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Phase transformation under thermal fatigue of high Mn-TWIP steel: Microstructure and mechanical properties

J.J. Roa [a,b,*], H. Besharatloo [a], G. Fargas [a,b], J. Calvo [a,c], A. Mateo [a]

[a] Departament de Ciència dels Materials i Enginyeria Metal·lúrgica, Universitat Politècnica de Catalunya, EEBE - Campus Diagonal Besòs, 08019 Barcelona, Spain
[b] CRnE, Universitat Politècnica de Catalunya, EEBE - Campus Diagonal Besòs, 08019 Barcelona, Spain
[c] CTM Centre Tecnològic, Plaça de la Ciència, 2, 08243 Manresa, Spain

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ABSTRACT

High Mn steels present both high tensile strength and good ductility, therefore they have attracted attention as promising candidates for the next-generation of automotive steels. However, slight changes during the manufacturing process or in service conditions (i.e. chemical composition, annealing temperature, among others) can promote significant variations in their microstructure, leading to a strong modification in their mechanical response. In this regard, this paper discusses the relationship between the different microstructures generated on a high Mn-twinning induced plasticity (TWIP) steel and its mechanical properties evaluated by means of Vickers's hardness, tensile testing and also high cycle fatigue response. Different conditions, namely: as received, annealed at 500 °C and thermally cycled at 500 °C during 15, 36, 56 and 75 cycles, have been analyzed. The results exhibit the development of a heterogeneous pearlitic microstructure with a plateau on its fraction content and Vickers's hardness at ~24% and 292 ± 5 HV, respectively, after 36 thermal fatigue cycles. Finally, pearlite colonies have been nucleated during the thermal fatigue treatment along the austenitic grain boundary producing a deleterious effect on the tensile and high cycle fatigue behavior.

1. Introduction

Automotive companies are trying to develop vehicles environmentally friendly. Therefore, weight reduction is mandatory to achieve less fuel consumption and also to diminish pollutant emissions. At the same time, vehicles must be safer for passengers. Encouraged by these needs of the automotive industry, in the last decades steel manufacturers have invested efforts to develop new high strength steel grades, such as transformation induced plasticity (TRIP) steels, dual phase (DP) steels, complex phases (CP) steels and, more recently, twinning induced plasticity (TWIP) steels [1]. These latter steels are characterized by high Mn contents (15–30 wt%) and they provide a great potential for weight reduction in energy absorption vehicle components, due to their excellent tensile strength and ductility combination [2–8]. The chemical composition and temperature are known to be the main factors in controlling the stacking fault energy (SFE) and, consequently, the main deformation mechanism operative under certain conditions [9,10]. It is considered that when $SFE \leq 20$ mJ m^{-2} martensite induced plasticity is favored [10,11], for $SFE \sim 25–60$ mJ m^{-2} the martensitic phase transformation is suppressed and mechanical twinning is enhanced [10], and, finally, for $SFE > 60$ mJ m^{-2} dislocations gliding is the single deformation mechanism. In TWIP steels, the objective is to control the SFE, through specific compositions, to promote twinning as the main deformation mechanism at room temperature. Moreover, this mechanism will also rely on the microstructure, and, in this sense, a fully austenitic microstructure is required at room temperature. Therefore, the composition of these steels in Mn, C, Al and Si contents is adjusted to control the SFE value and stabilize the austenitic phase.

During the last years, an extensive number of investigations on the microstructure evolution of high Mn-TWIP steels have been carried out [1,3,4,12–14]. Also their mechanical properties have been investigated: tensile testing [3,4,15–21], low cycle fatigue and fatigue life [22–25] and scarce investigations on high cycle fatigue [26]. Furthermore, there are some researches dealing with the effects of thermal and mechanical treatments to modify the austenitic microstructure of those high Mn-TWIP steels [3,12,13,27].

* Corresponding author at: Departament de Ciència dels Materials i Enginyeria Metal·lúrgica,Universitat Politècnica de Catalunya, EEBE - Campus Diagonal Besòs, 08019 Barcelona, Spain.
E-mail address: joan.josep.roa@upc.edu (J.J. Roa).

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Previously, Xiao et al. [28] investigated the phase transformation of austenitic grains, where the main transformation mechanisms results from the combined effect of short-distance Fe diffusion across the interface, with plastic deformation predominantly accelerating the latter. After that, Van Tol *et al.* [29] investigated the pearlitic formation during aging in the temperature range 500–600 °C in undeformed and deformed austenitic manganese-based steel by means of in-situ magnetization measurements and microscopy techniques. However, scarce information related to thermal fatigue phase transformation and their microstructural and mechanical characterization for these complex steels is available in the literature. In this regard, along this manuscript, the effects of phase transformation (from austenite to pearlite) under thermal fatigue and their correlation with the mechanical properties of high Mn-TWIP steel have not been systematically studied yet. Within this framework, the major aim of this study was to investigate the effect of thermal fatigue cycles on the duplex (austenitic/pearlitic) microstructure and understanding the correlation between this microstructure and the mechanical properties (hardness at micrometric length scale, tensile testing and high cycle fatigue). A better understanding of the role of the pearlite in austenitic high Mn-TWIP steel may be an important factor to improve the service lifetime of structural components subjected to thermal cycles at intermediate temperatures in the automotive industry.

2. Experimental procedure

In this work, the studied material was a high Mn-TWIP steel provided by POSCO (South Korea) in the form of sheets of 2 mm thickness. The chemical composition is presented in Table 1.

Six different sets of specimens were investigated: as received (AR), specimens annealed at 500 °C during 15 min and quenched in air (500Q) and four specimens subjected to thermal fatigue at 500 °C during 15, 36, 56 and 75 cycles, respectively (500-TF-15cycles, 500-TF-36cycles, 500-TF-56cycles and 500-TF-75cycles). The thermal fatigue cycle was composed of two different steps: maintaining the specimens at the desired temperature (500 °C) for 1 h and subsequently air cooling for 20 min. After that, each specimen was first grinded and polished prior the microstructural characterization using silicon carbide paper, polished until 3 μm diamond suspension and a final polishing step using a neutral suspension of 20–40 nm alumina particle.

The average grain size and the pearlitic fraction were determined by the conventional linear intercept method and using the imageJ software, respectively; using a total of twenty micrographs obtained by means of field emission scanning electron microscopy (FESEM, Jeol 7001F) at 20 kV, in order to have statistical significance.

Thermodynamic calculations were conducted using FactSage® thermo-chemical software [30] to calculate the equilibrium phase fractions as a function of the temperature for the chemical composition presented above. The FSstel database, containing data for solutions and compounds [31], was used. The calculations were carried out in the temperature range between 200 and 1500 °C, every 10 °C with the search for transition temperatures.

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

C	Si	Mn	S	Mo	Al	Nb	Ti	V	Fe
0.72	0.071	17.8	0.015	0.34	1.9	0.021	0.096	0.037	Bal.

The N content was not specifically determined, although it is considered that there is always some N (ranged between 0.010 and 0.025 wt%), which could remain in the steel from the casting stage.

The response to sharp contact was achieved by the indentation method at microscopic length scale at 1 kgf by means of MKV-HO Akashi hardness tester. Fifteen imprints were done per specimen.

For tensile and high cycle fatigue tests, specimens were machined by laser cutting, with the main axis parallel to the rolling direction. After that, the tensile and fatigue specimens were thermally treated at 500 °C following the procedure previously described. The main dimensions for the tensile and fatigue specimens are summarized in Table 1.

Tensile tests were conducted until rupture at room temperature and a constant crosshead rate of 3 mm min^{-1} using an Instron 8562 computerized universal machine according to ASTM E 8-04 standard [32]. On the other hand, to eliminate the possible deleterious effects induced by the laser cutting [33], prior to fatigue testing, the surfaces of the fatigue specimens were ground in successive stages by SiC papers from 240 up to 1500 grit to obtain smooth surfaces, and polished mechanically using a diamond suspension with size of 3 μm to get mirror finishing. Afterwards, high cycle fatigue tests were conducted under load control mode in a resonant testing machine (Rumul MIKROTRON) according to ASTM E 466-96 [34] standard. Frequencies around 150 Hz were used and the load ratio was keep constant to 0.1 ($R = \sigma_{\min}/\sigma_{\max}$). The initial maximum stress was taken as 50% of the ultimate tensile strength (σ_{uts}) of the corresponding steel condition, directly extracted from the tensile tests. Subsequently, if the specimen was able to reach 10^6 cycles without fail, then σ_{max} value was increased 10%, and so on until fracture, following the staircase method [35], but only with three specimens per condition. Finally, the fracture surfaces as well as the damage induced during tensile and high cycle fatigue tests were examined by FESEM (Jeol-7100F) at 20 kV.

3. Results and discussion

Metallographic evaluation was performed to understand the evolution of the high Mn-TWIP steel microstructure after the different thermal fatigue tests at 500ºC. Five specimens were analyzed corresponding to the as received specimen (Fig. 1a) and after different number of thermal cycles: 15, 36, 56 and 75 (Fig. 1b–e). The preliminary characterization of the annealed specimen, not subjected to thermal cycling, revealed polygonal and equiaxial grains for the as received specimen with an average grain size of 6.2 ± 1.5 μm, with the presence of some annealing twins. The specimen thermally fatigued during the lowest number of cycles (Fig. 1b) presented some islands of pearlite phase (see white arrows), reaching a fraction of around 7.2 ± 4.2%. The big scatter associated with this measurement is related to the heterogeneous nucleation and growing process of the pearlitic phase. Electron microscopy images corresponding to other specimens with a higher number of cycles and located close to pearlitic colonies are depicted in Fig. 1c–e. The amount of pearlitic phase created during the thermal fatigue experiment reached a value of around 24 ± 2% after 36 cycles, which remained almost unaltered for the two longest treatments. For these specimens, the average grain size was not determined due to the difficulty to clearly distinguish the grain boundaries at the pearlitic colonies.

It is well known that the pearlitic microstructure of steels and cast irons [36,37] presents a layered microstructure composed of alternating layers of α-ferrite and cementite. This microstructure can be appreciated in Fig. 2, corresponding to a totally pearlitic zone of a specimen subjected to 75 cycles. As seen in this figure, the orientation of the pearlite layers vary from one grain to another because the pearlitic phase is strongly dependent on the crystallographic orientation of the original phase from which it