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# A unified material model to predict ratcheting response in head-hardened rail steel due to non-uniform hardness distributions

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ABSTRACT

The non-uniform hardness distribution, metallurgy and ratchetting behaviour of head-hardened Australian rail steel (AS60 HH) are studied. In a bid to extrapolate material properties across the rail head continuum, a unified material model of the rail head has been developed, in which only the hardness of the material is variable. This simplification is shown to enable the material model to reasonably describe ratchetting behaviour across the rail head for heat-treated pearlitic steels. Finally, homogeneous material ratchetting models are used to study the evolution of plastic strain deformation under realistic rail-wheel contact conditions. The results show that non-uniform material properties may compromise ratcheting response with wear progression, thus impacting lifetime of AS60 HH rail steel and re-railing frequency.

## 1. Introduction

During service, rail steel is prone to the formation of a work-hardened surface layer with rail traffic; if the shakedown limit is exceeded, then severe rolling contact fatigue damage can result. Preventive/corrective grinding is performed regularly to remove the damaged layers before cracks can grow to exceed the critical size. The grinding passes not only remove the weakened and cracked metal layers but also restore desired rolling contact geometry. It is therefore useful to understand the role of material properties on the development of the plastically deformed layer, its effect on wear and the formation and growth of cracks that could lead to serious railway failures, including derailment, if not corrected in a timely manner.

In recent research, tests have been conducted to observe the ratcheting behaviour of head-hardened Australian Standards rail steel (AS60 [kg/m] HH) [1]. Four test coupons were obtained at different sampling depths from the rail head surface and each of these was subjected to cyclical stress- and strain-controlled tests. For otherwise identical test conditions, different ratcheting responses were observed for the different test coupons, corresponding to the non-uniform hardness each exhibited. The purpose of these experiments was to understand variations of material cyclic elastoplastic behaviour in relation to hardness and microstructure, and to correlate this information with rolling-contact fatigue (RCF) wear behaviour. A key motivation for this work originates from the observation that very few researchers have paid attention to the issues of material property gradients, with most expediently considering the rail material to be homogeneous throughout the rail head.

The present research also focuses on calibrating the Chaboche et al. [2] plasticity model parameters to explore non-uniform hardness and ratchetting behaviour of AS60 HH rail steel. Non-uniform material properties arise due to limitations of both the material and the manufacturing process, primarily due to economic considerations. As rail tracks, will be in service for many years, wear resistance and material properties should be guaranteed up to a certain depth from the virgin rail surface to ensure adequate service reliability and safety.

Rail network operators have introduced wear limits for each rail grade within which a minimum material quality is expected to be retained. For example, the AS60 HH rail standard specifies the following risk control measures: rail head height loss of 20 mm requires special monitoring, while maximum allowable height loss of 22 mm results in the rail being condemned and removed from service (CoP-ARTC-2013 [3]). Therefore, it is important to understand the mechanical behaviour of the rail head corresponding to these depths, as any non-uniform distribution of material properties may compromise rolling contact fatigue resistance, resulting in progressively accelerating wear, and potentially putting safety and reliability of the rail network at risk.

The non-uniform material behaviour of AS60 HH rail material has already been detailed in a previous research article [1]. It is challenging

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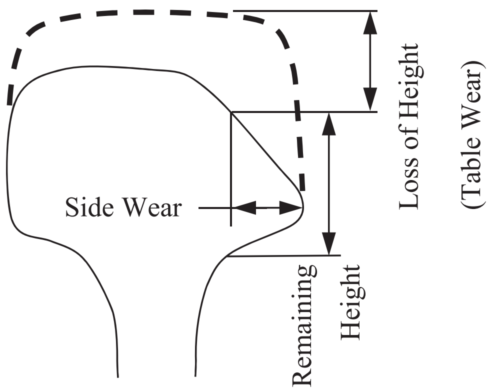


**Fig. 1.** Wear limits of the rail material. Adapted from CoP-2013, ARTC [3].

to develop a comprehensive model that accurately reflects material behaviour so that useful numerical simulations can be devised. Addressing this challenge is the primary concern of the work presented in this paper. The objectives of this work can be summarised in three parts:

1. Characterisation and modelling of material properties in terms of microstructure, hardness and ratchetting or cyclic elastoplastic response;
2. Development of a unified cyclic plasticity material model, based on the Chaboche et al. model and an isotropic hardening model [4] defined in terms of hardness and demonstration of its plausibility;
3. Highlighting the importance of material property gradients in governing the fatigue wear life of head hardened rails.

## 2. Problem background

Rail head wear is often quantified using percent head loss or height loss; as defined, for example, by the ARTC code of practice [3]. Bi-directional measurements are recorded in the field using callipers, which measure height loss (table) and gauge face (side) wear, as shown in Fig. 1. When the specified head loss limits of rail material are reached, new material is required to address potential safety risks. Head-hardened rail materials exhibit hardness distribution gradients, which may contribute to accelerating wear and fatigue rate with rail-head material loss. Therefore, investigation of the ratcheting response of the different layers under cyclic loading is important in understanding the diverse wear responses exhibited by rails with non-uniform head hardness distributions.

Researchers [5,6] have investigated the surface ratcheting behaviour of Australian premium rail steels (HE1, HE2 LAHT) using uniaxial and biaxial loading tests, where uniform hardness distributions typically exist. These studies highlight that the best ratcheting performance is obtained with hypoeutectoid rail steel (HE1) with low carbon percentage. Monotonic tensile load testing using test coupons obtained from different positions [7] was conducted on AS60 HH rail, highlighting substantial yield strength degradation of the rail material with depth from the surface. More significantly, data on the cyclic response of head-hardened rail steel at different depth levels have only become available recently in the open literature [1].

The effect of material hardness is well known to be an important property in determining rail materials' resistance to rolling contact fatigue. For example, the ratcheting behaviour of flash butt welded joints in premium rail steel has been studied where increased susceptibility to RCF cracks has been observed [8]. The rail material near these joints is subjected to severe thermal gradients during the welding process. The resulting heat-affected zone gives rise to non-uniform hardness distributions in proximity of the welded joint. The weld zone's response to ratchetting has yet to be quantified in detail and, therefore, the opportunity exists to observe the material's fatigue behaviour using the experimental techniques presented in this work. The ratcheting response of the heat-affected zone of AS60 HH rail steel was quantified using a set of uniaxial cyclic stress and strain controlled test data [1,9]. This data has been used in the present paper to develop a material model that permits more extensive evaluation of the ratcheting damage mechanism under conditions of non-uniform hardness distribution. The original experimental data showed a softening ratcheting behaviour with increasing depth from the surface that was consistent with the reduced hardness of the material as shown in Fig. 2.

A further development involved simulating the ratcheting behaviour of the hardened layers under more realistic rolling-contact load conditions using the finite element (FE) method. This was practically implemented using the Abaqus® finite element suite after the material constitutive models were obtained from the experimental cyclic data, as detailed in a subsequent part of this paper. A combined kinematic/isotropic hardening model was used to describe the cyclic elastoplastic

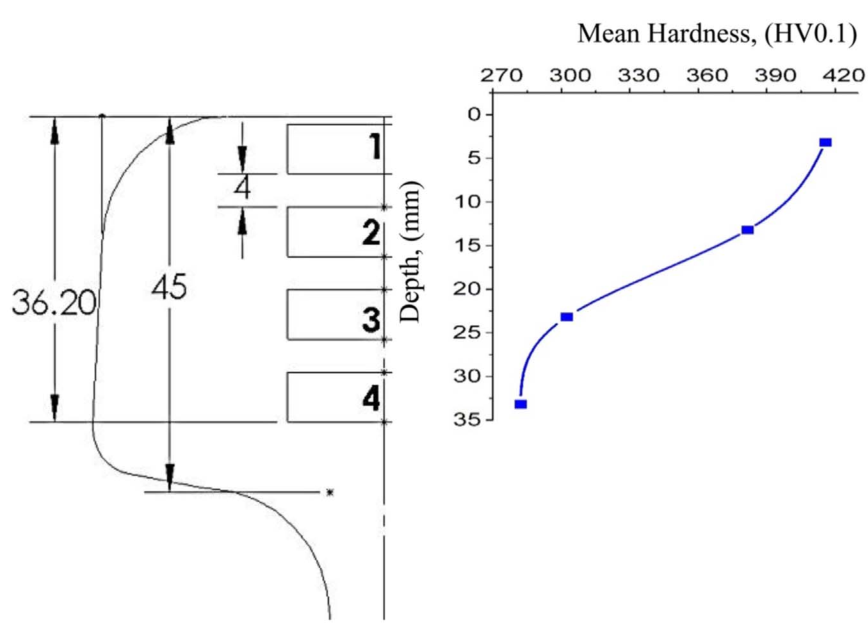


**Fig. 2.** Rectangular coupon sampling positions within the AS60 HH rail head and mean hardness distribution.

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