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New Rail Steel for the 21st Century: Advanced Alloy Thermo-Mechanical Processing Development

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Summary

The Transportation Technology Center, Inc. (TTCI) has been working closely with the research team at the University of Pittsburgh in order to design a new rail steel capable of exceeding the American Railway Engineering and Maintenance of Way Association (AREMA) specifications for premium rail steel. This *Technology Digest* offers an update of this research funded by the Association of American Railroads' Strategic Research Initiatives Program. The following describe some of the milestones achieved to date:

- The identification of pro-eutectoid cementite at the prior-austenite grain boundaries as a major cause of rolling contact fatigue (RCF), wear, and low mechanical properties of the rail.
- The design of a number of rail chemistries that virtually eliminate the presence of pro-eutectoid cementite in the rail.
- The design of a number of thermo-mechanical processes (TMPs) to target specific rail microstructures that are homogenous, and meet or exceed the AREMA specification for hardness level in premium rail steel.
- The implementation of these TMPs into macro-sized samples in order to investigate the mechanical properties of the new rail steel.

Rail deteriorates due mainly to wear and RCF. The industry has put in place a number of preventive measures to extend the life of the existing rails. They include lubrication in curves and periodic rail grinding. These measures have worked well, and as a result current rails stay in service for longer periods of time. However, an effort is underway to develop rail steels that will provide superior in-service performance, mainly because rails are a major asset of the rail industry. In 2006, 43 percent of intercity freight transportation ton-miles in the United States was done by rail. In 2007, 44 percent of the ton-miles originated by rail was coal, which is the largest single commodity group in terms of revenue, and one of the heaviest products that the rail industry transports on a regular basis. More rail lines need to handle large tonnage, but currently only 8 percent of the rail in use is over 140 lb/yard in weight.¹ Considering these numbers, the drive to improve the rail performance by implementing new, more durable rail designs is underway.

*Note: Work was done by the University of Pittsburgh for TTCI.



INTRODUCTION

The premium rails currently being tested at the Facility for Accelerated Service Testing (FAST) at TTCI provide the latest advances in the rail manufacturing methods and meet the stringent AREMA specifications,² as previous tests indicate.³ Nevertheless, in some cases they still exhibit relatively poor service performance, which is manifested by excessive RCF. TTCI asked the University of Pittsburgh (UoP) research team to help develop a customized TMP for each of the proposed five advanced alloy rail chemistries in order to produce a homogenous rail microstructure with superior mechanical properties that meet or exceed the AREMA specifications for premium rails and remedy the occurrence of RCF.

This report summarizes the current UoP – Basic Metals Processing Research Institute’s work. Emphasis is on the developed TMP, and post-TMP alloy microstructures.

Main Concerns with Current Rails

The main detrimental effects facing the current generation of rail steels are rail wear and RCF. A number of research initiatives to date document these problems.^{4,5,6} The UoP research team determined that the presence of the hard and brittle pro-eutectoid cementite phase along the prior austenite grain boundaries contributes significantly to rail wear and RCF (see Figure 1, which is a scanning electron microscope (SEM) micrograph). Other significant factors are nonmetallic inclusions that affect cleanliness, as well as the matrix hardness, the austenite grain size, and the interlamellar spacing in the pearlite structure, which (except for nonmetallic inclusions), are all controlled by the cooling rate during rail TMP.

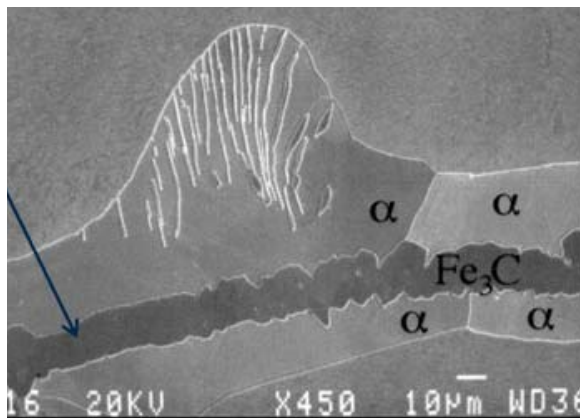


Figure 1. SEM micrograph indicating the presence of pro-eutectoid cementite (arrow) along the prior-austenite grain boundary in a rail steel sample.

TMP Research Goals

TMP of the steel during rail formation affects the final rail microstructure. Fundamental understanding of the TMP process is crucial in microstructural control in the rail. The decomposition behavior of austenite during TMP is affected by several parameters: 1) the composition and microstructural condition of austenite prior to TMP, 2) the effect of cooling

rate on both the formation of pro-eutectoid cementite, and control of interlamellar spacing in pearlite, and 3) the effect of the isothermal holding time on the final rail microstructure (be it pearlitic or bainitic).

UoP researchers conducted a series of experiments using a controlled mechanical testing system (MTS) high temperature deformation apparatus to design the TMP process tailored to a specific rail chemistry, which would provide the optimum rail microstructure with superior mechanical properties. The mechanical testing is ongoing and will include yield strength (YS), ultimate tensile strength (UTS), elastic and plastic elongations, impact toughness (Charpy test), fracture toughness (K_{IC} test), and wear tests. All the properties listed above have to meet or exceed the AREMA specification for premium rail steel. The work to date has focused on designing the TMP in the MTS apparatus and controlling the isothermal holding conditions in an effort to yield a uniform rail microstructure.

Target Rail Chemistries

The selection of carbon content affects the formation of pro-eutectoid cementite at the austenite grain boundaries. In hyper-eutectoid steel (where the carbon content is above the eutectoid composition) the pro-eutectoid cementite tends to form at the grain boundaries prior to the formation of pearlite. This is a concern, because this cementite is hard and brittle, exhibiting low ductility and low impact toughness.

As a result, in hypereutectoid steels, pro-eutectoid cementite becomes the preferred site for crack nucleation. The UoP research team attempted to suppress this cementite formation by adding substitutional solutes in order to modify the rate of cementite precipitation. The retardation of precipitation at the nucleation sites of pro-eutectoid cementite is a major objective of this ongoing study.

The selected solute element had to meet the conditions of low solubility in the carbide (Fe_3C) phase, and high solubility in the ferrite (α) phase. As a result, this element retards the growth rate of the Fe_3C , thereby reducing its amount at the grain boundaries. The selected solute element suppressed the Fe_3C formation (as element level \uparrow then Fe_3C growth rate \downarrow). Chromium along with this element act synergistically to improve the mechanical properties of the steel by solid solution strengthening and by preventing the coarsening of Fe_3C phase. Manganese additions reduce the amount of pro-eutectoid ferrite and lower the temperature at which Fe_3C begins to form. In addition, every heat was targeted with a very low level of Sulfur, hence the level of impurities were kept to a minimum. Some of the developed chemistries were outside the range of the AREMA chemistry specification for elements in standard rail steel.

TMP and Transformation Studies

Each of the five vacuum treated laboratory heats were poured into 300-pound ingots. Half of the ingot from each heat was used for the MTS – TMP experiments, and the other half was used for the hot rolling experiments.

MTS – TMP Experiments

The MTS system exhibits very accurate control of the reheating temperature, the deformation temperature, the amount of deformation, the strain rate, the delay time between deformations, the cooling rate between deformations, and the temperature during the isothermal holding and continuous cooling conditions. As a result, the MTS was used to develop the TMP conditions to achieve the AREMA requirements to target the Rockwell-C hardness (HRC) levels and a target microstructure. The acquired steel microstructures were fully homogenous, and either fully pearlitic for some steels, or fully bainitic for one other steel. The AREMA specification calls for HRC to be at 38 for premium rail steels, which was the standard used in the assessment of the TMP’s effectiveness.

The reheating temperatures for each steel type were chosen in order to target a similar grain size prior to deformation. These temperatures were strongly related to the steel chemistry. For each steel type a predetermined holding time at the reheating temperature was used to allow homogenous microstructural development prior to the 1st reduction. The 2nd reduction was performed below the recrystallization temperature of austenite. The amounts of deformation at each reduction step, and the strain rates were closely monitored. A specific cooling was implemented until the prescribed transformation temperature of either pearlite or bainite was achieved. The samples were then held isothermally at the transformation temperature until the full development of the desired microstructure. Figure 2 shows a schematic of the MTS - TMP process.

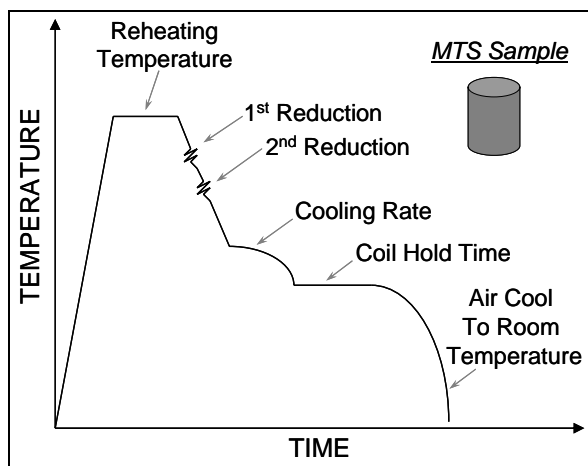
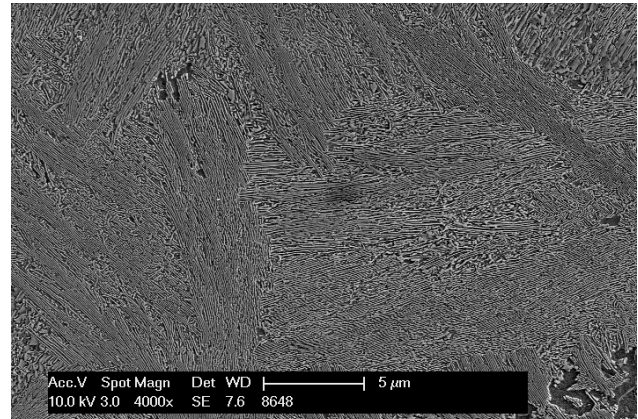


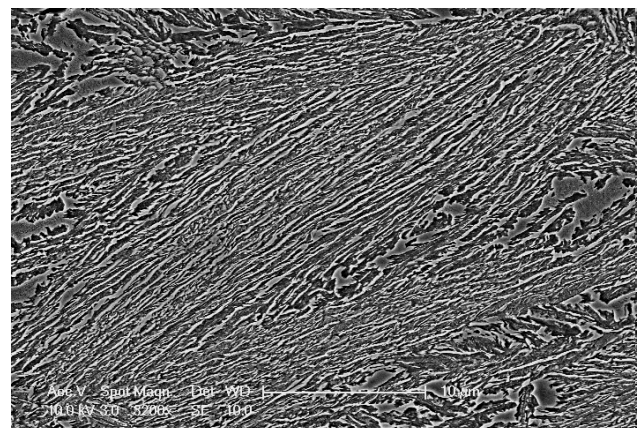
Figure 2. Schematic design of the MTS process conducted for each of the five steels. Reheating temperatures, reduction temperatures, and coil hold times varied between the five steels investigated.

Microstructural analysis of the post-TMP steels indicates that the requirements for each of the steel types were achieved. Four of the steels achieved a fully pearlitic microstructure with an HRC equal to or higher than 38 (the AREMA specification for premium rail steel). One of the steels investigated achieved a fully bainitic microstructure, with HRC above 38 as

well. Typical post-TMP fully pearlitic and fully bainitic microstructures achieved are given in Figure 3.



(a) example of a post-TMP fully pearlitic microstructure in one of the steels.



(b) example of a post-TMP fully bainitic microstructure in one of the steels.

Figure 3. Examples of post-TMP fully pearlitic, and fully bainitic microstructures achieved in the investigated steels.

In order to investigate the effect of isothermal holding on microstructural development in each steel type, additional coil holding temperatures and times were studied. Subsequent measurements of the pearlitic interlamellar spacing were used to assess the effectiveness of each isothermal holding, and to predict the YS each steel type will achieve. This was done in order to achieve a YS that would meet the AREMA specification for premium rail steel (YS=120ksi). Based on those calculations, the TMP for each steel chemistry was slightly modified for the hot rolled plates in order to meet the AREMA specification for YS.

Hot Rolling Experiments

Following the optimization of the TMP on the MTS apparatus, a modified TMP was applied to the other half of the vacuum treated ingots. The purpose of this TMP was to achieve the AREMA target microstructures and mechanical properties. Figure 4 shows a schematic of the process along with sample geometry.

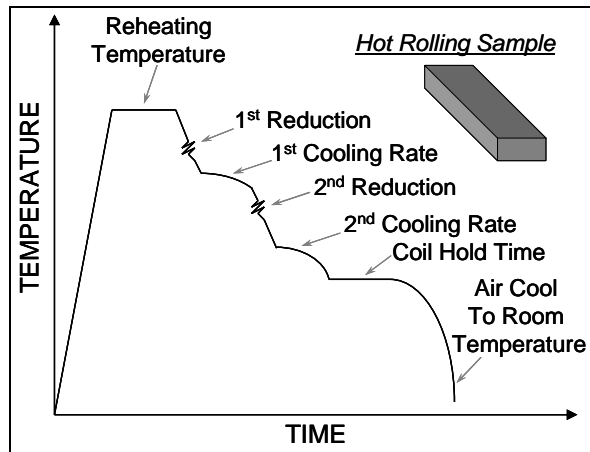


Figure 4. Schematic design of the hot rolling process conducted for each of the five steels. Reheating temperatures, reduction temperatures, and coil hold times varied between the five steels investigated.

The hot rolled sections are still in the early stages of testing. Complete microstructural analysis and mechanical test results will be published as they become available.

CONCLUSIONS AND FUTURE WORK

The research in new rail steel development for the 21st century conducted at UoP offers new ways of reducing the occurrence of pro-eutectoid cementite at the austenite grain boundaries. This is done through tight control of the rail chemistries, and a number of TMPs designed to target pearlitic microstructures that exceed the AREMA specification for premium rail steel. A fully bainitic microstructure was also developed in a hypoeutectoid steel. All the microstructures developed were fully homogenous, which should help in achieving uniform mechanical properties in each steel type.

Future research will focus on the assessment of the hot plate mechanical properties, and their detailed microstructural analysis. This will be done in order to verify the presence of AREMA target microstructures in four of the rail steels, and a bainitic microstructure in one rail steel. Following that research, the chosen chemistry and TMP will be implemented into an industrial process at a selected rail manufacturing facility.

A major challenge will be to transfer the designed TMP method into an industrially viable process for rail manufacture. Obstacles to consider are the variation in the surface area and the cross-sectional area that the processed rail ingot experiences during the hot-working operations, which has a

profound impact on heat dissipation during cooling and the resulting microstructural development in the rail.

The TMP implementation will need to address the number of reduction steps currently in use by rail manufacturers, as well as rail transfer temperatures between individual reductions, and associated cooling rates between individual steps. It is unlikely that it will be possible to transfer the proposed UoP TMP process into production without any alterations. TMP will require special tailoring to meet the process requirements for steel mills.

Nevertheless, the work done to date at the University of Pittsburgh indicates that full microstructural control during ingot processing is possible to reach the proposed rail requirements, and to develop a rail of superior quality.

Acknowledgements

The authors thank TTCI and the Association of American Railroads for providing funding for this research endeavor.

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