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Defects and Thermal Hardening of Reinforcement Rolled from Continuous-Cast Billet

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Abstract—Defects of carbon and low-carbon steel reinforcement of periodic profile are investigated. Optimal heat-treatment conditions for reinforcement used in Kazakhstan are investigated in laboratory tests.

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Technical specifications TU 5510 RK 39047093 TOO-002–2004 govern the manufacturing and monitoring of reinforcement 12–28 rolled from continuous-cast Ст5 and 35ГС steel billet. The reinforcement, with a periodic profile, takes the form of a smooth rod with two longitudinal fins and with crescent-shaped transverse projections (height h at the midpoint) inclined to the rod's longitudinal axis. These projections do not intersect with the longitudinal fins and travel along a multiturn helical line, which has different directions on different sides of the rod.

In reinforcement samples (Fig. 1), there are defects (often repeating) that run along the rolling directions: cracks and also coarse cleavage pits. The microstructure of a sample with a longitudinal crack consists of pearlite and ferrite (Fig. 2). The grain size corresponds to 8 (in a few cases, 7) on the scale proposed in State Standard GOST 5639. On a transverse microsection, the crack propagates (perpendicular to the surface) into the sample to a depth of 4 mm. The crack is linear; it is broad at the surface and narrow at the end; the walls are oxidized at some points, partially carburized, and associated with aggregations of complex nonmetallic inclusions. In the region of the crack, the metal is contaminated with silicates and complex nonmetallic inclusions in the forms of chains at depths exceeding the crack depth. Etching reveals that the chains of nonmetallic inclusions propagate only along the ferrite grains.

The microstructure of a sample with coarse cleavage pits is shown in Fig. 3. The sample microstructure consists of pearlite + Widmanstatten. The grain size corresponds to 6–7 (in a few cases, 5) on the scale proposed in State Standard GOST 5639. Inspection of a transverse microsection reveals a crack propagating at an angle to the surface, through practically the entire sample cross section. The crack is coarse and has slight branching; at points there are coarse oxides. Coarse complex nonmetallic inclusions are seen in the cracks. The crack walls are considerably decarburized. In the region of the crack, there are silicates and chains of nonmetallic inclusions within the ferrite phase. Surface defects (cracks and cleavage pits) are formed on rolling on account of rolling scabs, which develop at defects of the continuous-cast billet. The microstructure of cracked sample 1 indicates some heating.

On some samples, there is a defect of tear type. On a gray impression, edge liquation bands are observed, along with slight point inhomogeneity. Inspection of a microsection reveals that the defect is completely decarburized and surrounded by coarse porosity. The grain boundary in the decarburization region is considerably oxidized. There is an increased content of small diffusional oxides. The microstructure consists of pearlite + ferrite and Widmanstatten. Considerable difference in grain size is observed: 3, 6, and 7 (and occasionally 2) on the scale proposed in State Standard GOST 5639. The surface defect is formed on account of local burnout in heating the billet before rolling.

As a rule, improvement of the rolled product involves additional capital and operating costs at the manufacturing stage. However, the use of higher-quality product reduces the purchaser's capital and operating costs. Higher-quality metal would improve the chances of filling the shortage of rolled products, because it offers the possibility of meeting customer

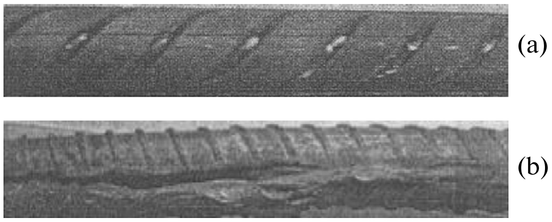

Fig. 1. Defects of 35ГС steel rebar: (a) sample with longitudinal crack; (b) sample with coarse cleavage pits.

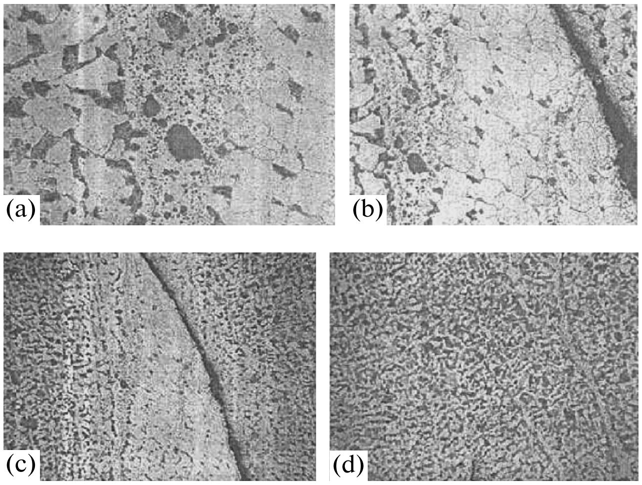

Fig. 2. Microstructure of sample with longitudinal crack: (a) coarse nonmetallic inclusions in a chain of small complex inclusions (×800); (b) chain aggregations of complex inclusions in the region of a crack (×500); (c) chain aggregations of complex inclusions in the region of a crack (×250); (d) chain aggregations of complex inclusions below the crack depth (×250).

demand by means of smaller quantities of stronger metal.

Strengthening is an effective means not only of obtaining high-strength low-alloy steel rebar but also of increasing the strength of carbon-steel rebar to match that of hot-rolled low-alloy steel rebar. Thermal hardening of regular Ст5 carbon steel rebar to strength class At-IIIS permits the replacement of low-alloy hot-rolled 35ГС steel of class A-III. The replacement of 35ГС steel by softer and more plastic Ст5 carbon steel also improves the rolling conditions (roller life, energy consumption, etc.) [1–3].

The selection of Ст5 carbon steel for the mass production of thermally hardened rebar is based on the following considerations:

—the possibility of smelting Ст5 steel using relatively inexpensive and plentiful reducing agents;

—convenience at all stages of metallurgical processing;

—the absence of crack formation in deformational and thermal strengthening and in welding.

Increasing the manganese and silicon content in 35ГС steel increases the stability of supercooled austenite in the range 400–600°C and hence increases the proportion of the pearlite component and the hardening of the ferrite as it dissolves alloying elements. This increases the strength from class A-II by 100 N/mm^2, on average, with slight loss in plasticity and weldability. However, the same strength may be obtained by heat treatment of regular steel, without increase in the alloying elements.

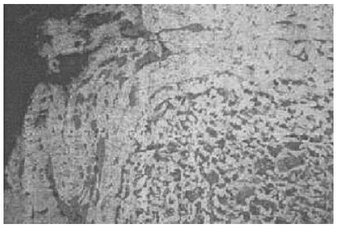

Fig. 3. Microstructure of sample with cleavage pits (×500); aggregations of coarse complex inclusions in the region of a crack.

The rebar used in ferroconcrete structures is the main component withstanding the tensile load, and thereby ensures the strength and reliability of the whole structure. In the manufacture of ferroconcrete structures, prestressed reinforcement is widely used, in order to limit the crack width in the concrete and increase the rigidity and durability of the structure. According to the operational specifications, steel reinforcement of periodic profile must have a certain level of mechanical properties—primarily fatigue strength—and also sufficient plasticity to permit redistribution of the load. Other requirements include resistance to corrosion cracking, weldability, and low-temperature strength [1].

Thermal hardening prior to rolling offers a real possibility of increasing the mechanical properties (strength and ductility, without loss of plasticity) to a level at which the rebar will correspond to another of higher strength class (A-IV and A-V). The mechanical properties of rebar after thermal or thermomechanical treatment must comply with State Standard GOST 10884.

Faster cooling (around 500°C/s) is necessary for thermal strengthening of low-carbon steel. Accordingly, we have proposed a cooling method and corresponding equipment to ensure rapid attainment of the final temperature of martensitic transformation within the rolling-mill line. In this case, besides utilization of the heat associated with rolling, the weakening processes after hot deformation are partially prevented. Consequently, the resulting properties are higher than in heat treatment with separate heating.

In laboratory conditions, experiments are conducted to determine the optimal thermocyclic-treatment parameters for steel reinforcement of periodic profile. In the experiments, we use Ст5 steel blanks for rebar 16 (length 250–260 mm). After heating to the temperature at the end of rolling (850–900°C), the blanks are quenched in water and cooled in air in accordance with the variable thermocyclic parameters. Then we assess the mechanical properties and also the macrostructure and microstructure of the rolled product from transverse templates.

The uniformity of cooling is monitored by mechanical tests of samples from the head, middle, and tail of the blank. It is found that the blank undergoes discontinuous tempering with self-quenching. The surface layer is quenched to martensite in water. The depth of this layer depends on the cooling time in

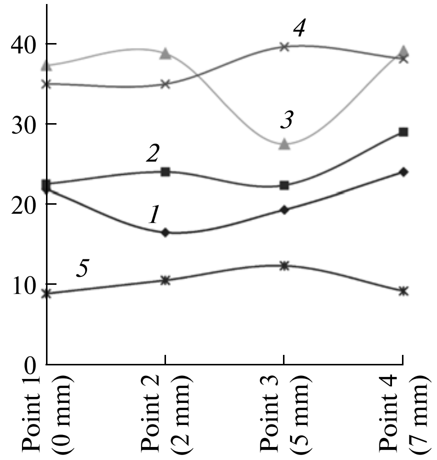

Fig. 4. Distribution of hardness *HRC* over the cross section of strengthened rebar 16, from the surface to the center of the blank; the sample numbers are given on the curves.

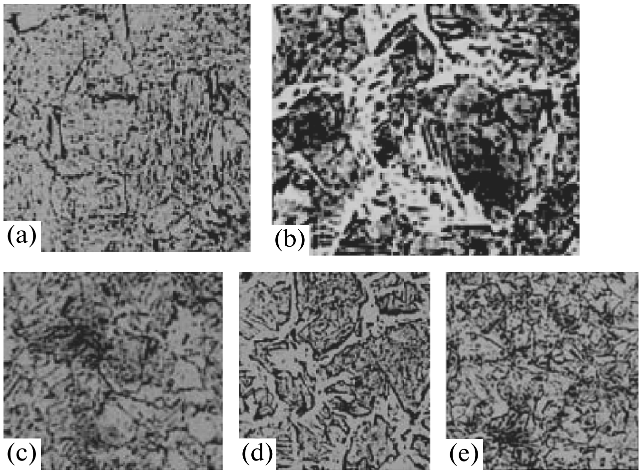

Fig. 5. Variation in microstructure over the cross section of strengthened Cт5 steel rebar 16 (×500): (a) surface layer; (b) center of cross section; (c–e) transition layers..

water. With further cooling in air, the outer zone may receive heat from the inner layers, with tempering of the martensite that has formed. As a result, a nonuniform gradient structure forms across the entire cross section [2].

Thermal strengthening facilitates the formation of structural homogeneity in the bar cross section—in particular, rings of different etchability. Such macrostructure corresponds to two patterns of austenite transformation in discontinuous tempering with self-quenching. The macrostructure of the thermally strengthened steel reinforcement includes an external ring and an internal ring, with a transition region. The austenite in the surface zone is converted to martensite or to martensite and bainite, with subsequent self-tempering. The austenite in the internal zone is converted to ferrite and pearlite. The transition zone includes aspects of both patterns. In the control sample of hot-rolled steel, no division in the macrostructure is seen, since the austenite breaks down to ferrite and pearlite across the entire cross section.

The structural inhomogeneity leads to a nonuniform hardness distribution over the bar cross section (Fig. 4). The table presents hardness measurements over the sample cross section in different heat-treatment conditions; mean hardness values for the three samples are given in the denominator. The samples corresponding to heat treatment 5 are the controls; they undergo no special heat treatment and retain the initial hot-rolled structure.

It is evident from the microstructure in Fig. 5 that the surface layer consists of martensite + tempering sorbite, with insufficient development of globularization and no change in particle orientation with respect to the formerly existing needles of quenching product. The central zone mainly contains ferrite grains, with cementite deposits (predominantly plate pearlite of different grain sizes). The transition layers consist of intermediate decomposition products of austenite, with a developing pearlite lattice. The structure of the first and third transition layers resembles pearlite; the second layer contains bainite and martensite. The pearlite component is pseudopearlite (quasi-eutectoid), with different carbon content.

The microstructure of the strengthened samples is compared with the control in Fig. 6. The optimal quality is obtained for the sample with heat treatment 3. The experimental results confirm that the mechanical characteristics of thermally strengthened Cт5 carbon steel match those of 35ГС low-alloy steel (class A-III) and comply with strength class A-400s for reinforcing steel in State Standard GOST 10884.

Measurements of hardness *HRC* of thermally strengthened Cт5 steel

Heat treatment	Hardness *HRC* at a distance from the surface (mm)			
	0	2	5	7
1. Water (1 s) + air	27.5; 10; 28/21.833	19; 18.5; 12/16.5	25; 19; 14/19.333	26.5; 21.5; 24/24
2. Water (1 s) + air (1 s) + water (1 s) + air	26; 17.5; 24/22.5	27; 21; 24/24	27; 17; 23/22.333	29; 21; 37/29
3. Water (2 s) + air (2 s) + water (1 s) + air (2 s)	38; 35; 39/37.333	44; 33; 39.5/38.833	26.5; 29; 27/27.5	38.5; 40; 39/39.166
4. Water (3 s) + air (2 s) + water (2 s) + air	33.5; 36.5; 35/35	32; 39; 34/35	38; 41; 40/39.666	34.5; 42; 38/38.166
5. Control	9.5; 8; 9/8.833	13; 8.5; 10/10.5	16; 9; 12/12.333	7.5; 11; 9/9.166

Technology and equipment have been developed for thermal strengthening of reinforcing steel with utilization of the rolling heat. A preliminary Kazakhstan patent has been obtained for this method, in which coolant is supplied to the surface of the rolled steel [3]. So as to increase the intensity, ensure uniform cooling, and reduce the size of the system and also coolant consumption and pressure, the design employs opposing coolant jets supplied through sprayers and cooling chambers that alternate in a specific order. This design permits regulation of the cooling by changing the size of the open cross sections in the active cooling zone and the total length of the material; as a result, the coolant consumption and pressure will change.

The design is successful in that the cooling of the rolled steel is intensified, cooling over the perimeter of the steel is uniform, the system is compact, and coolant flow rate and pressure are reduced. However, in contrast to familiar methods, the moving blank is cooled by opposing coolant jets, which alternate. The coolant flow rate in the opposing jets is at least twice that in the forward jets.

The number of sections required to cool the steel to the required self-tempering temperature depends on the thermophysical characteristics of the steel, its thickness, the temperature at the end of rolling, the speed of the blank, and also the coolant pressure and flow rate. Cooling water is sent under pressure along an annular slot to the cooling chamber, while the moving blank, as it passes through the cooling chamber, interacts with the water and undergoes thermal strengthening. The cooling rate depends on the pressure and flow rate of the water in the cooling chamber. In turn, the water flow rate in the cooling chamber depends on the size of the annular slot; the annular gap between the external diameter of the cooled profile and the internal diameter of the in the cooling chamber's guide tube, with specified chamber length; and the size of the annular gap between the cooling chambers of the forward and opposing sprayers in the given section.

The alternation of the opposing cooling sprays intensifies thermal strengthening of the steel and improves its mechanical properties and structural uniformity. The counterflow cooling chamber interrupts the vapor jacket formed at the surface of the steel in the forward-flow chamber, ensures its removal and the complete collection of the spent cooling water, and creates controllable pressure and flow rate in each section.

After preliminary cooling, the steel is split by flying cutters and sent to modules for deep cooling (forward-flow cooling jets, collecting baths, and counterflow air jets to remove moisture residues from the steel surface). The thermal strengthening of the reinforcement is regulated by changing the number of cooling sections in the module.

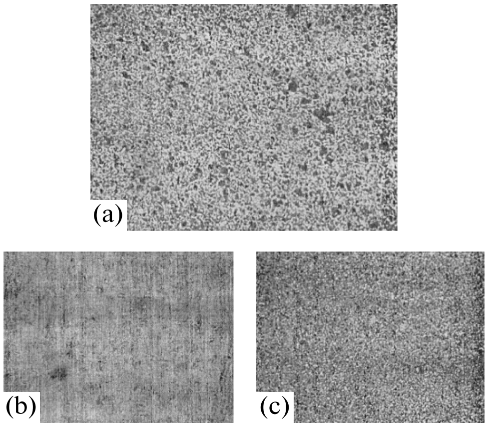

Fig. 6. Microstructure of Ст5 steel reinforcement samples over a transverse template (×100): (a) control sample 5, ferrite + pearlite, grain size 8; (b) sample 3, sorbite, grain size 9; (c) sample 2, ferrite + pearlite, grain size 9.

The thermal strengthening of the reinforcement is based on discontinuous cooling from the final rolling temperature of 900–850°C to the self-tempering temperature of 300–600°C, which is established in accordance with the required strength class. The mean mass temperature may be used as the self-tempering temperature. The reinforcement is cooled by means of a moving water flow supplied under pressure.

Raising the pressure increases the boiling point of the water and prevents the formation of a vapor jacket. This results in more rapid and uniform cooling. At the same time, the water flux ensures hydraulic transportation of the reinforcement from the finishing cell of the mill to the cooling unit. The reinforcement moves as a result of the force due to interaction of the moving water flux and the transverse projections on the reinforcement. Precise regulation of the steel properties is possible by adjusting the water pressure and flow rate [5].

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