Dynamic Transformation Above the $\text{Ae}_3$

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Introduction

Because of its industrial importance, several researchers have studied grain refinement by phase transformation during cooling and/or while undergoing deformation. In the case of the grain refinement brought about by deformation, the strain-induced $\gamma \rightarrow \alpha$ transformation is usually produced below the $\text{Ae}_3$. However, in the 1980s, Yada and co-workers produced fine ferrite grains in the size range 1 to 2 μm by deforming above the $\text{Ae}_3$ in two low C steels containing 0.11%-1.00%Mn-0.02%Si and 0.14%-1.06%Mn-0.33%Si. They also observed that there was a critical strain for DT of about 0.5. Subsequent research on two low carbon steels, a niobium steel and a medium-carbon steel [6] has shown that a reverse $\gamma \rightarrow \alpha$ transformation (labeled RT in this work) takes place during isothermal holding after deformation. The occurrence of dynamic transformation above the $\text{Ae}_3$ has also been modeled by means of computer simulations.

The previous investigations were largely restricted to observations of DT and its reverse transformation after deformation. In the present investigation, the effects of strain, strain rate, deformation temperature and temperature on DT and RT during deformation were investigated by means of torsion testing. By examining the microstructure along the radius of deformed and quenched specimens, the changes in phase proportion at different strains and strain rates could be readily determined, which in turn provided useful information regarding the processing of DT and RT during deformation.

Experimental Procedure

The chemical composition and $\text{Ae}_3$ temperature of the investigated steel are given in Table Bellow:

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Al</th>
<th>Ni</th>
<th>Cu</th>
<th>Cr</th>
<th>Mo</th>
<th>Nb</th>
<th>V</th>
<th>N</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06</td>
<td>0.5</td>
<td>0.07</td>
<td>0.008</td>
<td>0.03</td>
<td>1.24</td>
<td>1.00</td>
<td>0.15</td>
<td>0.10</td>
<td>0.01</td>
<td>0.15</td>
<td>0.01</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>

The gage section dimensions of the cylindrical torsion specimens were 3.15 mm in radius and 22.4 mm in length, the cylinder axes being parallel to the rolling direction. A schematic representation of the thermomechanical schedule for the torsion tests is provided in Figure 1. The specimens were heated (1°C/s) to 1200°C, held for 1 min, and then strained to $2.0 \text{ s}^{-1}$ at a strain rate of $0.4 \text{ s}^{-1}$ to condition the austenite prior to deformation. After holding for 20 min at 1200°C, the specimens were cooled (1°C/s) to the various test temperatures. Prior to the second deformation, the specimens were held for 1 min and then deformed to outer radius strains in the range $0.25-5.0 \text{ s}^{-1}$ at a strain of $0.4 \text{ s}^{-1}$ in the McGill servo-hydraulic computer-controlled MTS torsion machine. After the second deformation, the specimens were quenched in water in about 1.5 s to preserve the as-deformed microstructure.

Transverse cross-sections of the deformed specimens were mounted and polished with SiC paper and then 3 and 1 mm diamond paste. After polishing, the specimens were etched in a 2% nital solution. An optical microscope equipped with an image analyzer was used to measure the ferrite grain size and percentages of ferrite in the deformed specimens.

In torsion testing, the stress, strain and strain rate are zero along the axis of the specimen and increase with radius.

Results

Representative flow curves are illustrated in Figures 2 and 3. Two hardening mechanisms: work hardening and reverse transformation (RT) and two softening mechanisms: dynamic transformation (DT) and dynamic recrystallization (DRX), were observed to operate. The softening produced by DT takes place because the ferrite that forms is softer than the austenite it replaces. This mechanism was observed to operate over the whole 40°C temperature range both at the lower ($0.04 \text{ s}^{-1}$) and higher ($0.4 \text{ s}^{-1}$) strain rates. As expected, softening by DRX was also observed under all testing conditions, even at the lowest temperature at the lowest strain rate. DRX occurred mainly in the austenite in the interior layers of the specimens, where the strains and strain rates were lower than in the outer layers.

![Thermomechanical schedule for the torsion tests.]{width=0.5\textwidth}

Conclusion

- The dynamic formation of ferrite can be induced at least 40°C above the $\text{Ae}_3$ in the present 0.06%C low carbon steel. This leads to the formation of nearly equiaxed ferrite grains, as reported in earlier studies.
- The ferrite grains produced by DT above the $\text{Ae}_3$ are about 1.5-5 μm in dia when strain rates of 0.04 and 0.4 $\text{s}^{-1}$ are employed. The finest grains were produced at the lower temperatures and higher strain rate. Still finer grains are expected to form at industrial strain rates. This indicates the potential for the development of new routes for grain refinement that differ from those associated with the traditional pancaking approach.
- The local critical strain for DT in this material is about 0.2 and the critical strain rate above which RT can be avoided is about 0.1 $\text{s}^{-1}$.
- During deformation in commercial mills, RT is unlikely to occur within the roll gap due to the high strain rates employed. However, insufficient information is available to assess the possible occurrence of RT in practical cases, which can be high as 10 s or more in plate mills.