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Statistical scatter in the fracture toughness and Charpy impact energy of pearlitic steel

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Abstract

The effect of microstructure on the fracture characteristics of high carbon hypo eutectoid steel was studied under conditions of quasistatic and dynamic loading. Experimentally determined sets of fracture toughness and Charpy impact energy values were statistically treated. A relationship was found between fracture toughness and Charpy impact energy. In the very brittle domain, the fracture toughness increases slightly with increasing Charpy impact energy. In the domain where the fracture toughness is higher, the rise in fracture toughness with increasing Charpy impact energy is more pronounced. Detailed SEM examination of fractured compact tension (CT) and Charpy V-notch (CVN) specimens showed that the fracture at ambient temperature occurred almost exclusively by cleavage. There were no visible differences in the morphology of cleavage facets on the fracture surfaces of Charpy and CT specimens. Mechanisms of cleavage initiation were revealed by the fractographical investigation of fracture surfaces. Whereas the fracture surfaces of broken CT specimens exhibit a number of cleavage origins, the fracture surfaces of CVN specimens usually show only one.

Keywords: Hypo eutectoid steel; Fracture toughness; Charpy impact energy; Ductile tearing; Cleavage; Miller–Smith mechanism; Griffith type defect

1. Introduction

Hypo eutectoid steels with predominantly pearlitic structure and small quantities of ferrite, though exhibiting reasonable strength and wear resistance, can suffer from poor ductility and toughness. Their use in producing railway wheels requires them to display a low risk of fracture initiation under both quasistatic and dynamic loading conditions. Although the mechanical properties of pearlite have been studied for many years, extensive discussion continues regarding the microstructural parameters controlling its yield and fracture. Since pearlite tends to promote brittle fracture, the physical–metallurgical parameters and geometrical characteristics of its microstructure and heat treatment play an important role in production design. The microstructural parameters, which have been identified as affecting the deformation process in pearlite, include the pearlite interlamellar spacing, the pearlite colony size, the cementite thickness and the prior austenite size. Previous research has shown that refinement of the pearlite interlamellar spacing increases the yield strength [1–3]. Increasing the prior austenite grain size reduces the ductility of pearlitic steels [1,4]. Since pearlite colony boundaries change the direction of the fracture path, a higher number of these mismatches increase the toughness of the steels [4,5]. The finer cementite of the pearlite structure of high carbon hypo eutectoid steels behaves in a more ductile manner, as it may rupture by necking rather than failing in a brittle manner [6,7].

Although the microstructural parameters controlling yield and fracture have already been determined, little work has yet been conducted on identifying differences between the microstructural features controlling toughness under dynamic and quasistatic loading conditions. Toughness as measured by dynamic Charpy impact testing, and fracture toughness obtained from the quasistatic loading of CT specimens, exhibit surprising scatter. This statistical scatter of toughness under different conditions of loading can be of assistance in identifying micromechanisms of fracture initiation and fracture surface creation. A newly developed probabilistic model for the pearlite-induced cleavage in steels [8] explained the effects of material parameters, temperature and sample thickness on the scatter of fracture toughness. However, the effect of dynamic loading of

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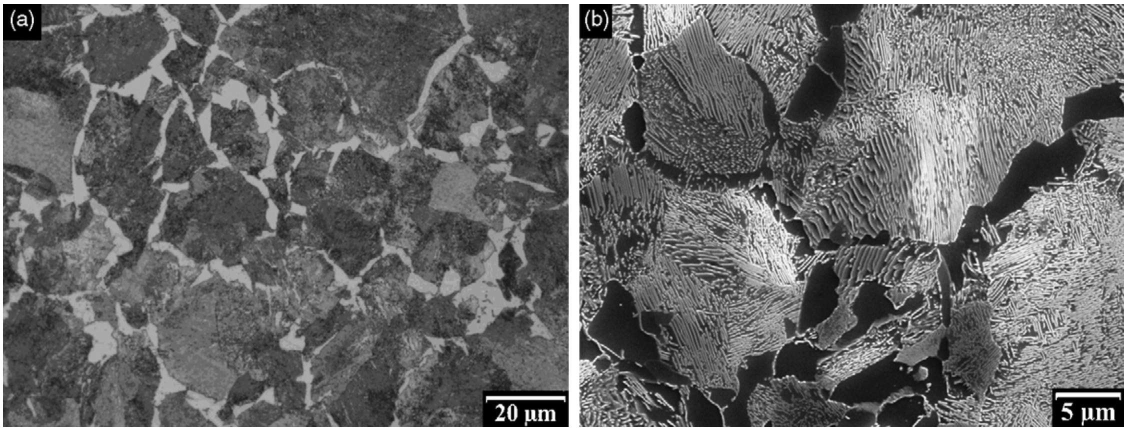

Fig. 1. Microstructure of studied R7T steel (3% Nital etched): (a) light microscopy; (b) SEM.

fracture behavior in these steels has not yet been investigated in detail. Thus, the primary goal of this study is to study differences in mechanisms of fracture in hypo eutectoid steels when dynamically and quasistatically loaded. This will help to explain differences in the statistical behaviors of fracture characteristics and their scatter. The subject of this study requires an understanding of the microstructural aspect of fracture surface formation under both conditions of loading. The determination of statistical scatter in the fracture toughness and Charpy impact energy of the investigated steel will be useful for a more precise calculation of the reliability of railway wheels manufactured from steel.

2. Experimental procedure and findings

All testing was conducted on specimens cut from a rail wheel supplied by Bonatrans, a.s., Bohumín, Czech Republic. The chemical composition was, 0.51 wt% C, 0.74 wt% Mn, 0.30 wt% Si, 0.24 wt% Cr, 0.16 wt% Ni, 0.04 wt% Mo, 0.003 wt% V, 0.005 wt% N, 0.08 wt% Cu, 0.009 wt% S, 0.012 wt% P, and the balance Fe, which conforms to the R7T designation [9]. The steel was heat treated in the following way: austenitization at 850 °C/water cooling and tempering at 520 °C. The final microstructure resulting from the heat treatment of the commercially produced wheel, in general terms, was a mixture of lamellar pearlite with a small quantity of ferrite. The microctructure showed only a featureless texture. The microstructure morphology of the steel is exhibited in Fig. 1a and b, with less than 20% of the area fraction ferrite grains observed using image analysis. The ferrite grain size measured by the linear intercept method from optical micrographs of the polished and etched surfaces was about 7 µm. The pearlite colony size was $D_\mathrm{p} = 15\ \mu\mathrm{m}$. The pearlite interlamellar spacing S_p was measured using a line drawn normal to the pearlite lamellae on metallography-prepared specimens heavily etched in 3% Nital and examined in a scanning electron microscope (SEM). The minimum interlamellar spacing S_p observed in several locations varied from 0.1 to 0.2 µm. This value was assumed to be the actual interlamellar spacing. The room-temperature tensile properties were ascertained from tensile specimens with a gage length of 100 mm and a diameter of 10 mm with a polished surface. The specimens were tested on a screw-driven Instron machine at an initial strain rate of $3.3 \times 10^{-3}\ \mathrm{s}^{-1}$. The yield stress at room temperature $R_\mathrm{e} = 552$ MPa, UTS = 910 MPa, ductility $A = 9.6\%$ and reduction of area $Z = 66.7\%$ were measured. The tensile properties of the tested material exhibited only a little scatter. The measured true stress vs. true strain diagram given in Fig. 2 was used to determine the coefficient of work hardening $n = 0.22$.

The dynamic and quasistatic fracture behaviors of the steel at room temperature were measured using standard Charpy V-notched (CVN) specimens and CT fracture toughness specimens. Both specimen types were machined so that the crack front, crack growth and loading directions, respectively, coincided with the radial, hoop and axial directions of the wheel rim. The CT specimens were $B = 30$ mm thick with chevron notches and fatigue precracks with the length in the interval from 30.10 to 31.92 mm. The fracture toughness K_Q was assessed from the dependence of load on displacement according to the ASTM E1820-99a standard [10]. According to the ASTM E1921 standard [11], the set of six experimental K_Q values was treated using the expression for the statistical distribution of fracture

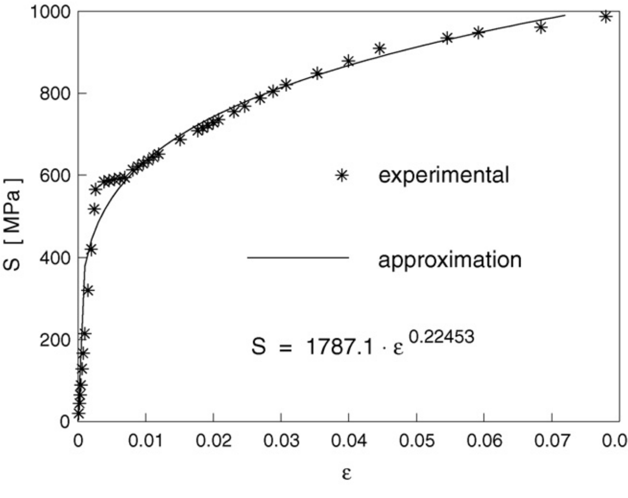

Fig. 2. True stress vs. true strain diagram and its analytical approximation of R7T hypo eutectoid steel at ambient temperature.