Low-carbon plain steels are widely used for a multitude of purposes. However, strengthening a steel with less than 0.2% by quenching is considered ineffective and, hence, rarely resorted to.

The interest in strengthening such steels by heat treatment has increased extraordinarily in recent years. Some authors [1, 3, 4] pointed out that by quenching rimmed low-carbon steels in water it is possible to obtain a practically non-aging material with improved physico-mechanical properties, entirely suitable to replace killed steels of similar composition. Quenching and tempering is able to develop mechanical properties comparable to those of heat-treated low alloy steels MK [4] [nominal composition: 0.12% C, 1.30-1.65% Mn, 0.80-1.10% Si, 0.25% Cu].

Water quenching of rolled stock with wall thicknesses up to 40 mm increases the mechanical properties of the steel: the yield stress improves to over 30 kg/sq. mm [1]. The practical applicability of plain, low-carbon steels quenched to high strength levels is demonstrated in [2]. However, the literature contains insufficient data on the properties of such materials.

This work is concerned with the effects of processing and testing conditions on the structure, strength and ductility of steels 10 and 15, Table 1:

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>S</th>
<th>P</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.13</td>
<td>0.58</td>
<td>0.27</td>
<td>0.03</td>
<td>0.022</td>
<td>0.07</td>
<td>0.11</td>
<td>0.14</td>
<td>0.053</td>
</tr>
<tr>
<td>15</td>
<td>0.16</td>
<td>0.62</td>
<td>0.24</td>
<td>0.032</td>
<td>0.026</td>
<td>0.10</td>
<td>0.13</td>
<td>0.53</td>
<td>0.026</td>
</tr>
</tbody>
</table>

A tempered sorbite structure is usually recommended for high mechanical properties. In a low carbon steel, the martensite does not decompose during quenching due to the feeble supersaturation of the solid solution which retains the carbon [5].

To produce a drastic quench, cooling can be effected in a 8-10% aqueous solution of sodium hydroxide; the maximum cooling rate at 550-600°C is 2400-2600°C/sec. The results of the heat treatment depend on the hardening temperature, the quenchant and the tempering conditions.

Fig. 1 demonstrates the effect of hardening temperature on the mechanical properties of steels 10 and 15. Quenching of blanks 10 mm dia with an initial strength of 45 kg/sq. mm from only 800°C increased the strength 1.5-3 times. From these blanks, 5 mm dia specimens with a gage length/diameter ratio of 5 were machined. The structure was a mixture of martensite and ferrite, Fig. 2,a. Strength and ductility kept increasing with the hardening temperature. The impact toughness increased particularly fast, reaching a maximum of 8-12 kgm/sq.cm after quenching of steel 10 from 850 and steel 15 from 875-900°C. The simultaneous increase in strength and ductility is explained by a uniform distribution of carbon in the solid solution. After quenching from 900-930°C, the structure consisted of typically acicular martensite, Fig. 2,b.

Inside the 10 mm dia specimen of steel 10, martensite forms only in the interior of the grains while ferrite (which prevents grain growth and reduces the hardness somewhat) remains at the boundaries, Fig. 2,c. Even after heating to 1000°C and considerable grain growth, there was still enough time for a continuous ferrite network to precipitate at the boundaries.

During hardening of steel 15, ferrite precipitated at certain locations along the grain boundaries as separate formations arranged as chains or stringers, Fig. 3,a. This type of precipitate was found in inherently coarse-grained steels.
While the investigated steels differed only in carbon and aluminum contents, they had different properties after quenching. This difference depended on the tendency of the steel to change its grain size during heat treatment. For instance, steel 10 was inherently fine-grained while steel 15 was coarse-grained. The first did not change its grain size after 90 min at 930°C, Fig. 3,a, while many large grains were found in steel 15 after heating for only 50 min, Fig. 3,b. In this work we used an 8-10% NaOH solution at 0, 12, 25 and 50°C as a quenching liquid.

Mechanical tests showed (Fig. 4) that the temperature of the quenchant did not affect the strength properties of the metal. However, the elongation and especially the impact toughness increased with increasing quenching bath temperature.

Microstructural examination showed that when the quenching bath was held at 50°C, a large amount of a ferrite-like component appeared in the form of needle colonies and separate small equiaxed areas. A similar structure in plain low-carbon steels was obtained during quenching in an 8-10% sodium hydroxide solution at 25°C.

The properties of the steels after tempering are given in Fig. 5. Tempering at 200°C reduced the strength slightly. The best combination of properties for steels 10 and 15 was obtained after tempering at 300 and 350°C. The strength fell somewhat but the ductility properties increased significantly; the precipitation of cementite was uniform over the entire volume.