International Journal of Engineering Science 78 (2014) 218–232

Contents lists available at ScienceDirect

International Journal of Engineering Science

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

A phenomenological modelling with thermo-mechanical coupling for Tribological Surface Transformations (TSTs)

Grégory Antoni

Haute Ecole d'Ingénierie et de Gestion du Canton de Vaud, Institut COMATEC, Route de Cheseaux 1, 1401 Yverdon-les-Bains, Switzerland

ARTICLE INFO

Article history:
Received 8 March 2013
Received in revised form 7 January 2014
Accepted 3 February 2014
Available online 13 March 2014

Keywords:
Tribological Surface Transformations (TSTs)
Thermo-mechanical modelling
Transformation Induced Plasticity (TRIP)
Contact problem
Finite element analysis

ABSTRACT

Irreversible solid–solid phase transformations can be observed on samples of some metallic materials subjected to repeated compression loads. These phenomena, which are also known as "Tribological Surface Transformations" (TSTs), have been affecting some of French railroad network's rails for about twenty years. Although the exact mechanisms responsible for apparition of the TSTs are not well understood so far, they seem to develop when the mechanical loads are combined with thermal effects occurring in the wheel/rail contact areas. The two thermo-mechanical models developed in the present study are based on the assumption that the thermo-mechanical loads may generate solid–solid phase transformations during the rolling contact. 2-D finite element analysis is conducted in order to illustrate the ability of these models to describe TSTs initiation and development in the immediate vicinity where the mechanical loads are applied.

1. Introduction

Over the years, the increase in both the weight and velocity of freight trains have led to the emergence of new physical phenomena known as "Tribological Surface Transformations" (TSTs) (Eleöd, Oucherif, Devecz, & Berthier, 1999). The TSTs, which have been observed mainly on some straight parts of the French railroad network are irreversible solid–solid phase transformations occurring near the surface of the rails where the mechanical loads are applied (Österle, Rooch, Pyzalla, & Wang, 2001) (cf. Fig. 1). After being gradually initiated by the passage of a number of trains, TSTs develop down to a very low depth of only several nanometers to one hundred micrometers or so, and can eventually lead to the emergence of cracks because of the strong, strain incompatibilities existing between the TSTs and the initial rail material. TSTs may be partly caused by a contact fatigue process resulting from heavy corrugation of the rails (Sato, Matsumoto, & Knothe, 2002; Saulot, 2005) (cf. Fig. 2): the valleys of corrugated rails (the undamaged part of the rail) consist of pearlitic steel whereas the hills (the damaged part, where TSTs develop) consist of "quasi-martensitic" steel (cf. Fig. 3). TSTs are characterized by the formation of a "White Etching Layer" (WELs) (Baumann, Fecht, & Liebelt, 1996, 1997; Baumann, Zhong, & Fecht, 1997; Österle et al., 2001; Wild et al., 2003; Wang, Pyzalla, Stadlbauer, & Werner, 2003) around the contact area and in its immediate vicinity, as shown in Fig. 4.

Although rail corrugation is known to be one of the main contact fatigue processes occurring in railroads (Carroll & Beynon, 2007a, 2007b), the development of TSTs on the hills of corrugated rails still remains to be fully explained. Some previous authors have attributed the development of TSTs to the existence of very high temperatures known as "Flash Temperatures" in the wheel/rail contact area during a very short period of only a few seconds (Archard & Rowntree, 1988; Ahlström & Karlsson, 1999). Suzuki and Kenedy (1991) have measured flash temperatures of around 1000°C lasting for 2 microseconds

E-mail address: antoni.gregory@yahoo.fr

http://dx.doi.org/10.1016/j.ijengsci.2014.02.001
0020-7225/

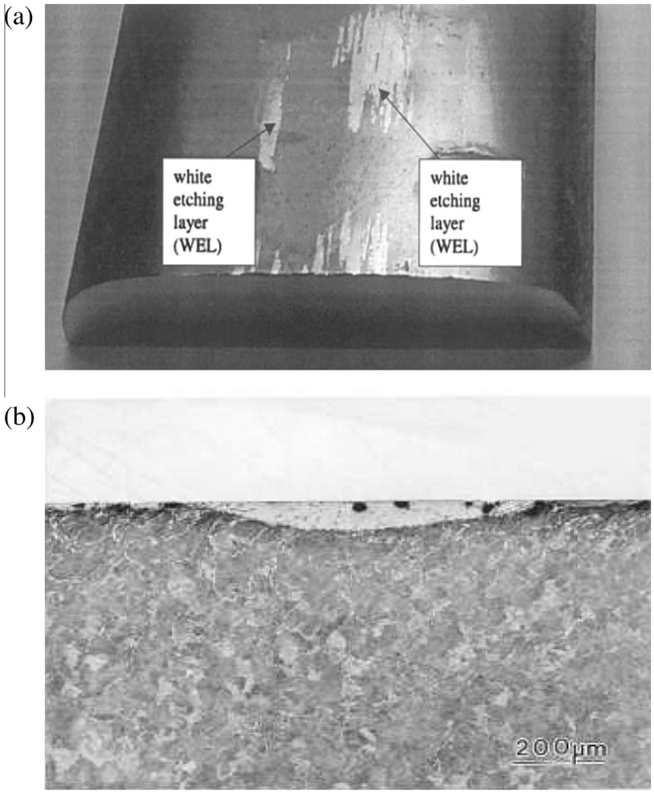

Fig. 1. (Extract from Österle et al., 2001) (a) Macroscopic view of the tread of a rail (which is made of S54/900A steel) showing TSTs (or a "White Etching Layer"); (b) Transverse cross-section of the upper part of a rail (a). The parent phase (the grey part of the picture) consists of pearlite and the daughter phase (the white part of the picture) occurring near the surface consists of "quasi-martensite".

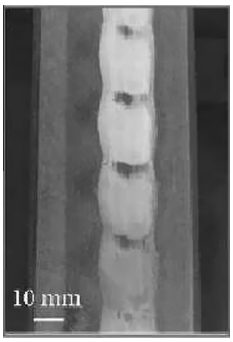

Fig. 2. (Extract from Saulot, 2005) Heavy corrugation of a rail.

in sphere/disk contacts. However, although the increasing temperature in the wheel/rail contact, mainly caused by the friction, the flash temperatures mentioned above have not been measured *in situ*. Van and Maitournam (1994) and Van, Maitournam, and Prasil (1996) have presented numerical results on the temperature field in the rail, based on various hypotheses about the stress field in the wheel/rail contact area in the case of a steadily moving train. These authors established that the increase in the temperature occurring on the contact surface under some loading and friction conditions does not exceed 150°C. On the other hand, Knothe and Liebelt (1995) and Ertz and Knothe (2002) presented a general analytical approach to predict the maximum increase in the temperature in the wheel/rail contact area involving the use of a convolution-type integral. These calculations also showed that the temperature increase in the contact area cannot reach the phase transformation temperature of the rail material. In line with this finding, Baumann et al. (1996) suggested that the normal and shear stresses superimposed on a temperature increase may generate solid–solid phase transformations. The main assumption adopted in the present study was that both the mechanical loads (which are mainly applied to the hills when-