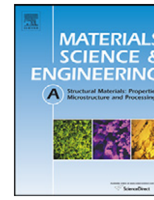
Materials Science and Engineering A 527 (2010) 2412–2417

Contents lists available at ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea



Fatigue crack growth—Microstructure relationships in a high-manganese austenitic TWIP steel

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ARTICLE INFO

Article history:
Received 17 September 2009
Received in revised form 3 December 2009
Accepted 4 December 2009

Keywords:
Twinning-induced plasticity
TWIP steel
Crack growth
Fatigue
Microstructure
TRIP

ABSTRACT

The crack growth behavior of a high-manganese austenitic steel, which exhibits the twinning-induced plasticity (TWIP) effect, was investigated under positive stress ratios. An experimental study making use of miniature compact tension (CT) specimens and thorough microstructural analyses including transmission electron microscopy and fracture analyses demonstrated that the microstructural evolution in the plastic zone of the fatigued TWIP CT specimens is substantially different as compared to the monotonic plastic deformation case. Specifically, the twin density in the plastic zone of the CT specimens is very low, leading to the conclusion that the deformation mechanisms depend drastically on the loading conditions. The absence of twinning under cyclic loading in the plastic zone of the CT specimens indicates that even large accumulated plastic strains are not sufficient to cause substantial twinning in the TWIP steel. This lack of hardening preserves the ductile character of the TWIP steel in the plastic zone ahead of the crack tip and provides for a crack growth rate in the Paris regime lower than reported for other high strength steels.

1. Introduction

Recently, remarkable effort has been spent on the development of new light-weight materials. Especially in the automotive sector and in aerospace applications light-weight construction has become one of the most important success factors. High strength steels are often the material of choice for light-weight structures as they combine various attractive properties such as formability, strength and weldability [1–4]. As compared to traditional mild steels with low strength values, the application of high strength steels allows for a significant decrease of the sheet thickness for several automotive components. Thus, in modern car bodies plenty of different high strength steels are in use, *e.g.* dual phase or complex phase steels and press hardened boron alloyed steels. The use of these steel grades in chassis components is linked to a change of design concepts since car components such as axles or suspension arms are mainly suffering from cyclic loads and the resulting fatigue damage. Quite often, thin walled light-weight structures can no longer be designed using simple material constants such as the fatigue endurance limit. Therefore, concepts based on fracture mechanics approaches [5–8] come into consideration. In other words, the presence of small cracks in a component is assumed and the number of cycles to failure based on a phase of stable crack growth is calculated. For the calculation of fatigue lives based on these approaches the knowledge of material constants under stable fatigue crack growth conditions in the so-called Paris regime is a prerequisite. For the recently developed high strength, high-manganese metastable austenitic steels featuring the transformation-induced plasticity (TRIP) or the twinning-induced plasticity (TWIP) effect there is a lack of such data. While there is a very limited number of publications on the crack growth behavior of low-alloy TRIP steel [9], there is, to the best of the authors' knowledge, no study available in the open literature reporting on crack growth in TWIP steel.

Studies on the monotonic and cyclic deformation behavior of these materials have shown that the relevant deformation mechanisms are significantly different from traditional steel grades [1,10–15]. Under monotonic loading the deformation behavior of TRIP and TWIP steels is well documented, *i.e.* deformation-induced phase transformation or deformation-induced twinning significantly influence the stress–strain response of these materials [10–12]. For instance, Barbier et al. observed a twin volume fraction of 9% in Fe–22Mn–0.6C TWIP steel after deformation to a true strain of 0.55 [16]. High-alloy TRIP and TWIP steels do not show phase transformation during typical processing or cooling, instead they need to reach a certain energy level in order to transform, which can be provided by mechanical deformation [10]. Low-alloy TRIP-assisted multiphase steels show phase transformation during

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doi:10.1016/j.msea.2009.12.012

processing in part of the volume upon cooling [17], and the retained austenite transforms upon mechanical deformation. Especially in the highly strained regions of the TRIP and TWIP steels, such as the necking zones, the necessary critical energy level can be attained. The mechanism of strain hardening in this class of steels has been shown to be tailorable by adjusting the content of alloying elements, such as manganese (Mn) and aluminum (Al) [18–20]. The stacking fault energy (SFE) of the material, which dictates the active deformation mechanism throughout deformation, is directly influenced by the alloying content of the steel [21]. However, the active deformation mechanism within a single grain is also affected by the orientation of the grain relative to the tensile direction through the corresponding Schmid factor. In general, decreasing the SFE promotes the planarity of slip and reduces the propensity of cross slip [21–23]. Typically, TRIP steels exhibit a very low SFE, while TWIP steels are characterized by higher SFE [1,10,11] and thus a high-Mn steel with a medium SFE may show both effects [1,18].

For TRIP-assisted multiphase steels a few studies are available that report on the fatigue properties and the corresponding microstructural evolution [13]. In the case of TWIP steel there are currently only two papers that report on the fatigue properties in the low-cycle and high-cycle fatigue regime [14,15]. In both cases it has been found that no new twins are formed under cyclic loading of smooth specimens. In how far this holds also true in the plastic zone in front of the crack tip of a TWIP steel sample featuring high accumulated plastic strains has not been investigated so far. It is, however, crucial to investigate this aspect in the light of the envisaged applications, and the current study was conducted in order to close this gap.

The TWIP steel investigated in the current study is characterized by a favorable combination of extraordinary ductility and high strength, *i.e.* an elongation to failure of 52%, a yield strength (σ_y) of 580 MPa and an ultimate tensile strength of 1160 MPa [14]. The extraordinary hardening capability is due to twinning, which delays the onset of necking. Accordingly, the TWIP effect prevents necking due to the local increase in strength and leads to a homogeneous deformation in the whole gage length [1,10,11]. In how far twinning influences the crack growth behavior in TWIP steel has been investigated in the current study. Compact tension (CT) specimens were tested to obtain fatigue crack growth rates as a function of the cyclic stress intensity factor (ΔK). These tests were accompanied by thorough microstructural investigations including characterization of crack surfaces by scanning electron microscopy (SEM) and twin densities by transmission electron microscopy (TEM). The findings presented herein were used in order to explain the crack growth curves obtained on a microstructural basis. The low inclination of the crack growth curve in the Paris regime is attributed to the absence of twinning in the cyclic plastic zone of the CT specimens, such that the TWIP steel is still dominated by its ductile character even under high cyclic loads. The results obtained are compared to results reported for a low-alloy TRIP steel, which show significant differences in crack growth behavior. The characteristics of the TWIP steel are promising for the use of TWIP steel in light-weight applications.

2. Experimental procedures

The material utilized in the current study was the high-Mn austenitic “XIP 1000” steel provided by Arcelor Mittal for Benteler Automotive. The chemical composition of this material as determined by spark spectrometry is summarized in Table 1. The material was received in a cold rolled state with a thickness of 1.6 mm and an average grain size of 2 μm [14]. Miniature CT specimens, similar to the ASTM standard E399-90 [25], were cut by electro-discharge machining. The geometrical dimensions of the miniature specimens are shown in Fig. 1. The miniature samples employed do not meet the minimum thickness criterion for determination of the critical stress intensity factor (K_{Ic}). Thus, the crack growth curves presented in this study are shown only up to the end of the Paris regime, where linear elastic fracture mechanics is still applicable. The specimens were taken from two different orientations of the initial sheet. This allowed for the investigation of cracks growing parallel and perpendicular to the rolling direction. After machining the specimens were mechanically ground to a grit size of 5 μm in order to allow for the investigation of fatigue-induced changes of the samples' surfaces. The mechanical tests were conducted in a servo-hydraulic test rig at room temperature in laboratory air. For measurement of the crack length the potential drop method [26] was used. In order to avoid any temperature increase, the current was limited to 5 A. The small resulting potential drops were measured using a voltmeter with nanovolt resolution. Commercial LabView software was used to determine the actual crack length from the potential drop measured and to calculate the actual stress intensity factor value. Tests with a constant frequency of 20 Hz were conducted in ΔK control with positive stress ratios of $R = 0.1$ and $R = 0.5$. The initial values for the tests with $R = 0.1$ and $R = 0.5$ were $\Delta K = 18\,\mathrm{MPa}\sqrt{m}$ and $\Delta K = 13\,\mathrm{MPa}\sqrt{m}$, respectively. In order to obtain crack growth rates in the near threshold regime, ΔK was decreased stepwise after a given amount of crack growth on a constant load level. For covering the Paris region, ΔK was then increased stepwise accordingly. In combination with the mechanical tests microstructural analyses were conducted. Crack surfaces and crack wakes were investigated in a SEM operating at a nominal voltage of 20 kV. The details of the microstructural evolution were characterized by TEM. TEM samples were taken from different areas of the fatigued samples as depicted in Fig. 1, *i.e.* the cyclic plastic zone (A) and the monotonically deformed zone resulting from final overload failure (B). Under the loading conditions used in the current study the size of the cyclic plastic zone is very small. In literature several equations

Table 1
Chemical composition of the TWIP steel investigated in the present study as obtained by spark spectrometry.

Element	Fe	C	Mn	V	Cr	Si
Weight Percent	Balance	0.52[a]	22.36	0.25	0.20	0.25

[a] C content might be slightly underestimated since spectrometry measurements tend to be affected by the high Mn content, and thus 0.6 wt.% is a more realistic value [24].

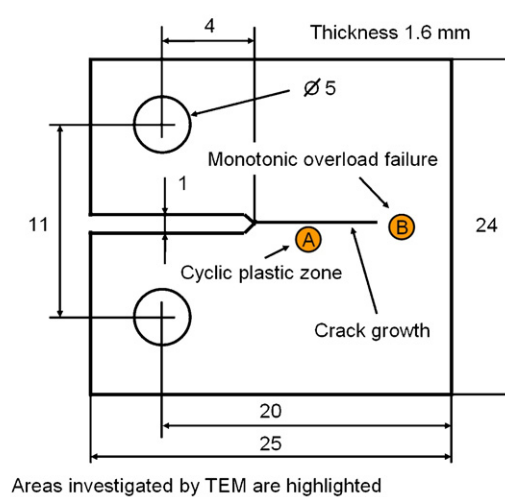

Fig. 1. The dimensions of the CT sample used in the current study (in mm). Highlighted are the areas from which a series of TEM samples were extracted (referred to as A and B in the main text).