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Fatigue crack growth behavior of a coarse- and a fine-grained high manganese austenitic twin-induced plasticity steel

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ABSTRACT

The fatigue crack growth behavior of a coarse-grained (CG) and a fine-grained (FG) high manganese austenitic twin-induced plasticity (TWIP) steel has been investigated at room temperature. Crack growth tests were performed at stress ratios of 0.1 and 0.6 under the control of stress intensity factor range using three-point bending specimens. The results indicate that at the two stress ratios, the CG steel exhibits a higher fatigue crack growth resistance than the FG steel in both the near threshold and Paris regimes. Furthermore, a decreased stress ratio and an increased grain size both lead to an increased fatigue crack growth threshold. Microstructural observations reveal that cracks propagate more tortuously in the CG steel than in the FG steel, accompanied by rougher fracture surfaces, which tends to generate more roughness-induced crack closure and thus a higher fatigue threshold value. Additionally, the CG steel shows much larger plastic zone sizes ahead of the crack tip than the FG steel, suggesting that plasticity-induced crack closure may also play an important role in decreasing the fatigue crack growth rate in the CG steel. By excluding the crack closure effects, the CG steel still demonstrates a higher effective crack growth threshold than the FG steel; this is considered to be due to the increased planarity of slip in the CG steel, as compared with that in the FG steel.

1. Introduction

Over the past several years, much attention has been paid to high manganese austenitic twin-induced plasticity (TWIP) steels. TWIP steels are one of the most attractive materials for structural applications in the automotive industry due to the combinations of high ultimate strength, excellent ductility and formability associated with the high work-hardening capacity of the steels, as a result of the formation of mechanical twins in the process of deformation [1–3]. Many authors have extensively investigated the monotonic tensile behavior of high manganese austenitic TWIP steels at different strain rates and temperatures, and obtained many important results [4–6]. But in practical applications, structural components and parts made of high manganese austenitic TWIP steels, such as chassis, axles and suspension arms, frequently suffer from cyclic loads which result in fatigue damage [3,7]. Thus, it is necessary to understand the fatigue properties of TWIP steels.

Recently, some researchers have studied the low- and high-cycle fatigue behaviors of high manganese austenitic TWIP steels [8–11]. Hamada et al. [8] investigated the high-cycle fatigue behavior of three high manganese austenitic TWIP steels with different grain sizes. They reported that the TWIP steels have higher fatigue strengths than some commercial austenitic stainless steels, and the fatigue strength increases with decreasing grain size. The low-cycle fatigue behavior of TWIP steels in the as-received and pre-strain conditions was investigated by Niendorf et al. [9] and Lambers et al. [10]. They found that the as-received state shows quick cyclic softening after cyclic hardening, and the fatigue behavior of the pre-strained TWIP steel is dominated by cyclic softening. Pre-strain enhances the fatigue property of TWIP steel due to the increase in mechanical twin density. However, very limited studies dealt with the fatigue crack growth (FCG) behaviors of high manganese austenitic TWIP steels. According to the authors' knowledge, only Niendorf et al. [7] studied the FCG behavior in a cold-rolled TWIP steel using miniature compact tension specimens at the stress ratios of 0.1 and 0.5. It was found that the TWIP steel has lower FCG rates than the same level of high strength steel, showing an improved FCG resistance.

Many authors have investigated the FCG properties in some other metallic materials, such as Al alloy [12], Cu alloy [13] and Cr–Mo steels [14,15]. It has been recognized that grain size and stress ratio affect significantly the FCG behavior, and it is generally accepted that the fatigue crack growth threshold decreases with increasing the stress ratio. However, the effect of grain size on crack threshold value in various materials remains to be understood. In the 7475 aluminum

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alloy [12] and 25Cr2NiMo1V steel [14], the FCG threshold increases with increasing grain size, but for the Cu alloy the threshold value decreases with increasing grain size [13].

The tensile properties and the work-hardening mechanisms associated with twin-induced plasticity effect in TWIP steels, primarily in solution heat treatment state [6,16–18], have been widely explored, and grain size effects on the monotonic deformation behavior have also been examined [5,19,20]; however, how fatigue crack propagates and, especially, to what extent grain size affects crack propagation behavior in this class of advanced steels are still not clear. The present paper addresses the FCG behavior of a commercial high manganese austenitic TWIP steel in solid solution treatment states, rather than in the cold-rolling state, with the focus on the effects of grain size and stress ratio.

2. Experimental procedures

2.1. Material preparation

The chemical composition of the high manganese austenitic TWIP steel was Fe–22 wt%Mn–0.6 wt%C. The steel was melted in an induction furnace and cast into round bars of 100 mm in diameter. The ingots were hot forged at ~1000 °C into billets with a cross section of 30 mm × 40 mm and then cold-rolled into plates with a 50% thickness reduction. The cold-rolled plates were solution treated at 1100 °C for 1 h and at 700 °C for 10 min, and subsequently water-quenched to room temperature, obtaining full austenitic microstructures. The average sizes of austenitic grains of the steel after solution treatment at two different temperatures are ~70 and ~5 μm (Fig. 1). The steels of large and small grain sizes are hereafter referred to as coarse-grained (CG) and fine-grained (FG) steels, respectively.

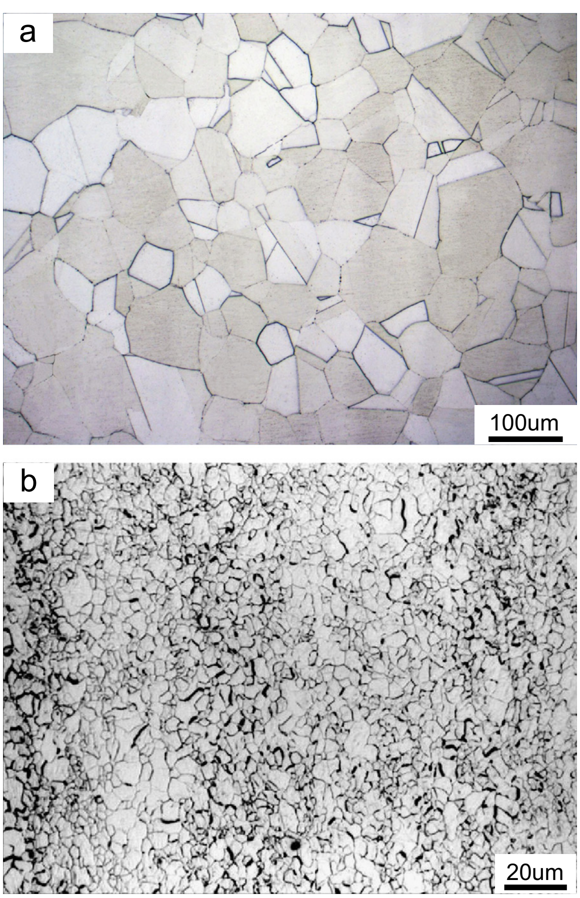

Fig. 1. Optical microstructures of (a) the CG and (b) FG Fe–22Mn–0.6C TWIP steels.

2.2. Tensile and FCG tests

Mechanical properties of the CG and FG TWIP steels were measured by tensile testing. Dog-bone flat tensile specimens with a nominal gauge section of 15 mm length, 10 mm width, and 3 mm thickness were extracted from the water-quenched plates along the rolling direction (RD). Tensile tests were conducted at room temperature under crosshead displacement control at a nominal strain rate of $2 \times 10^{-3}\ s^{-1}$. The true stress versus true strain curves obtained are shown in Fig. 2, and the tensile property parameters are summarized in Table 1. It is noteworthy that the yield strength and ultimate tensile strength are obviously improved but the total elongation is reduced with the grain refinement.

Standard three-point bending (3PB) specimens with a notch were machined with the crack growth direction perpendicular to the RD. The length (L), width (W) and thickness (B) of the 3PB specimen are 132, 30, and 10 mm, respectively. The ratio of the span (S) to the width is 4:1. The notch size was 0.14 mm in width and 3.5 mm in depth. The detailed geometry of the 3PB specimen is shown in Fig. 3. The surfaces of the specimens were ground in successive stages by abrasive papers from 150 to 1500 grit to obtain smooth surfaces and then polished mechanically using the diamond suspension of size 2.5 μm to get mirror finishing. Prior to

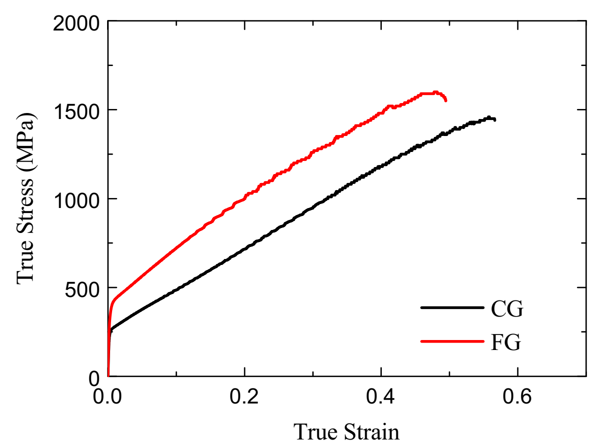

Fig. 2. True stress–true strain curves of the CG and FG Fe–22Mn–0.6C TWIP steels.

Table 1
Tensile properties of the CG and FG steels.

Steel	Grain size (μm)	YS (MPa)	UTS (MPa)	TEL (%)
FG	5	375	1010	64
CG	70	253	845	76

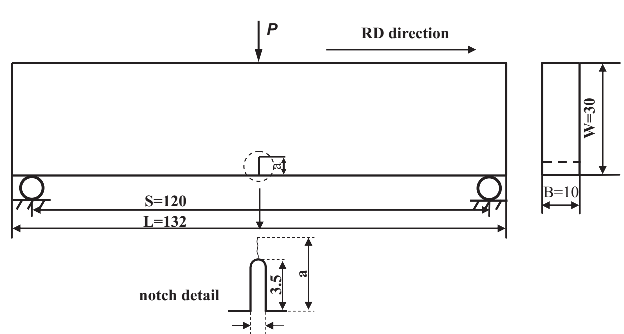

Fig. 3. The geometry of the 3PB specimen (units in mm).