Wear 271 (2011) 1174–1180

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Microscale experimental and modeling wear studies of rail steels

Ki Myung Lee [1], Andreas A. Polycarpou *

Department of Mechanical Science and Engineering, 1206 West Green St., University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

ARTICLE INFO

Article history:
Received 13 November 2010
Received in revised form 10 May 2011
Accepted 18 May 2011
Available online 26 May 2011

Keywords:
Rail steel
Microscale wear
Sliding contact
Finite element model

ABSTRACT

Rail steel with bainite microstructure was developed to further increase steel hardness for improved durability and wear. Even though bainitic steel has higher bulk hardness, it showed worse wear performance than pearlitic steel, which was attributed to the superior work hardening capabilities of conventional pearlitic steel under severe operating stress conditions. As the effects from the wheel/rail contact are confined to the topmost surface and sub-surface layers, convenient and well-instrumented wear experiments at the microscale were performed and compared with model results. Specifically, a finite element model was developed to simulate microscale wear, including repeated sliding contact to investigate tangential plastic strain. It was found that a simple scratch wear technique along with a computational model could investigate rail wear as well as used as a design tool in developing new rail steels.

1. Introduction

In the pursuit for more durable rail steels, there have been many strives to increase the hardness of steels, since hardness usually has a positive effect on the wear performance of rail. Conventional rail steels have been made of carbon–manganese pearlitic steels, however, the hardness limit that can be achieved with pearlitic steels has almost been reached [1–4]. Thus, it has become difficult to further advance rail steel wear performance with pearlitic microstructures. To this extent, research has been conducted towards designing rail steels with alternative finer microstructures, including the development of several types of bainitic steels. Despite the improved initial high bulk hardness of the developed bainitic steels, they could not compete with conventional, lower hardness pearlitic rail steels as far as their wear resistance is concerned [1–6]. Clayton and Jin found that it was possible to produce bainitic steel that exhibits wear behavior that competes with conventional rail steel [6,7]. Specifically one of the bainitic steels, coded J6, showed higher bulk hardness of 415 HB compared to premium pearlitic rail steels (340–390 HB) and was expected to show significantly better wear performance. Note that the carbon content decreased for J6 bainitic, while increased carbon usually results in higher hardness for pearlitic steels. However, in realistic field wear tests, the J6 bainitic steel showed worst wear performance than the conventional pearlitic steel, even though its resistance to rolling contact fatigue (RCF) was better than pearlitic steel [3,8]. It was shown that the main reason of the improved wear performance of pearlitic steel could be attributed to significant work hardening under severe stress conditions [5].

The majority of rail wear experiments are performed in the laboratory since full-scale field wear rail tests are costly and time consuming. To simulate the wheel/rail contact in the laboratory, a so-called twin-disk system is typically utilized, which consists of two rail steel disks rotating at different speeds (this enables different slip/roll ratios to be obtained) [9]. Such a system could create rolling and sliding contact between the two disks, similar to the contact between wheel and rail. Another type of wear experiments is referred to as pin-on-disk (or ball-on-disk) pure sliding wear experiments, which do not account for rolling that is seen in general wheel/rail contacts. Olofsson and Telliskivi [10] showed that pin-on-disk experiments can simulate the sliding contact at the rail gauge corner-wheel flange contact, while the twin-disk experiments can simulate the rolling/sliding contact at the rail head-wheel flange contact. Lee and Polycarpou [11] and Hernandez et al. [3,4] showed that controlled pin-on-disk pure sliding wear experiments could predict hardening of rail steels, and thus improved wear performance, which were in agreement with full-scale wheel/rail experiments [3,4]. Even though wheel/rail wear in the field is a more complex phenomenon than what could be captured by laboratory sliding ball-on-disk experiments, in a comprehensive comparative study between laboratory ball-on-disk and full-scale rail performance tests [4], it was confirmed that a simple accelerated ball-on-disk test method not only predicted wear performance but also rail crack tendency. A limitation of the ball-on-disk method, however is that it cannot fully assess the total life of rail steels, even though it can be used to pre-screen rail performance. The reason for the good agreement between laboratory

* Corresponding author. Tel.: +1 217 244 1970; fax: +1 217 244 6534.
E-mail address: polycarp@illinois.edu (A.A. Polycarpou).
[1] Currently with Seagate Technology, LLC, USA.

0043-1648/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.wear.2011.05.021

and full-scale tests is that the significant contributors to rail wear, such as plastic deformation and strain/work hardening behavior are captured by the laboratory tests. Moreover, as it was discussed in Ref. [4], several of the wheel/rail wear mechanisms observed in the field were also seen in the laboratory tests, further validating the accelerated sliding laboratory tests as a means to predict wear of rail steels.

In this work, pure sliding microscale (ball-on-disk) wear experiments were performed to investigate the wear behavior of J6 bainitic and conventional pearlitic rail steels. A computational finite element model (FEM) was also built to simulate wheel/rail microscale wear and compare with the experiments.

2. Rail steel microscale wear experiments

2.1. Experimental instrument and samples

Along with instrumented micro/nanoindentation, the micro/nanoscratch technique has been used to measure mechanical properties (such as modulus, hardness, and yield strength) of bulk as well as thin solid films, and also to study wear at small scales [12–15]. The scratch technique was applied to investigate the wear behavior of rail steels at the microscale using repeated scratches (at the same location). A scratch apparatus which consists of a capacitive force transducer and a 60° conical diamond stylus with an end tip radius of 1 μm were used. The force transducer is an attachment to a standard multimode atomic force microscope (AFM) and consists of a two-dimensional sensor to obtain in situ normal and lateral forces and displacements.

The rail samples used in this study were obtained from full-scale field wear tests performed at the Transportation Technology Center Inc. (TTCI), using standard pearlitic and J6 bainitic rail steels [5]. The field tests were conducted for a full-scale evaluation at a nominal 5° curve with heavy axle loads (approximately 39 tons for each pass) under unlubricated conditions. The rail heads (where the wheel/rail contact occurred) were taken from these field test tracks at various testing stages. Specifically, unused (virgin) samples and samples that undergone 500 million gross tonnage (MGT), denoted as high rails, were used. High rail samples are steels located on the outer rail in a curved track with a curvature of 5°, which were heavily deformed, indicating extreme contact conditions. The samples from the high rail heads were sectioned in such a way that the contact surfaces were not altered through any surface preparation technique. This was done to ensure that the topmost surface layers were not affected, and thus measure the wear behavior of these topmost surface layers. Virgin samples were cut 5 mm away from the surface to avoid the softer decarburized layer, which is formed during the manufacturing process of rail steels. Sectioning was carrying out using electrical discharge machining to reduce surface residual stresses, which may affect the properties of the topmost layers. The dimensions of the samples sectioned from the rail heads are 12 mm × 7 mm × 4 mm, which could be readily accommodated in the multimode AFM for the scratch experiments.

2.2. Multiple scratch wear experiments

An experimental protocol was established such that a scratch was repeated at the exact same location for a prescribed number of cycles. The sample surface was first scanned with a low normal load to measure the surface roughness, waviness, and slope of the location where scratch experiments will be performed. This pre-scanned surface profile is later subtracted from the scratch data to determine the true scratch profile. The stylus is then lifted away from the surface and returned back to its original position to initiate the first scratch with a prescribed constant normal load. Scratches are made on the sample repeatedly at the same location and in the same direction for a prescribed number of cycles. Practically, the maximum number of repeated scratches cannot be very large due to instrumentation issues. Once the scratches are finished, the residual depth is then measured by scanning the scratched sample with a low normal load. During the experiments, in situ normal and lateral forces and displacements are also recorded. In this work, the scratches made were 6 μm long and they were repeated 10 times, with each experiment taking more than 10 min to perform (it was found that 10 cycles is the optimal number of repetitions without significant transducer drift). For these tests, the normal load was set either to 2 mN or 3 mN, corresponding to initial Hertzian contact pressures (when no plastic deformation is assumed) of 23.8 GPa and 35.7 GPa, respectively. These calculated theoretical elastic values are higher than the actual contact pressure that occurs during nanoscratch, as confirmed with the FEM discussed in Section 3.1. Compared to the wheel/rail contact pressures of 1–3 GPa, the experimental microscale contact pressures as well as the FEM simulated contact pressures (which are around 10 GPa) are higher. As also discussed in Ref. [4], full-scale field rail performance data are typically very expensive and time consuming and different type of laboratory experiments have been performed to simulate field data. Specifically, twin disk machine tests that could simulate wheel/rail contact (as far as contact pressure and slip/roll effects are concerned) are unable to produce sufficient wear within a reasonable time, whereas mesoscale ball-on-disk sliding tests (using a ruby sapphire/rigid ball and at similar pressures as seen in practice) were able to produce accelerated rail wear (of the order of 1000 cycles) with good agreement with field tests [4]. The present work is similar to the mesoscale ball-on-disk tests, with the main difference being that the contact pressures involved are higher, thus causing further accelerated wear (of the order of 10 s of cycles). As it will be discussed below, the microscale data are in qualitative agreement with the mesocasle and field wear data, thus confirming their validity.

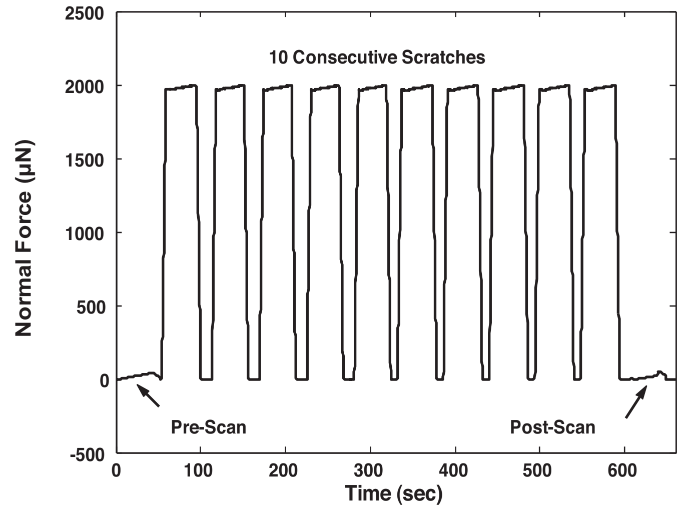

Fig. 1. Typical normal force measurements for a multiple scratch wear experiment.

Fig. 1 shows typical normal force measurements for a multiple scratch wear experiment, which consists of a pre-scan, 10 consecutive scratches and a post-scan (note that the normal force during scratching and during the pre- and post-scans increases slightly, possibly due to sample surface flatness imperfections.

The in situ normal displacement (wear depth) of each scratch was averaged and plotted versus the number of scratches and is depicted in Fig. 2. Fig. 2a shows the results of the virgin and high rail samples for both J6 bainitic and pearlitic rails at 2 mN load. Note