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Influence of Intermittent Quenching and Self-Tempering on the Mechanical Properties of Rebar Steel

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Abstract—The influence of deformation and heat treatment on the mechanical properties of rebar steel is investigated on a pilot system. Specifically, with intermittent quenching and subsequent self-tempering, the intense-cooling time determines the tempering temperature of the quenched steel and hence the final mechanical properties of the rebar. The influence of the water pressure in the intense-cooling chamber on the uniformity of the mechanical properties is studied for steel with 0.31, 0.32, and 0.35% C; the water pressure is varied from 0.2 to 0.6 MPa. On that basis, it is established that the water pressure in the cooling chamber must be no less than 0.3 MPa, and the carbon content in the steel must be more than 0.32% in order to ensure that the mechanical properties of the rebar steel conform to the AT500 strength class according to State Standard GOST 10884–2004.

Keywords: rebar steel, intermittent quenching, self-tempering, hardening mechanism, strength class, cold working, austenite, martensite, pilot plant

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The deformation and heat treatment of rebar steel significantly improves the mechanical and operational properties of low-alloy and carbon steel rebar.

Such treatment permits considerable savings in energy and material resources [1, 2]. In the manufacture of ferroconcrete structures, all of the metal (all of the rebar) is irreversibly consumed, remaining in the concrete. Therefore, decrease in metal content of ferroconcrete structures by increasing their strength is of great importance. Deformation and heat treatment may be used for that purpose.

Energy resources are saved by using the residual heat from the metal after hot rolling for purposes of deformation and heat treatment (quenching). In this case, heat treatment is combined with plastic deformation. Another source of savings is the replacement of tempering in a furnace, which requires considerable capital expenditures, with self-tempering, that does not require additional power consumption (since no tempering furnace is required).

The production of rebar is often based on intermittent quenching and self-tempering. In this method, intense cooling at a supercritical rate continues until the martensitic layer at the surface reaches a specified thickness. Then the accelerated cooling is interrupted, and the temperature equalizes itself over the cross section.

With increase in the cooling time, the thickness of the quenched martensitic layer at the surface increases. After the quenching is interrupted, the martensite is heated to lower temperatures. Correspondingly, the degree of self-tempering is decreased, and the plastic properties of the rebar are impaired. Therefore, the self-tempering temperature is the most important factor determining the mechanical properties of the rebar steel [3].

EXPERIMENTAL MATERIAL AND METHODS

We study Ст5сп carbon steel rebar (diameter 20, 22, and 25 mm) corresponding to State Standard GOST 380–2004, with the specified variation in carbon content. The research is conducted on an industrial pilot plant with direct-flow and counter-flow pumps for deformation and heat treatment of the rebar on the basis of continuous-cast billet in the rolling system [4].

The operating principle of the pilot plant is that the cooling water is pumped under high pressure through an annular slot to the cooling chamber, while the rebar

Table 1. Influence of the carbon content in the steel, the intense-cooling time, and the water pressure (0.2/0.4/0.6 MPa) in the cooling chamber on the mechanical properties of Ст5сп carbon steel rebar (diameter 20 mm)

C, %	τ, s	σ_u, N/mm^2	σ_y, N/mm^2	δ_5, %
0.28	1.5	520/560/620	410/440/490	28.0/23.0/21.0
	2.0	600/650/710	470/530/580	25.0/22.0/20.0
	3.0	650/710/780	510/580/640	22.0/20.0/19.09
0.32	1.5	560/600/650	440/500/540	26.5/21.5/19.0
	2.0	660/700/760	520/590/630	23.5/20.0/18.0
	3.0	710/780/830	570/660/700	21.5/19.0/17.0
0.35	1.5	610/660/690	450/530/570	24.0/21.0/18.5
	2.0	720/760/820	540/630/660	22.0/18.5/16.0
	3.0	790/860/890	610/710/750	21.0/15.0/13.0

moves through the chamber and interacts with the water. In the process, it undergoes deformation and heat treatment. The cooling rate depends on the water flow rate and its pressure in the cooling chamber. In turn, the pressure and flow rate of the water in the cooling chamber depend on the ratio of the slot dimensions and the annular cross section of the cooling chamber, which vary as a function of the rebar diameter and the internal diameter of the tubular chamber, with constant chamber length.

The mechanical properties of samples subjected to deformation and heat treatment are determined on an Instron unit, with sample preparation according to State Standard GOST 1497–2004. Individual mechanical tests are paired with nondestructive monitoring of samples from the rebar by a KIFM-1 instrument, which makes thermal-probe readings of the coercive force, on the principle that there are stable correlations between the mechanical and magnetic properties of the rebar. The temperature dependence obtained by means of the KIFM-1 instrument shows that nondestructive monitoring of Ст5сп steel rebar is possible at rebar temperatures up to 150°C; for 35ГС steel rebar, measurements are possible up to 100°C. The samples used in microstructural analysis are produced by the standard method, ruling out disruption of the initial structure.

Flow rates of the cooling water in the range 40–100 m^3/h are measured by means of a DM-4 differential manometer. The pressure of the cooling water in the chamber is 0.2–0.6 MPa; an OVM-1-160 manometer is employed. The time between the end of hot rolling and the onset of intense cooling is 1.5–3.0 s. The final temperature in rolling is recorded by means of a FEP-4M photoelectric pyrometer. The self-tempering temperature is determined by means of a magnetometer, which measures the saturation magnetization of ferromagnetic materials.

INFLUENCE OF THE CARBON CONTENT ON THE MECHANICAL PROPERTIES OF THE REBAR

To establish the influence of carbon in the steel (within the limits set by State Standard GOST 380–2004) on the mechanical properties of surface-hardened rebar, we conduct experiments for steel with carbon contents of 0.28, 0.32, and 0.35%; the intense-cooling time and the water pressure in the cooling chamber are maintained constant for each carbon content. Table 1 presents the experimental results. We see that the outcome of deformation and heat treatment depends significantly on the carbon content in the steel. For example, with increase in carbon content from 0.28 to 0.35% in Ст5сп steel rebar (diameter 20 mm), σ_u increases from 650 to 760 N/mm^2 at specified water pressure in the cooling chamber (0.4 MPa) and with intense cooling for 0.2 s. That corresponds to increase in carbon content in the steel by 0.01%. In the same conditions—that is, with 0.01% increase in carbon content—σ_y increases by 14 N/mm^2, while δ_5 declines by 0.8%. If the water pressure in the cooling chamber is increased from 0.2 to 0.6 MPa, with a carbon content of 0.32%, σ_u increases from 660 to 760 N/mm^2, with intense cooling for 2.0 s. That corresponds to increase in σ_u by 25 N/mm^2 with increase in water pressure by 0.01 MPa. In the same conditions—that is, with increase in water pressure by 0.01 MPa—σ_y increases by 25 N/mm^2, while δ_5 declines by 1.4%.

The behavior of 25-mm rebar on deformation and heat treatment is the same as that of 20-mm rebar. However, the change in the mechanical properties with change in carbon content is slower for the rebar of larger cross section. For example, with increase in carbon content from 0.28 to 0.35% in 25-mm rebar, σ_u increases by 10–12 N/mm^2 and σ_y by 5–10 N/mm^2, while δ_5 declines by 0.4%. If the water pres-