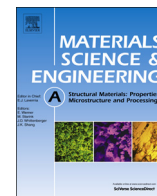




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Effect of prior austenite carbon partitioning on martensite hardening variation in a low alloy ferrite–martensite dual phase steel



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ABSTRACT

The aim of this research work is to investigate in detail the carbon partitioning within prior austenite developed during austenite to ferrite phase transformation, and consequently its relation to the martensite hardening variation in a low alloy ferrite–martensite dual phase (DP) steel. For this purpose, a wide variety of ferrite–martensite DP samples with different volume fractions of ferrite and martensite have been developed using step quenching heat treatment processes at 600 °C for various holding times after being austenitized at 860 °C for 60 min. Both spot and line scan energy dispersive X-ray spectroscopy for carbon analyses have been used in conjunction with nanoindentation tests to follow the variation of carbon partitioning within prior austenite areas and consequently the associated martensite hardening response in the DP specimens. Experimental results showed that the martensite hardening behavior was quite variable in the ferrite–martensite DP samples and even within a specific martensite area within a specific DP microstructure. A higher level and also a more scattered nanohardness were observed for martensite in the DP samples treated at 600 °C for longer holding times. These results were rationalized due to the variation of carbon partitioning within the prior austenite area developed during isothermal holding in the ferrite–austenite DP region. Longer isothermal holding times were associated with more carbon redistribution within prior austenite as a consequence of more ferrite formation, which resulted in the formation of harder martensite with a more scattered hardening response. Furthermore, compared to the central locations of martensite area, those nearer to the ferrite–martensite interfaces contained higher carbon concentration and consequently higher hardening responses.

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1. Introduction

Low carbon low alloy ferrite–martensite dual phase (DP) steels are one of the most important categories of engineering steels in which a unique combination of strength and ductility has been developed in comparison with that of microalloyed high strength low alloy steels [1–5]. The microstructural features of these engineering steels are composed of soft ductile ferrite matrix in conjunction with that of hardener martensite islands. Several investigators have studied the relationship between microstructural constituents and mechanical behavior of low carbon low alloy ferrite–martensite DP steels, reporting quite contradicting results in this regard. Fallahi et al. [6] have investigated the effect of microstructural constituents on the mechanical behavior of a low carbon low alloy ferrite–martensite DP steel containing 0.1% C, and showed that a ferrite–martensite DP microstructure containing 35–40% of martensite volume fraction has been associated with the optimized tensile and impact properties.

Bag et al. [7] have studied the relationship between microstructure and mechanical properties of low alloy ferrite–martensite DP steel consisting of higher martensite volume fraction and observed that the DP microstructure with an equal amount of finely dispersed martensite and ferrite microphases was related to the optimum combination of ductility, toughness and tensile strengths. Movahed et al. [8] have concluded that the tensile strengths, elongation and fracture energy of a low carbon ferrite–martensite DP steel were increased with increasing of the martensite volume fraction until the peak values were attained around 50% martensite and then decreased with further increasing of the martensite volume fraction in the DP microstructures. The results of these studies were in contrast with the reporting of some other investigators which believed that the tensile strength of low carbon low alloy ferrite–martensite DP steels is only affected by the martensite volume fraction and increases linearly with increasing martensite volume fraction according to the general mixture rule [9–12]. These arguments are still underway and no agreement has been reached yet. Moreover, there have been quite contradicting reports even by the linear/non-linear group, that probably the major difference can be due to the investigated steel compositions.

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It is a well-known fact that beside the effect of ferrite and martensite volume fractions, tensile strengths and ductility of low alloy ferrite–martensite DP steels are influenced by some of the other microstructural variables, e.g. the prior austenite grain size and carbon concentration, the morphology and distribution of martensite, and the nature and amount of ferrite. These factors are related to each other and should be carefully investigated in order to evaluate the separate effect of each parameter on the hardening responses, tensile strengths and ductility. Our systematic experimental works [13–15] have been concerned to report in detail the individual mechanical behavior of ferrite and martensite microphases in relation to the overall mechanical properties of a wide variety of ferrite–martensite DP microstructures. Our recently published study [15] has been focused on the ferrite hardening variation in a low carbon low alloy ferrite–martensite DP steel reporting that the ferrite hardening response is quite variable, depending on the ferrite volume fraction, ferrite morphology and the mutual interaction of ferrite with martensite in the ferrite–martensite DP microstructures. The present work tries to investigate the effect of carbon partitioning within prior austenite on the individual mechanical behavior of martensite in the ferrite–martensite DP microstructures using a commercial grade of AISI4140 steel.

2. Material and experimental procedure

In this study, a commercial grade of AISI4140 steel was used with the chemical composition shown in Table 1. The proposed heat treated specimens were cut from the as received 20 mm diameter steel rod and were first normalized to get a mixture of fine ferrite–pearlite microstructure after being heated at 860 °C for 60 min. Then, the proposed DP samples were heat treated to achieve various ferrite–martensite DP microstructures. The heat treatment processes consisted of the following sequential stages: (a) reheating at 860 °C for 60 min to get a fine and homogenized austenitic structure; (b) soaking in a predetermined salt bath at 600 °C for 20–45 s in order to develop various ferrite volume fractions; and (c) quenching in a 70 °C hot oil bath to transform all of the remaining metastable austenite to martensite. For the microstructural observation in scanning electron microscopy (SEM), samples were ground and polished mechanically, and then etched using 2% nital etchant solution for 20 s. The microstructural observations were carried out under SEM model TESCAN-VEGA-II operating at an accelerated voltage of 15 kV. For comparing the level of carbon partitioning developed within prior austenite areas during austenite to ferrite phase transformation in the ferrite–austenite DP region, both of the spot and line scan analyses for carbon concentration were carried for the short (20 s) and long time (45 s) treated DP specimens with energy dispersive X-ray spectroscopy (EDS) technique. The spot EDS analysis of carbon was carried out widely at different locations of martensite areas for the 20 and 45 s treated DP specimens including the central and peripheral regions as well as some other locations between these regions. The line scan EDS analysis was also performed for the 45 s treated DP sample along two different directions. The first direction covered two martensite areas which were separated from each other by a ferrite grain, while the second one crossed a martensite area surrounded by two different ferrite grains. The

specimen surfaces for nanoindentation tests were mechanically polished and subsequently electropolished to remove all of the damaged layers. Nanoindentation tests were conducted within martensite areas of the 20, 30 and 45 s treated DP specimens at various locations using a CSM machine model NHTX S/N: 001-03119 having a Berkovich indenter. The Berkovich indenter was calibrated by using fused silica as a reference specimen. For each of the nanoindentation tests, a load–unload displacement curve was obtained in which the ordinate showed the value of load while the abscissa corresponded to the penetration depth of indentation. Analyses for the tip calibration and the calculation of nanohardness numbers were carried out based on the Oliver and Pharr [16] method using a peak load of 10.00 mN in association with a 20 mN/min loading rate.

3. Results

3.1. Microstructural observations

Fig. 1 shows typical scanning electron microscopic (SEM) micrographs of ferrite–martensite DP microstructures developed at 600 °C for various holding times. Fig. 1(a) indicates the formation of fine ferrite grains in the vicinity of martensite areas, while Fig. 1(b) through (d) are in association with the formation of larger and larger polygonal ferrite with martensite. As can be observed, both of ferrite and martensite micro-constituents have been distinguished from each other with sharply contrasted high angle ferrite grain boundaries, and that the only indicative characteristic of martensite is the difference in its contrast with ferrite, where martensite seems to be slightly brighter due to its higher carbon concentration. These results indicate that applying a longer isothermal holding time in the ferrite–austenite DP region has resulted in the formation of higher ferrite volume fraction and simultaneously changed the ferrite morphology. The DP samples isothermally transformed at 600 °C for a short time of 20 s were accompanied by fine grain boundary ferrite morphology while those of longer times of 30, 35 and 45 s treated DP samples were in association with the formation of large polygonal ferrite appearance. On the other hand, at the early stage of austenite to ferrite phase transformation, fine ferrite grains were nucleated at the prior austenite grain boundaries as thin crystals with a remarkable continuity while at the lateral stage of isothermal transformation on the subsequent holding times, the ferrite–austenite interfaces were grown into the prior austenite grains and consequently coarser ferrite grains were formed in the DP microstructures.

3.2. Carbon partitioning within prior austenite

3.2.1. Spot EDS analysis of carbon content

An attempt has been made in order to investigate in detail the carbon partitioning within austenite grains developed as a consequence of prior austenite to ferrite phase transformation during isothermal holding at 600 °C. It is obvious that these carbon enriched austenite grains have been transformed to high carbon martensite on the subsequent rapid hot oil quenching and so the condition of carbon partitioning within austenite can be developed as the same fashion within the associated martensite areas at

Table 1
Chemical composition of the investigated AISI4140 steel (in wt%).

C	Si	Mn	S	P	Cr	Mo	Ni	Cu	Fe
0.384	0.208	0.673	0.0063	0.0093	0.971	0.154	0.0161	0.0234	Balance

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