AREMA-HH is the current grade of rail steel used by Steel Dynamics, Inc (SDI) and has the following properties: hardness of 390 HB, yield strength of 145 ksi, and ultimate tensile strength of 190 ksi. By analyzing three new chemistries proposed by SDI, the goal was to achieve greater values for hardness and strength than AREMA-HH. This was achieved by performing heat treatments with stagnant air and varied accelerated air-cooling pressures ranging from 9 – 140 psi. Through hardness testing and SEM after each cooling method, the effect of the cooling rate and impact of the microalloying elements in each chemistry could be investigated.

**Project Background**
The main steps of this project were to cast, process, and characterize new chemistries and compare their mechanical properties to the existing SDI grade American Railway Engineering and Maintenance-of-Way Association – Head Hardened (AREMA-HH).

**Objectives:**
To develop a rail with higher hardness than AREMA-HH (390 HB), while maintaining the desired microstructure of fine pearlite with 60-80 nanometer interlamellar spacing. The increase in hardness is expected to increase the life of the rail by improving upon the wear-resistance and fatigue-resistance of AREMA-HH. After analyzing these trial chemistries, the goal was to recommend one of them for a full-scale production trial.

**Expectation for new chemistries:**
- Microstructure: 100% fine pearlite because it is more resistant to rolling contact fatigue compared to bainite and martensite.
- Hardness: 420 HB

**Figure 1:** Example of rolling contact fatigue; an indentation in the running surface caused by subsurface fatigue crack. [1]

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**Chemical Compositions for Analysis**
The composition of AREMA-HH is shown in Table 1. It is characterized by a surface hardness of 390 HB, yield strength of 145 ksi, and ultimate tensile strength of 190 ksi [2].

<table>
<thead>
<tr>
<th>Table 1: Elemental composition of standard grade AREMA-HH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element</td>
</tr>
<tr>
<td>AREMA-HH</td>
</tr>
</tbody>
</table>

To better combat the effects of rolling contact fatigue, SDI generated 3 experimental chemistries, shown in Table 2, to be analyzed, with expectations to achieve greater hardness and tensile strength than AREMA-HH.

**Table 2: Chemical compositions of the 3 new chemistries**

<table>
<thead>
<tr>
<th>Grade</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>V</th>
<th>Mo</th>
<th>Al</th>
<th>Cr</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>0.56</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
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<tr>
<td>2</td>
<td>0.5</td>
<td>0.56</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>0.56</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
</tbody>
</table>

- **Effect of Mn:** Increase hardenability and tensile strength
- **Effect of Ti:** Increase toughness but decrease hardness

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**Experimental Procedure**

**Thermomechanical deformation**
- Austenization at 950 °C for 10 minutes
- 10 sample bars (25.4 mm x 12.3 mm x 76.2 mm) of each chemistry reduced to a thickness of 7 mm
- SDI machined to 5 mm x 0.25 mm x 100 mm tensile bars

**Heat treatment**
- Samples reaustenitized
- Stagnant cooling or accelerated air cooling performed with cooling apparatus at pressures of 9, 11, 13, 15, 20, 140 psi

**Hardness testing**
- At least 4 measurements taken along the grip region with macroscale Rockwell-C hardness tester

**Tensile testing**
- Hold tensile bars at 200 °C for 2 hours for stress relief
- Perform 3 tests on each chemistry: air cool, 13 psi, 140 psi

**SEM**
- Take images of microstructure in air cooled and 140 psi samples to determine the interlamellar spacing

**Figures 2-7:**
- Figure 2: a) Setup of apparatus attached to regulator and compressed air tank and b) underside of apparatus with cooling helix
- Figure 3: Representative stress-strain curve for AREMA-HH (left), stagnation cooled and forced air at 13 psi for the three chemistries (right)
- Figure 4: SEM micrograph of several pearlite colonies in AREMA-HH as processed by SDI. This is the desired microstructure of 100% fine pearlite, with an average interlamellar spacing of about 60-80 nanometers.
- Figure 5: SEM micrograph of a single pearlite colony of chemistry 3, cooled in stagnant air. The microstructure is not as pearlitic, but is similar to that of an interlamellar spacing of about 90-100 nanometers.
- Figure 6: SEM micrograph of chemistry 1, cooled at 140 psi. The microstructure is predominantly bainitic due to a faster cooling rate.

**Results**

**Cooling rates**
- Forced air cooling at 9 psi was approximately 2 °C/s, 2 psi was 3 °C/s, and 140 psi 8 °C/s.

**Hardness**
- Hardness of forced air at 9,11,13,15, and 20 psi did not show much difference.
- The highest hardness produced was for forced air at 140 psi for chemistry 2 (369 ± 14 HB).

**Table 3:** Bending hardness values (converted from HRC) for different cooling (stagnant and forced air) for the new chemistries and AREMA-HH

<table>
<thead>
<tr>
<th>Hardness (HB)</th>
<th>5 psi</th>
<th>11 psi</th>
<th>13 psi</th>
<th>15 psi</th>
<th>20 psi</th>
<th>140 psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>AREMA-HH</td>
<td>286</td>
<td>286</td>
<td>286</td>
<td>286</td>
<td>286</td>
<td>286</td>
</tr>
<tr>
<td>Chemistry 1</td>
<td>321</td>
<td>321</td>
<td>321</td>
<td>321</td>
<td>321</td>
<td>321</td>
</tr>
<tr>
<td>Chemistry 2</td>
<td>321</td>
<td>321</td>
<td>321</td>
<td>321</td>
<td>321</td>
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<tr>
<td>Chemistry 3</td>
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<td>321</td>
<td>321</td>
<td>321</td>
<td>321</td>
<td>321</td>
</tr>
</tbody>
</table>

**Table 4:** Shows the ultimate tensile strength (UTS) for AREMA-HH and stagnation cooled and 13 psi for the new chemistries

<table>
<thead>
<tr>
<th>Chemistries</th>
<th>UTS (ksi)</th>
<th>Air cool</th>
<th>13 psi</th>
<th>Arema-HH</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>52</td>
<td>52</td>
<td>52</td>
<td>52</td>
</tr>
<tr>
<td>C2</td>
<td>54</td>
<td>54</td>
<td>54</td>
<td>54</td>
</tr>
<tr>
<td>C3</td>
<td>54</td>
<td>54</td>
<td>54</td>
<td>54</td>
</tr>
</tbody>
</table>

**Conclusion**

**Stagnant cooling generally yielded the lowest microstructure to the desired fine pearlite, and 140 psi resulted in the least preferred (bainitic) microstructure of the cooling rates tested.**

**Cooling rates used for AREMA-HH may not be compatible for the new chemistries, as shown by differences in hardness values.**

**The results of C2 and C3 demonstrate that the addition of Mn improves hardenability, and Ti increases strength.**

**References**


**Recommendations**

Although Chemistry 2 yields the highest hardness for the same cooling rates as C1 and C3, the microstructure was not the desired fine pearlite at this hardness. Further investigation is needed to find the ideal cooling method and to optimize the microstructure for this chemistry before a full-scale production trial is conducted.