In 2008, a casting and rolling system equipped with a system for thermal hardening of reinforcement in the line of the 280 mill went into operation at the LPZ plant in Yartsevo (Smolensk region). This system was installed by the efforts of Russian manufacturing plants, on the basis of design work at the Russian Research Institute of Metallurgical Machinery and OAO VNIIMT [1, 2].

The system permits heating of 125 × 125 mm continuous-cast billet supplied for rolling in the hot (from OAO MNLZ) or cold state. After rolling on a continuous 18-cell mill, the reinforcement (rebar 12–18) is sent immediately to the thermal hardening system (12 sections, grouped in four blocks) for accelerated controlled water cooling to specified mean-mass temperature [3]. Considerable hardening of the surface layer results. The mean-mass temperature, which serves as the control parameter in thermal hardening, is calculated by a special program on the basis of the surface temperature, measured by a pyrometer ahead of the cooling unit. After leaving the thermal hardening system, the bar is completely cooled on the roller conveyer and in the cooling unit. In the initial period, as a result of equalization of the temperature over the cross section, self-tempering occurs in the surface layer on account of the heat from the center of the bar.

In the present work, we consider the thermal hardening technology (discontinuous quenching with self-tempering) in the line of the mill so as to obtain Cr3cn steel rebar (diameter 14–18 mm) of strength class A500S according to the STO ASChM 7–93 standard.

The chemical composition of the billet from successive melts of Cr3cn steel corresponds to State Standard GOST 380 (Table 1). The metal from three melts is heated after supply in the hot state; the remainder is supplied in the cold state. The conditions of accelerated cooling are varied by adjusting the number of cooling sections and the water flow rate. In all the

Table 1. Chemical composition of Cr3cn steel melts (wt %)

<table>
<thead>
<tr>
<th>Melt</th>
<th>Ceq</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.32</td>
<td>0.16</td>
<td>0.61</td>
<td>0.19</td>
</tr>
<tr>
<td>2</td>
<td>0.33</td>
<td>0.17</td>
<td>0.63</td>
<td>0.21</td>
</tr>
<tr>
<td>3</td>
<td>0.34</td>
<td>0.18</td>
<td>0.59</td>
<td>0.20</td>
</tr>
<tr>
<td>4</td>
<td>0.33</td>
<td>0.18</td>
<td>0.55</td>
<td>0.19</td>
</tr>
<tr>
<td>5</td>
<td>0.34</td>
<td>0.19</td>
<td>0.56</td>
<td>0.18</td>
</tr>
<tr>
<td>6</td>
<td>0.33</td>
<td>0.16</td>
<td>0.61</td>
<td>0.18</td>
</tr>
<tr>
<td>7</td>
<td>0.33</td>
<td>0.18</td>
<td>0.60</td>
<td>0.32</td>
</tr>
<tr>
<td>8</td>
<td>0.33</td>
<td>0.17</td>
<td>0.58</td>
<td>0.23</td>
</tr>
<tr>
<td>9</td>
<td>0.33</td>
<td>0.19</td>
<td>0.60</td>
<td>0.21</td>
</tr>
<tr>
<td>10</td>
<td>0.32</td>
<td>0.18</td>
<td>0.59</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Requirements of STO ASChM 7–93 standard (no more than)

<table>
<thead>
<tr>
<th>Ceq</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>0.22</td>
<td>1.60</td>
<td>0.90</td>
</tr>
</tbody>
</table>

Requirements of State Standard GOST 380–94

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.14–0.22</td>
<td>0.40–0.65</td>
<td>0.15–0.30</td>
</tr>
</tbody>
</table>
thermally hardened bar, the strength and plasticity exceed the requirements for strength class A500S, with satisfactory cold flexure (Table 2). Thus, such thermal hardening yields Ст3сп steel rebar of strength class A500S. In other words, its strength is almost double that in the hot-rolled state according to State Standard GOST 5781–82, which relates to the manufacture of Ст3сп steel rebar of strength class A240, with a regulated yield point (no less than 235 N/mm²). For the mass production of rebar 14–18 of strength class A500S, supplied in the hot or cold state, the mean-mass self-tempering temperature is confined to the range 565–575°C. The selected conditions of accelerated controlled water cooling are most economical, since they result in optimal strength and plasticity (exceeding the standard levels) when using only the first two three-section blocks in the thermal hardening system.

Table 2. Mechanical properties of experimental rebar

<table>
<thead>
<tr>
<th>Melt</th>
<th>Diameter, mm</th>
<th>(v), m/s</th>
<th>(\sigma_y), N/mm²</th>
<th>(\sigma_B), N/mm²</th>
<th>(\delta_5), %</th>
<th>(\sigma_B/\sigma_y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>14</td>
<td>11.4</td>
<td>604</td>
<td>680</td>
<td>17</td>
<td>1.12</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>16</td>
<td>588</td>
<td>666</td>
<td>21</td>
<td>1.13</td>
</tr>
<tr>
<td>5*</td>
<td></td>
<td>8.2</td>
<td>625</td>
<td>683</td>
<td>21</td>
<td>1.13</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>607</td>
<td>669</td>
<td>21</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>632</td>
<td>687</td>
<td>19</td>
<td>1.08</td>
<td></td>
</tr>
<tr>
<td>8*</td>
<td></td>
<td>587</td>
<td>657</td>
<td>19</td>
<td>1.12</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>584</td>
<td>663</td>
<td>19</td>
<td>1.12</td>
<td></td>
</tr>
<tr>
<td>10*</td>
<td></td>
<td>617</td>
<td>681</td>
<td>17.5</td>
<td>1.10</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>546</td>
<td>617</td>
<td>24</td>
<td>1.13</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>18</td>
<td>7.4</td>
<td>684</td>
<td>746</td>
<td>17</td>
<td>1.09</td>
</tr>
</tbody>
</table>

Requirements of STO ASChM 7–93 standard for strength class A500S (no less than)

|        | 500 | 600 | 14 | 1.05 |

* Hot billet supply for rolling.

In Fig. 1, we show typical cross-sectional macrostructure for thermally hardened Cr3cn steel rebar of strength class A500S. There is a distinct surface layer, including the rigid edge, followed by two intermediate layers (light and dark layers), and the core of the bar (inner light circle). The microhardness is measured over the radius (from the edge to the center) at 0.3-mm intervals using a PMT-3 instrument (load 0.1 N; magnification 487), for bar supplied in the hot or cold state (Fig. 2). We may clearly distinguish a hardened surface layer (microhardness 2680–2900 N/mm²) and a core (1800–2000 N/mm²). Between these zones, there are two intermediate layers, with gradually declining microhardness. The total depth of the hardened layer for 16-mm rebar is 3.8–4.2 mm.

The microstructure of these four zones is shown in Fig. 3. The surface layer (depth 1.8–2.0 mm) consists of martensite tempered by the heat flux from the inner layers. The intermediate layers (total thickness 2.0–2.4 mm for 16-mm bar) is characterized by mixed structure, consisting of the products of \(\gamma\rightarrow\alpha\) transformation by shear and diffusion mechanisms. In the first intermediate layer, bainite structure predominates, but there are sections with packet martensite and ferrite; the second layer consists almost completely of the ferrite component. The structure of the core (diameter 7.8–8.4 mm) consists of the products of \(\gamma\rightarrow\alpha\) transformation by the diffusion mechanism; it is actually formed on the roller conveyer and in the cooling unit after the bar leaves the accelerated-cooling system. The grain size is markedly less in the core than in the second intermediate layer.

The microstructure of rebar of strength class A500S is also investigated on a Philips SEM535 raster electron microscope (Fig. 4). The relief obtained in the recordings (×1000) confirms that the products of martensitic transformation are formed in the surface layer.
on discontinuous quenching and self-tempering; in the core, granular products of diffusional $\gamma \rightarrow \alpha$ transformation are formed.

Transmission electron microscopy provides clearer data on the components of the fine structure in the thermally hardened bar. The phase composition and substructure are studied at different distances from the bar’s surface. To this end, a disk (thickness $\sim 5$ mm) is cut from 16-mm rebar by electrospark erosion, parallel to the normal axis, in plates (thickness $\sim 0.3$ mm) corresponding to all the given zones. The plates are mechanically thinned to 100–150 $\mu$m and then polished in standard electrolytes, to obtain a thickness suitable for electron transmission in the JEC-200CX microscope.

Electron-microscopic analysis shows that the structure of the surface layer (1.8–2.0 mm) is due to martensitic transformation, with the formation predominantly of packet martensite (Fig. 5). The dislocation density in the crystals is $\sim 10^{11}$ cm$^{-2}$ in the quenched state, as a rule [4]. Subsequent heating of the bar on account of the heat flux from the inner layers is accompanied by tempering of the martensite, with relaxation in the dislocation structure and decrease in dislocation density (Fig. 5a). At the same time, the carbon-supersaturated solid solution breaks down, with the formation of cementite particles predominantly at the grain boundaries (see the arrows in Fig. 5). No recrystallization is observed in this layer, perhaps on account of the relatively low time and the brief exposure to heat from the inner layers.

In the core, ferrite grains with a relatively low dislocation density predominate (Fig. 6a). The grains exhibit a fragmented dislocation structure with subgrains (Fig. 6b). Cementite particles in the form of thin layers lie at the grain and subgrain boundaries, as a rule (see the arrows in Fig. 6b).

The phase composition of the intermediate layers is more diverse. The layers closer to the surface are characterized by a mixed structure: rack martensite (Fig. 7a) and bainite (Fig. 7b), with an increased dislocation density. Cementite in globular form lies in
rows predominantly along the boundaries of the martensite racks (arrows in Fig. 7a) and within the bainite grains (arrows in Fig. 7b).

The structure of the intermediate layers closer to the central zone layer consists mainly of large ferrite grains, with a dislocation substructure of grid type (Fig. 8a). The cementite particles are predominantly at the grain boundaries, forming extended interlayers (Fig. 8a), or in globular form (Fig. 8b); smaller particles are also found within the ferrite grains.

CONCLUSIONS

Thermal hardening (discontinuous quenching with self-tempering at 565–575°C) in the line of the 280 mill at LPZ rolling and casting plant (Yartsevo) produces Ст3сп steel rebar (diameter 14–18 mm) of strength class A500S.

The thermal properties are obtained in thermal hardening of the bar and subsequent cooling on the roller conveyer and in the cooling unit, thanks to the formation primarily of tempered martensite in the surface layer and ferrite and cementite in the core. The two intermediate layers contain mainly the decomposition products of austenite from the adjacent zone.

Thermal hardening in the line of the 280 mill produces Ст3сп steel rebar of strength class A500S. In other words, its strength is almost twice that of hot-rolled rebar.

REFERENCES

OJSC Scientific-Research Institute of Metallurgical Heat Engineering (VNIIMT) established in 1930 as Ural Division of All-Union Heat Engineering Institute is widely known in Russia and the CIS. The Institute focuses on development of high-technology heat engineering units, energy efficient and ecologically friendly technologies in ferrous and non-ferrous metallurgy, machine-building and other fuel-consuming branches of industry.

Highly-qualified academic researchers, unique experimental and production facilities and own research and design centre enable efficient scientific-and-research, design-and-experimental, engineering and project works, delivery of equipment, designer's supervision and commissioning works including execution of turnkey contracts in the following areas:

**Sintering:**
- development of techniques and modes of metal raw material heat treatment;
- design of energy-efficient agglomeration hearths and agglomeration gas heat recovery circuits allowing to reduce energy consumption and dust and gas emissions.

**Pellet production:**
- optimal traveling grate pelletizing furnaces for heat treatment of iron-ore pellets from various concentrates (hematite, magnetite, etc.) with optimal automatic process control system.

**Preparation of metallic and nonmetallic raw materials:**
- technique of iron-ore raw material dephosphorization by roasting and leaching;
- installations for drying high-moisture dispersive materials of various designs;
- efficient techniques of magnetizing roasting and subsequent dressing;
- technique of rare-earth element extraction (for example, germanium from germanium iron ores).

**Blast-furnace ironmaking:**
- explosion-proof near-furnace systems of blast furnace slag granulation giving a high-quality product for cement production;
- optimal control system for hot blast stoves;
- an innovative bench for drying hot metal and steel-smelting ladles;
- copper coolers and tuyeres of blast furnaces.

**DRI (direct reduction of iron)**
- improvement of the reduction technique in shaft furnaces for radical improvement of technical and economic indicators of their operation (productivity is increased twice);
- technique of raw material reduction in rotary furnaces using coal as the reductant.

**Lime production:** development of the technique and increase of lime production process efficiency:
- in shaft furnaces;
- in double-shaft furnaces;
- in rotary furnaces;
- in “stacked-tower preheater - rotary furnace” installations;
- in “shaft calciner - rotary furnace” installations (VNIIMT innovative technology).

**Granulation of metal melts:**
- development of technologies and designs of explosion-proof plants for near-furnace granulation of metallurgical slag, molten metal, etc., including heat recovery;
Reheating furnaces:
- development of new and update of the existing designs of furnaces for stock heating;
- high-performance systems of reheating furnace firing with recovery and regeneration firing systems based on the innovative burner units designed by VNIIMT;
- switching the furnace firing systems to cheaper fuel types;
- development and implementation of optimal furnace operating parameters.

Heat-treatment furnaces development of techniques and equipment for heat treatment of roll stock and metal products including those with protective atmospheres:
- thermochemical treatment conditions ensuring retention or directional change in chemical composition of metal surface;
- gas dampers for heat-treatment furnaces;
- spray quenching units and other elements of convective cooling systems;

Furnaces with protective atmosphere and gas treatment units:
- development of the furnace structure, design, manufacture, delivery and commissioning works;
- development of a technology for treatment of articles and devices for protective gas generation;
- calculation, development and manufacture of endogas and exogas atmosphere generators for metal product thermochemical treatment units;
- gas analysis systems for monitoring and control of physico-chemical properties of protective process atmospheres.

Reheating, heat-treatment and drying furnaces with convection heat transfer:
- development, design and manufacture using industrial heat-resistant (up to 900 °C) furnace fans designed by VNIIMT.

Rolled products:
- techniques and units for controlled high-speed air-to-water cooling (quenching) of rolled ferrous and non-ferrous metal products including thick plate on mill 5000;
- replacement of oil quenching technology with VNIIMT's eco-friendly air-to-water technique;
- innovative technique of oily mill scale processing;
- line of wire rod accelerated air cooling with process improvement.

Manufacturing manufacture and delivery of:
- high-performance burner units;
- heat-resistant (furnace) fans (up to 900 °C);
- copper coolers for blast furnaces and nonferrous furnaces based on VNIIMT technology;
- Pitot tubes for measuring flow rates and pressures.

OJSC VNIIMT developments are widely used in metallurgical enterprises of Russia, Ukraine, Kazakhstan, China, India and others.

For detailed information on institute developments, please visit OJSC VNIIMT site at www.vniimt.ru

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