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Characterisation of head-hardened rail steel in terms of cyclic plasticity response and microstructure for improved material modelling

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ABSTRACT

Stress- and strain-controlled tests of heat treated high-strength rail steel (Australian Standard AS1085.1) have been performed in order to improve the characterisation of the said material's ratcheting and fatigue wear behaviour. The hardness of the rail head material has also been studied and it has been found that hardness reduces considerably below four-millimetres from the rail top surface. Historically, researchers have used test coupons with circular cross-sections to conduct cyclic load tests. Such test coupons, typically five-millimetres in gauge diameter and ten-millimetres in grip diameter, are usually taken from the rail head sample. When there is considerable variation of material properties over the cross-section it becomes likely that localised properties of the rail material will be missed. In another case from the literature, disks 47 mm in diameter for a twin-disk rolling contact test machine were obtained directly from the rail sample and used to validate ratcheting and rolling contact fatigue wear models. The question arises: How accurate are such tests, especially when large material property gradients exist? In this research paper, the effects of rail sampling location on the ratcheting behaviour of AS1085.1 rail steel were investigated using rectangular-shaped specimens obtained at four different depths to observe their respective cyclic plasticity behaviour. The microstructural features of the test coupons were also analysed, especially the pearlite inter-lamellar spacing which showed strong correlation with both hardness and cyclic plasticity behaviour of the material. This work ultimately provides new data and testing methodology to aid the selection of valid parameters for material constitutive models to better understand rail surface ratcheting and wear.

1. Introduction

Railway systems play a crucial role in many countries in terms of social and economic development, especially countries like Australia, Canada, North America, South Africa and China which have mining-driven economies. In Australia, heavy-haul, intermodal and freight rail expertise is broad and diverse, operating the largest heavy-haul trains in the world (Fortescue Metals Group Ltd.) with axle loads of 40- tonnes and a trailing load of 35.2 kt with 24 h a day operation [1]. In comparison, the United States of America, Canada and China have trailing loads of 22, 20.7 and 20 kt respectively, with axle loads under 30 tonnes. BHP Billiton in the Pilbara region of Western Australia runs iron-ore trains at 40 -tonnes axle load on 68 kg/m rails, with maximum speeds of 75 km/h. In order to maintain such high levels of performance, the quality of rail materials is very important for reducing wear and other forms of rail degradation.

In Australia, heat treated high-strength hypereutectoid rail steel is used according to Australian Standards specification AS1085.1, exhibiting hardness in the range 360–420 HV at the railhead. Standard rail steels have been supplied by different manufacturers potentially using different manufacturing processes and heat treatments to acquire the desired rail material properties. Material specifications aim to provide a benchmark for performance but it appears that field performance of the materials has not been studied comprehensively.

Rails are subjected to repetitive loads and the damage mechanism is governed by plastic deformation of the rail surface. This phenomenon is also known as cyclic plasticity. Rails are subjected to a variety of stress and strain conditions which can vary depending on location and severity of operation. Under stress-controlled cyclic behaviour, accumulation of plastic deformation called ratcheting takes place. The accumulated plastic strain is called the ratcheting strain.

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Robust material modelling helps to make better predictions about the onset of rolling-contact fatigue and wear at the rail–wheel interface. The parameters used in material modelling may be obtained through stress- and strain-controlled cyclic load testing. Numerous researchers have carried out investigations on fatigue life and hardening/softening effects of materials under varying conditions of mean stress, amplitude and pre-load conditions.

In 2013, Pun et al. [2] performed an experimental study on the cyclic deformation characteristics and ratcheting behaviour of hypereutectoid high-strength rail steel used in Australian heavy-haul rail applications. They conducted tests on a 68 kg/m rail sample (50 and 60 kg/m rails are also commonly used in the industry [3]). Although Pun et al.'s study was limited to a low number of cycles (100-cycles typically), it was discovered that kinematic hardening is the dominant ratcheting behaviour of the material. The rail steel used in their research was premium rail steel which has relatively uniform material properties throughout the rail head.

Some researchers [4–8] have used material models to predict rail wear and the formation of other defects in the rail–wheel interface. The small twin-disk machines (SUROS and LEROS) used rail disks which were obtained from rail and wheel samples [7–10]. The results generated from the twin-disk machine tests using these wheels were subsequently used to validate the relevant wear models.

From the present authors' work, hardness varies substantially across the cross-section of a heat-treated head-hardened rail, as shown in Fig. 1. According to the distribution profile, hardness reduces considerably as depth increases. Thus, it is apparent that errors would arise in the prediction of wear and ratcheting behaviour using test-wheels obtained from rails with significantly varying material properties.

Problems may also arise with cyclic load tests used for material modelling where significant hardness gradients exist across the test coupons. This problem is less pronounced for quasi-homogeneous materials, where it should be sufficient to scale plastic properties in proportion to hardness [2]. Therefore, it is acceptable to use cylindrical test coupon to determine cyclic plasticity for the rail materials with small gradients in hardness and microstructure [11–13]. Surface hardened rail materials exhibit higher gradients of hardness and microstructure and therefore it becomes necessary to use a more elaborate methodology for determining material behaviour, as explained in this paper. For example, a typical circular test coupon 10 mm in grip diameter narrowing to a gauge diameter of 5 mm is reasonable if the rail head has uniform hardness; but with the surface hardened rails, there is a good chance of missing the actual material properties at the rail surface, thus leading to inaccurate material model data being obtained.

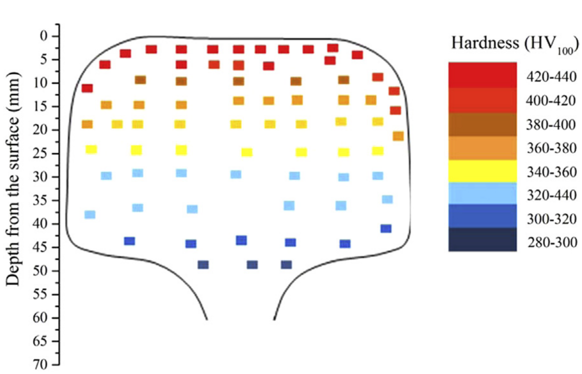

Fig. 1. Vickers hardness (HV100) data combined with the profile of the rail head.

Heat treated head-hardened rail steel exhibits a non-uniform distribution of material properties due to variations in manufacturing and heat treatment processes. Any non-uniformity could give rise to excessive sub-surface plastic strain accumulation from unintended material softness that could lead to damage and failure of the rail head. Moreover, the material layers removed by wear and preventive maintenance grinding potentially expose the softer regions of the rail head to the surface. Consequently, rail service life will be reduced substantially, especially at small-radius curves.

Such behaviour may also be exhibited in premium rails which have undergone additional thermal modification, such as where connections are made using, for example, the flashbutt welding technique. Mutton et al. [14] observed that softening of the rail in the heat affected zone (HAZ) can lead to increased gauge corner cracking and severe plastic deformation. Their research also studies the hardness deviation and microstructural changes in the HAZ area of the weld joint.

In this paper, the limitations and effects of the sampling depth on the ratcheting and fatigue response of head hardened rail steel are investigated. Moreover, microstructural characterisation of the rail head is conducted to investigate the relationship between mechanical and metallurgical properties of the material.

2. Experimental approach

2.1. Material

The material tested was cut from new 60 kg/m, grade AS1085.1 rail, with elemental composition given in Table 1. The material microstructure was studied at different depths in both transverse and longitudinal directions. To aid visualisation of the microstructure the polished surfaces were etched with 5% Nital. In summary, the transverse section shows that the microstructure changes from fine pearlite to a coarse pearlite with increasing depth. Grain distortion and inclusions (MnS) can be observed in the longitudinal section due to the rolling process. The laminar spacings of pearlite microstructures were recorded using Zeiss SEM images at different rail head depths as shown in Fig. 2.

2.2. Sample location

As the material properties vary down the cross-section of the rail head, it is important to select the sampling location with care. Sampling positions were chosen according to the hardness profile and practical limitations related to cutting the samples from the rail head. As shown in Fig. 2, the top sample is very close to the rail-head surface while the fourth sample is 33 mm below the rail surface. According to the hardness profile (Fig. 1), the 1–5 mm layer exhibits high Vickers hardness (410–430 HV), which then drops significantly as the depth increases.

Rectangular-shaped test coupons (according to ASTM E466 specification) were obtained from each sampling location. The dimensions of the test coupons are shown in Fig. 3. A major problem with the rectangular shape is that the test coupon can buckle

Table 1
Chemical composition.

Element	Composition (%)
C	0.7–0.82
Mn	0.7–1.1
P	0.04
S	0.04
Si	0.1–0.35

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