Microstructure and mechanical properties of 980MPa grade Fe-Mn-Al-C lightweight steel

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Abstract. Fe-Mn-Al-C lightweight high strength steel, adding more Mn, Al and C elements into conventional AHSS, shows amazing mechanical properties, corrosion resistant and weight reduction than conventional AHSS. The mechanical properties and microstructure of Fe-15Mn-6.8Al-0.9C-0.2Ti steel after annealing process were investigated. The results show that the microstructures consisted of secondary phases TiC precipitate and ferrite in the austenite matrix. The tensile strength and elongation of the steel are 985MPa and 36%, respectively. The density is 6.86g/cm\textsuperscript{3}. Continuous strain hardening behavior provides Fe-Mn-Al-C lightweight steel with perfect combination of strength and ductility.

1. Introduction
Recently, much research on the reduction in greenhouse gases and the effective control of global warming has been conducted. In particular, the reduction in vehicle’s weight has been devoted to improve fuel efficiency and to reduce vehicle’s exhaust emission, which can result in advantages such as eco-friendliness and economic feasibility in automotive steel industries [1-2]. In addition to lightweight needs, automotive steels require a combination of strength and ductility for forming complex shapes as well as sustaining automotive structures [3-4].

Currently, the method of increasing the strength and elongation of steels is to lower the density by adding light element Al to conventional AHSS is mentioned [5-6]. Concepts of Fe-Al-Mn-C-based lightweight steels are fairly simple, but primary metallurgical issues are complicated [7-8]. This is because the lightweight steels can have ferritic, austenitic, or even multiphase structure, depending on contents of primary alloying elements of C, Mn, or Al, which complicately changes deformation mechanisms as well [9-10].

In the current study, the microstructural and mechanical properties of Fe–Mn–Al–C steels were investigated. Deformation mechanisms were also investigated in relation with annealed microstructures, and mechanical properties were compared with those of conventional AHSS.

2. Experimental procedure
Alloying elements used for lightweight steels mainly include Mn, Al and C because they decrease the specific weight, due to substitutional or interstitial atoms work to reduce the weight. Both Mn and C
are well-known austenite formers. The high C-high Mn grades needed to expand the austenite phase region to improve the ductility. Although Fe–Al-Mn-C steels have attracted interest as lightweight steels, the κ-carbide with perovskite structures occurs with increasing Al content, which causes brittleness of a Fe–Al-Mn-C steel with a high Al content [11-12]. So the formation of κ-carbide was inhibited by adding precipitation hardening element Ti. The lightweight steel used in this study was fabricated by a vacuum induction melting method, and its nominal composition is Fe-0.9C-15Mn-6.8Al-0.2Ti (wt. %). After thick plates of 60 mm in thickness were homogenized at 1150 °C for 2 hour, they were hot-rolled 950 °C. They were then cooled in a furnace from 550 °C after holding at this temperature for 1 hour in order to simulate a coiling procedure. The hot-rolled steel sheets of 3 mm in thickness were rolled at room temperature to make 1-mm-thick steel sheets. The sheets were annealed at 830 °C for 500s in a continuous annealing simulator. The density of the studied steel was calculated using JMatPro and then compared with the measurements obtained by Sartoius BSA2245 electronic balance. The mechanical properties of the steels were examined using tensile test machine. Microstructure observations were performed by light optical (LOM) and electron back-scatter diffraction (EBSD). Structural characterization was carried out by X-ray diffraction (XRD) with Cu K radiation and transmission electron microscopy (TEM). The chemical composition was determined by energy-dispersive X-ray (TEM-EDS).

3. Results and discussions
The prediction value obtained using JMatPro was 6.93g/cm3 (Figure 1). It is worth mentioning that the calculated and experimental values show a very good correlation. The density of the lightweight steel was measured to be 6.86g/cm3 by an electronic balance which shows an apparent reduction of 12% in comparison to conventional steels.

Figure 1. Density vs. temperature predicted for Fe-15Mn-6.8Al-0.9C-0.2Ti lightweight steel by JMatPro software.

Figure 2a shows optical micrograph of the annealed lightweight steel. This microstructure (Figure 2a) contains a small percentage of the ferrite (white-phase) in the austenite matrix (gray-phase). X-ray diffraction pattern of the annealed lightweight steel is provided in Figure 2b. Peaks of austenite and ferrite are observed, there is no peak of κ-carbide, which may be related to Ti addition.

Figure 3 shows the stress-strain curve and strain hardening index (n)-strain curve, which are indicated by black, blue and red line, respectively, for the DP, TRIP and lightweight steels. In the Figure 3a the lightweight steel displays much higher total elongation (36%) and yield strength (700MPa) than DP and TRIP steels. Figure 3b shows the n values of DP and TRIP steels increase at small strains, reach a maximum value. The lightweight steel exhibits much larger strain hardening capability over the whole uniform plastic deformation in comparison to DP and TRIP steels. The n of lightweight steel persists at higher strains where the strain hardening of DP and TRIP steel begins to diminish, which is closely related to the strain-induced twin deformation during tensile deformation.
Figure 2. a) Optical micrograph and b) XRD profile of the annealed lightweight steel.

Figure 3. (a) stress–strain curves and (b) strain-hardening index (n)-strain curves, which are indicated by black, blue and red line, respectively, for DP, TRIP and lightweight steel.

TEM micrograph of the lightweight steel after deformation (Figure 4) shows the thin and straight deformation twins with a thickness of a few ten nanometers, which are introduced by tensile deformation. Figure 5 shows EBSD IQ map of lightweight steels as a function of strain. The volume fraction of deformation twins increases with strain progressively. Therefore, the continuously increased volume fraction of deformation twins is the dominant continuous strain hardening mechanism of lightweight steel at higher strain levels.

Figure 4. TEM micrograph of tensile deformed lightweight steel.
Figure 5. EBSD IQ maps of the lightweight steel as a function of strain

The TEM micrograph of lightweight steel is shown in Figure 6. Figure 6 shows well dispersed particles of a few ten nanometres, which was identified as TiC precipitates due to their chemical composition. This result shows a good agreement with the previous observations that the addition of Ti caused the TiC precipitates to prevent \( \kappa \)-carbide precipitates. And the high YS of lightweight steel is probably owing to precipitation hardening of TiC particles.

Figure 6. TEM micrograph of precipitates in lightweight steel.

4. Conclusion
Microstructure and mechanical properties of Fe-0.9C-15Mn-6.8Al-0.2Ti lightweight steel were investigated in the present study. The lightweight steel showed a small percentage of the ferrite in the austenite matrix with dispersed TiC particles. The elongation and yield strength of the lightweight steel were higher than those of the DP and TRIP steels. And the lightweight steel displays the continuous strain hardening behavior, which was mainly due to the strain induced deformation twins. The suppressed \( \kappa \)-carbide in the lightweight steel was probably attributed to TiC particles.
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