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Fatigue behavior and retained austenite transformation of Al-containing TRIP steels

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ABSTRACT

In material selection for the design of advanced lightweight automotive steel components, fatigue performance is of particular significance. High strength TRIP steels offer very good cyclic behavior, especially under cyclic plastic strains, which is assisted by the Transformation Induced Plasticity effect (TRIP). In the present study the TRIP effect has been quantified under both elastic (HCF regime) and plastic (LCF regime) cyclic strains for two Al-containing TRIP steels with similar chemical composition and different initial retained austenite (RA) content. The results illustrate that transformation behavior differs for the two materials under elastic and plastic cyclic straining and fatigue behavior is in both cases linked to the amount of RA transformation. The latter is discussed in the paper considering relevant RA microstructural aspects like content and particle size. In the investigation the fatigue crack initiation resistance of the materials has been experimentally evaluated, resulting in different damage tolerance ability for the two steels. A numerical simulation is developed to determine the local strains at the notch tip under monotonic loading conditions and is used with the LCF material characteristics to discuss the differences obtained in crack initiation resistance.

1. Introduction

The excellent formability and strength properties of TRIP steels [1,2] have made them competitive materials with regard to new aluminum alloys for use in automotive industry to meet the criteria for reduced structural weight. The unique properties of TRIP steels are attributed to the deformation induced transformation of metastable retained austenite [3–6].

The amount of transformation mainly depends on deformation conditions and on the size [7], dispersion, and stability of retained austenite [8]. Under cyclic plastic deformation, TRIP steels offer excellent performance [9–12] and the cyclic material response is considerably influenced by the plastic strain amplitude and TRIP material microstructure [13,14]. In [13], cyclic hardening at low strain amplitudes followed by cyclic softening at higher strain amplitudes was reported for a TRIP750 steel. In [14] a reversed behavior was observed for a TRIP780 steel with cyclic softening diminishing with increasing strain amplitude. In [15] cyclic hardening was found to be dependent on the martensite formation rate, related to the plastic strain amplitude in cast austenitic TRIP steel. Austenite transformation was found not to influence significantly the cyclic hardening effect of TRIP steels but contribute to a low softening ratio.

The High Cycle Fatigue (HCF) performance of TRIP steels has also been linked with deformation induced transformation resulting in an improvement of fatigue strength [16,17]. Under elastic alternating stresses the transformation effect still exists [17] and fatigue limit values close to the material's yield strength have been reported [18,19]. In [20] the high fatigue limit value of quenched and partitioned steel was attributed to a delay in crack propagation caused by phase transformation. Fatigue strength was found to be dependent on the initial retained austenite (RA) volume fraction, while similar observation was reported in [21]. In [17] it was demonstrated that the stability of retained austenite is a significant parameter affecting the fatigue performance of TRIP steels. It was concluded that the TRIP steel with more stable retained austenite (lower M_s^σ value) exhibits more gradual transformation with increasing elastic alternating stresses, improving the fatigue behavior.

Despite the importance of RA transformation on cyclic behavior of TRIP steels, experimental evidence with quantification of the transformation effect under both elastic and plastic cyclic strains on a specific TRIP material is missing. In this experimental study the Low and High cycle fatigue behavior (including notch effect

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Nomenclature

A_{25}	elongation at fracture	R	stress/strain ratio
b	fatigue strength exponent	α	crack length
c	fatigue ductility exponent	$\Delta\alpha/\Delta N\|_{avg}$	average crack growth rate
E	Young's modulus	$\Delta\sigma$	stress amplitude
FL	fatigue limit	ε_e	elastic strain amplitude
FL_N	fatigue limit notched	ε_f'	fatigue ductility coefficient
H	strength coefficient	ε_p	plastic strain amplitude
H'	cyclic strength coefficient	ε_{total}	total strain amplitude
K_f	fatigue notch factor	ε_{yy}	normal strain in the loading direction
K_t	elastic stress concentration factor	ν	Poisson's ratio
n	strain hardening exponent	σ_a	stress amplitude
n'	cyclic strain hardening exponent	σ_f'	fatigue strength coefficient
N_f	fatigue life	σ_{max}	maximum stress in the loading direction
$N_{initiation}$	number of cycles required for detection of a 250 μm crack	σ_{UTS}	ultimate tensile strength
		σ_{yy}	normal stress in the loading direction
q	notch sensitivity factor	$\sigma_{y0.2}$	yield strength (offset 0.2%)

analysis) is investigated for two Al-containing TRIP steels. The deformation induced martensitic transformation in the LCF and HCF regimes is quantified by performing RA measurements using the saturation magnetization technique. The fatigue results are discussed with regard to the RA microstructural characteristics of the materials.

Another significant fatigue problem associated with the design of structural components is the material's crack initiation resistance. At locations with stress concentrations (e.g. notches), local plasticity at the root of the geometrical discontinuity favors RA transformation and the local material behavior at the notch tip controls the crack initiation problem. Limited attention has been paid in the literature on this issue and most investigations have focused on the notch effect on fatigue limit. In [19] it has been reported that the formation of hard martensite due to strain induced transformation, suppresses the crack initiation in notched TRIP aided-annealed martensitic steel. In [18] the notched fatigue limit of TRIP-aided bainitic ferrite steels with 10–13.7% initial RA volume fraction linearly increased with increasing hardness, while the notch sensitivity decreased. In [22,23], among several high strength steels used in automotive industry, TRIP steels presented the highest smooth and notched fatigue limit values. Retained austenite to martensite transformation has been also found to be beneficial on the rate of the growing crack. In [11,24] the transformation ahead of the crack tip was found to reduce the energy absorption leading to high fatigue crack growth resistance in a low alloy TRIP steel. Crack initiation from the notch tip is assessed in the present study for both Al-containing TRIP steels experimentally. The differences obtained in crack initiation behavior of the steels are discussed considering local LCF conditions at the notch root taking into account the LCF material behavior. A numerical simulation is performed to determine the local monotonic material response at the notch root resulting to the development of local strains at the notch tip.

2. Experimental procedure

2.1. Materials

The materials used in the investigation were a hot-rolled TRIP700(A) steel with thickness of 1.8 mm and a cold-rolled, 1.5 mm thick, TRIP700(B) steel in sheet form. The percentage (%) retained austenite (RA) values were measured with the saturation magnetization technique, which is described in more detail in Section 2.4.1. The RA values were 11.8 vol.-% and 15.8 vol.-% for TRIP700 steels (A) and (B) respectively. Both materials are Al-containing steels with small differences in chemical composition, as shown in Table 1.

2.2. Metallography

The microstructural characteristics in as-received condition were assessed using optical microscopy. A stepped color tint-etching procedure was employed using the De-etching method [25] in order to reveal the steels' microstructures. The samples were first dipped into a 3% Nital solution for 5 s and then placed into a solution of 10% $Na_2S_2O_5$ for 60 s. The average grain sizes of ferrite and retained austenite of the steels were measured using image analysis software, with data taken from several micrographs to avoid estimation errors due to the large dispersion of the phases. The retained austenite volume fraction after the mechanical tests was measured using the saturation magnetization technique.

2.3. Mechanical testing

Static tensile tests were carried using an INSTRON 8801 servo-hydraulic machine with 100 kN load capacity. Mechanical properties were determined in accordance with ASTM E8M at a constant crosshead velocity of 0.5 mm/min. The specimens were tested in the longitudinal (L) direction using a 25-mm gage length clip-on extensometer.

Fully reversed ($R = -1$) cyclic tests were performed in accordance with SEP 1240 [26] specification. The geometry of the LCF specimen is shown in Fig. 1. Strain amplitudes in the range of 0.002–0.02 were applied using a 10-mm gage length clip-on extensometer at a frequency range of 0.1–3 s^{-1}. To prevent buckling under compressive strains, an anti-buckling external fixture was used. The stabilized hysteresis loop was determined from the half number of cycles required for onset of crack initiation. Crack initiation is determined as the number of cycles that corresponds to a 10% change of the maximum cyclic load [26]. For determining the

Table 1
Chemical composition of TRIP700 steels (wt.-%).

Steel	C	Mn	Al	Si	P	Fe
(A)	0.18	1.61	1.45	0.7	–	Balance
(B)	0.202	1.99	1.07	0.35	0.009	Balance