Structuring and Deposition of Nanoparticles in X70 Steel during Coiling and Subsequent Cooling

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Abstract—The influence of strip winding on the structure formation and microalloying of X70 steel with added Ni, Cu, and Mo is investigated. Decrease in winding temperature increases the content of transformation products of nonpolygonal morphology. The temperature conditions in which nanoparticles (3–8 nm) of Nb and V carbides are formed in the steel after winding are established. At OAO Severstal, tests have been conducted on the production of X70 steel strip (thickness 14–16 mm) with uniform mechanical properties. It is found that sheet of measured length may be supplied.

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Globally, major pipeline construction employs spiral-seam electrowelded pipe (wall thickness 14–16 mm), made from steel of strength category X70. Because of the important role of the shaping angle and the absence of expansion in spiral-seam pipe production, strict requirements must be imposed on the mechanical properties of the initial strip and their uniformity over its length.

The production of coiled strip for gas and oil pipeline components of strength category X70 today is based on controlled rolling with accelerated cooling. This yields finely disperse ferrite–bainite structure and ensures the required strength, plasticity, and cold strength of steel with less than 0.08\% C and with added Mo, Cu, Ni, Cr, and Nb, which improve the welding properties [1].

Taking account of the reduced carbon content, we should use not only grain-boundary and dislocational strengthening mechanisms but also dispersive strengthening in order to obtain 16-mm strip of strength class X70. To this end, the steel is microalloyed with carbide-forming elements—vanadium and niobium.

In accordance with the thermokinetic diagrams, the morphology and proportion of structural components depend on the cooling rate and the final temperature of accelerated cooling, i.e., the winding temperature $T_{wi}$. The content and size of carbonitride particles deposited in the ferrite after rolling are also determined by the conditions of slow cooling from the winding temperature. Given that the cooling rate is mainly determined by the capacities of the equipment, we may regulate the formation of the rolling microstructure and the deposition of ferrocariades by means of the winding temperature, its distribution over the length of the strip, and the cooling conditions of the strip coils.

With natural cooling of the coils, a nonuniform structure is formed. Hence, the mechanical properties are nonuniform over the strip length, since the external and internal turns are cooled more rapidly than the middle turns: they practically undergo self-tempering. This results in stress relaxation and the growth of ferrite grains in the C–Mn steel and also coagulation of the carbonitride particles in microalloyed steel [2]. To avoid a cooling-rate gradient and ensure uniform mechanical properties over the length of the strip, the coils of microalloyed pipe steel at OAO Severstal are subjected to accelerated cooling.

In the present work, we determine the optimal temperature conditions for the winding of (15.7–16)-mm X70 steel strip so as to ensure uniform strength and cold strength over the length, by forming ferrite–bainite structure and by dispersive strengthening on the basis of carbonitride particles, even in the middle of the coil.

In the experimental rolling of X70 steel on a 2000 mill, tests are conducted with several types of winding for steel strip of three compositions, differing in the content of manganese, vanadium, niobium, titanium, and other elements. Their chemical composition (wt \%), carbon equivalent $C_e$, and crack resistance $P_{re}$ are as follows (no more than 0.002\% S in all cases):

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Mn</th>
<th>V</th>
<th>Nb</th>
<th>Ti</th>
<th>Other elements</th>
<th>$C_e$, %</th>
<th>$P_{re}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>≤0.07</td>
<td>1.55–</td>
<td>0.061</td>
<td>0.079</td>
<td>0.081</td>
<td>Ni; Cu</td>
<td>0.42</td>
<td>0.20</td>
</tr>
<tr>
<td>B</td>
<td>≤0.07</td>
<td>1.45–</td>
<td>0.047</td>
<td>0.075</td>
<td>0.013</td>
<td>Ni; Mo</td>
<td>0.41</td>
<td>0.18</td>
</tr>
<tr>
<td>C</td>
<td>≤0.07</td>
<td>1.30–</td>
<td>0.068</td>
<td>0.044</td>
<td>0.015</td>
<td>N; Cu; Mo</td>
<td>0.37</td>
<td>0.17</td>
</tr>
</tbody>
</table>
The steel is smelted in a 350-t converter, using batch components that are free from harmful impurities: desulfurized hot metal and metal scrap. Ladle treatment is associated with the removal of sulfur, degassing, adjustment of the chemical composition, and reduction. Steel slabs (thickness 250 mm) are produced on a curvilinear continuous-casting machine. Before rolling to (15.7–16)-mm strip, the slab is heated to ensure complete solution of niobium and vanadium. In accordance with the principles of controlled rolling, the strip on the intermediate roller conveyer is cooled to retard austenite recrystallization. The strip thickness is optimized to ensure structure formation consistent with DWTT requirements. The rolling of the metal in the finishing cells ends in the lower part of the austenitic region. This is followed by laminar cooling, with subsequent winding into coils that are placed in accelerated-cooling equipment.

The test samples are selected in the transverse direction from the second turn of the coil (steel A) and also from points at one quarter, one-half, and three-quarters of the coil length and at the end of the coil (steels B and C). Flat samples undergo tensile tests, with fivefold repetition. The cold strength of the strip is tested between C). Flat samples undergo tensile tests, with fivefold repetition. The cold strength of the strip is tested between

The microstructure is investigated on a Neophot-21 microscope (magnification 100, 400, and 500). The sections are taken from a point at one quarter of the strip thickness and etched in 2–4% alcoholic HNO₃ solution. For more profound study, we use scanning electron microscopy on a Horiba EMAX-8500E microscope (magnification 700–7000) and transmission electron microscopy on JEM-7 (100 kV) and JEM-200CX (120 kV) microscopes.

We employ a BAHR-805 deformational dilatometer to plot thermokinetic diagrams of austenite decay in steel A, in conditions simulating controlled rolling in a 2000 mill, taking account of the austenite grain size. The samples (diameter 6 mm; length 10 mm) are heated to 1150–1200°C. Then they undergo deformation with ε = 15–20% at 1050 and 850°C in slow cooling, with subsequent cooling at 0.5–50°C/s. The cooling rate (W₈₀₀₋₇₀₀) is measured in the range from 800 to 700°C.

According to the thermokinetic diagrams (Fig. 1), the formation of ferrite–bainite structure (without pearlite) in X70 steel with added Ni + Cu may occur at cooling rates no less than 2°C/s. This corresponds to the cooling of (12–16)-mm strip on the exit roller conveyer of the 2000 mill.

In the first stage of the study (steel A), the winding temperature varies in the range 500–600°C, without change in the other rolling parameters. The winding temperature corresponds to the point at which the sample is taken.

Data on the microstructure at winding temperatures around 600, 550, and 500°C show the presence of ferrite of the following morphology (in order of formation as the temperature falls): polygonal ferrite, quasi-polygonal ferrite (ferrite with irregular grain boundaries and increased dislocation density), and acicular ferrite. The electron-microscope data show that the phase that is darkly etched on the optical-microscope images consists of pearlite, degenerate pearlite (a disperse mixture of low-temperature pearlite and ferrite), and upper bainite. In all cases, the microstructure of the steel is characterized by slight striation and, according to the data of transmission electron microscopy, there are no inclusions of residual austenite or martensite/austenite phase.

The change in the content of structural components in the matrix on reducing the winding temperature Tₜ wi from 600 to 500°C is estimated by the Glagolev point method on optical-microscope photographs of the

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2 With the assistance of A.A. Efimov.