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Effect of temperature on deformation and fracture behaviour of high strength rail steel

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ABSTRACT

Fracture toughness (K_{Ic}), Vickers hardness, and constitutive equation under tensile loading for high strength rail steel were determined at −40, −10 and 23 °C. K_{Ic} and hardness were directly determined from experimental testing, while the constitutive equation also relying on finite element (FE) modelling because of the non-uniform deformation during the necking process. The constitutive equation was verified by enabling the FE model of tensile specimen to regenerate the experimentally measured load–elongation curve and cross-section reduction, and applied to the FE model of Vickers indentation to mimic the load–depth relationship. This paper also discusses relevance of the results with those reported in literature.

1. Introduction

The frequency of brittle fracture in continuously welded rails (CWR) elevates with the increase of heavy axle load (HAL) and high speed operations. The brittle fracture causes train derail, thus a severe safety concern. For this reason, lots of efforts have been made in the last 40 years to improve the rail steel, through approaches such as refining metallurgy and thermo-mechanical processes [1]. Although the improvement has been significant, brittle fracture is still the major problem for the rail track due to the inherent poor toughness of the pearlite microstructure [2]. The problem is worsened in the cold regions due to a combined effect of HAL and contraction and fracture toughness reduction of rail at low temperature [3]. This has driven renewed interests in characterizing mechanical properties for the newly developed high strength rail steels. In the previous studies, Szablewski et al. [4] evaluated mechanical properties for 10 premium and 8 intermediate hardness rail steels in both head and foot regions at room temperature, to investigate the potential variation in mechanical properties over the cross section. Wang et al. [5] measured fracture toughness for rail steels at low temperature, but only in the head region. Bandula-Heva and Dhanasekar [6] focused on establishing a true stress–strain relationship for the head region of the rail steels at room temperature, but did not consider the possibility of neck formation before the fracture. In fact, to our knowledge, a comprehensive study on all of the above material properties over the entire cross section of high strength rail steel is scarce in the literature. In view of the extremely harsh winter condition in Canada, with the temperature dropping possibly down to −40 °C, it is desirable to evaluate all of those mechanical properties for the newly developed high strength rail steels at the rail head, web, and foot at low temperature.

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Nomenclature

a	user-defined coefficient for constitutive equation
b	user-defined coefficient for constitutive equation
B	thickness of SENB specimen
c	user-defined coefficient for constitutive equation
d	user-defined coefficient for constitutive equation
e	user-defined coefficient for constitutive equation
E	Young's modulus
F	indentation load
k	user-defined coefficient for constitutive equation
l	diagonal length of indent
n	user-defined coefficient for constitutive equation
S	span length of SENB specimen
V	crack mouth opening distance
W	width of SENB specimen
α	user-defined coefficient for constitutive equation
β	user-defined coefficient for constitutive equation
γ	user-defined coefficient for constitutive equation
ν	Poisson's ratio
σ	equivalent stress
ε	equivalent strain
φ	area reduction at minimum cross section
a_0	average initial pre-crack length
A_0	original cross sectional area
A_f	minimum cross section area at fracture
F_f	force at fracture
K_{Ic}	plane-strain fracture toughness
K_Q	conditional stress intensity factor
P_Q	provisional force
σ_f	fracture stress
σ_u	ultimate tensile stress
σ_y	yield stress
ε_e	recovered elastic strain
ε_f	fracture strain
ε_l	equivalent linear elastic strain
ε_n	equivalent strain at necking
ε_p	plastic strain after fracture
ε_y	equivalent strain at yielding
HV	Vickers hardness
gf	gram-force
UTS	ultimate tensile stress

Due to the complex procedures involved in the rail steels production [7], material properties may vary over the rail cross section [4]. In this study, true stress–strain relationship, fracture toughness (K_{Ic}), and Vickers hardness on rail head and foot are investigated at 23, −10, and −40 °C. K_{Ic} is also determined in the web region. In view that the new generation of high strength rail steel may involve necking before the onset of tensile fracture, the conventional test-based approach to determine the true stress–strain curve is no longer valid, especially in the strain range after the peak load [8]. Bridgman [9] proposed a revised formula to convert the results from the mechanical testing to the material true stress–strain curve, while others through the combination of mechanical testing and FE analysis [10–13]. In the present work, the latter approach is used to establish the entire true stress–strain curve for tensile loading of a high-strength rail steel (CZECH TZ IH) under large plastic deformation including necking. The true stress–strain curve is then applied to an FE model of Vickers indentation test to mimic the experimentally determined load–depth curve. The paper also discusses the relevance of the results with those reported in the literature.

2. Mechanical testing and simulation

All the mechanical testing was conducted on specimens sampled from the high strength rail steel CZECH TZ IH with intermediate hardness, supplied by the Canadian National Railway Company (CN). An Instron hydraulic universal testing machine, equipped with an Instron environmental chamber, was used for the uniaxial tensile and three-point bending tests