



Effect of alloying element partitioning on ferrite hardening in a low alloy ferrite-martensite dual phase steel

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ABSTRACT

In this paper, the effect of carbon and other alloying elements partitioning on ferrite hardening behavior were studied in details using a low alloy AISI4340 ferrite-martensite dual phase (DP) steel. To do so, various re-austenitised samples at 860 °C for 60 min were isothermally heated at 650 °C from 3 to 60 min and then water-quenched to obtain the final ferrite-martensite DP microstructures containing different ferrite and martensite volume fractions. Light and electron microscopic observations were supplemented with electron dispersive spectroscopy (EDS) and nanoindentation tests to explore the localized compositional and hardening variations within ferrite grains in DP samples. The experimental results showed that the ferrite hardness was varied with progress of austenite to ferrite phase transformation in DP samples. In the case of a particular ferrite grain in a particular DP sample, despite a homogeneous distribution of carbon concentration, the ferrite hardness was significantly increased by increasing distance from the central location toward the interfacial α/γ areas. Beside a considerable influence of martensitic phase transformation on adjacent ferrite hardness, these results were rationalized in part to the significant level of Cr and Mo pile-up at α/γ interfaces leading to higher solid solution hardening effect of these regions. The reduction of potential energy developed by attractive interaction between C-Cr and C-Mo couples toward the carbon enriched prior austenite areas were the dominating driving force for pile-up segregation.

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1. Introduction

The origin of invention and development of advanced low alloy ferrite-martensite dual phase (DP) steels have been the permanent interest of automotive industry to manufacturing light, safe and cheap vehicles. Outstanding mechanical properties of DP steels have attracted a huge interest in research, modification, and development of new generation of these steels for decades [1–11]. Some of these investigations have been precisely focused on property-microstructure relationships of DP steels reporting that the strength of DP steels is related to chemical composition, internal stresses resulted from martensitic phase transformation, mean free path, stresses generated due to plastic incompatibility between soft ferrite and hard martensite microphases, and also the size and morphology of microconstituents [1,2,6,8,10]. In general, the strength of DP steels is governed not only by the strength and volume fraction of microconstituents but also by the interaction of microphases with each other which in turn can be controlled by thermal coefficient mismatch, the nature of bonding

between microphases, and the heat treating cycles [12,13]. The interaction between ferrite and martensite microconstituents has been believed to introduce unpinned dislocations generated within ferrite during subsequent martensitic phase transformation.

There is now a broad consensus that the excellent mechanical properties of low alloy DP steels such as low elastic limit, continuous yielding and high strain hardening rate are developed as a consequence of austenite to martensite phase transformation, which involves volume expansion inducing plastic deformation into adjacent ferrite grains, and therefore creating a high density of unpinned geometrically necessary dislocations within ferrite causing a higher work hardening effect of ferrite. Several investigations [6,14,15] have revealed induced geometrically necessary dislocations pile-up at ferrite-martensite interfaces and so the special strain hardening behavior of DP steels is in part the result of this phenomenon. This heterogeneous distribution of dislocations can be associated with a considerable inhomogeneity in ferrite hardening. Besides mechanical impacts, ferrite and martensite have mutual compositional relations to each other which definitely affect their microstructural and mechanical characterizations in DP microstructures. In this way, numerous attempts have been dedicated to describe carbon and alloying elements

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partitioning developed between ferrite and austenite during progress of ferritic transformation [16–19].

Newly conducted experimental works have been focused on carbon partitioning within ferrite and respective significant variation of mechanical properties within a particular ferrite grain in a particular DP microstructure [6,20]. Also, the partitioning of other alloying elements such as Mn, Cr, Ni, Mo, Co, etc. during formation of proeutectoid ferrite has been studied in detail experimentally and modelled through different theories [21]. Some of these investigators [22–24] have reported that the ferrite formation in an Fe-C-Mn or Fe-C-Ni alloy has given rise to Mn and Ni pile-up at phase transformation fronts. Experimental and numerical examinations attempted by Bradley and Aaronson [25] have shown that the ferrite formation has been accompanied by segregation of Cr (as a carbide forming element) to α/γ interfaces. In spite of the extensive researches on alloying element partitioning during austenite to ferrite phase transformation in low alloy steels for several decades [26–29], there are still doubts concerning partitioning behavior of some alloying elements such as Ni [30]. Moreover, most of these studies have been restricted to effect of such partitioning on kinetic aspects of phase transformation, while, the distribution of alloying elements can affect severely the mechanical properties of low alloy DP steels particularly localized ferrite and martensite hardening responses. Therefore, this paper is aimed to evaluate the influence of ferrite volume fraction as well as the ferrite carbon and other alloying elements partitioning on ferrite hardening variation in a medium carbon low alloy AISI4340 ferrite-martensite DP steel over a wide range of martensite content.

2. Materials and experimental procedure

In this study, a commercial grade of low alloy AISI4340 steel with the chemical composition shown in Table 1 was chosen to investigate. All of the proposed DP samples were cut off a 20 mm diameter bar of as-received hot rolled steel and were first normalized after being heated at 860 °C for 60 min, to obtain a more homogenous starting microstructure. Then, each proposed DP specimen was heat treated through the following steps to achieve various volume fractions of ferrite and martensite in DP microstructures: (1) austenitizing at 860 °C for 50 min, (2) soaking in a salt bath (1NaNO₃, 1KNO₃) at 650 °C for 3, 5, 10, 20, 40 and 60 min to obtain various ferrite-metastable austenite microstructures with different ferrite volume fraction and ferrite morphology, (3) water-quenching to transform all of metastable austenite to martensite. Using standard metallographic practice, heat treated specimens were ground, polished and etched with 2% nital etchant to distinguish the microstructural constituents from each under optical microscopy. The volume fraction of ferrite and martensite microphases were measured using Image J, an image processor and analyzer software.

For accurate examination on hardening variations within ferrite grains, nanoindentation tests were conducted on the mechanically polished, electropolished and etched surfaces of DP specimens, using a CSM machine model NHTX S/JN: 00103119 with a Berkovich indenter by applying an increasing force up to 5 mN with a loading-unloading rate of 10 mN/min. Electropolishing step was done to remove all the contaminations and strain-hardened layers

due to mechanical polishing. The nanoindentation hardness number was deduced from the force-displacement curves, using the method of Oliver and Pharr [31]. The microstructural observations were also performed with the aid of a field emission scanning electron microscope (FE-SEM) model TESCAN-MIRA III, operated at an accelerated voltage of 15 kV. In order to determine the concentration variations of carbon and other main alloying elements in ferrite grains, line scan energy-dispersive X-ray spectroscopy (EDS) analysis was carried out on various hypothetical lines, beginning from the central location of a ferrite grain toward the prior α/γ interfaces.

3. Results

3.1. Light and electron micrographs

Typical microstructural features of DP specimens heat treated at 650 °C over a wide range of isothermal holding time are illustrated in Fig. 1. Fig. 1(a) and (b) show the nature of austenite to ferrite phase transformation including nucleation and growth of ferrite grains at prior austenite grain boundaries. Ferrite nuclei growth has been continued afterwards resulting in quite distinctive ferrite grain morphology in association with prior austenite areas. On the subsequent water quenching from 650 °C to room temperature, the metastable prior austenite areas have been transformed into martensite developing various ferrite-martensite DP microstructures. Hence, the microstructural features are consisted of a mixture of grain boundary ferrite allotriomorph dispersed in a martensitic matrix for holding times of 3 and 5 min as illustrated by optical micrographs shown in Fig. 1(a) and (b), respectively.

Fig. 1(c) and (d) are light micrographs for DP specimens soaked at 650 °C for longer holding times of 20 and 60 min, respectively. In these conditions, the ferrite morphology has been apparently turned into a mixture of grain boundary ferrite with some jagged boundaries, which is consistent with morphological feature of quasi polygonal ferrite, and partly polygonal which ferrite has been also characterized by more curved boundaries. This phenomenon is due to the driving force for austenite to ferrite phase transformation generated at late stages of holding time. In fact, the mobility of semi-coherent α/γ interfaces into the parent austenite phase has been enhanced by the induced driving force and gradually has been followed by more diffusional mode of austenite to ferrite phase transformation during long period of holding time, causing ferrite morphology to be more and more polygonal in the microstructures (Fig. 1(c) and (d)).

Fig. 2 shows the progress of ferrite formation in the samples treated at 650 °C for various holding times. It can be seen that the progress of ferrite formation can be associated with a typical S-shaped curve indicating that the ferrite formation has been followed by ferrite nucleation and growth in the microstructures. A significant higher rate of ferrite formation has been occurred at early stage of austenite to ferrite phase transformation. Fig. 2 shows that nearly 29% ferrite has been produced after 10 min holding time, while the extra holding time of 50 min has resulted in just 15% rise in ferrite formation.

Fig. 3 indicates ferrite-martensite microstructural evolutions under FE-SEM for DP samples isothermally treated at 650 °C for various holding times, which points out to morphological changes in ferrite and martensite areas. The microconstituents are different in etching rate causing a greater topographical contrast that simplifies determination of microphases and following their morphological variations with good contrasting resolution. Harmonious with optical micrographs, these microstructures also show a significant increasing of ferrite volume fraction, ferrite

Table 1
Chemical composition of the investigated low alloy AISI4340 steel (in wt%).

C	Si	Mn	S	P	Cr	Ni	Mo	Cu	Fe
0.360	0.230	0.746	0.023	0.0098	1.46	1.34	0.225	0.021	Balance

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