B. Laser Glazing of Railroad Rails to Reduce Friction

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Objective

- Determine the potential of laser glazing to lower parasitic energy losses between the flange and rail in rail transport.
- Develop a fundamental understanding of the metallurgy associated with the formation of low-friction surface layers during the laser glazing processing, and how these layers reduce friction between rail and wheel.

Approach

- Develop an advanced laser glazing processes to form glazed regions on carbon steels.
- Perform benchtop tests, full-scale rig tests, and field tests of glazed steels and rails to quantify the impact of glazing on parasitic friction losses.
- Characterize glazed and nonglazed steels to elucidate the impact of glazing on the microstructure.

Accomplishments

- Optimized laser processing conditions under which uniform glazed surfaces form on carbon steels.
- Evaluated friction and wear performance of glazed (and unglazed) rail steel by using benchtop and wheel/rail rig tests.
- Characterized the microstructure and hardness of glazed steels.
- Developed a deformation theory for nanocrystalline materials to model friction in glazed steel.

Future Direction

- Perform full-scale rig tests at the Canadian National Research Council (CNRC) facility in Ottawa, Ontario.
- Make go/no-go decision to proceed with development of rail-glazing technology.

- If decision is to proceed, (1) establish contract with Transportation Technology Center, Inc. (TTCI), Pueblo, Colorado, to test glazed rails on a full-scale rail test loop and (2) commercialize rail-glazing technology with Harsco Track Technologies (the railroad track maintenance equipment and service organization of Harsco Corporation).

Introduction

Wheel/rail interactions account for a significant fraction of the energy consumed in rail transport. Past studies have indicated that energy savings could be as high as 24% when friction at the wheel/rail interface is properly managed. The key aspect is control of the friction forces. At the locomotive, high friction between the rail (specifically the top of the rail) and the wheel is desired to ensure adequate traction to keep wheels from slipping and sliding when power is applied. Friction is also required under braking conditions to control the speed of downhill-bound trains or to bring a train to a safe stop. The trailing cars, however, require much lower friction levels under normal train operations. For these cars, a low, controllable friction is desirable because less friction can significantly reduce the energy required to pull a train. Two regions account for most of the frictional losses between the wheel and the rail: the region between the top of the rail and the wheel tread, and the region between the wheel flange and the gage face of the rail. Current wheel/rail lubrication (e.g., application of degradable greases and lubricants) is inconsistently applied and often disengaged by train crews. The research described here focuses on the development of a laser-glazing technique that imparts a durable, low-friction surface to the gage face of the rails to reduce parasitic frictional losses between the flange and rail gage.

Approach

The objective of this research is to develop an advanced laser modification process to form a glaze on the gage face of the rail. Initial results and models predicted the formation of a nanocrystalline surface layer that would impart low-friction properties at the interface. The tasks associated with this project involve

- Process development (laser glazing)
- Friction and wear testing of laser-modified surfaces (glazed and shot-peened)
- Microstructural characterization of laser-modified surfaces
- Development of a model (of surface deformation)

Results

The process development effort primarily focused on laser glazing. Parametric studies were performed to optimize the conditions under which a glazed layer forms on 1080 steel when an Electrox 1.6-kW, pulsed Nd:YAG laser with fiber-optic beam delivery and special beam shaping optics is used in Argonne National Laboratory's (ANL's) Laser Applications Laboratory. Two approaches were developed: one that involved a single pass of the laser over a given area, and one that involved multiple overlapping passes (Figure 1). The Knoop hardness of the martensitic glazed regions was 2–3 times greater than that of the substrate, depending on whether a single-pass (factor of 3 times harder) or multipass (slightly over 2 times harder) process was employed.

A commercial laser-glazing process that utilized high-power diode laser technology was also investigated. In this case, bars of 1080 steel were processed by a commercial vendor (NuVonyx - http://www.nuvonyx.com/) and subsequently tested at ANL (Figure 2a). A third laser modification process (laser shot-peening [LSP]) was also evaluated. Bars of 1080 steel were processed by LSPT (LSP Technologies - http://www.lspt.com/home.asp) to "peen" near-surface

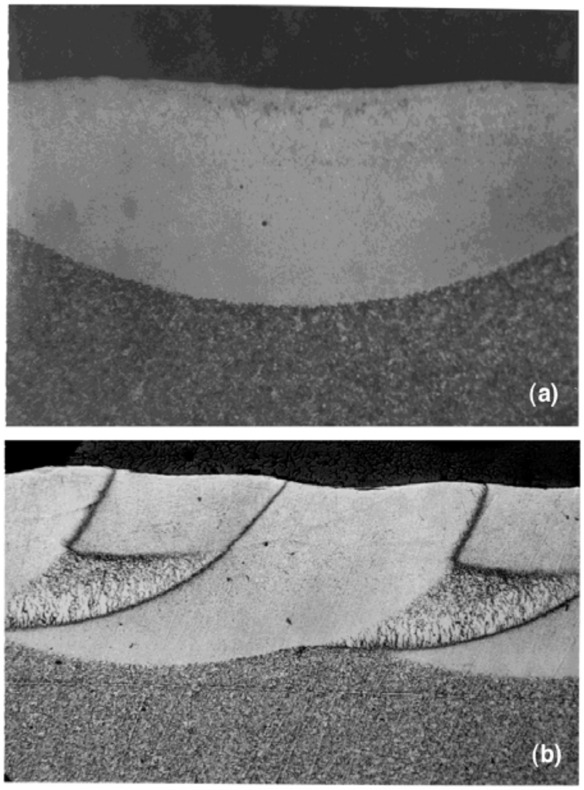

Figure 1. (a) Single-pass laser glazed cross section (b) Multi-pass laser glazed cross section.

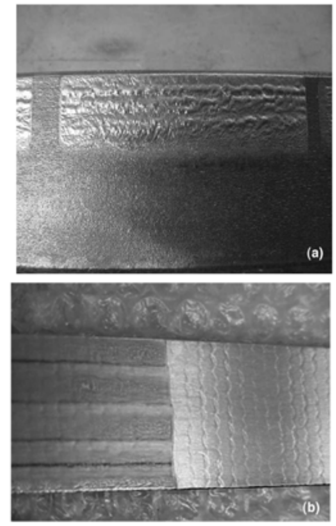

Figure 2. (a) 1080 steel glazed with a high-power diode laser. (b) 1080 steel laser peened (right side) and gazed and peened (left side).

regions (Figure 2b). LSP does not involve melting near-surface regions; rather, it utilizes a laser to shock near-surface regions, thereby introducing high compressive stresses and increased hardness.

Friction and wear tests were performed on laser-treated (primarily ANL's glazed steels) to evaluate the potential of glazing to reduce frictional losses between the wheel flange and gage face of the rail. Initial tests were performed at Falex Corporation by using a low-speed, block-on-ring configuration, and at the AAR test facility in Pueblo, Colorado, by using a full-scale ring/wheel-on-block/rail, operated under controlled slip conditions. Detailed tests were performed at ANL on twin-roller, pin-on-disc (POD), and reciprocating pin-on-flat configurations. Future tests in a full-scale twin-roller configuration are planned at the CNRC facilities in Ottawa, Ontario.

The block-on-ring tests at Falex measured the breakaway (i.e., static friction coefficient) torque/force required to initiate rotation (defined as 0.013 rpm) under various loads (445–4005 N [100–900 lb]) in 100-lb (445-N) increments. (The ring in this case was a Falex standard ring made of S-10 steel with an Rc of 58–63; the block was 1080 rail steel, as received or as-glazed.) Dynamic block-on-ring tests were not performed because earlier tests showed debris accumulation produced unreliable comparisons under dry heavily loaded conditions. The Falex test results showed static friction coefficients of ≈0.35–0.45 for untreated 1080 steel that dropped to values ranging from 0.2 to 0.4 for differing glazing conditions.

The AAR tests were similar to the Falex tests in that they measured the breakaway friction (friction to start rotation) and the friction during maintained rotation. The AAR tests were performed on a segment of rail that was glazed on the top of the rail; the top of the rail was subjected to pure rolling and, at the end, to rolling/sliding contact (Figure 3). The static friction coefficient of the untreated 1080 rail steel varied from 0.2 to 0.5, depending on the applied load, whereas the friction coefficient of the glazed regions varied from 0.1 to 0.25. Dynamic friction coefficients for the glazed regions varied from 0.2 to 0.35, depending on load, compared with 0.2 to 0.55 for unglazed regions.

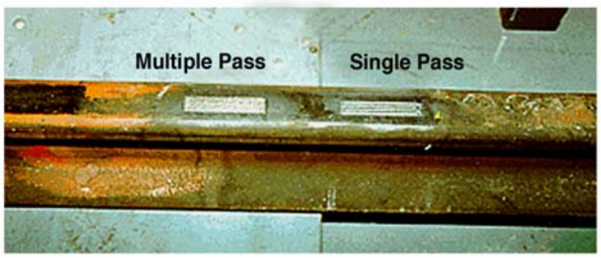

Figure 3. Segment of laser-glazed 1080 rail used in AAR friction tests.

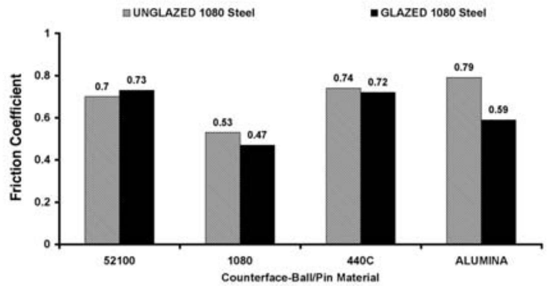

Figure 4. Pin-on-disc friction coefficient data for glazed and unglazed steel sliding against different pin materials.

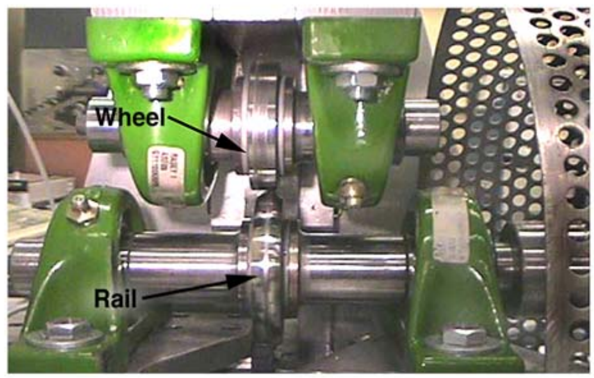

Figure 5. LA-4000 twin-roller test rig used to simulate high contact stresses.

The benchtop tests at ANL were more controlled than the full-scale tests at the AAR facilities. The environment was more repeatable in terms of surface contaminants and more consistent in terms of relative humidity, two factors that significantly affect the frictional response. The POD tests used flats of 1080 steel, glazed and unglazed, that rubbed against stationary balls or pins (52100, 1080 steel, 440C, or alumina). The tests revealed that the composition of the pin/ball had a significant impact of the friction coefficient (Figure 4). The general trend was that the glazing reduced the friction coefficient by 3–35%, depending on the material. The greatest reduction was for the alumina ball sliding against the 1080 steel, suggesting that a strong chemical adhesion mechanism may be active with the metallic counterparts.

A twin-roller test configuration (Figure 5) was also employed to more closely simulate the rolling contact stresses present at wheel-rail interfaces The system shown in Figure 5 was used extensively to simulate the stresses present in 100-ton rail cars. The system is configured to measure the lateral friction forces. Tests were performed with 1045 steel rail and wheel discs that were through hardened (Rc 40) or glazed. The glazing effectively reduced the friction coefficient from roughly 0.4 for the unglazed condition to 0.3 for the glazed rail rotating an unglazed 1045 steel counterpart (Figure 6).

Similar tests were performed on 1045 steel rollers that were treated with a diode laser by a commercial vendor (NuVonyx). The NuVonyx-treated samples also exhibited lower friction than the untreated steel; however, the low-friction behavior did not endure for as long as that of the ANL-treated coupons. The difference in endurance is due in part to the fact that the NuVonyx laser treatment was not as well optimized as the ANL treatment.

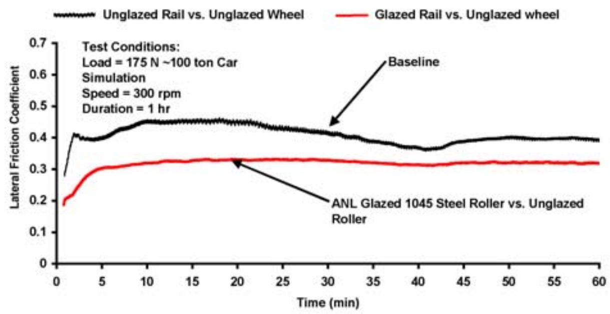

Figure 6. Twin roller friction data on glazed and unglazed 1045 steel.

Tests were also performed to evaluate the durability of the glazed region, in particular to determine whether the glazed region would delaminate from the underlying steel. This is a major concern for railroad applications because delamination could be a precursor to the formation of cracks that lead to rail degradation. Long-term (24–48 h) twin roller tests at a high angle of attack were performed on the twin-roller rig shown in Figure 5. A 24-h test simulates the passage of ≈1100 100-car trains (each loaded at 100 tons). In all cases, the glazed region remained intact and showed no evidence of delamination.

Microstructural characterization of glazed steel coupons was performed to determine whether a “white layer” was produced that could account for the reduced friction. Optical and electron microscopy (both scanning and transmission microscopy [SEM and TEM]) were used to characterize the microstructure. Microhardness was also measured in the glazed regions as a function of depth into the substrate.

Characterization by cross-sectional SEM of as-glazed 1080 steel coupons indicated a martenisitic region (glaze) over the base 1080 steel (pearlitic). High-resolution cross-sectional SEM of multipass laser-glazed 1080 steel that was subjected to rolling-sliding wear at the TTCI confirmed the presence of martensite. The martensite/glazed region consisted of two grain structures: equiaxed and columnar, as shown in Figure 7.

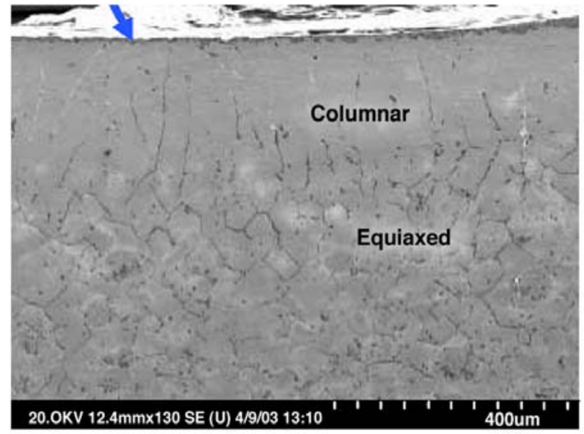

Figure 7. Cross-section SEM of multipass glazed steel subjected to rolling-sliding wear.

The presence of a thin white layer with a different microstructure was not confirmed. A thin layer (2–10 micrometers thick) was observed, but this was attributed to edge rounding that occurred during sample preparation.

The microhardness of several samples was measured. The results were very consistent from sample to sample, even between samples produced by the ANL process and the NuVonyx process. The 1080 substrate hardness was 300–400 Knoop, increasing to ≈1100 Knoop and decreasing to 800–900 Knoop near the surface. Samples that were exposed to multipass laser treatments were softened, the near-surface regions maintained a hardness of 800–900 Knoop; however, in regions further from the surface, the hardness decreased to 500–600 Knoop.

DiMelfi of our group is developing a model for deformation in nanocrystalline metals that is consistent with the observed deformation characteristics of such materials. The model is relevant to this project in that if rapid solidification by laser glazing leads to a nanocrystalline surface layer, that layer will deform in accordance with those observed characteristics. These deformation characteristics support reduced friction and wear. Like metallic glasses, nanocrystalline metals exhibit very high yield strength because plastic flow is not facilitated by crystal dislocations in such materials. Also, after yielding, flow in nanocrystalline metals is nonhardening, and, therefore, perfectly plastic.

Related to this is the observation that flow is restricted to narrow, shear bands in these materials. This phenomenon leads to plastic instability and limited bulk ductility in tension, but allows considerable plastic flow in compression. In theory, plastic flow is accomplished by sliding along grain boundaries, which, in as-formed nanocrystalline metals, are in a higher energy state than they are in the same metal with a conventional grain size. Physical properties of the boundary—such as atomic arrangement, excess free volume, and other deformation-related properties—are tied to the grain boundary diffusivity. As in many shear-banding situations, flow must initiate at some local stress concentration or weak boundary. The sliding boundary will induce sliding in neighboring boundaries, not so favorably oriented, by imposing an additional local shear stress on them.

In addition, a sliding boundary can experience an increase in excess free volume because flow must occur in a non-conservative way by moving atoms past one another without the aid of dislocations. This excess free volume makes the deformed boundary more susceptible to further flow. Therefore, shear not only propagates across the material from one sliding boundary to another, but it is restricted to a narrow shear band associated with the deformation-weakened boundaries. The result of this mode of deformation can result in not only nonhardening flow (because there are no dislocations), but also strain softening, albeit at a very high flow stress. Hence, energy losses (friction) from plasticity are limited because of the high yield stress, and, if yield does occur, it does so in a nonhardening manner, which mitigates delamination wear.

Conclusions

The technological feasibility of utilizing laser glazing to improve the friction (and wear) performance of steels has been demonstrated. Laser-glazed segments of steel commonly used in railway applications exhibited lower friction in large-scale rolling-sliding and benchtop tests.

Future tasks will address several major barriers that must be overcome before this technology is adopted by the railroad industry as a method to improve fuel economy. These tasks include demonstration tests at the CNRC Ottawa test facilities, and the TTCI test loop in Pueblo, Colorado. The TTCI tests will involve glazing a large segment of rail and placing it in one of the test loops, where it will be exposed to train traffic. Before the TTCI tests, full-scale wheel tests will be performed on glazed rail/wheel sets to confirm that the friction (and durability) improvements observed in prior tests are achievable under full-scale geometries. The CNRC tests are also designed to confirm that the glazed regions will not undergo delamination and potential train derailments at the TTCI test loop.

Publications and Presentations

Saud Aldajah, George R. Fenske, Oyelayo O. Ajayi, and Sudhir Kumar, "Investigation of Top of Rail Lubrication and Laser Glazing for Improved Railroad Energy Efficiency," presented at 2002 ASME/STLE International Joint Tribology Conference Cancun, Mexico, October 27–30, 2002.

Saud Aldajah, "Tribological Effect of Laser Glazing and Top-of-Rail Lubrication on Wheel-Rail Interaction," Ph.D. dissertation, Illinois Institute of Technology, Chicago, Illinois, December 2003.