Slow cooling of hot rolled bars to eliminate hydrogen induced cracks in Cr-Mo steels

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Hydrogen shows a high diffusivity in the solid phase and tends to escape during cooling, which reduces its concentration in steel. Low concentration of hydrogen is advantageous as it prevents hydrogen induced cracks. To ensure maximum removal of diffusible hydrogen, slow cooling of steel bars is investigated at JSW Steel Ltd, Salem Works (JSWSL). The hot rolled bars of Cr-Mo steel blooms such as 42CrMo4 and SCM 440H are slow cooled in a thermally insulated mild steel box. The effect of slow cooling on the microstructure, hardness and ultrasonic testing of bars are studied. The present paper discusses the results of slow cooling experiments conducted with Cr-Mo steel blooms and compares the properties of slow cooled and air-cooled bars. The slow cooled bars exhibited reduced hardness up to 78 BHN and are found to be free from ultrasonic defects when compared with air-cooled bars.

Keywords: Ultrasonic testing, Defects, Microstructure, Hardness, Hydrogen induced cracks, Slow cooling

When the metal solidifies all the hydrogen that exceed the solubility limit migrates from the solid and concentrates in the adjacent spaces that are still solidifying. When the concentration exceeds locally the solubility in liquid, bubbles form which may generate blow-holes. After solidification, while temperature and solubility decrease, the residual hydrogen tends to concentrate in the discontinuities inside the material, called “traps” such as cavities, grain boundaries, interfaces between non metallic inclusions and matrix, where it can recombine to molecular hydrogen and create very strong localized pressures, which may exceed the strength of the steel and cause fractures or hydrogen flakes. Flaking is more difficult to avoid in ultra clean steels and with the advent of ultra clean steels, hydrogen flaking is observed even in steels with less than 2 ppm hydrogen. 

Hydrogen diffusion is considered paramount to obtain high quality blooms with low hydrogen content. Diffusible hydrogen is considered to be mobile at or near room temperature, whereas the remaining residual hydrogen is trapped in the metal. Total hydrogen is the combination of the two fractions. Residual hydrogen can be retained through interaction with micro structural discontinuities or by the formation of hydrides with alloying elements.

Hydrogen has a high diffusivity in iron and steel. Because of larger inter-atomic spacing, the diffusivities of H in body centered cubic iron (α-Fe, δ-Fe) are greater than those in face centered cubic iron (γ-Fe). At 300°C, only 30-40 s are needed for hydrogen to move over a distance of 1 mm. The diffusion coefficient is strongly temperature dependent. Hydrogen is present in steel in atomic state and owing to its small atomic radius, hydrogen shows a high diffusivity in the solid phase, therefore it tends to escape during cooling. The amount of hydrogen removed during cooling depends on initial concentration, size of the product, steel grade and cooling rate. At JSWSL, hydrogen induced cracks contributed more to ultrasonic rejections in Cr-Mo and high manganese steels, which was subsequently minimized by increasing argon flow rate during vacuum degassing. The present paper discusses the study conducted to completely eliminate the hydrogen induced cracks by slow cooling in Cr-Mo grade steels such as 42CrMo4 and SCM 440H, which are being used in critical applications in making automotive components such as crank shafts, gear, screw, winch etc.

Experimental Procedure

The chemical composition of steels was determined by ARL-4460 optical emission spectrometer and hydrogen content was determined by Leco RH-402
hydrogen analyser. Microstructure of steel was studied by Leica optical microscope, model DMI5000M. Ultrasonic testing was carried out as per ASTM A388. Hardness was measured by using Brinell Hardness testing machine, model TKB 3000. Temperature was recorded by using optical pyrometer, model Raynger 3I-Raytek. The chemical composition of Cr-Mo steels is given in Table 1.

The steel making route followed at JSWSL is Blast Furnace - Energy Optimising Furnace – Ladle Refining Furnace - Vacuum Degassing – Continuous Casting. At JSWSL, the percentage of ultrasonic defects was found to be more prevalent in SCM 440H and 42CrMo4 grades and hydrogen-induced cracks were found to be the major factor contributing to ultrasonic defects.

To eliminate the hydrogen induced cracks, slow cooling experiments were conducted wherein, 340 × 400 mm blooms of SCM 440H and 42CrMo4 were hot rolled into bars with a diameter of 125 mm. Some of these hot rolled bars were slow cooled in a mild steel box and other bars were air-cooled as per normal practice. After cooling, microstructure, hardness and ultrasonic properties of these bars were studied separately to determine the effects of slow cooling.

Method for slow cooling

Slow cooling of bars was carried out in mild steel box and its schematic is shown in Fig. 1.

A mild steel box having a capacity of 20 tons, capable of housing bars of 6 m long and lined inside with 40 mm thick glass wool to insulate it from atmosphere during cooling is used for the study. After rolling, the hot bars are placed inside the box and the box is immediately closed with an insulated top door. The bars are allowed to remain inside the box until it cools down to around 200°C. The box is provided with a sliding door for measuring temperature of bars.

Results and Discussion

During the cooling experiments, the temperatures of bars were recorded using a calibrated optical pyrometer having ±1% as its measure of uncertainty. The initial temperature of bars after rolling at the exit pass is found to be between 900 and 920°C. The temperatures were recorded at various intervals directly after the exit pass until the temperature of bars came down to around 200°C. Cooling data were plotted as temperature versus time and Fig. 2 presents the temperature profiles of slow-cooled and air-cooled bars.

Cooling data revealed that, air-cooled bars required only 168 min, whereas slow-cooled bars required 640 min to cool to 200°C, indicating approximately a fourfold increase in time for slow cooling. After cooling, the slow-cooled and air-cooled bars were subjected to hardness, microscopic and ultrasonic examinations to determine the effect of slow cooling on these properties.

Hardness of bars was measured at various locations such as sub-surface, mid radius and center. Table 2

<table>
<thead>
<tr>
<th>Grade</th>
<th>C (%)</th>
<th>Si (%)</th>
<th>Mn (%)</th>
<th>P(%)</th>
<th>S (%)</th>
<th>Al (%)</th>
<th>Cr (%)</th>
<th>Mo (%)</th>
<th>H (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCM 440H</td>
<td>0.39</td>
<td>0.18</td>
<td>0.77</td>
<td>0.020</td>
<td>0.015</td>
<td>0.026</td>
<td>0.98</td>
<td>0.17</td>
<td>1.85</td>
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<tr>
<td>42CrMo4</td>
<td>0.43</td>
<td>0.23</td>
<td>0.72</td>
<td>0.014</td>
<td>0.023</td>
<td>0.022</td>
<td>1.13</td>
<td>0.26</td>
<td>1.92</td>
</tr>
</tbody>
</table>
Table 2 – Comparison of hardness of air-cooled and slow-cooled bars

<table>
<thead>
<tr>
<th>Type of cooling</th>
<th>Grade</th>
<th>Bars *</th>
<th>Hardness (BHN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>At center</td>
</tr>
<tr>
<td>Air cooled</td>
<td>A1</td>
<td>229</td>
<td>255</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>248</td>
<td>269</td>
</tr>
<tr>
<td></td>
<td>SCM</td>
<td>269</td>
<td>292</td>
</tr>
<tr>
<td>Slow cooled</td>
<td>S1</td>
<td>219</td>
<td>235</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>207</td>
<td>217</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>212</td>
<td>217</td>
</tr>
</tbody>
</table>

*A&S signifies air cooling and slow cooling

The slow-cooled bars are found to possess lower hardness at all the measured locations than the corresponding locations from the air-cooled bars. The reduction in hardness is observed to be as high as 78 BHN in some bars. The higher hardness of air-cooled bars is indicative of the presence of hard phases in its microstructure. Microscopic examination was carried out on these bars after etching with 2% Nital at various locations such as sub-surface (5 mm from surface), mid-radius (30 mm from surface) and at core. For ease of comparison, the micrographs were captured at 200X and are presented in Fig. 3.

Fig. 3 – Micrographs of air-cooled and slow-cooled bars captured at various locations
It is observed from the micrographs that the slow-cooled bar consist of ferrite and pearlite microstructure, whereas the micrographs of the air-cooled bar shows the presence of bainite. The lowered hardness of the slow-cooled bars correlate well with softer ferrite and pearlite whereas, the higher hardness of air-cooled bars is because of the presence of harder bainite.

The reason for the presence of the bainite could be attributed to the process of air cooling and the faster cooling rate. It is known that, bainite similar to martensite, resist the diffusion of hydrogen and is most sensitive to the presence of hydrogen\(^5\). Its resistance to hydrogen embrittlement is small with high value of embrittlement index\(^9\). Furthermore, due to faster air cooling, the time available for diffusible hydrogen to escape from the bar is reduced, which results in incomplete removal of diffusible hydrogen.

But in the case of slow cooling, the presence of ferrite and pearlite\(^5\) and availability of more time for cooling allow more of diffusible hydrogen to escape easily. Hence, the removal of diffusible hydrogen is expected to be comparatively higher during slow cooling than with air cooling. As an evidence, the results of microscopic examinations revealed that hydrogen induced cracks were observed in few air-cooled bars, whereas no such cracks were observed in any of the slow-cooled bars. Figure 4 presents unetched and 2% nital etched micrographs of hydrogen induced cracks observed at the core in a defective bar.

In order to determine the concentration of hydrogen in air-cooled and slow-cooled bars, samples were collected from sub-surface, mid-radius and at center and analyzed by Leco hydrogen analyser. The results are given in Table 3.

Table 3 reveals that, the concentration of hydrogen is much higher in air-cooled bars than in slow-cooled bars at all locations measured. This indicates that, during slow cooling, most of hydrogen diffuses out resulting in low hydrogen concentration in slow-cooled bars.

The reason for presence of cracks in some of the air-cooled bars could be attributed to the incomplete removal of diffusible hydrogen. The diffusible hydrogen remaining in the steel are free to move about in the steel matrix from reversible hydrogen traps. In reversible hydrogen traps, the hydrogen atoms are weakly bonded and can move by diffusion through a crystal lattice for a long time until they find a suitable place where atomic hydrogens may combine to form molecular hydrogen and create localized pressure, which can lead to hydrogen induced cracking\(^1\). It can also move from one place to another and cause additional stress in a crystal lattice, which can result in a delayed fracture\(^10\). The rate of growth of cracks depends on the rate of supply or diffusion of hydrogen to the crack\(^2\). Furthermore, in the case of air-cooled bars, the microstructure being bainite and acicular ferrite, the hydrogen trapped at the interfaces of strained regions could have assisted in cracking. On the contrary, low hydrogen concentration and absence of strained regions in slow-cooled bars have resulted in defect free bars. Thus, slow cooling proves to be beneficial as it results in the formation of desirable ferrite microstructure.

![Fig. 4 – Hydrogen cracks in (a) unetched and (b) etched specimens observed in air-cooled bar at the core](image-url)
and pearlite and takes a much longer time for cooling. These factors facilitate and ensure the elimination of more of diffusible hydrogen.

Ultrasonic testing was performed on air-cooled and slow-cooled bars and Table 4 presents the defect levels observed in these bars. Ultrasonic testing reveals that, a defect level of 15-35% at a depth of 60-70 mm was observed in air-cooled bars whereas slow-cooled bars were found to be free from such defects. It was found that, the accumulation of hydrogen is much higher in air-cooled bars than in slow-cooled bars and the high concentration of hydrogen in air-cooled bar is likely to have assisted in cracking, which was subsequently detected during ultrasonic testing. Thus, hydrogen cracks were responsible for defects detected in air-cooled bars during ultrasonic inspection.

Conclusions

Slow cooling is proved beneficial as it ensures the maximum removal of diffusible hydrogen from the increased time available for diffusion and increased ferrite phase in microstructure. Experiments revealed that, the concentration of hydrogen is much higher in air-cooled bars than in slow-cooled bars at all locations measured. This indicates that, during slow cooling, most of hydrogen diffuses out resulting in low hydrogen concentration in slow-cooled bars. Bainite and acicular ferrite microstructure in air-cooled bars might be responsible for inhibiting hydrogen diffusion and the hydrogen trapped at the interfaces of strained regions could have assisted in cracking. Slow cooled bars exhibit reduced hardness of up to 78BHN when compared with air-cooled bars. The reduced hardness of slow-cooled bars is found to be beneficial, as it facilitates formability during the process of forging. The hydrogen cracks observed in air-cooled bars might be responsible for defects observed during ultrasonic testing. Slow cooling resulted in defect-free steel, rather than the defect level of 15-35% observed in air-cooled bars.

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References