

Influence of Thermomechanical Processing Modes on the Formation of Structure and Properties of Rolled Strip for Coiled Tubing [†]

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Abstract

This study presents the results of investigations into a new low-alloyed steel grade CT80 designed for coiled tubing (CT) with increased cold resistance requirements. Based on data concerning the structural-phase transformations of overcooled austenite, various thermomechanical treatment modes were defined and tested on a reversing hot rolling mill DUO-500 combined with an accelerated cooling system. Controlled rolling and accelerated cooling regimes were established, ensuring the formation of the most favorable microstructure for achieving a high level of ductile-plastic properties at the specified strength level of CT80-class steel.

Keywords: coiled tubing; low-alloy steel; CT80 strength class; processing modes; controlled rolling; accelerated cooling; structure; mechanical properties

1. Introduction

The work is aimed at creating new import-substitute materials for the oil and gas complex of Russia, specifically steels for coiled tubing (CT), which are particularly promising for extracting hard-to-retrieve reserves as well as enhancing oil recovery from old fields.

Within Russia, Engelsspetsstrubmash LLC is engaged in CT production. However, this company used hot-rolled coil made from low-alloy steel produced by foreign companies as raw material, whose supplies became complicated due to sanctions pressure.

At the same time, apart from the issue of import substitution, there is currently a necessity to use CT in remote regions of the Far North and Arctic areas. The specifics of operation in northern regions dictate the need for CT materials that meet both the requirements of international standard API Specification 5ST “Specification for Coiled Tubing” for CT80-grade steel: ultimate tensile strength $UTS \geq 610$ MPa, elongation $A50 \geq 20\%$, hardness $HRC \leq 22/HRB \leq 99$, and also exhibit improved cold resistance down to temperatures of minus 60 degrees Celsius compared to imported analogs. Achieving such a combination of properties will enable their application in conditions of the Far North and Arctic regions.

The high demand for such rolled strips necessitates the development of domestic production technology. Obtaining a sufficiently narrow range of strength characteristics ($UTS \geq 610$ MPa and $HRC \leq 22$) on rolled strips is a challenging task. This can be achieved



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through the use of a regulated chemical composition and parameters of thermomechanical processing technology combining controlled rolling with accelerated cooling.

Thus, the objective of the work is to identify thermomechanical processing temperature parameters that provide maximum impact toughness values at the specified strength level of CT80 steel for a new chemical composition steel for coiled tubing.

2. Materials and Methods

The work was carried out on laboratory samples of CT80-grade steel with an original chemical composition containing no more than the following percentages (% mass): $\leq 0.16\%$ C; $\leq 0.50\%$ Si; $\leq 1.00\%$ Mn; $\leq 0.70\%$ Cr; $\leq 0.80\%$ (Ni + Cu + Mo); $\leq 0.050\%$ (Nb + V + Ti). Melting, continuous casting, and thermomechanical processing of steel with the specified chemical composition were performed using equipment from the scientific and production complex of the Engineering Center of FSBEI HE “Nosov Magnitogorsk State Technical University”.

Dilatometric tests of the steel were conducted on the Pocket Jaw module of the Gleeble 3500 complex. Heating of samples with diameters of 6–10 mm to the austenitic state was carried out in vacuum at a rate of $3.3\text{ }^{\circ}\text{C/s}$ by direct current passage up to a temperature of $930\text{ }^{\circ}\text{C}$. Subsequent cooling was performed at rates ranging from 1 to $100\text{ }^{\circ}\text{C/s}$.

Metallographic studies of samples after different modes of controlled rolling and accelerated cooling were carried out at the Shared Use Center of the Nanosteel Research Institute of FSBEI HE “Nosov Magnitogorsk State Technical University”. Microsections were prepared according to standard methodology on Buehler’s sample preparation line. Analysis of microstructure was performed on a light microscope Zeiss Axio Observer with the Thixomet PRO image analysis system and scanning electron microscope (SEM) JSM 6490 LV. Quantitative analysis was carried out using the Thixomet PRO 4 (2020) software package based on light and electron microscopic images of the microstructure.

A comprehensive set of mechanical tests was performed according to standard methodologies. Tensile mechanical tests were conducted on no fewer than 6 specimens for each processing regime, and impact toughness tests were performed on no fewer than 12 specimens from a single billet.

3. Results and Discussion

To effectively manage the properties of rolled strip, phase-structural transformations during the decomposition of undercooled austenite were investigated, and a thermokinetic diagram was constructed for steel with an original chemical composition containing no more than the following percentages (% mass): $\leq 0.16\%$ C; $\leq 0.50\%$ Si; $\leq 1.00\%$ Mn; $\leq 0.70\%$ Cr; $\leq 0.80\%$ (Ni + Cu + Mo); $\leq 0.050\%$ (Nb + V + Ti) [1,2]. As a result, temperature-rate conditions were identified for forming fine-dispersed ferrite–bainite structures, providing CT80 steel with hardness within the specified range (from 190 HV/90 HRB to 240 HV/99 HRB).

Based on the obtained data, thermomechanical processing modes for experimental CT steel were developed and implemented on a reversing hot rolling mill DUO-500 integrated with an accelerated cooling system. The results of mechanical testing of laboratory samples of hot-rolled coil manufactured according to the selected modes are presented in Table 1.

Metallographic studies showed that in steel samples with a chemical composition (% mass) of $\leq 0.16\%$ C, $\leq 0.50\%$ Si, $\leq 1.00\%$ Mn, $\leq 0.70\%$ Cr, $\leq 0.80\%$ (Ni + Cu + Mo), $\leq 0.050\%$ (Nb + V + Ti), post-deformation spray cooling at a rate of $10\text{--}25\text{ }^{\circ}\text{C/s}$ allowed for the formation of a mixed ferrite–bainite structure.

After controlled rolling and accelerated cooling according to mode No. 1 (start temperature of accelerated cooling $T_{a.c.s.} = 870\text{ }^{\circ}\text{C}$ and end temperature of accelerated cooling

Ta.c.e. = 650 °C), the microstructure contains ferrite (30%), bainite, and a small amount (5%) of pearlite regions (Figure 1a).

Table 1. Temperature regime of controlled rolling and accelerated cooling.

Processing mode	Controlled Rolling and Accelerated Cooling Modes						Strength Class	Mechanical Properties						
	Temperature, °C					Cooling Rate, °C/s		Tensile Testing			HRB	HRC *	KCV, J/cm ²	
	Heating for Rolling	End of Phase 1	End of Phase 2	Start of Accelerated Cooling	End of Accelerated Cooling			YS, MPa	UTS, MPa	A ₅₀ , %			−40	−60
	API Specification 5ST Standard						CT80	551–620	≥610	≥20	-	<22	-	-
1	1200 ±10	1000 ±40	880 ± 10	870 ± 10	650 ± 10	10–25	CT80	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 GOST 9013-59, the measurement range on the “C” scale is ≥20 units of hardness.

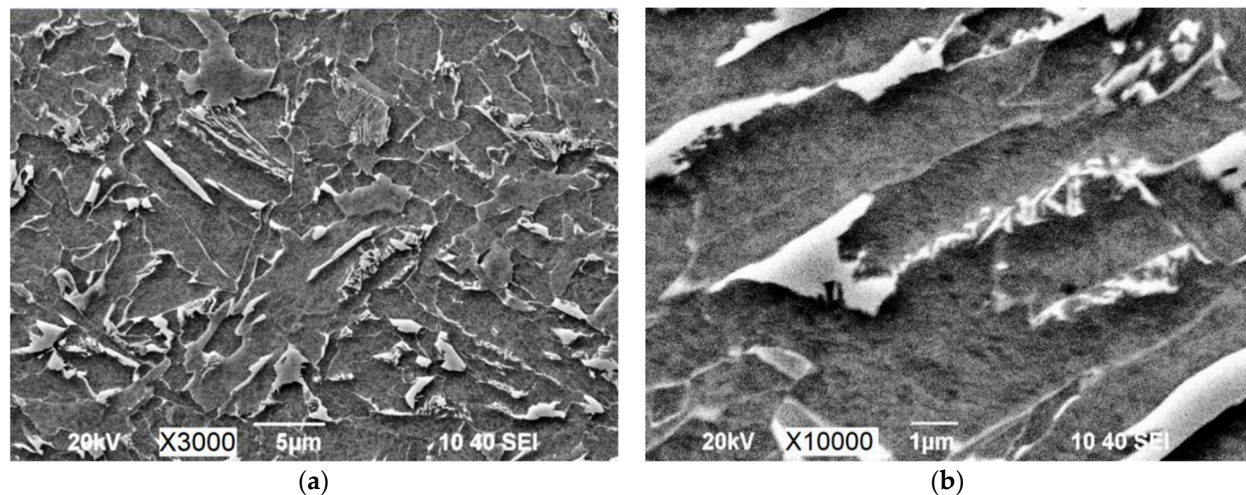


Figure 1. Microstructure of the studied steel according to mode No. 1: Ta.c.s. = 870 °C and Ta.c.e. = 650 °C. (a) 3000×, (b) 10,000×.

The presence of ferrite phase in such volume is due to the completion of accelerated cooling in the ferrite interval of the transformation temperature. The bainite has predominantly granular morphology.

However, lath bainite regions are also observed in the structure. Granular bainite represents quasi-polygonal ferrite with islands of the second component distributed between its grains. In this case, the second component in such bainite may have different structures: cementite particles, martensite–austenite (MA) zones, pearlite, and degenerate pearlite in the form of small regions. Lath bainite consists of elongated α -phase plates organized into packets with extended MA zones located at the boundaries of the plates (Figure 1b).

After processing according to mode No. 2 (Ta.c.s. = 870 °C and Ta.c.e. = 600 °C), the amount of ferrite decreases (<5%). Compared to roll No. 1, this is explained by the reduction in the temperature at the end of accelerated cooling. The bainite mainly consists of granular bainite (80%) and a small amount of lath bainite (15%) (Figure 2a). The second component, both in granular and lath bainite, is MA zones and pearlite (Figure 2b), which is also associated with the relatively high temperature at the end of accelerated cooling.

After processing according to mode No. 3 (Ta.c.s. = 870 °C, Ta.c.e. = 550 °C), the microstructure also contains a small amount (<5%) of quasi-polygonal ferrite and bainite, which morphologically divides into granular and lath types in approximately equal quan-

tities (Figure 3a). For this mode, the second component in the bainite consists only of martensite–austenite regions in the form of islands and lamellae (Figure 3b).

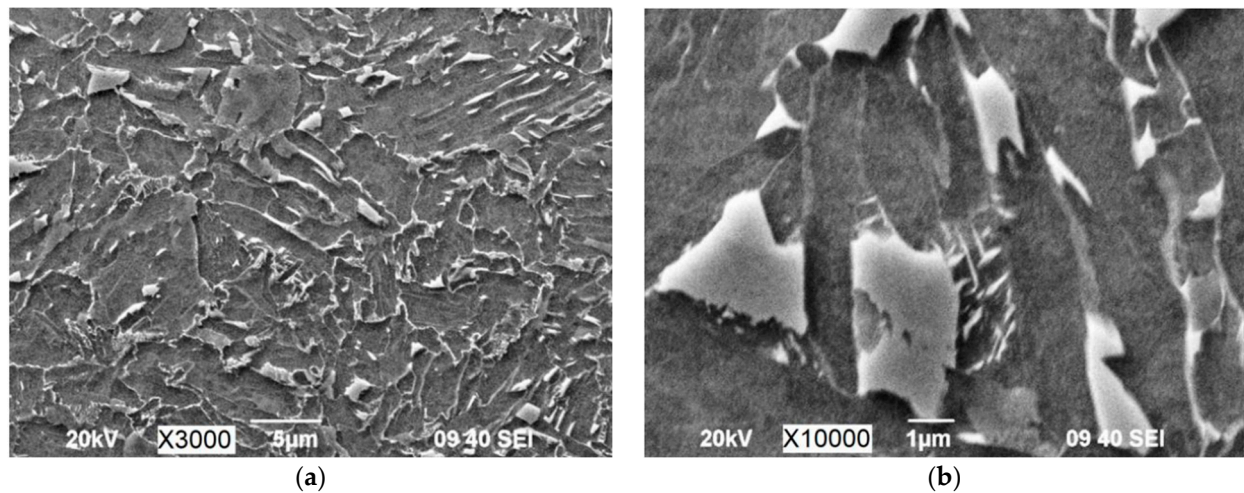


Figure 2. Microstructure of the studied steel according to mode No. 2: Ta.c.s. = 870 °C and Ta.c.e. = 600 °C. (a) 3000×, (b) 10,000×.

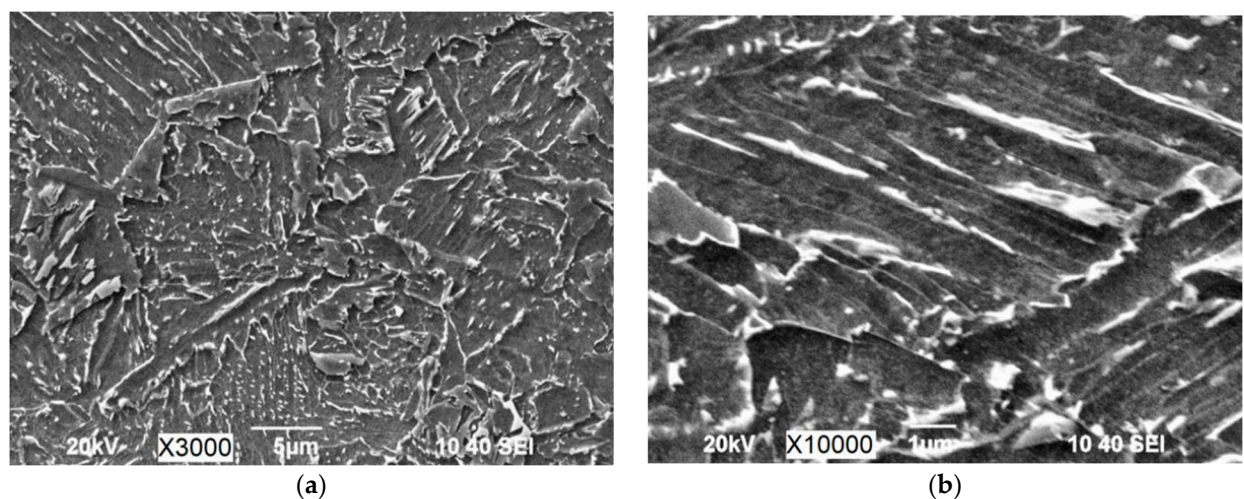


Figure 3. Microstructure of the studied steel according to mode No. 3: Ta.c.s. = 870 °C and Ta.c.e. = 550 °C. (a) 3000×, (b) 10,000×.

After processing according to mode No. 4 (Ta.c.s. = 830 °C and Ta.c.e. = 600 °C), the microstructure (Figure 4) is similar to that shown in Figure 2, obtained according to mode No. 2 (Ta.c.s. = 870 °C and Ta.c.e. = 600 °C). However, it differs since it has smaller ferrite grain sizes and higher dispersion of the bainitic component. This is explained by lower values of the finishing rolling temperature and the starting temperature of accelerated cooling.

Comparison of the microstructures and mechanical properties of samples No. 2 and No. 4 revealed that reducing the temperature at the end of controlled rolling from 870 °C to 830 °C contributed to the formation of a finer-grained structure. In sample No. 4, the maximum diameter of ferrite grains is 5 µm, the maximum thickness of laths in lath bainite is 1 µm, and the size of MA regions in granular bainite is 2 µm. In sample No. 2, these values are grade 7 µm, 5 µm, and 3 µm, respectively.

Additionally, there is an increase in the proportion of lath bainite in the steel structure from 15% to 50%. This resulted in an improvement in the strength characteristics of the

steel strip, as well as an increase in impact toughness values at test temperatures of $-40\text{ }^{\circ}\text{C}$ and $-60\text{ }^{\circ}\text{C}$.

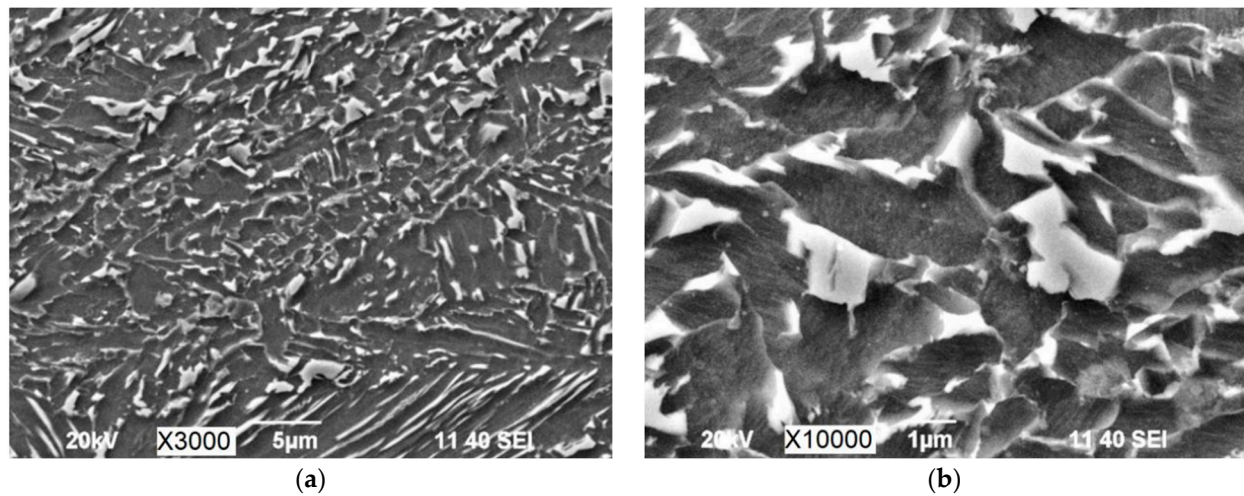


Figure 4. Microstructure of the studied steel according to mode No. 4: Ta.c.s. = $830\text{ }^{\circ}\text{C}$ and Ta.c.e. = $600\text{ }^{\circ}\text{C}$. (a) $3000\times$, (b) $10,000\times$.

Fine-grain ferritic structure and the presence of bainitic phase with lath morphology consisting of thin α -phase plates separated by thin layers of carbon-enriched stable residual austenite favorably affect resistance to brittle fracture at low temperatures [3–7]. At the same time, the presence of pearlite as the second constituent in bainite (samples No. 1 and No. 2) may negatively influence impact toughness [8,9].

The best results in terms of mechanical properties for the selected chemical composition of steel were obtained on sample No. 4 after thermomechanical treatment involving accelerated cooling from rolling heat from $840\text{ }^{\circ}\text{C}$ to the final cooling temperature of $600\text{ }^{\circ}\text{C}$. Under these conditions, a structure forms consisting of lath bainite (48%) and granular bainite (48%), along with a negligible amount of quasipolygonal ferrite (up to 5%). These conditions yield the following mechanical properties: YS—583 MPa, UTS—723 MPa, A50—22.5%, hardness—96 HRB, impact toughness KCV^{-40} —122 J/cm²; KCV^{-60} —110 J/cm².

4. Conclusions

Based on the results of structural-phase transformation studies conducted at the Laboratory Complex of the Engineering Center of FSBEI HE “Nosov Magnitogorsk State Technical University” on the reversing hot rolling mill DUO-500 combined with an accelerated cooling system, experimental thermomechanical processing modes were implemented for CT80-grade steel for coiled tubing with an original chemical composition containing no more than the following percentages (% mass): $\leq 0.16\%$ C; $\leq 0.50\%$ Si; $\leq 1.00\%$ Mn; $\leq 0.70\%$ Cr; $\leq 0.80\%$ (Ni + Cu + Mo); $\leq 0.050\%$ (Nb + V + Ti).

As a result of the conducted research on the effect of various thermomechanical processing modes on the formation of structure and properties of the developed materials, it was found that achieving the highest level of ductile-plastic properties ($\text{KCV}^{-40} = 122\text{ J/cm}^2$ and $\text{KCV}^{-60} = 110\text{ J/cm}^2$) at the achieved strength level of CT80 steel according to API Specification 5ST (YS = 583 MPa, UTS = 723 MPa, 96 HRB (HRC < 20)) is ensured after controlled rolling with subsequent accelerated deformation cooling under the following conditions: acceleration cooling start temperature of $830\text{ }^{\circ}\text{C}$ and acceleration cooling end temperature of $600\text{ }^{\circ}\text{C}$. This is achieved through the formation of a target fine-dispersed ferrite–bainite structure.

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