Application of decreased hot-rolling reduction treatments for improved mechanical properties of quenched and highly-tempered low alloy structural steels

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Decreased hot-rolling reduction treatments from 98% $\equiv 50$ elongation to 80% $\equiv 5$ elongation, which modify the sulphide-inclusion shape from a stringer to an ellipse, have been applied to improve the mechanical properties of quenched and highly tempered low alloy structural steels. The decreased hot-rolling reduction treatments significantly increased the transverse fracture ductility at similar strengths and uniform elongation levels independent of the type of steel. The treatments also improved the transverse Charpy U-notch (CUN) impact energy independent of the type of steel. The effect of test temperature on CUN impact energy fell into two categories; (1) the treatments significantly improved transverse CUN impact energy in temperature regions which exhibited a ductile fracture mode, (2) the improvement in the mechanical properties was reduced when the temperature decreased and a brittle fracture mode appeared. The results are briefly discussed in terms of a model involving large voids initiated at sulphide-inclusion sites and local shear bands developed between the large voids.

1. Introduction
Commercial structural low alloy steels have generally been used for many engineering components in quenched and highly-tempered conditions. In spite of the best efforts of design engineers, the engineering components still fail in service from time to time and the failure is mainly responsible for mechanical anisotropy. Although the mechanical anisotropy occurs by microstructural banding which is a manifestation of the segregation of one or more elements, in the majority of cases it is closely associated with sulphide inclusions elongated in the rolling direction, thus the metallurgist may be required to investigate the development of the mechanical properties through modification of the sulphide-inclusion shape by an economical method. So far, considerable research effort has been directed toward modifying the inclusion shape of steels. For example, the technical importance of chemical means, i.e., the addition of calcium or rare earth elements to molten steels to modify the sulphide-inclusion shape by an economical method. The calcium or rare earth modification is, however, generally impracticable and quite expensive in commercial practice because some difficulty may be encountered in commercial steelmaking practice: (1) the calcium element is apt to vaporize because of its low boiling point and poor solubility to the molten steel. (2) The rare earth elements are liable to react with activated oxygen $[O]$ in the molten steel and refractory materials and atmosphere. (3) The rare earth oxide and oxy sulphide accumulate at the bottom of the ingot and cause deterioration of the ductility and toughness of steel. (4) The calcium or rare earth injection into the melt in the ladle requires comparatively high technique and operating costs. In such a situation, the potential approach, which is economical in commercial practice and effective for the large-sized applications, has been suggested by the author whereby sulphide inclusions are modified and the mechanical properties are significantly improved. Most recently, the author has shown [2] that decreased hot-rolling reduction treatments from 98% $\equiv 50$ elongation to 80% $\equiv 5$ elongation modified the sulphide-inclusion shape from a stringer to an ellipse and improved the plane strain fracture toughness of quenched and lightly tempered structural low alloy steels. The effectiveness in improving the mechanical properties is attributed to the fact that modified sulphide inclusions act to blunt and arrest cracks propagating across the specimen which would normally cause failure, and considerably suppress lamellate fracture which occurs in a brittle manner along the interfaces of the sulphide inclusion and matrix at the crack tip.

In the present work, the decreased hot-rolling reduction treatments have been applied to improve the mechanical properties of quenched and highly tempered structural low alloy steels used as engineering components in commercial practice.
TABLE 1 Chemical composition of steels used, wt%

<table>
<thead>
<tr>
<th>Designation of steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel A</td>
<td>0.40</td>
<td>0.28</td>
<td>0.81</td>
<td>0.017</td>
<td>0.019</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Steel B</td>
<td>0.40</td>
<td>0.26</td>
<td>0.72</td>
<td>0.016</td>
<td>0.021</td>
<td>1.10</td>
<td>0.25</td>
<td>--</td>
</tr>
<tr>
<td>Steel C</td>
<td>0.40</td>
<td>0.30</td>
<td>0.79</td>
<td>0.016</td>
<td>0.019</td>
<td>0.87</td>
<td>0.26</td>
<td>1.89</td>
</tr>
<tr>
<td>Steel D</td>
<td>0.40</td>
<td>0.34</td>
<td>0.79</td>
<td>0.008</td>
<td>0.001</td>
<td>0.85</td>
<td>0.26</td>
<td>1.87</td>
</tr>
</tbody>
</table>

2. Experimental procedure

Four low alloy structural steels whose chemical compositions are given in Table I were used in this investigation. Steels A, B, and C were prepared as $30 \times 10^3 \text{ kg}$ air-melted and vacuum-degassed heats. Their ingots ($2.5 \times 10^3 \text{ kg}$) were hot-rolled to two different forms at a temperature of 1473 K: (1) 80 mm diameter hot-rolled bar stock (98% $\times 50$ elongation hot-rolling reduction) (98% HRT steel) and (2) 250 mm diameter hot-rolled bar stock (80% $\times 5$ elongation hot-rolling reduction) (80% HRT steel). Steel D was prepared as $30 \times 10^3 \text{ kg}$ vacuum arc-melted heat and the ingots ($2.5 \times 10^3 \text{ kg}$) were hot-rolled to 80 mm diameter (98% VAR steel D). Mechanical test steels were cut in the longitudinal and transverse orientation (Fig. 1) from the bars and machined to the required dimensions. Each steel was fully annealed at 1173 K for 7.2 ksec.

The test steels were heat treated by austenitization under dynamic argon atmosphere for 7.2 ksec at a temperature of 1173 K followed by direct quenching in water (for steel A) or oil (for steels B and C). The test steels were subsequently tempered at 923 K for 7.2 ksec followed by water cooling. The mechanical properties were determined by tensile and Charpy impact tests. The tensile specimens as shown in Fig. 2a were pulled with an Instron machine at room temperature (293 K) at a constant strain rate of $6.70 \times 10^{-4} \text{ sec}^{-1}$. The standard full size Charpy U-notch (CUN) impact specimens (Fig. 2b) were broken at temperature from 77 to 293 K in Charpy impact machine.

The non-metallic inclusions were identified using an electron probe microanalyser (EPMA). The volume fraction and shape of sulphide inclusions were determined at a magnification of 400 by optical microscopy. Fracture morphology was characterized by scanning electron microscopy. Prior austenite grain size was determined by linear analysis by optical microscopy. In order to determine the affect of hot-rolling reduction on texture, (100) pole figures in the sections parallel to the rolling direction were measured by X-ray diffraction using MoK$\alpha$ radiation.

3. Results and discussion

3.1. Metallographic observations

Identification of non-metallic inclusions was made by EPMA and the volume fraction and their shape were determined by optical microscopy. The results are shown in Figs 3 and 4, and Table II. The results are summarized as follows. (1) The majority of the non-metallic inclusions were sulphide, i.e., MnS, independent of the type of steel (Fig. 3). (2) The volume fraction of the sulphide inclusions had similar levels independent of hot-rolling reduction for each steel. (3) The shape of the sulphide inclusions was modified from a stringer to an ellipse as hot-rolling reduction decreased from 98 to 80% independent of the type of...