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Prediction of residual stresses in low carbon bainitic–martensitic railway wheels using heat transfer coefficients derived from quenching experiments

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Low carbon bainitic–martensitic (LCBM) steels have been recently developed for railway wheels and have been shown to provide superior properties compared to conventional pearlitic railway wheel steel grades. Pearlitic railway wheels are generally quenched at the tread region to promote the formation of compressive residual stresses in the rim to mitigate the initiation and propagation of cracks due to fatigue. However, this conventional quenching method has been shown to be unsuitable for LCBM railway wheels. Alternative quenching methods were evaluated using a FE model to develop a successful quenching process to produce LCBM railway wheels. Heat transfer coefficients were determined by employing a full scale experimental rig and were used in the FE model to model various coolant spray intensities and configurations. The FE model was used to determine optimal quenching conditions that impart compressive residual stresses to the rim of the LCBM railway wheel and the prediction of residual stresses were verified experimentally.

1. Introduction

In the past decade, the mining industry and heavy-haul freight service in Australia have been growing due to the increasing worldwide demand for natural resources such as iron ore and coal. It is estimated 352,000 railway wheels are in service across the Australian rail network, with an estimated annual maintenance cost of \$60–\$190 M [1]. This figure is expected to increase as more tracks and railway vehicles are added to the rail network to meet the growing demands. Hence, rail operators, driven by profitability, have been working to reduce maintenance costs while increasing performance, reliability and safety of railway wheels.

Most railway wheels are made using the specified Association of American Railroads (AAR) Class steel compositions which have a pearlitic–ferritic microstructure [2]. Over the years, their performances have been enhanced mainly by cleaner steel production and by micro alloying of elements to increase the strength of pearlitic wheel steels [2]. However, researchers agree that there is limited scope for further strength improvements in this class of steels [2–6]. Merely increasing the carbon content to increase strength and hardness would inevitably contribute to lower toughness and higher sensitivity to brittle fracture and increased risk of spalling failure [2].

Lonsdale and Stone [2] conducted a review of other steel compositions with the potential to improve the life of railway wheels including martensitic steels and Constable et al. [4] studied the suitability of low carbon bainitic martensitic (LCBM) steels for railway wheels. Low carbon bainitic martensitic steels (0.20%C, 4.0%Mn, 0.75%Si, 0.004%Mo, 0.003%V, and 0.005%Nb) were found to have superior strength, hardness and toughness compared to AAR Class A to C wheel steels [4]. LCBM steels achieved strength levels up to 1130 MPa in standard mechanical tests which is a 40% improvement over the conventional micro-alloyed AAR Class C grade steel [4]. LCBM steels have also shown enhanced resistance to rolling contact fatigue (RCF) and thermal fatigue, which are expected to reduce the need for wheel re-profiling and lead to substantial savings in maintenance costs. Additionally, LCBM steels employ low cost alloying elements and are not expected to result in additional production costs compared to what is currently used for AAR Class railway wheels.

Constable et al. [4] have reported an improvement of 69% in fracture stress for LCBM steels (290 MPa) compared to micro-alloyed AAR Class C steel (160 MPa) at a crack length of 30 mm [4]. Hence, LCBM steels are likely to provide greater safety due to improved fracture toughness compared to AAR Class C grade steels. Furthermore, fatigue studies by Peng et al. [7] have estimated a 30% increase in the service of railway wheels made from LCBM steels compared to AAR Class B railway wheels. Rail manufacturers in Europe have also investigated the use of bainitic type microstructure steels to improve wear of rails [2].

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Although, bainitic as well as martensitic type steels can offer higher strength and hardness levels when compared to pearlitic steels at similar carbon content, their use as railway wheels is limited because tensile stresses are formed in the rim of the wheel under the conventional quenching process [2]. Most standards for railway wheels such as AAR M-107/M-208 [8], BS 5892-3 [9] and EN 13262 [10], require that railway wheels are manufactured with compressive rim circumferential residual stresses to retard the initiation and propagation of cracks due to fatigue and since the introduction of these practices, the number of wheel-related derailments in North America has fallen by an order of magnitude [11].

Current AAR railway wheels are typically rim-quenched (quenched at the tread's surface) to promote the formation of compressive residual stresses in rim of the wheel. Upon quenching, austenite transforms to pearlite and thermal contraction which imparts compressive stresses in the tread region of the rim. Typical as-manufactured compressive residual stresses in AAR wheels are reported to be approximately 250 MPa at the tread's surface [12].

However, during rim-quenching of martensitic type railway wheels, the transformation from austenite to martensite in the rim is accompanied by a volume expansion of approximately 4%. In comparison, there is only a 1% volumetric expansion during phase transformation of austenite to pearlite in conventional pearlitic railway wheels (as shown in the dilatometry cooling curves in Fig. 1 [13]. Hence, there is a net volumetric expansion after austenite has transformed to martensite in the rim of the wheel and upon cooling to room temperature, this large volumetric expansion results in compressive stresses in the inner rim region and tensile stresses near the tread's surface.

Instead of applying conventional rim-quenching, Lingamanaik and Chen [13] have shown that the quenching process can be modified to achieve compressive residual stresses in the rim of the LCBM wheel. Their studies were based on FE modelling of the quenching process based on estimated Heat Transfer Coefficients (HTC) from the literature [14]. However, HTC values are known to be highly variable depending on the actual quenching conditions since factors such as geometry of the part, characteristics of the coolant sprays, the temperature of the quenched surface and even the surface finish or roughness can influence the heat transfer in a part and its final stress distribution [15–20]. In the present study, a full-scale experimental quenching rig was constructed and instrumented with thermocouples in selected regions of the railway wheel to determine actual values of HTC during quenching of LCBM railway wheels for different spray intensities and spray configuration. These experimentally determined HTC were used in a thermo-mechanical finite element model to develop a set of viable quenching conditions for LCBM railway wheels to achieve compressive stresses in the rim of the railway wheels.

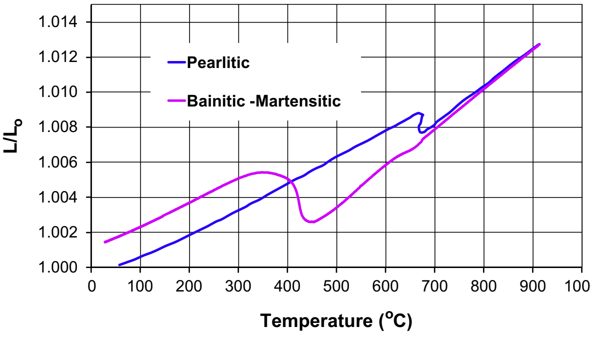

Fig. 1. Dilatometric cooling curves showing phase transformation characteristics of pearlitic and bainitic–martensitic steels [13].

2. Methodology

2.1. ABAQUS/DANTE thermo-mechanical finite element model

A Finite Element (FE) software ABAQUS 6.7.1 and a heat treatment package DANTE 3.3 were used to model the quenching process of railway wheels and to predict the formation and distribution of residual stresses in railway wheels [13]. In DANTE 3.3, user-defined material subroutines are used to predict and track the volume fractions of metallurgical phases as austensite transformed to pearlite, ferrite, bainite and martensite as the part is cooled. Subsequently, thermal loadings and temperature dependent material properties incorporated in DANTE are used to predict final residual stresses [21–23].

For steels undergoing martensite phase transformation, the transformation kinetics is written in the form of a rate equation as shown in Eq. (1) with a strong dependency on the cooling rate [22]:

$$\frac{d\Phi}{dt} = \upsilon_M(C)\Phi^{\alpha(C)}(1-\Phi)^{\beta(C)}U(M_S-\theta)\frac{d\theta}{dt} \qquad (1)$$

$U(M_S-\theta)$, is the unit step function i.e.

$U(M_S-\theta) = 1, \quad \theta \geqslant M_S$

$U(M_S\theta) = 0, \quad > M_S$

and $\upsilon_M, \ \alpha, \ \beta$ are material carbon dependent quantities determined from TTT quench data [22].

By integrating the phase transformation strain rate over a time step Δt, the phase transformation can be computed for each phase. The dilatational transformation strain increment is given in the following equation:

$$E_p^x = \frac{(E_p - E_A)}{1 + E_A} \qquad (2)$$

The transformation strain for austenite and product phases are taken to be linear and cubic functions. For martensite, $E_p = E_M$:

$$E_M = M_0 + M_1\theta + M_2\theta^2 + M_3\theta^3 \qquad (3)$$

The Eq. (3) is temperature dependent and its coefficients are carbon-dependent.

In DANTE's mechanics module, a hypoelastic response for each phase is assumed and the effective stress to cause plastic flow in each phase is given in Eq. (4). The inelastic deformation rate in Eq. (5) is expressed in terms of deviatoric stresses:

$$|\xi^i| = |\sigma'^{(i)} - \alpha^i| - k^{(i)} \qquad (4)$$

$$D_p^{(i)} = f^{(i)}(\theta)\sinh\left(\frac{|\xi^{(i)}| - Y^{(i)}(\theta)}{V^{(i)}(\theta)}\right)\frac{\sigma'^{(i)} - \alpha^{(i)}}{|\sigma'^{(i)} - \alpha^{(i)}|} \qquad (5)$$

where $f^{(i)}(\theta)$ and $V^{(i)}(\theta)$ describe the rate dependence of the yield stress at constant temperature while the function $Y^{(i)}(\theta)$ is the rate-independent yield stress. Mechanical properties for the material for the various metallurgical phases such as modulus of elasticity and yield strength are obtained from tension and compression tests as functions of metallurgical phase, temperature, carbon content, strain level and strain rate and are implemented in DANTE's user-defined subroutines [22].

Phase transformation kinetics parameters can be obtained by several sources which includes CCT diagrams, TTT diagrams, Jominy Hardness test and dilatometry data. While TTT diagrams are mainly used for diffusive transformations such as pearlite, CCT diagrams offer data for both diffusive and martensitic transformation as reported by Li et al. [23]. Jominy tests alone are not adequate for determining kinetic phase transformations since strain–time data