Characterization of High Strength, Fatigue Resistant Rail Grades

PURDUE UNIVERSITY®

Materials Engineering

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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 measured 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.

This work is sponsored by Steel Dynamics, Inc, Columbia City, IN

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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]

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 1: Elemental composition of standard grade AREMA-HH

	C	Mn	P	S	Si	V	Ni	Mo	Al	Cr
AREMA-HH	0.74 - 0.86	0.75 - 1.25	0.02 max	0.02 max	0.1- 0.6	0.01 max	0.25 max	0.06 max	0.01 max	0.3 max

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

Grade	C	Mn	P	S	Si	V	Ni	Mo	Al	Others
1	0.8- 0.92	0.4	0.02 max	0.02 max	0.1- 0.6	0.01 max	0.25 max	0.06 max	0.01 max	Cr, Nb
2	0.8- 0.92	0.5	0.02 max	0.02 max	0.1- 0.6	0.01 max	0.25 max	0.06 max	0.01 max	Cr, Nb
3	0.8- 0.92	0.4	0.02 max	0.02 max	0.1- 0.6	0.01 max	0.25 max	0.06 max	0.01 max	Cr, Nb+Ti

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

Experimental Procedure

Thermomechanical deformation

- Austenitization 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 6.25 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

Cooling apparatus for accelerated cooling

a) 

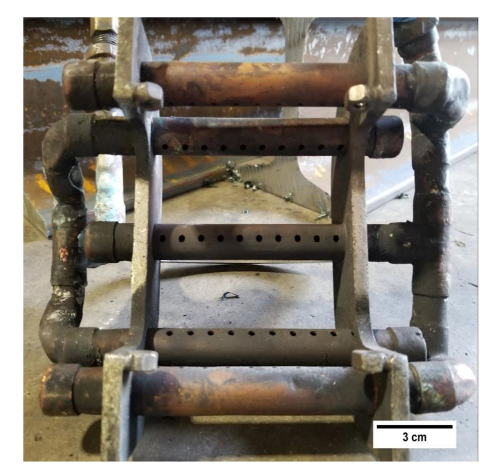
b) 

Figure 2: a) Setup of apparatus attached to regulator and compressed air tank and b) underside of apparatus with cooling holes

Results

Cooling rates

- Forced air cooling at 9 psi was approximately 2 °C/s, 20 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: Brinell hardness values (converted from HRC) for different cooling (stagnant and forced air) for the new chemistries and AREMA-HH

Hardness (HB)	Aircool	9 psi	11 psi	13 psi	15 psi	20 psi	140 psi
Chemistry 1	326	295	306	320	316	292	362
Chemistry 2	325	303	329	319	304	300	369
Chemistry 3	313	297	326	290	284	291	353
Arema-HH tensile bar	363	-	-	-	-	-	634

Tensile Testing

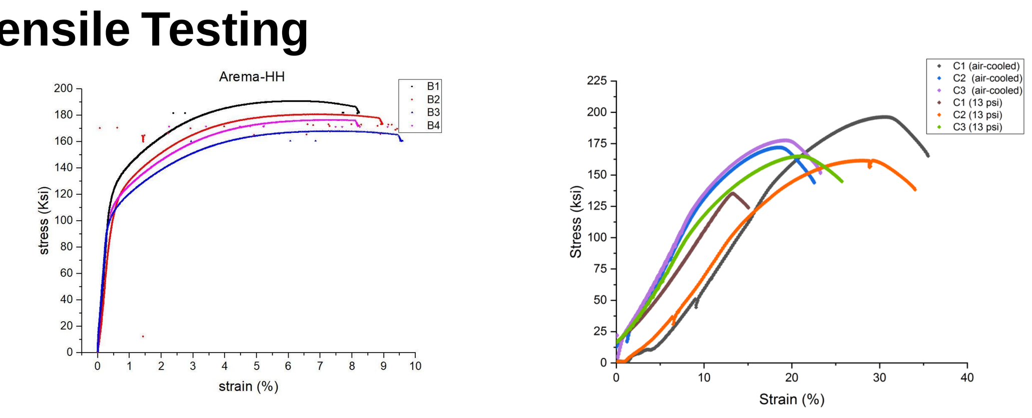


Figure 3: Representative stress-strain curve for AREMA-HH (left), stagnant cooled and forced air at 13 psi for the three chemistries (right)

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

UTS (ksi)	Air cool	13 psi	Arema HH
C1	135	196	184
C2	162	172	-
C3	165	178	-

SEM

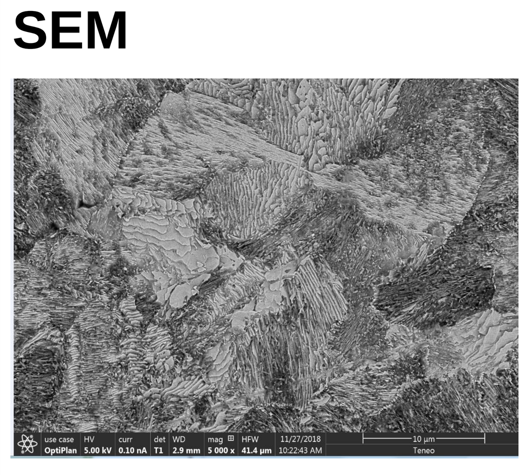


Figure 4: SEM micrograph of several pearlite colonies in AREMA-HH as processed by SDI. This is the desired microstructure of 100% fine pearlite, with an interlamellar spacing of about 60-80 nanometers.

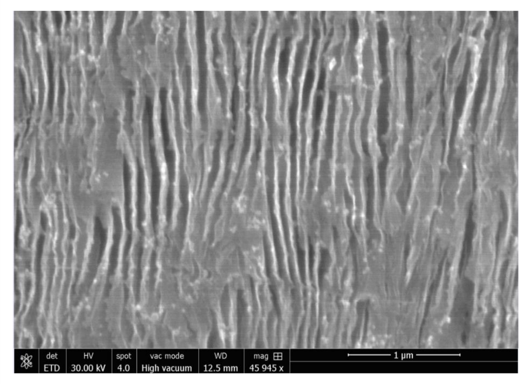


Figure 5: SEM micrograph of a single pearlite colony of chemistry 3, cooled in stagnant air. The microstructure is 100% pearlite, but slightly coarser than ideal with an interlamellar spacing of about 90-100 nanometers.

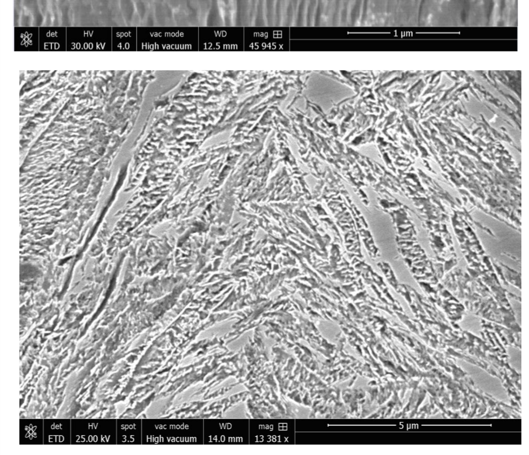


Figure 6: SEM micrograph of chemistry 1, cooled at 140 psi. The microstructure is predominantly bainite due to a faster cooling rate.

Discussion

Cooling rates

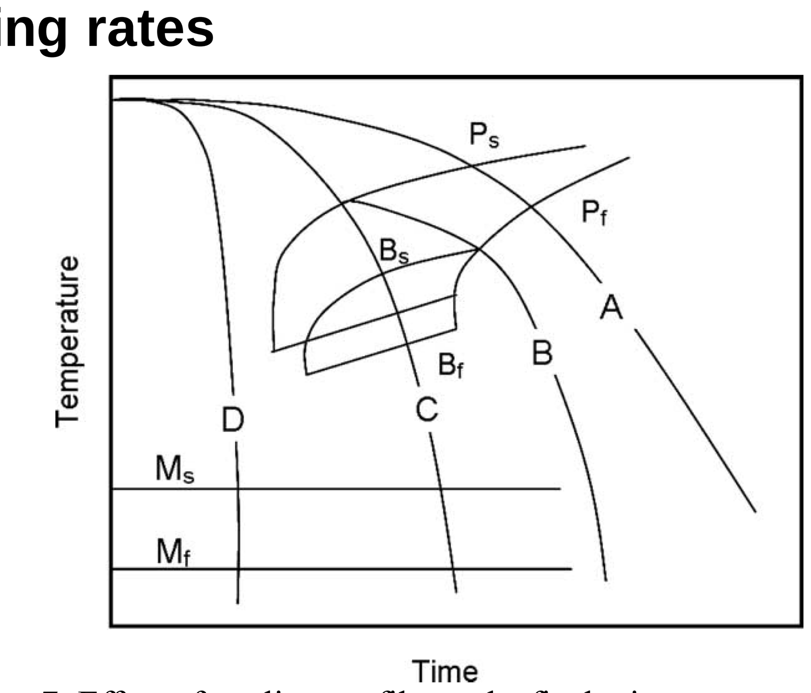


Figure 7: Effect of cooling profile on the final microstructure [3]

Path B: Similar to stagnant cooling

- Rapidly cooled to a lower pearlitic start temperature that is located above the bainite start temperature
- Highly desired fine pearlitic microstructure with excellent hardness, wear resistance, and fatigue properties is expected.
- Lower hardness compared to AREMA-HH might be because of shift in cooling profile for new chemistries.

Path C: Similar to 140 psi

- Cooling rate is increased, and the cooling path crosses pearlite and bainite transformation boundaries.
- Mixed microstructure with low wear resistance is expected.
- Mostly bainite microstructure, highest hardness achieved

Alloying Elements

Manganese

- Increases hardenability and strength of steel through the appearance of fine, pancaked grains
- Chemistry 2, which contains more Mn than C1 and C3, typically displayed the highest hardness values, such as 369 HB at 140 psi.

Titanium

- Reduced hardness but greater toughness
- Chemistry 3, with Ti addition, showed the lowest hardness values, but had the greatest UTS of 165 ksi after air cooling, compared to C1 and C2.

Conclusions

- Stagnant cooling generally yielded the closest 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

[1] LINMAG - Rail milling & Rail grinding Service - Process. (n.d.). Retrieved from http://www.linmag.com/en/process-en
[2] Lawrence, Michael. *SDI PocketGuide. 2019.*
[3]Satyam, S., Mohapatra, G., Totten, G.(2009) Overview of Pearlitic Rail Steel: Accelerated Cooling, Quenching, Microstructure, and Mechanical Properties. *Journal of ASTM international* Vol.6, No.7.

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.