ABSTRACT

To meet the growing demand of enhanced mechanical performance and reduced density, Al-added medium-Mn steels have emerged over the past few years as third-generation advanced high-strength steels. The development of medium-Mn steels heavily relies on alloying additions, thermomechanical processing and annealing conditions. In this work, three medium-Mn steels with varying Al contents of 1.23 wt.% (S1), 3.25–3.5 wt.% (S2), and 5.1 wt.% (S3) have been designed based on calculated stacking fault energy and thermodynamic phase diagrams. The steels have been produced via a conventional melting–casting route followed by thermomechanical processing. The annealed S1 steel exhibits an alternating lath microstructure of α-ferrite and γ-austenite. However, with increasing Al content, the microstructure evolves to δ-ferrite and γ-austenite phases in S3, while the S2 steel with intermediate Al-content shows a mixed microstructure comprising α-ferrite, γ-austenite, and δ-ferrite. It has been observed that the addition of more than ~3 wt. % Al promotes the formation of δ-ferrite in the studied steels. Diffusion simulations reveal preferential partitioning of Mn and C from δ-ferrite to γ-austenite, leading to its enhanced mechanical stability. The maximum (*k*~0.49) and minimum (*k*~7.30) austenite stability are observed in S1 and S3 steels, respectively that lead to inferior mechanical properties. In contrast, S2 steel, with an intermediate δ-ferrite content (~34%), exhibits optimal austenite stability (*k*~ 2.50), enabling an effective TRIP effect and resulting in superior tensile properties.

S2 exhibits the optimum tensile performance among the investigated steels; therefore, further investigations have been conducted to understand the effects of processing parameters on microstructural evolution and mechanical properties. Accordingly, two deformation routes have been employed prior to identical annealing conditions: hot rolling and the same hot rolling followed by cold rolling. The samples have been designated as HRA and CRA, respectively. Although both samples contain similar phases, their γ-austenite morphologies differ: HRA shows lath and blocky austenite, while CRA exhibits a nearly equiaxed structure. The higher dislocation density resulting from cumulative deformation promotes enhanced recrystallization and elemental partitioning in the CRA sample with an equiaxed microstructure, as well as increased austenite stability. Interestingly, the HRA sample exhibits a strength-ductility synergy of ~38.3 GPa%, which is 20% higher than that of CRA (~32 GPa%). This is attributed to differences in their austenite stability, corresponding TRIP effect, and the contribution of δ-ferrite during deformation. Furthermore, annealing durations have been varied from 1 to 72 h to study microstructural evolution, deformation behavior, and mechanical properties of the S2 sample. The longer annealing time leads to austenite transitions from a lath-like to nearly equiaxed morphology, accompanied by a reduction in local strain that indicate enhanced recrystallization. Further, tensile strength decreases, while ductility first increases from the 1 h annealed sample to the 21 h annealed sample, followed by a reduction in the 72 h annealed sample. An optimal strength–ductility balance (~42 GPa%) is achieved at 7 h and 21 h annealing. With prolonged annealing, elemental enrichments of Mn and C significantly lower the extent of TRIP effect due to enhanced austenite stability, while the contribution of δ-ferrite deformation increases due to its slow but gradual recrystallization.

Fatigue performance is critical for structural materials, as components experience cyclic loading, hence fatigue fracture is a major cause of service failure. Therefore, understanding the cyclic behavior of the studied medium-Mn steels becomes essential. Thus, the low-cycle fatigue behavior for 1 h and 21 h annealed samples has been evaluated using an incremental step fatigue test (ISFT). This approach more closely represents service conditions by applying non-uniform strain amplitudes, varying from a minimum of 0.3% to a maximum of 2%. Both samples exhibit distinct cyclic behavior, with the 1 h annealed sample showing a higher fatigue life than the 21 h annealed sample. The low mechanical stability, coupled with a progressive increase in plastic strain amplitude during cycling, results in a dominant TRIP effect in the 1 h annealed sample. The prominent austenite transformation during cyclic deformation delays strain localization, facilitates local stress field relaxation, and generates residual compressive stresses. These factors lead to crack closure and pronounced crack branching, thereby enhancing the fatigue life. Overall, austenite stability and the applied strain amplitude critically govern the cyclic deformation behavior of TRIP-aided medium-Mn steels and are crucial for application-based alloy design.

This dissertation highlights that Al addition and processing parameters such as deformation routes and annealing duration critically control the microstructure, including phase evolution, morphology, austenite stability, and the resulting mechanical behavior of TRIP-aided medium-Mn steels. In addition, Al addition lowers the density of steel, which is increasingly important for automotive applications. Therefore, these findings are expected to provide useful guidelines for developing third-generation AHSSs for automotive industry.

Keywords: Medium-Mn steels; TRIP; Austenite stability; δ-ferrite; Phase transformation; Intercritical annealing; Deformation; Tensile properties; low-cycle fatigue; Incremental step fatigue behavior.