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INFLUENCE OF COIL COOLING CONDITIONS ON THE MICROSTRUCTURE AND PROPERTIES OF HOT-ROLLED STRIP STEEL

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ABSTRACT

Improving the quality of hot-rolled sheet steel is one of the key challenges in modern metallurgical production, since cooling conditions at different stages of the technological process have a significant influence on the formation of the microstructure and the mechanical properties of the metal. The aim of this study was to establish the patterns of structural transformations in low-carbon steel under various cooling regimes and to determine the optimal thermomechanical processing parameters for improving the quality of hot-rolled products. The research was carried out on samples of hot-rolled St3sp steel using optical metallography, scanning electron microscopy, and energy-dispersive microanalysis. The influence of cooling regimes on the formation of the metal microstructure was evaluated, and the features of structural changes occurring during coil cooling after coiling were investigated.

It was established that the temperature–time parameters of cooling have a decisive effect on grain size, the morphology of structural constituents, and the nature of phase transformations in steel. It was shown that the selection of an optimal cooling regime ensures the formation of a more homogeneous fine-grained microstructure and reduces the likelihood of unfavorable structural constituents. It was found that changes in the properties of the metal during coil cooling are more closely associated with cementite spheroidization processes than with ferrite grain growth. A relationship was established between the degree of cementite spheroidization and changes in the mechanical properties of hot-rolled steel.

The obtained results can be used to improve cooling practices on hot strip mills in order to enhance the quality of sheet products and ensure the stability of their service performance characteristics.

INTRODUCTION

The intensification of modern rolling production is based on the continuous increase in productivity and the required quality of finished products. The majority of hot-rolled strip steel is produced on continuous hot strip mills, and the use of forced cooling systems for rolled strips is one of the most important factors affecting the efficiency of hot rolling mills and the improvement of the performance characteristics of hot-rolled products (Naizabekov et al., 2014; Mashekov et al., 2007).



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The production technology of strip steel on hot strip mills involves cooling the strips on the run-out table and coiling them at temperatures of 550–750°C. The coils are then transferred to the storage area, where they cool to 20–80°C over a period of 2–3 days, depending on the coil weight. The microstructure and properties of hot-rolled steel are largely determined by the cooling conditions on the run-out table and during cooling after coiling (Mashekov et al., 2007).

During coil cooling from the coiling temperature, processes of ferrite grain growth through normal recrystallization and spheroidization of pearlitic cementite lamellae develop (Meleshko et al., 1980; Shkatov et al., 1991). The extent of these structural transformations during coil cooling affects the physical and mechanical properties of hot-rolled steel and depends on the coiling temperature as well as the cooling rate of the coil, which in turn is determined by the coil weight and the cooling method employed (natural cooling, air cooling, or forced accelerated cooling).

To improve the quality of hot-rolled strips and reduce material and energy costs associated with strip transportation and cooling, various run-out table designs have been developed for hot strip mills (Baigunchekov et al., 2006; Mashekov et al., 2009).

The next stage of the present work involved comparing different cooling regimes and the spheroidization behavior of lamellar pearlite in order to determine the optimal lengths of air-cooling and forced water-cooling sections on the run-out table (Mashekov et al., 2007; Mashekov et al., 2008; Mashekov et al., 2008; Mashekov et al., 2008).

MATERIALS AND METHODS

For the present study, St3sp steel a low-carbon structural steel produced according to GOST 380-2005 produced by the basic oxygen furnace (BOF) process, continuously cast on a continuous casting machine, and subsequently rolled on a 1700 mm continuous hot strip mill was used. The main physical, mechanical, and chemical characteristics of this steel grade are specified in GOST 380–2005 (Carbon Steel of Ordinary Quality. Grades) (GOST 380-2005, 2008).

Samples 4 mm thick were cut from the hot-rolled strip and heated in a furnace at a rate of 20°C/min to the temperatures listed in Table 1, followed by holding at the target temperature for 30 minutes. The total austenitization time (approximately 40 minutes) ensured complete homogenization of the austenite (Meleshko et al., 1980).

During the experiments, the cooling temperature, air-cooling time, and forced water-cooling time were varied according to the regimes presented in Table 1 (Mashekov et al., 2008; Mashekov et al., 2008; Mashekov et al., 2008).

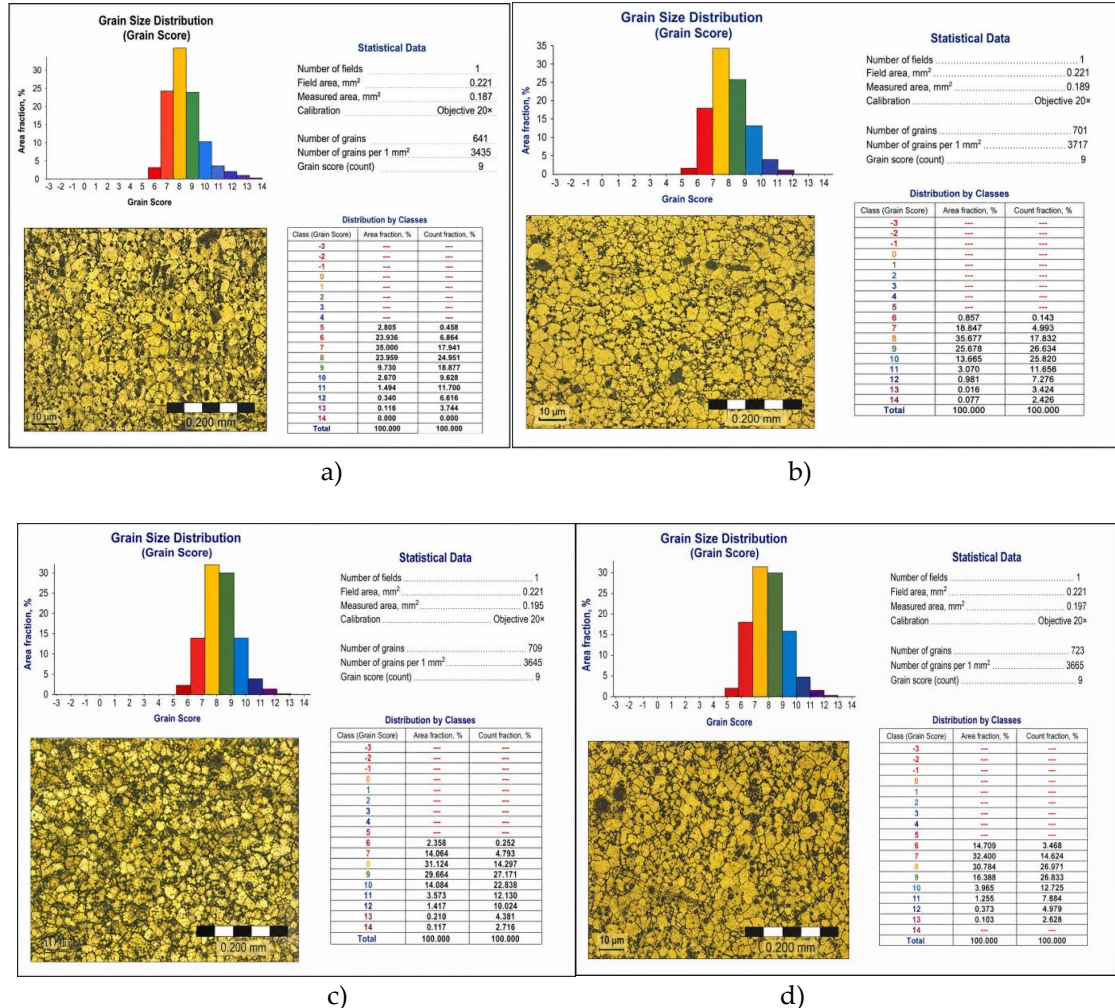
To investigate the kinetics of lamellar pearlite spheroidization, the specimens were annealed at 600°C for 1, 3, 5, and 10 h.

Metallographic examinations were performed using an Axiovert 200 MAT optical microscope at magnifications of $\times 200$, $\times 500$, and $\times 1000$. Image analysis was carried out using the VideoTesT-Metall 1.0 software package. Microstructural characterization and chemical microanalysis were additionally conducted using a JNCA Energy energy-dispersive spectrometer (Oxford Instruments, UK) mounted on a JEOL electron probe microanalyzer operated at an accelerating voltage of 25 kV (Absadykov et al., 2010). The magnification range of the JEOL instrument extends from $\times 40$ to $\times 40\,000$.

The operating principle of the microanalyzer is as follows: a high-energy (25 keV) narrow electron beam (approximately 1 μm in diameter) is directed onto the specimen surface and scanned in a raster pattern. During scanning, secondary electrons emitted from the specimen are detected and recorded. The resulting images are similar to optical micrographs; however, owing to the extremely small diameter of the electron beam (approximately 1–2 μm), the depth of focus is considerably greater than that of optical microscopy. This makes it possible to achieve much higher magnifications and, consequently, to resolve finer microstructural constituents of the material.

RESULTS AND DISCUSSION

Microstructural examination of the experimental specimens subjected to different cooling regimes revealed that the ferrite grain size ranged from 16 to 22 μm (Figures 1–4). No evidence of grain-size heterogeneity was observed under any of the cooling conditions investigated.



(a) cooling schedule I; (b) cooling schedule II; (c) cooling schedule III; (d) cooling schedule IV.

Figure 1. Microstructures of St3sp steel heated to 840°C and cooled according to different cooling schedules.

Note – compiled by the authors

In the equilibrium microstructure, the volume fraction of lamellar pearlite is determined by the carbon content of the steel and by the displacement of the eutectoid point in the Fe–Fe₃C phase diagram caused by alloying elements and impurities. For St3sp steel, manganese and silicon are the principal elements influencing the eutectoid composition. For St3sp steel, manganese and silicon are the principal elements influencing the eutectoid composition. The eutectoid points shift by 0.07 wt.% C for each 1 wt.% Mn and by 0.10 wt.% C for each 1 wt.% Si (Shkatov et al., 1991). Thus, the equilibrium pearlite fraction may be estimated using the lever rule $P_o = (C - 0.02) / (0.78 - 0.07 \text{ Mn} - 0.1 \text{ Si})$, where C, Mn, and Si are the mass fractions of carbon, manganese, and silicon, respectively (wt.%). For St3sp steel with the chemical composition investigated in this study, the equilibrium pearlite fraction was calculated to be 16.9%. The measured pearlite volume fraction (*P*) may exceed the equilibrium value owing to the relatively

low temperature of the pearlitic transformation. Conversely, it may be lower than the equilibrium value if structurally free cementite precipitates from pearlite during cooling of the specimens.

Table 1. Experiment plan

Furnace temperature (°C) No. 1	Variants			
	I	II	III	IV
1) 840	1) 840	1) 840	1) 840	1) 840
2) 920	2) 920	2) 920	2) 920	2) 920
3) 1000	3) 1000	3) 1000	3) 1000	3) 1000
4) 1080	4) 1080	4) 1080	4) 1080	4) 1080
Air cooling (c)	4	6	8	10
Water cooling (c)	14	10	6	2
Air cooling (c)	4	6	8	10
Furnace temperature (°C) No. 2	600	600	600	600

Note – compiled by the authors

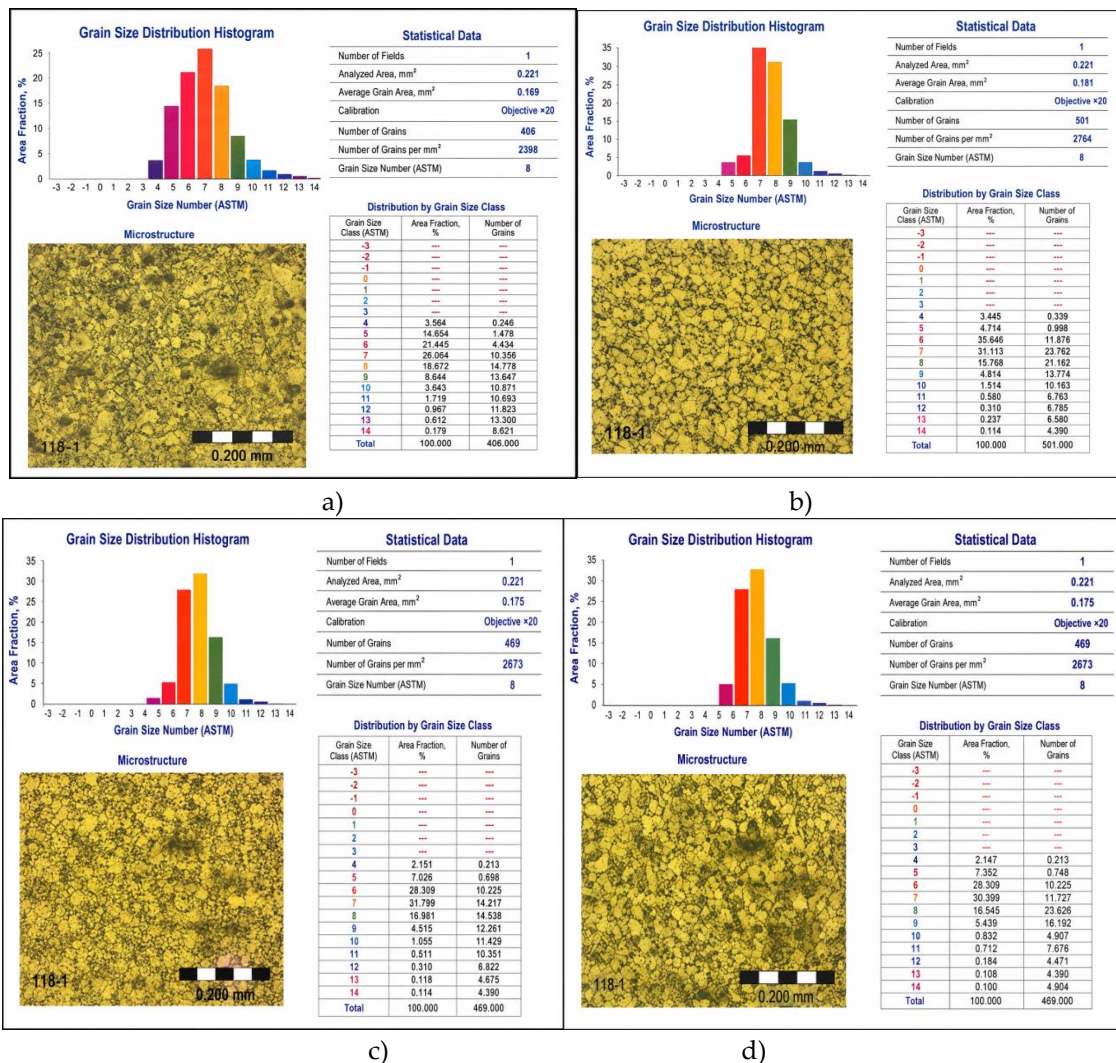
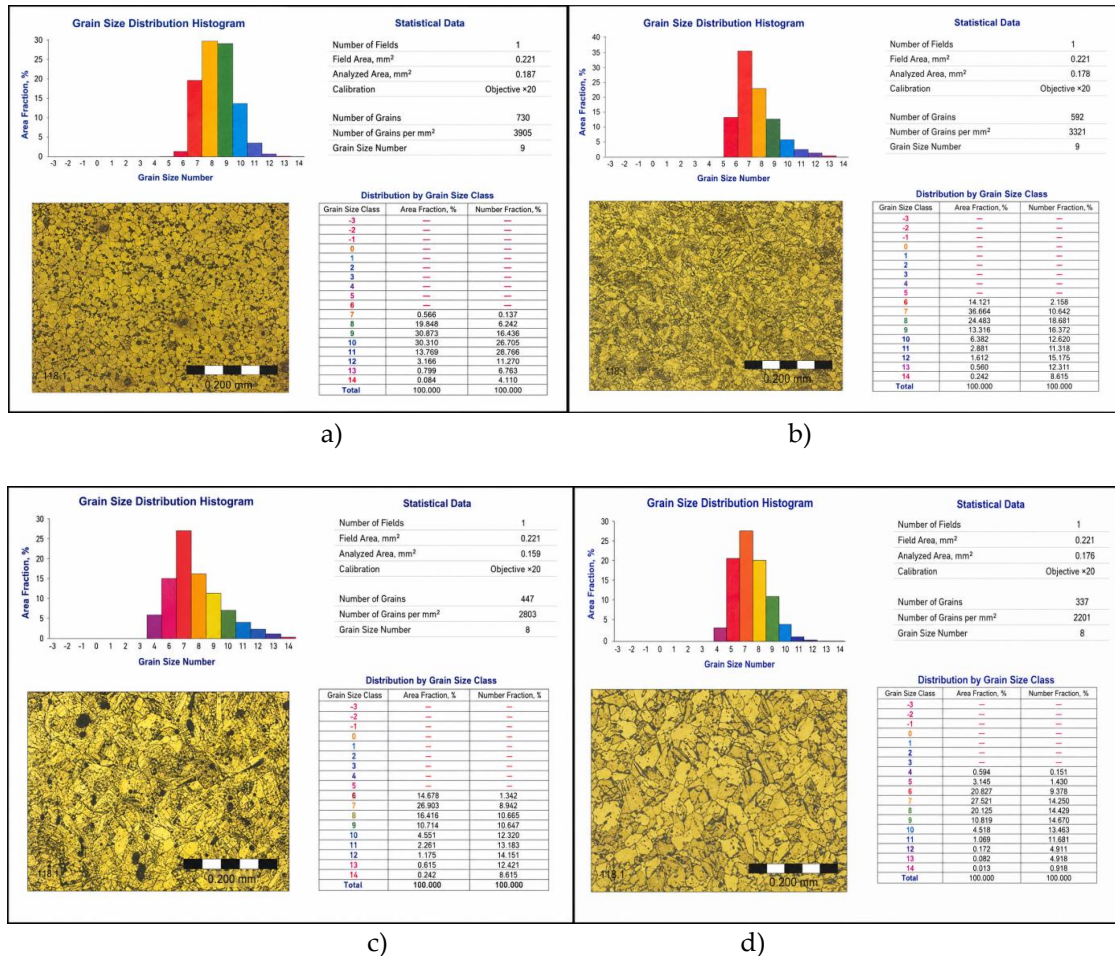


Figure 2. Microstructure of St3sp steel after heating to 920 °C:

(a) Variant I; (b) Variant II; (c) Variant III; (d) Variant IV

Note – compiled by the authors

**Figure 3.** Microstructure of St3sp steel after heating to 1000 °C:

(a) Variant I; (b) Variant II; (c) Variant III; and (d) Variant IV

Note – compiled by the authors

The microstructural analysis of specimens cooled under different cooling regimes within the temperature range of the eutectoid transformation of austenite showed that cooling schedules I–IV resulted in a normal transformation mechanism irrespective of the heating temperature. In all cases, the P/P_0 ratio was significantly greater than unity (98% confidence level according to Student's t-test) (Figures 5–8).

Cooling of the specimens according to Variant I resulted in the formation of relatively small pearlite colonies along ferrite grain boundaries (Figure 5). However, the carbon diffusion rate in ferrite remained low, thereby limiting the decomposition of pearlite into coarse cementite. When the specimens were cooled according to Variants II, III, and IV, the size of pearlitic regions increased significantly (Figures 6–8).

The high temperature at the onset of quenching and the corresponding high cooling rate promoted the formation of a Widmanstätten microstructure near the specimen surface, consisting of acicular ferrite and interlayers of pearlite.

Heating some specimens to 1000 and 1080 °C resulted in the formation of coarse-grained austenite. Owing to its higher thermal stability, this austenite transformed during cooling into ferrite predominantly through a shear mechanism rather than by diffusional transformation with the formation of equiaxed ferrite grains. As a consequence, a more or less pronounced Widmanstätten structure was formed (Figures 3 and 4).

The study demonstrated that, in order to obtain a fine-grained microstructure and minimize the thickness of the Widmanstätten structure in the deformed sheet, rolling should be carried out with a finishing rolling temperature in the range of 840–920 °C.

To evaluate the effect of coiling conditions on the microstructural evolution, the kinetics of phase transformations in hot-rolled St3sp steel were investigated within the temperature range corresponding to strip coiling. For this purpose, specimens cooled according to regimes II–IV (with a heating temperature of 920 °C) were subsequently annealed at 600 °C for 1, 3, 5, and 10 h.

During annealing for 1–10 h, the ferrite grains increased in size by less than one ASTM grain size number, and grain growth occurred uniformly throughout the microstructure. Using regression analysis with variable linearization transformations, it was established that ferrite grain growth can be described, with a confidence level of at least 95% (according to the Fisher criterion $F = \frac{S_{aA}^2}{S_d^2}$, where $S_{aA}^2 = \sum_{i=1}^N \frac{\Delta d_i^2}{f}$ – is the adequacy variance; $\Delta d_i = d_{\text{эКС}} - d_{\text{pac}}$;

$f = N - (k + 1)$ is the number of degrees of freedom; N – is the number of measurements; k – is the number of fitted coefficients; $S_d^2 = \sum_{i=1}^N (d_i - \bar{d})^2 / (N - 1)$ – experimental variance by the well-known equation (Shkatov et al., 1990; Shkatov et al., 1991):

$$\bar{d} = \bar{d}_0 + A \exp\left(-\frac{Q}{RT}\right) \tau, (1)$$

The activation energy was determined to be $Q = (136 \pm 18) \text{ kJ/mol}$ while the pre-exponential factor was $A = (5.2 \pm 0.56) 10^8$. In Eq. (1), $\bar{d}_0$ and $\bar{d}$ – represent the initial and current grain sizes, respectively (μm); T – is the absolute temperature (K), τ is the annealing time (h), and R is the universal gas constant.

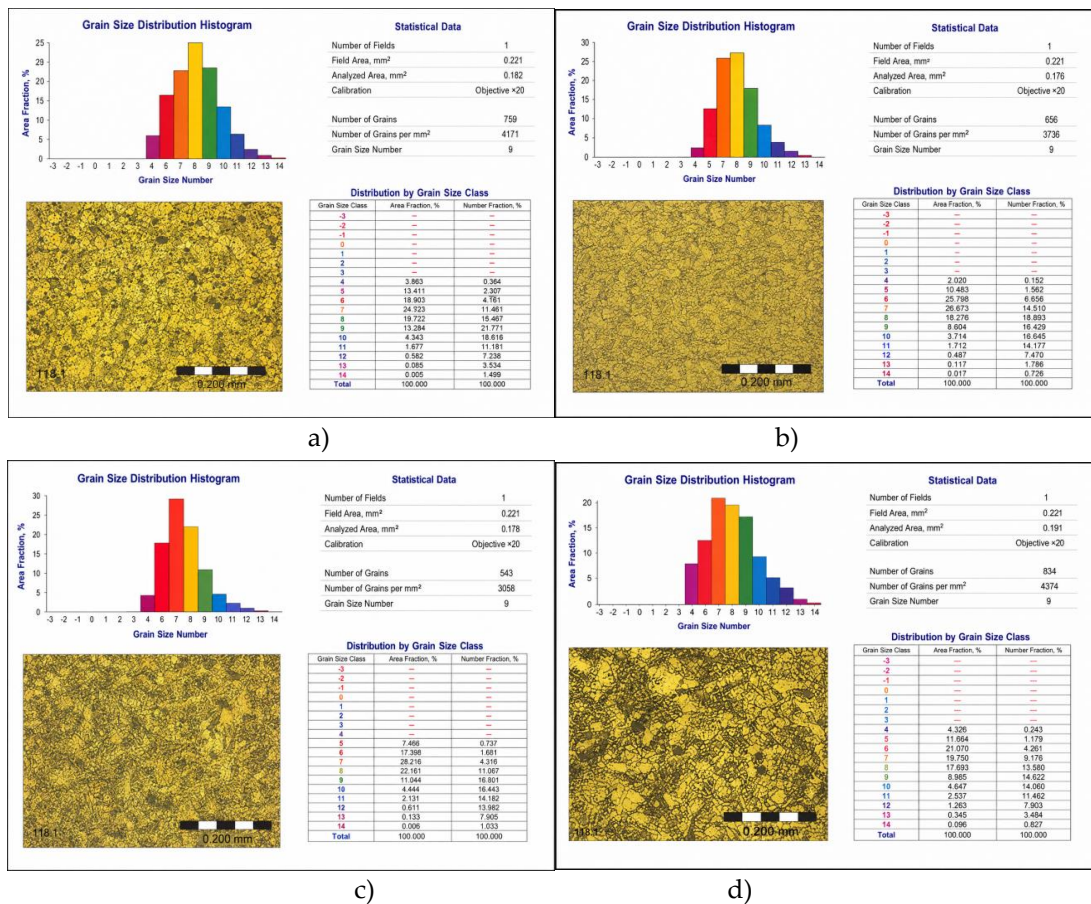


Figure 4. Microstructure of St3sp steel after heating to 1080 °C:

(a) Variant I; (b) Variant II; (c) Variant III; and (d) Variant IV.

Note – compiled by the authors

During annealing at 600 °C for 10 h, the fragmentation of pearlitic cementite lamellae, followed by their coagulation and coalescence, resulted in the formation of structurally free cementite corresponding to grades 0–1 according to GOST (GOST 5640-2020, 2023). Cementite globules with sizes up to 1–2 µm were located predominantly along ferrite grain boundaries. No grain-boundary cementite network was observed.

The degree of transformation of lamellar cementite into globular (spheroidized) cementite, e , was determined from the fraction of lamellar pearlite, P , remaining in the microstructure of the annealed specimen relative to the initial pearlite fraction before annealing (Shkatov et al., 1990; Shkatov et al., 1991). Thus, $e = 1 - (P/P_0)$.

It follows from Eq. (4.81), as well as from the experimental data, that grains with an initial size of $\bar{d}_0 = 16\text{--}22\text{ }\mu\text{m}$ increased in size by no more than $\Delta d = d - d_0 = 0.1\text{--}0.6\text{ }\mu\text{m}$ during cooling of the coil from 600 °C. Under the same cooling conditions, the transformation of lamellar cementite into globular cementite was not completed, and the degree of spheroidization reached only $e = 30\text{--}50\%$. These results indicate that changes in the mechanical properties of hot-rolled steel in coils are primarily associated with cementite spheroidization rather than ferrite grain growth.

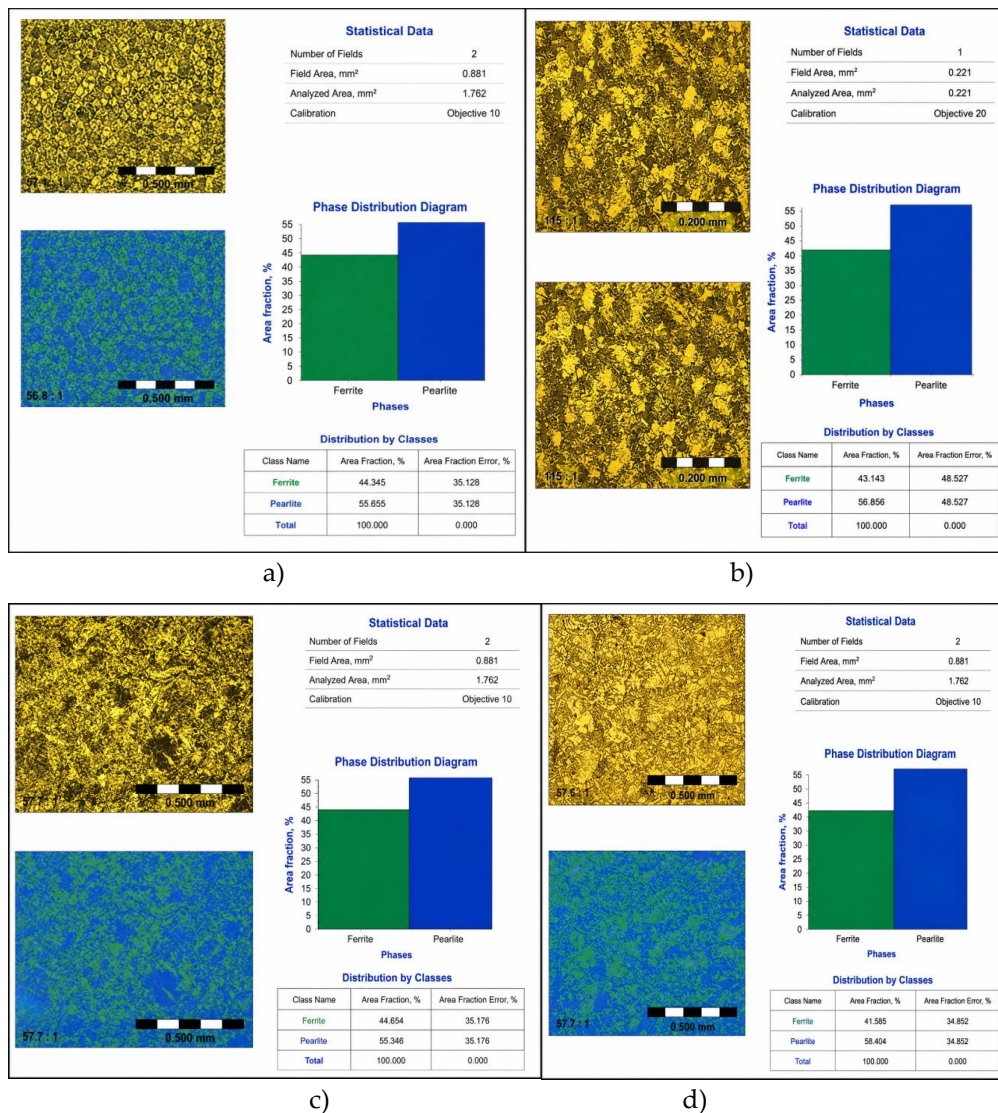


Figure 5. Microstructures and phase distribution diagrams of St3sp steel processed according to Variant I at heating temperatures of (a) 840 °C, (b) 920 °C, (c) 1000 °C, and (d) 1080 °C.

Note – compiled by the authors

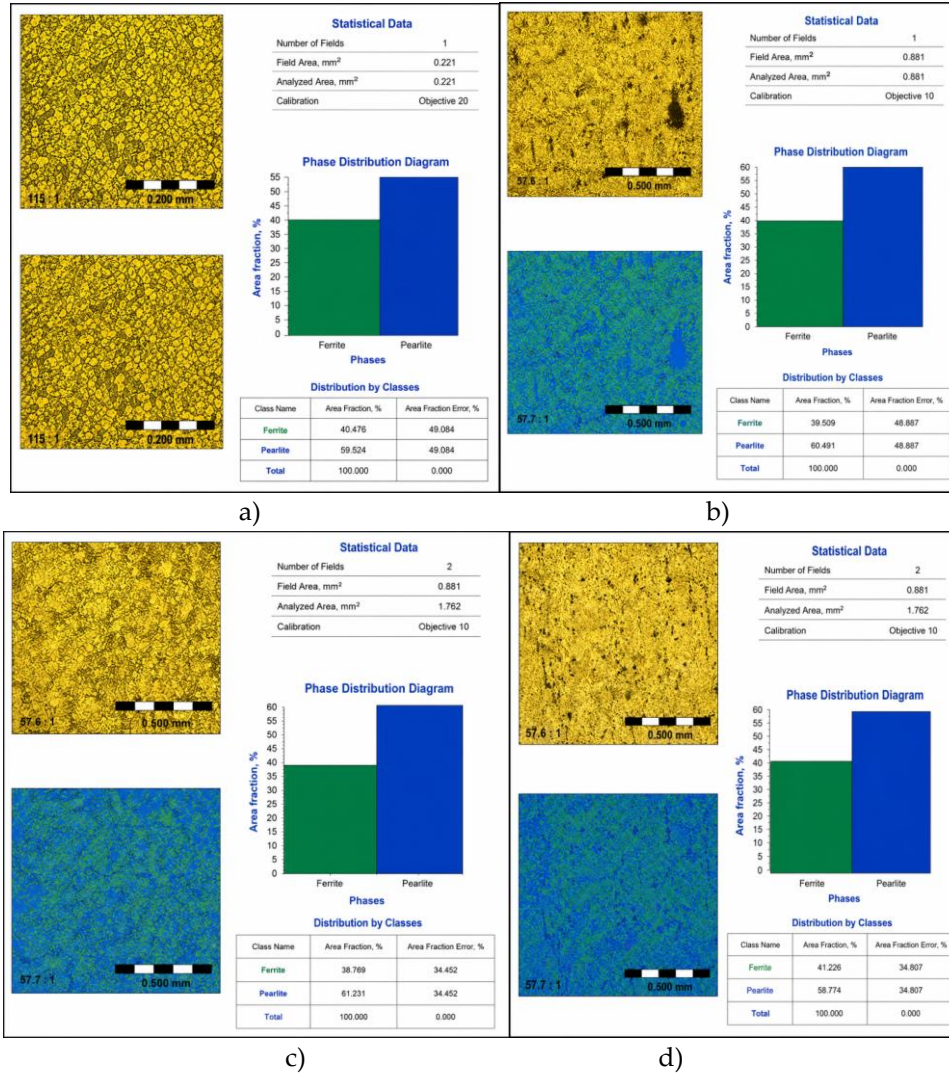
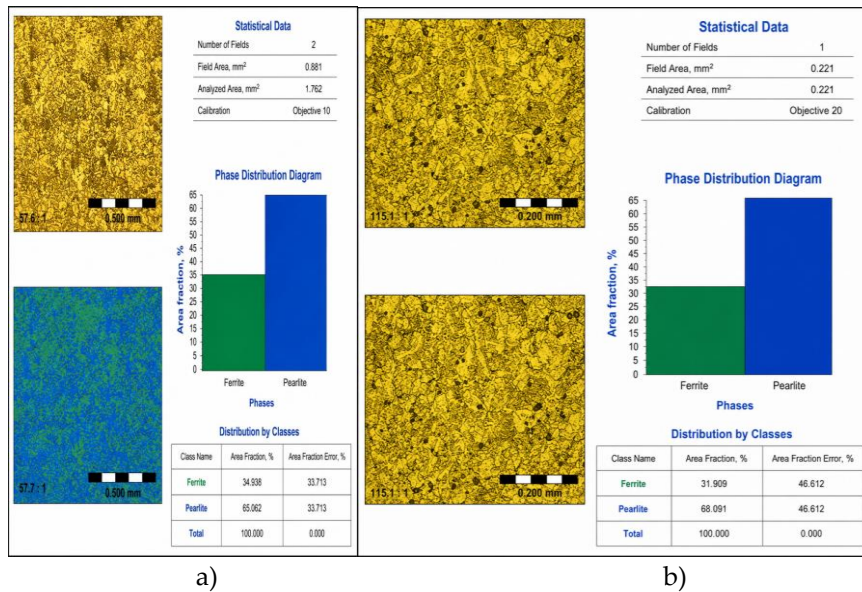


Figure 6. Microstructures and phase distribution diagrams of St3sp steel processed according to Variant II at heating temperatures of (a) 840 °C, (b) 920 °C, (c) 1000 °C, and (d) 1080 °C.
Note – compiled by the authors



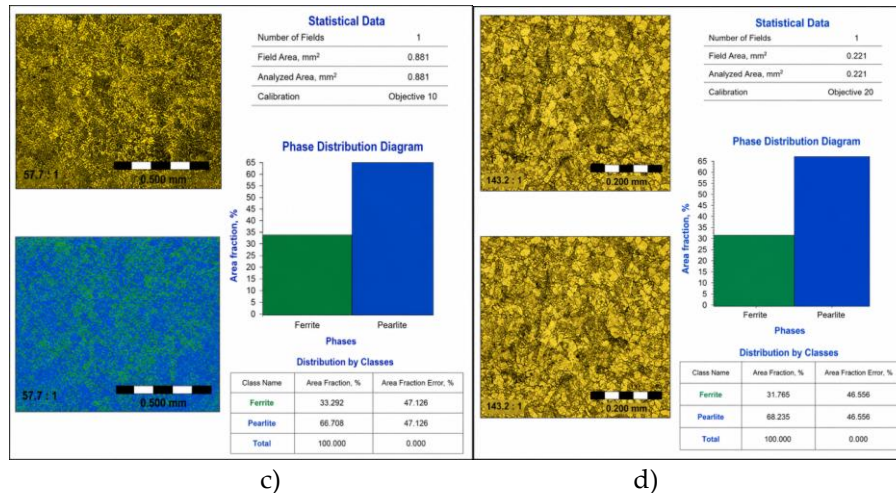


Figure 7. Microstructures and phase distribution diagrams of St3sp steel processed according to Variant III at heating temperatures of (a) 840 °C, (b) 920 °C, (c) 1000 °C, and (d) 1080 °C.

Note: compiled by the authors

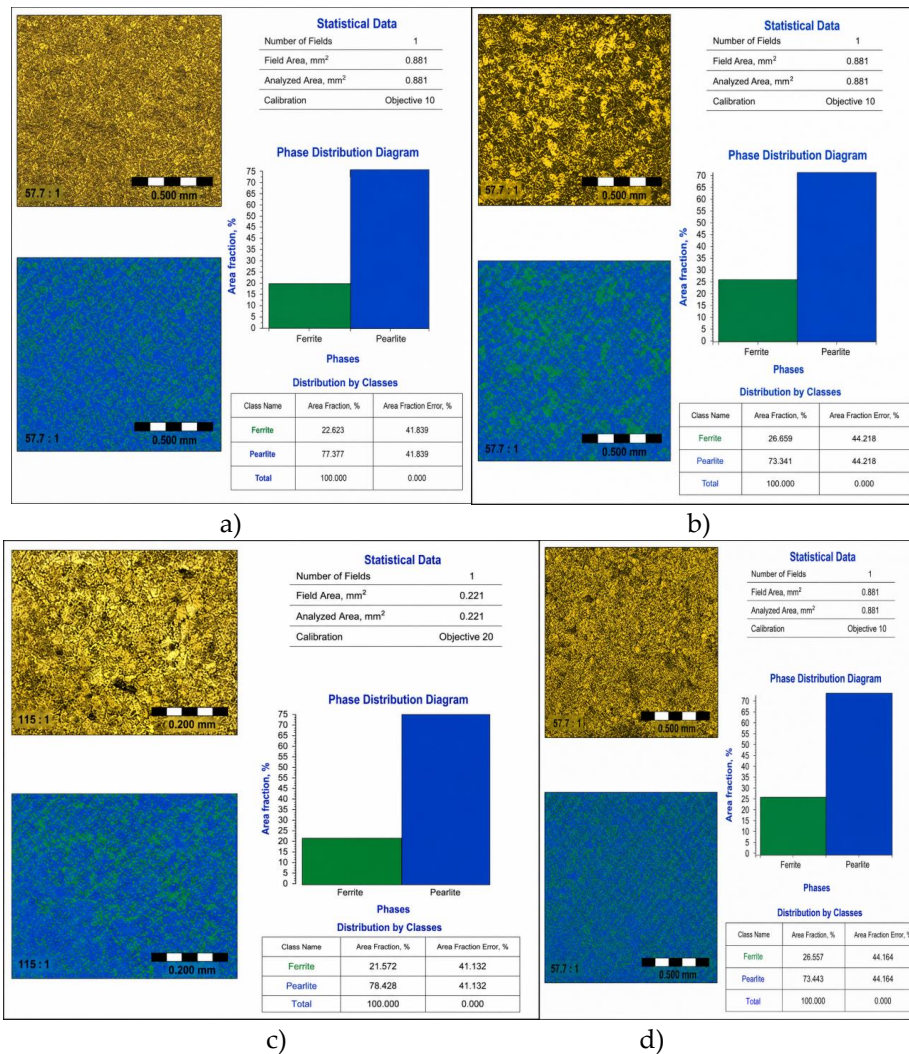


Figure 8. Microstructures and phase distribution diagrams of St3sp steel processed according to Variant IV at heating temperatures of (a) 840 °C, (b) 920 °C, (c) 1000 °C, and (d) 1080 °C.

Note – compiled by the authors

CONCLUSIONS

1. The influence of cooling regimes on the microstructural evolution and properties of steel during the transportation of hot-rolled strips on the run-out table was investigated. The results demonstrated that the optimal processing conditions for producing high-quality hot-rolled low-carbon sheet steel involve the application of a delayed cooling regime, with a finishing rolling temperature of 920 °C and a coiling temperature of 600 °C.

2. It was found that changes in the mechanical properties of hot-rolled steel in coils are primarily associated with cementite spheroidization. A strong linear relationship was established between the mechanical properties and the degree of transformation of lamellar cementite into globular cementite.

3. It was established that increasing the heating temperature to 1000–1080 °C promotes the formation of coarse-grained austenite, which subsequently leads to the development of a Widmanstätten microstructure during cooling and reduces the microstructural homogeneity of hot-rolled steel.

4. It was shown that increasing the holding time at 600 °C promotes cementite spheroidization. The degree of transformation of lamellar cementite into globular cementite reached 30–50% after 10 h of annealing.

5. It was determined that ferrite grain growth during coil cooling is limited and does not significantly affect the microstructural evolution of the steel, indicating the stability of the ferritic constituent formed after rolling.

6. The experimental results confirmed the effectiveness of combined air- and water-cooling regimes for controlling microstructural development in low-carbon steel and improving the quality of hot-rolled sheet products.

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INFORMED CONSENT STATEMENT: Informed consent wasn't required because this study did not involve human participants.

DATA AVAILABILITY STATEMENT: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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