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Analysis of Rail Crack Initiation

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Summary

According to statistics published by the Association of American Railroads,[1] the North American railroad industry has spent approximately $10 billion over the last 5 years on rail replacement. In order to preserve the longevity of the investment, an analytical model has been developed to investigate the relationship between fatigue life and material properties.

This *Technology Digest* (TD) presents details of the numerical simulation research conducted at the University of Illinois at Urbana-Champaign. The rolling contact fatigue (RCF) model described was developed under joint funding provided by the Federal Railroad Administration and the Association of American Railroads. The model simulates crack initiation based on a stress-strain model taking into consideration the effects of ratcheting, fatigue, work-hardening, and the material characteristics of rail steels.

To illustrate the capabilities of the model, head hardened pearlitic rail steel and experimental medium carbon bainitic rail steel were evaluated. The following results were obtained:

- Bainitic rail (J6) demonstrates better RCF performance when compared to pearlitic rail because J6 has better ratcheting performance.
- Damage, under dynamic and cyclic load conditions, to rails in revenue service occurs mainly due to:
  - Rail fatigue (internal fatigue defects, such as transverse defects or vertical split heads)
  - Ratcheting (surface fatigue defects or RCF)
- The major damage on the surface of the rails occurs under high shear stresses because under these conditions both fatigue and ratcheting affect the surface of the rail.
- Under laboratory conditions, bainitic rails support higher rolling contact loads than pearlitic rails. This could be attributed to the low shear forces. However, rails in revenue service are subjected to a multi-directional stress environment. Pearlitic rail is more ductile and has a good work hardening ability that makes it more competitive for railroad applications.

The results of the simulations shown here are in close agreement to the observations of the J6 bainitic and premium pearlitic rails observed at the Facility for Accelerated Service Testing and in revenue service, as reported in previous TDs.[2,3]

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Introduction

A stress-strain model was designed to predict the amount of ratcheting accumulated per cycle. Additionally, a multi-axial fatigue damage model was introduced to predict the fatigue life of the material based on the stress-strain state of rail materials. This TD presents the main details used to develop the RCF model.

Rails are subjected to various types of damage, including fatigue-ratcheting (dynamic load), creep due to residual and thermal stresses (static load), wear, and corrosion. Damage is defined as “a physical harm that is caused to something that impairs its function or appearance.”[4] For instance, wear damage is the result of surfaces moving over each other and generally involves progressive loss of material.[5] Corrosion damage is the progressive deterioration of a materials due to its exposure to the environment.[6] This TD focuses on the effects of dynamic loads on rail performance, including the accumulation of strain (ratcheting), which promotes crack formation that is susceptible to fatigue.

Pearlitic steel is commonly used for rail applications. The material properties of the currently used rails are similar to those of 1080 steel.[7] Generally, as material hardness increases, wear resistance and performance also increase. Specifically, the resistance to crack initiation increases with hardness for yield strength at least up to 1400 MPa (203 ksi).[7] Therefore, it has been proposed that by using a harder material; i.e., J6 bainitic steel, rail performance can be directly improved minimizing maintenance expenses considerably.

Ratcheting Experiments

Ratcheting experiments can be used to determine material properties using an iterative approach, which aims to find a value that aligns simulated ratcheting rates with experimental data.[8] Figures 1 and 2 show the results of a ratcheting test at several stress range levels. Figure 1 and 2 are clear examples that for the investigated bainitic steels the accumulated strain response is significantly lower than that of the pearlitic ones when subjected to uni-axial cyclic loads (compare number of fatigue cycles vs. strain). These results also reveal that multiple ratcheting tests must be analyzed to determine accurate values for the materials characteristics.

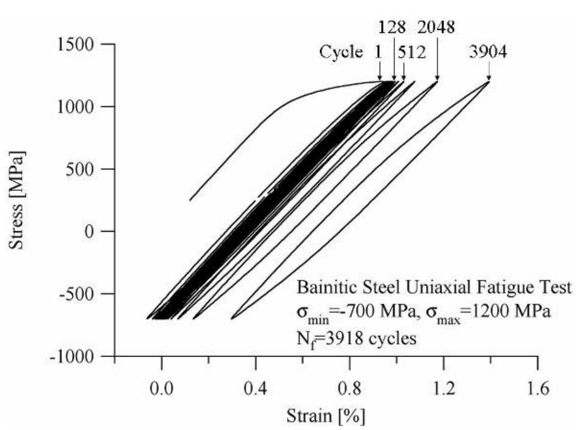

Figure 1. Ratcheting Data for Bainitic Steel under a Uni-Axial Test from -700MPa to 1200MPa[7]

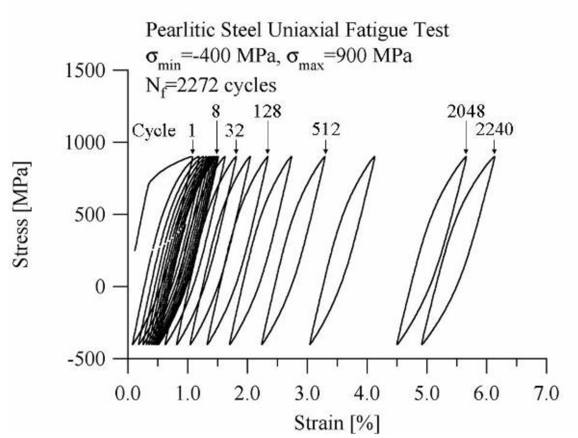

Figure 2. Ratcheting Data for Pearlitic Steel under a Uni-Axial Test from -400MPa to 900MPa[7]

Rolling Contact Simulations

Bainitic steel displays plastic shakedown or ratcheting arrest after an initial transient period. The pearlitic steel, however; exhibits fairly constant surface displacement per cycle after the initial transient region (Figures 3 and 4, respectively).

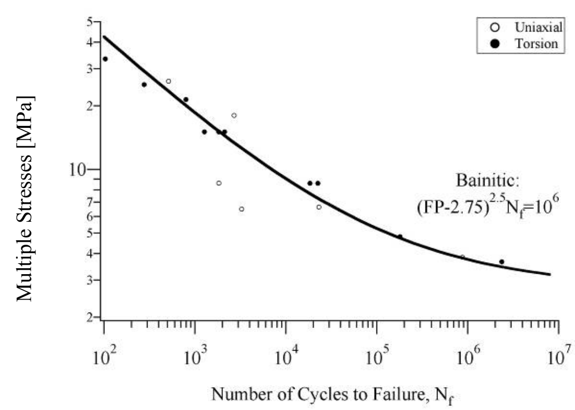

Figure 3. Fatigue Results for Uni-Axial and Torsional Tests on Bainitic Rail Steel[7]

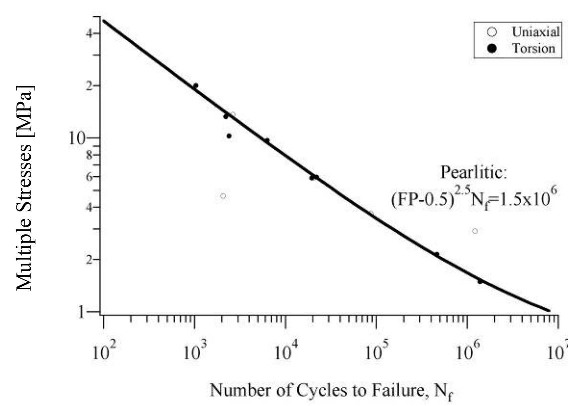

Figure 4. Fatigue Results for Uni-Axial and Torsional Tests on Pearlitic Rail Steel[7]

Crack initiation data calculated for bainitic and pearlitic rail steels (Figure 5) reveals that the crack initiation life can be determined based on a given normal (P) and shear load (Q). For this purpose, a fatigue crack initiation map is used. This map is a diagram that shows the normal and shear loads that lead to failure after a specified number of cycles. Due to computational costs, it is impractical to run the simulations for more than 10^3 or 10^4 cycles. When generating fatigue crack initiation maps, it is often desirable to determine the loading conditions that would lead to crack initiation at a greater number of cycles. If the logarithm of damage is plotted against the logarithm of cycles, the observed behavior is fairly linear after an initial transient region. Therefore, 10^3 cycles are typically sufficient to determine the trend of the damage parameter that is extrapolated to a larger number of cycles as shown in Figure 5.[7]

In the present study, fatigue crack initiation curves were generated for loading conditions that lead to failure after 10^4 and 10^6 cycles (Figure 6). A noteworthy observation is that when the Q/P ratio is between 0.0 and 0.2, the load curves vary gradually in the fatigue crack initiation maps. For all other Q/P ratios, the fatigue crack initiation data falls into a transient region. (In Figures 5 and 6, P_0 expresses the applied normal load for the various Q/P conditions.)

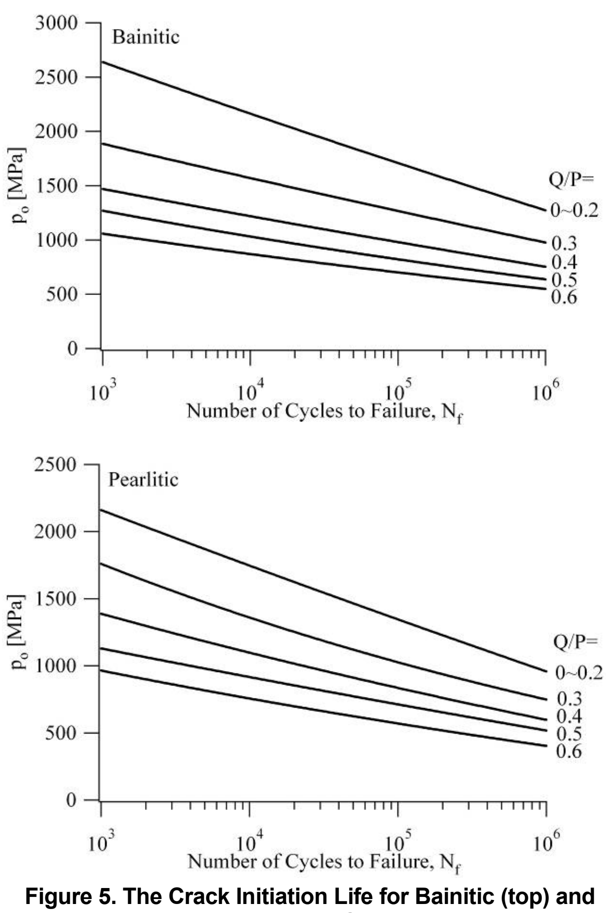

Figure 5. The Crack Initiation Life for Bainitic (top) and Pearlitic (bottom) Rail Steels given the Normal and Shear Load[7]

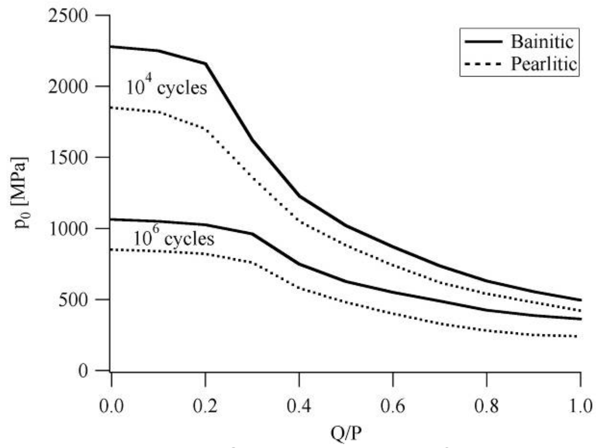

Figure 6. A Fatigue Crack Initiation Map for Pearlitic and Bainitic Rail Steels displaying the Loading Conditions that will Lead to Failure after 10,000 and 1,000,000 Cycles[7]

CRACK INITIATION MODELING

Plasticity Model

Jiang and Sehitoglu (J-S model) developed an isotropic and a kinematic hardening plasticity model that predicts the ratcheting behavior observed during proportional and nonproportional loading.[9] The J-S constitutive model begins through employing the Von Mises yield function. Due to the complexity of the state of stresses on rails, the J-S model was used for the current numerical simulations to better represent and estimate rail's dynamics.[7]

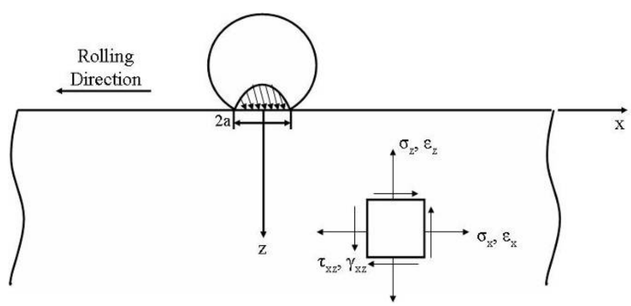

Figure 7. Coordinate System Implemented in Rolling Contact Simulations[7]

Semi-analytical stress analysis

The wheel-rail contact profiles are modeled as Hertzian contact. Shear loading is assumed to be proportional to the normal pressure at every point in the distribution (Figure 7), as dictated by the Q/P ratio. For this model, the stress in the body throughout the loading cycle was considered equal to the elastic stress field. Following the passage of the load, stress, and strain components are different than zero based on the elastic stress cycle. However, the geometrical constraints require these stresses and strains to be zero after the passage of the load.[9,10] Consequently, a proportional relaxation procedure is implemented to relax the appropriate residual stress and strain components to zero. This procedure has been found to return comparable stress-strain values to those obtained from a finite element model. After the residual stresses and strains are determined, the surface displacement or surface flow can be determined (Figure 8).

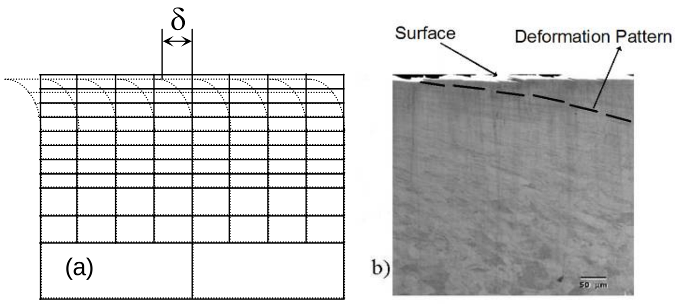

Figure 8. (a) Schematic Drawing Illustrating the Surface Displacement δ resulting from Ratcheting and (b) an Experimental Specimen displaying Surface Displacement after a Ratcheting Experiment[7]

Fatigue Model

The fatigue life of a rail under rolling contact loading was established using a multi-axial fatigue model. For the multi-axial model, many different parameters have been proposed regarding the determination of the critical plane. These parameters include: normal stress range, shear stress range, maximum normal stress, maximum shear stress, normal strain range, normal plastic strain range, shear strain range, and maximum normal strain.[11] However, rolling contact experiments show that none of these parameters leads to a correct determination of the plane of failure. Therefore, the J-S multi-axial fatigue parameter was implemented due to its versatility for certain nonproportional loading scenarios.[12,13]

Damage Model

Damage is accumulated in rail material with each passage of a wheel over the rail. The damage model implemented in the current study considers two types of damage, namely ratcheting and fatigue. Both forms of damage vary with the depth of the material, so the damage parameter is calculated at discrete depth planes in the material, and the plane with the maximum damage governs crack initiation.

For the current model, the values of accumulated ratcheting strain and the fracture strain of the material were obtained from pure torsion experiments. Also the amount of shear strain accumulated per cycle is normalized by the critical shear strain, and crack initiation occurring when the accumulated ratcheting strain equals the critical shear strain. If only ratcheting damage is considered, crack initiation will occur once the ratcheting damage parameter equals unity.[7]

The fatigue damage is assumed to accumulate linearly, and the damage per cycle is the reciprocal of the number of cycles to failure. When only fatigue damage is taken into account, crack initiation is defined when the fatigue damage parameter reaches unity.[7-11,14]

Conclusions

- The lower ratcheting of bainitic rails (J6) suggest that J6 rails will have a better RCF performance when compared to pearlitic rails.
- Surface damage on rails occurs due to fatigue under rolling contact conditions.
- Ratcheting damage occurs at the subsurface of the rail when the shear to normal force ratio (Q/P) is less than approximately 0.2. However, when Q/P is greater than approximately 0.3, the ratcheting damage occurs at the rail's surface.
- The major damage to rails occurs when $Q/P \geq 0.3$ because both ratcheting and fatigue affects the surface of the rail. This suggests that high adhesion locomotives are potential problems to rail life.
- Bainitic rails support higher rolling contact load than pearlitic rails when the shear forces are minimal, which means that when the J6 rail is tested under pure vertical stresses (i.e., laboratory conditions), it will perform better than pearlitic rail. However, the low ductility of J6 rail under a multi-directional stress environment, in particular the tangential forces, nullifies its increased strength. On the other hand, pearlitic rail, due to its higher ductility but mostly to its work hardening ability, is more suitable for railroad applications.[2,3]

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