ABSTRACT

Increasing CO_2 emissions from automobile tailpipes have intensified the demand for lightweight structural steels to improve fuel efficiency in this sector. Therefore, in this study, two lightweight advanced high-strength steels (AHSS) were designed and developed: a low (~3 wt%) Al-added, low-density, medium-Mn steel (S1) and a high (~5 wt%) Al-added, low-density, medium-Mn steel (S2). Both steels were produced via a melting-casting route using an open-air induction furnace, followed by hot forging, hot rolling, and intercritical annealing. Comprehensive investigations were conducted to establish structure-property correlations in the as-developed conditions. Microstructural characterization was performed using optical microscopy (OM), scanning electron microscope (SEM) equipped with energy-dispersive spectroscopy (EDS), electron backscatter diffraction (EBSD), transmission electron microscope (TEM), and atom probe tomography (APT). Mechanical properties were evaluated through micro-hardness, nano-hardness and uniaxial tensile testing. Steel S1 exhibited a multiphase microstructure consisting of δ-ferrite and a lamellar ferrite/tempered martensite-austenite structure in the annealed condition. In contrast, steel S2 showed a microstructure comprising δ-ferrite, austenite, reverted austenite, and intercritical ferrite (α). Steel S1 intercritically annealed at 720 °C for 1 h exhibited a high product of strength and elongation (PSE) of ~34,000 MPa%, whereas steel S2 annealed at 750 °C for 1 h showed a comparatively lower PSE of ~8,000 MPa%. The reduced PSE of S2 is primarily attributed to its higher fraction of soft δ-ferrite and increased mechanical stability of austenite that suppresses the transformation-induced plasticity (TRIP) effect. Furthermore, both steels (S1 and S2), that are having high PSE, were successfully welded in a butt-joint configuration using a fiber-coupled diode laser at a power of 2.7 kW and a welding speed of 10 mm/s, without the formation of major fusion-zone defects, such as micro-cracks and microporosity. Microstructural analysis of the fusion zone (FZ) in steel S1 reveal a multiphase microstructure consisting of δ-ferrite dendrites and a martensite-austenite mixture. In contrast, the FZ of steel S2 exhibited columnar δ-ferrite dendrites, Widmanstätten austenite (WA) at the δ-ferrite interfaces with needle-like spikes growing into δ-ferrite grains, and rod-shaped austenite within δ-ferrite, attributed to the higher Al content. The welded joints of both steels demonstrated 100% joint efficiency in terms of strength. However, the joint efficiency in terms of total elongation was significantly reduced compared to the base metal. This reduction in ductility is primarily due to the presence of hard zones in the weld region that restrict uniform strain distribution along the gauge length. To mitigate the formation of hard martensite and improve ductility in the welded joint, the as-welded low (~3 wt%) Al-added steel (S1) was subjected to post-weld heat treatment (PWHT) at 450 °C for durations of 1, 2, and 3 h. Additionally, higher-temperature PWHT at 550 °C and 650 °C for 1 h each was employed to further enhance ductility. The results indicate no significant changes in the microstructure and hardness of the base metal after PWHT up to 650 °C, primarily due to the relatively low heat-treatment temperatures (below the intercritical annealing temperature) and the inherent phase stability conferred by the alloying additions. In contrast, the fusion zone exhibited a progressive decrease in hardness and dislocation density with increasing PWHT temperature and duration, attributed to the dissolution of martensite into ferrite/tempered martensite and austenite. Fusion zone analysis further suggests that carbon diffusion is dominant at lower PWHT temperatures (450 °C), whereas at higher PWHT temperatures (550 °C and 650 °C), manganese diffusion plays a key role in stabilizing retained austenite. The calculated tensile properties of the fusion zone indicate that the PWHT temperature has a more pronounced effect on the mechanical response than the heat-treatment duration. Furthermore, texture analysis of the BCC phase in the fusion zone reveals a decrease in Cube texture intensity accompanied by a corresponding increase in Copper texture intensity with increasing PWHT temperature. This texture transition is beneficial for enhancing the strength-ductility synergy of the welded joint.

Keywords: Aluminium Added Low Density Medium Mn Steel, Laser Welding, Post-Weld Heat Treatment, Microstructural Evolution, Mechanical Properties, Texture.