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# Microstructure and mechanical properties of high strength and high toughness micro-laminated dual phase steels

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ABSTRACT

A series of steels with the micro-laminated dual phase microstructure were produced by hot rolling and air cooling processes in this study. Different volume fractions and morphology of the ferrite and martensite phases were obtained by adding different carbon contents in the steels containing 3 wt% aluminum. The microstructure of the dual phase steels was examined by optical microscopy (OM), scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD). It was shown that the microstructure was composed of large ferrite and martensite lamellae. Small martensite laths and a miniscule amount of residual austenite were also found in the martensite phase. The tensile, impact and hardness tests revealed that the dual phase steels had an excellent combination of mechanical properties. The mechanical properties had a great relationship with the martensite volume fraction and the micro-laminated microstructure. The fractography of impact specimens was examined to explore the toughening mechanism of the micro-laminated dual phase steels.



## 1. Introduction

Traditional dual phase (DP) steel is one of high strength low alloy steels [1]. It is a typical composite material with a soft granular ferrite (F) matrix and hard granular martensite or austenite (MA) islands. Because of its good comprehensive mechanical properties, such as low yield strength, continuous yielding, high ultimate tensile strength, good plasticity and good formability, the traditional DP steel has been widely used in the manufacturing industry, especially in the automotive industry. Three main traditional DP steels, DP590, DP780 and DP980, have been researched in regard to organization and microstructure, mechanical properties, failure mechanism, simulation and other aspects [2–7]. New varieties of dual phase steel, which have better or special performances, need to be developed. Ultrafine grain DP steel is one of the DP steel research directions. Strength and ductility of the DP steel were further improved by refining grain and organization [8,9]. Changing the phase type in the DP steel is another research direction. High bainite dual phase (HBDP) steel has high strength and special strain hardening behavior compared with the traditional DP steel [10,11]. However, these studies still belong to the traditional DP steel research area because they have the same fabrication process with the traditional DP steel: thermomechanical process followed by controlled cooling process or cold rolling process followed by continuous annealing process.

Aluminum has a great effect on promoting the formation of the ferrite phase in steel. It does not only increase the stabilization of α-ferrite but also expands the δ-ferrite phase region [12]. The dual phase microstructure can be fabricated by hot rolling directly when an appropriate amount of aluminum is added into the steel. This method saves much time and costs compared with the fabrication method of the traditional DP steel. Adding more aluminum into the high manganese steels can reduce the density of the alloy further. Low density steel is one of the focuses in iron and steel research.

The dual phase region of ferrite and austenite at high temperature could be obtained through the control of the alloy elements content in Fe–Mn–Al–C alloys. Hot rolling in the dual phase region at high temperature leads to the formation of micro-laminated dual phase microstructure. Suh et al. [13] showed the microstructure as the auxiliary work of medium-alloy manganese-rich TRIP steels, the dual phase microstructure was made up of martensite matrix and a small amount of ferrite. Park et al. [14] also exhibited the similar microstructure, high manganese content resulted in the appearance of

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stable austenitic laminae. However, few systematic studies were done on this special microstructure and its effect on the mechanical performances.

In this study, the microstructure and the mechanical properties of a series of the newly designed dual phase steels were examined to understand the influences of composition and process. Good comprehensive mechanical properties and ultrahigh impact toughness were obtained, which had a great relationship with the special micro-laminated dual phase microstructure. Tentative explanation was given to explore the strengthening and toughening mechanisms of the steels.

## 2. Methodology and experiment

Three steels with the chemical composition of (A) 0.05C5Mn3Al, (B) 0.10C5Mn3Al and (C) 0.15C5Mn3Al (in wt%) were designed in this study. Chemical compositions with different carbon contents were designed to obtain different phase ratios of ferrite and martensite phases. The designed steels were first smelt in a 50 kg vacuum induction furnace and cast into ingots. The ingots were then forged into square slabs with the thickness of 30 mm. These slabs were homogenized at 1200 °C for 2 hours (h), and subsequently hot rolled to 11 mm, followed by air cooling to room temperature. Fig. 1 shows the schematic illustration of the hot rolling process.

The samples for microstructure analysis were machined from the hot rolled plates. They were polished and etched in 4% nital. The microstructure was examined by optical microscopy (OM), scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD). The micro-hardness of different phases was measured in the transverse plane. Two groups (L–S and L–T) of standard samples for Charpy V-notch impact tests were cut with different sampling directions to examine the anisotropy of the impact toughness. L–T (resp. L–S) configuration was investigated in which L corresponds to the axial direction and T (resp. S) to the notch direction. The impact tests were measured at both −40 °C and 25 °C. The dog-bone shaped tensile specimens were cut with the axial orientation parallel to the rolling direction (L direction). The tensile tests were conducted in a universal testing machine at room temperature with a strain rate of $10^{-3}\ s^{-1}$. More details of the sampling information are shown in Fig. 2.

## 3. Results

### 3.1. Microstructure

Fig. 3 shows the optical microstructure of these steels. The bright and dark regions correspond to the ferrite phase and the

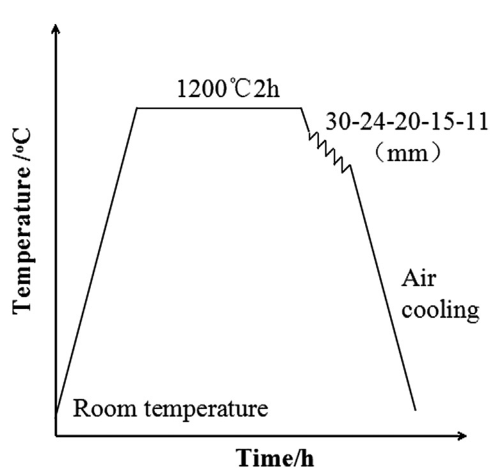


**Fig. 1.** The schematic illustration of the hot rolling process.

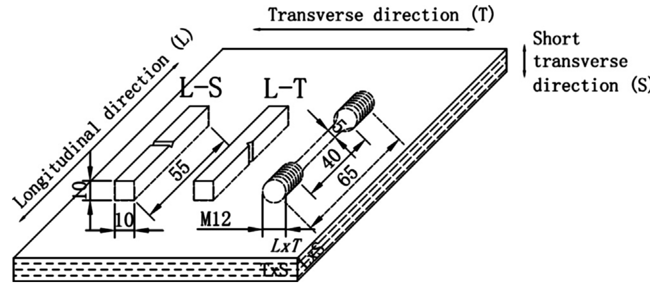


**Fig. 2.** Schematic diagram of the Charpy V-notch impact test specimens and the tensile specimen.

martensite phase, respectively. The ferrite phase existed stably during the hot rolling process due to the addition of aluminum, while the martensite phase transformed from the austenite during the air cooling process. It can be seen that ferrite and martensite phases arrange alternatively along the short transverse direction. The martensite volume fraction increased with increasing carbon content. No evidence of pearlite formed from austenite was observed in these steels after air cooling.

Fig. 4 shows SEM micrographs of these steels. The blocks, packets and laths prove the authenticity of the martensite. These steels have smooth phase interfaces between ferrite and martensite phases. Fig. 4(a), (c), and (e) also shows the long and thin ferrite phase and the sharp ends of the ferrite laminae, which would confirm that the ferrite was elongated severely along the rolling direction during hot rolling process. On the contrary, the shape of the martensite is more rounded than that of the ferrite. Plastic deformation occurred more severely in the matrix along the longitudinal direction than along the transverse direction through the comparison of the images in the L × S plane and the T × S plane. The ratio of length to width of the different phases in the T × S plane is less than that in the L × S plane.

The phase interface between the ferrite and martensite phases is further described through the analysis of EBSD as shown in Fig. 5. The results show that the phase interface between ferrite and martensite and the grain boundary of martensite are mostly large angle boundary ($\theta > 15°$). Low angle grain boundaries ($2° < \theta < 15°$) distribute more intensively in martensite than ferrite. Low angle grain boundaries in the ferrite phase are more likely to exist in the local region with high martensite volume fraction, which may be related to the extent of inhomogeneous deformation. The FCC phase region (shown by the arrow) indicates that a miniscule amount of residual austenite exist in martensite phase in C steel as shown in Fig. 5(d). FCC phase regions were also found in A and B steels, while the quantity is less than that in C steel. It can be concluded that the microstructure of these new designed steels is composed of large-sized ferrite lamellae, small-sized martensite laths and a miniscule amount of residual austenite.

### 3.2. Mechanical properties

Fig. 6(a) shows the engineering stress–strain curves of these steels. As can be seen, deformation behaviors strongly depend on the alloy composition under the same rolling process. The tensile strength increases remarkably whereas the uniform elongation and total elongation decrease slowly with increasing carbon content. However, different carbon contents have no obvious influence on the yield/tensile ratio in these steels. The stress–strain curves of these steels also exhibit continuous yielding behavior like traditional DP steels. The mechanical properties are given in Table 1. The Charpy V-notch impact absorbing energy of different test surfaces and temperatures is given in Table 2. The results in the L–S direction show extreme advantages and good regularity. The Charpy V-notch impact