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Fatigue crack growth in TRIP steel under positive *R*-ratios

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Abstract

Load-controlled fatigue tests are conducted for four positive *R* values on a low-alloy TRIP steel for two different heat treatments: an optimal treatment leading to a multiphase microstructure containing retained austenite, ferrite, bainite and martensite, and a non-optimal treatment leading to a ferritic–martensitic dual-phase microstructure. A significantly increased resistance to fatigue crack growth is found for the optimal case with respect to the non-optimal case. The amount of crack closure is found to be larger in case of the non-optimally treated (ferritic–martensitic) steel. Close to the crack tip, an increased hardness suggests martensite formation. An EBSD technique is used to quantify the volume of retained austenite ahead of the crack tip, within the plastic zone. It is found that martensite formation only occurs within the monotonic plastic zone during fatigue. By evaluation of the retained austenite fraction during straining in static tensile tests, the plastic strain levels within the plastic zone are assessed. Additionally, the effect of martensite formation on fracture toughness is estimated.

Keywords: Fatigue crack growth; Tensile loading; Crack growth path; Martensite transformation; EBSD; Fracture toughness

1. Introduction

Low-alloy multiphase transformation-induced plasticity (TRIP) steels are used for safety-based car bodies, because of the high energy absorption potential under dynamic loading during car crashes [1]. Furthermore, the usage of TRIP steels is thought to be extendable to cyclically loaded wheel rims, suspensions and door hinges, where ferritic–martensitic steels are currently used [2]. Therefore, there is a need to also understand the fatigue behaviour of TRIP steels. Until now research indicated that TRIP steels exhibit cyclic hardening, which is mainly associated with the development of internal stresses [2,3]. In TRIP steels, retained austenite can transform into martensite in the plastic zone. When this results in crack closure, the crack growth rate can be reduced [4]. Furthermore, compressive residual stress caused by transformation from retained austenite

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to martensite due to the cyclic load can retard the propagation of the microcracks [5]. However, research on the fatigue crack growth behaviour of TRIP steels is still very limited, especially with respect to the crack growth path and the microstructural evolution.

In the present study, the fatigue crack growth rate, crack path and microstructural changes under fatigue loading with different (positive) R values in a low-alloy TRIP steel are observed. Two different heat treatments are applied to obtain a maximum and a minimum amount of retained austenite, respectively. Electron backscatter diffraction (EBSD) measurements are performed to quantify the volume fraction of retained austenite within the crack tip plastic zone. The objective of the present study is to elucidate the role of the TRIP effect during fatigue crack growth.

2. Material and experimental procedures

The material used in this study is a cold-rolled (1.8 mm thick) low-alloy TRIP steel. Table 1 gives the chemical composition. Si and Al play a key role in the retention of austenite, because they inhibit cementite formation during the bainitic transformation.

Initially all test specimens were annealed at 600 °C for 24 h and slowly cooled down in order to reduce residual stresses as much as possible.

On a number of specimens a heat treatment was carried out at an intercritical annealing temperature of 800 °C for 30 min, creating a microstructure of ferrite and austenite. This was followed by fast cooling to the bainite formation temperature regime (400 °C) and holding this temperature for 1 min, during which a certain amount of ferritic bainite formed. Finally, the material was quenched to room temperature after which the least stable austenite is transformed into martensite. In the resulting material, the microstructure consists of ferrite, bainite, retained austenite and a little martensite. The volume fraction of retained austenite, determined by X-ray measurements using the method described in [6], is found to be 4.9%. This heat treatment is designated as “optimal”.

In order to access the influence of the TRIP effect, an alternative heat treatment was carried out on another set of specimens, which were water quenched after intercritical annealing at 800 °C for 30 min. After such heat treatment the microstructure of the steel consists of ~50% ferrite and ~50% martensite with a negligibly small amount of retained austenite, which did not exceed 1% and can not be recognized on the metallographic pictures [7]. This heat treatment is designated as “non-optimal”.

Standard sheet-shaped tensile specimens according to ASTM E8M, with a gauge length of 32 mm and a width of 6 mm, were used for static tensile tests to measure the mechanical properties of the material after the optimal and the non-optimal heat treatments, respectively. These tensile tests were carried out by an INSTRON 5500R-4505 testing machine with 100 kN load capacity.

Load-controlled fatigue tests were performed at room temperature on centre-notched specimens, using a servo-hydraulic test machine (MTS810, 100 kN load capacity). Cyclic tension was applied to the specimens at a frequency of 10 Hz. Four values of the load ratio $R(=\sigma_{\min}/\sigma_{\max})$, 0.1, 0.3, 0.5 and 0.7, were employed, using the same maximum stress for all tests ($\sigma_{\max} = 142$ MPa). The specimens were prepared according to ASTM standard ASTM E647, as is shown in Fig. 1.

The development of the fatigue crack was monitored by using a four-wire pulsed potential-drop method during the tests. After failure, the fracture surfaces were characterised using a scanning electron microscopy (SEM). Furthermore, cross sections of the crack on planes parallel to the loading direction and perpendicular to the surface were observed to characterise the crack path and possible transformation of retained austenite to martensite due to the TRIP effect.

EBSD mapping was carried out in a hexagonal scan grid and a step size of 0.1 or 0.08 μm in the crack tip zone and its close vicinity in order to evaluate the characteristic microstructural changes in the material related

Table 1
Chemical composition of the TRIP steel (wt.%)

C	Mn	Si	Al	P
0.188	1.502	0.254	0.443	0.015