ABSTRACT

A comparative study has been carried out to optimize the suitable microstructure, thereby obtaining a high strength-toughness combination in low-carbon steels used for construction, line pipe, automobiles, pressure vessel, naval, and defence applications. Three sets (S1, S2, and S3) of low-carbon steel plates and bars were received from industries and subjected to different heat-treatment schedules. The heat-treatment schedules were designed to vary the microstructural parameters, i.e., prior austenite grain size, the volume fraction of phases and other second phase particles, size and distribution of different microstructural constituents, crystallographic orientation, etc. The reheating temperature was varied from 950℃ to 1250℃ for controlling the prior austenite grain size of S1 and S2 steels. After austenitization, different cooling treatments (i.e., furnace cooling (FC), air cooling (AC), and water quenching (WQ)) were carried out to achieve various combinations of phases. Besides obtaining the equiaxed or quasi-polygonal microstructure morphology following conventional FC and AC treatments, typical heat-treatments were applied in S3 steel (plate) for developing ferrite-bainite dual-phase steel having blocky and fibrous microstructure morphology. Correlating the heat-treatment process parameters and microstructure with tensile and impact properties, it was found that quenching from a lower austenitization temperature can reduce the effective grain size (7.2 ± 2.2 μm). Such a quenching followed by tempering treatment leads to the enhancement of strength (YS ~ 550 MPa, UTS ~ 748 MPa) and reduction of ductile to brittle transition temperature (DBTT ~ -115 ℃) at the expense of impact energy absorption capacity (Upper Shelf Energy, USE, ~ 73 J). The reduction of impact energy absorption is associated with limited plasticity due to a higher dislocation density present in the martensitic structure. Development of dualphase or multiphase microstructures consisting of different combinations of tempered martensite, bainite, fine polygonal ferrite, and acicular ferrite was found to improve impact properties (27J-ITT ~ 19 ℃, USE ~ 154 J), sacrificing a small amount of strength (YS ~ 384 MPa, UTS ~ 626 MPa). An impressive improvement in strength and impact toughness has been achieved by developing a fibrous microstructure with alternate lamella (2–4 μm thick) of ferrite and bainite through intermediate cooling (IC) treatment. Fine film-like structure with large orientation difference across the ferrite-bainite interface boundaries not only increased the strength (YS ~ 740 MPa, UTS ~ 1143 MPa) but also resulted in frequent deflection in cleavage crack propagation path, which improved the impact toughness and reduced the DBTT (USE ~ 222 J, DBTT ~ -54 ℃). Considering the effect of second phase particle on fracture micromechanism, it is known that the presence of coarse cuboidal TiN particles (>1μm) in coarse ferrite grain structure increases the DBTT by promoting the particle-controlled cleavage crack propagation. The small size and fraction of precipitates (like TiN, Nb, and V carbonitrides) present in the investigated S1 steel reduced the possibility of particle-controlled crack propagation and grain size-controlled crack propagation, aided by fine grain structure resisted the cleavage fracture. Therefore, the presence of fine second phase particles or precipitates (TiN ≤ 0.4 μm) with fine effective grain size (7 - 12 μm) can be recommended for achieving high strength, high USE, and low DBTT (YS: 500 – 550 MPa, USE: 220 – 230 J, DBTT: ~ 115 ℃) in low-carbon low-alloy steels. Besides the conventional microstructure, the effect of gradient microstructural morphology in thermomechanically treated rebar (S3 steel bar) on impact transition behaviour has been studied. Considering the difficulty in preparing standard geometry Charpy V-notch specimens from the TMT rebar, a new specimen design, on semi-circular cross-section, is proposed in the present study for the impact testing of rebars. Among the investigated rebars (having a diameter of 10, 12, and 16 mm), higher section rebar (16 mm) showed the best combination of strength, ductility, and impact toughness, possibly due to the higher tempered martensite rim fraction and the presence of degenerated pearlite and lower-bainite at the core region of that rebar. Moreover, compressive residual stress distributed inside the rebar has also influenced this steel's impact transition behaviour. Considering the safety aspects, the life of a fire-affected building reinforced with the TMT rebar would be in danger if those rebars inside the concrete experience temperature at or above 550℃. In this situation, the gradient microstructure became highly affected and the beneficial compressive residual stress distributed inside the rebar got released to deteriorate the strength and impact properties.

Keywords: Low-carbon Steel, Heat-treatment, Microstructural constituents, Microstructural morphologies, Multiphase microstructure, Grain refinement, Strength, Ductility, Charpy impact toughness.