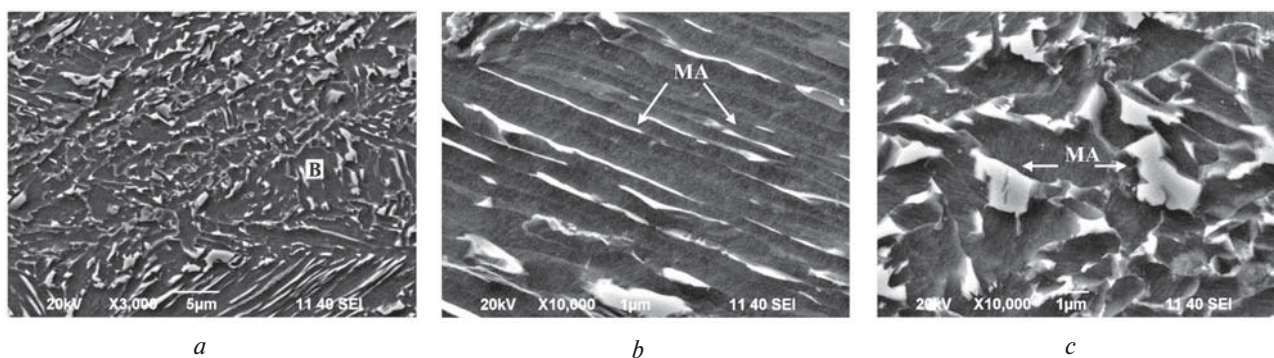


Fig. 5. Microstructure of the examined steel, which was processed via the procedure No. 4 ($T_{s.a.c.}=830^{\circ}\text{C}$ and $T_{f.a.c.}=550^{\circ}\text{C}$): *a* – bainite; *b* – MA-areas in lath bainite; *c* – MA-areas in granular bainite

It was found that after processing according to the procedure No. 4 ($T_{s.a.c.}=830^{\circ}\text{C}$ and $T_{f.a.c.}=600^{\circ}\text{C}$), that steel microstructure (Fig. 5, *a*) is identical to steel microstructure obtained according to the procedure No. 2 (see Fig. 3, *a*) with $T_{s.a.c.}=870^{\circ}\text{C}$ and $T_{f.a.c.}=600^{\circ}\text{C}$, but it differs by smaller ferrite grain size and larger dispersity of bainite component; it is explained by lower values of starting temperature of final rolling and finishing temperature of accelerated cooling.

Comparison of microstructure and mechanical properties of the samples from rolled pieces No. 2 and No. 4 showed that lowering of the finishing temperature of controlled rolling from 870°C to 830°C promotes forming more dispersed structure (see Fig. 5, *a*). Maximal diameter of ferrite grain in the rolled piece No. 4 makes $5\ \mu\text{m}$ (see Fig. 5, *a*), maximal thickness of plates in lath bainite makes $1\ \mu\text{m}$ (Fig. 5, *b*) and size of MA-areas in granular bainite makes $2\ \mu\text{m}$ (Fig. 5, *c*). As for the rolled piece No. 2, these sizes are equal to $7\ \mu\text{m}$, $5\ \mu\text{m}$ and $3\ \mu\text{m}$ respectively (see Fig. 2). Additionally, increase of the lath bainite part from 15 % to 50 % is observed in the steel structure, what provided rise of strength parameters of steel rolled products as well as increase of impact strength at the testing temperatures -40°C and -60°C .

Fine-dispersed ferrite structure and presence of bainite phase with lath morphology, which consists of α -phase plates separated by thin layers of carbon-enriched stable residual austenite, has positive effect on resistance to brittle destruction at low temperatures [12–16]. At the same time, pearlite presence in bainite as the second component can have negative effect on impact strength [12, 17].

The best results for mechanical properties of the steel with selected chemical composition (ST80 strength class) were obtained in the sample No. 4 after thermal deformation processing. This process includes accelerated cooling with the rolling heating from 840°C to the finishing cooling temperature 600°C . It finalizes in forming the structure containing lath and granular bainite (both up to 50 %) as well as small amount of quasi-polygonal ferrite (up to 5 %). This steel has the following mechanical properties: yield strength $\sigma_{0.2} = 583\ \text{MPa}$, tensile strength $\sigma_b = 723\ \text{MPa}$, relative elongation $A50 = 22.5\ \%$, hardness $\text{HRB} = 96$, impact strength $\text{KCV}^{-40} = 122\ \text{J/cm}^2$, $\text{KCV}^{-60} = 110\ \text{J/cm}^2$.

Conclusion

Based on the results of examination of structural and phase transformations of pilot steel with ST80 strength class for coiled tubing, with the following original chemical composition, % (mass.): $\leq 0.16\ \text{C}$; $\leq 0.50\ \text{Si}$; $\leq 1.00\ \text{Mn}$; $\leq 0.70\ \text{Cr}$; $\leq 0.80\ (\text{Ni}+\text{Cu}+\text{Mo})$; $\leq 0.05\ (\text{Nb}+\text{V}+\text{Ti})$, were selected and realized in the reversed hot rolling mill DUO-500, which is combined with the accelerated cooling system. The experimental procedures of thermal and deformation treatment, providing hardness within the defined range (from $190\ \text{HV}/90\ \text{HRB}$ to $240\ \text{HV}/99\ \text{HRB}$), were determined as well.


Taking into account the results of qualitative and quantitative metallographic analysis of coiled rolled pilot samples, the following features of structure forming depending on the processing indicators were revealed:

- microstructure of the samples after controlled rolling and accelerated cooling from the temperature 870°C , which

is above the starting temperature of $\gamma \rightarrow \alpha$ transformation, and down to the temperature 650 °C, consists (in volumetric parts) of quasi-polygonal ferrite (up to 30 %), granular and lath bainite (up to 65 %) and pearlite (up to 5 %);

– microstructure of the samples, subjected to cooling from the starting accelerated cooling temperature 870 °C down to the finishing cooling temperature within the range 550–600 °C, consists mainly of granular and lath bainite with martensite-austenite component in the form of “islands” and lathes, as well as quasi-polygonal ferrite with volumetric part not exceeding 5 %;

– lowering the starting accelerated cooling temperature from 870 to 830 °C (above the point A_{r3} by ~10–20 °C) at the equal temperature conditions of cooling finishing (600 °C) promoted forming more dispersed structure as well as increase of lath bainite part in steel structure; in also provided rise of strength parameters of steel rolled products as well as increase of impact strength values at the testing temperatures –40 °C and –60 °C.

It was established on the base of the mechanical testing results that achieving of the most high impact strength values ($KCV_{-40} = 122 \text{ J/cm}^2$, $KCV_{-60} = 110 \text{ J/cm}^2$) for the steel with ST80 strength class according to the requirements of API Specification 5ST ($\sigma_T = 583 \text{ MPa}$, $\sigma_B = 723 \text{ MPa}$, 96 HRB (HRC < 20)) is provided by the following processing parameters: the starting accelerated cooling temperature 830 °C and the finishing accelerated cooling temperature 600 °C, due to forming of fine-dispersed ferrite-bainite structure. 

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