Abstract

In the present work, attempts have been made to design and develop low-carbon, low-alloy high strength carbide-free bainitic steels for heavy haul rail tracks through the usual melting-casting-hot rolling-air cooling route. Available thermodynamic and kinetic models were used to understand the influence of alloying elements on several parameters related to bainite transformation (*viz.* bainitic hardenability, T_0 temperature, cementite precipitation, stability of austenite, bainite-start temperature *etc*.). Similarly empirical models available in literature were used to estimate the strength and ductility of bainitic steels from the chemical compositions and microstructural parameters. Microstructures of the developed steels primarily consisted of carbide-free plates of bainitic ferrite having 120-300 nm thickness interspersed with films of retained austenite having 21- 130 nm thickness. These steels possess UTS of 1200-1600 MPa, TE of 14-18% and room temperature Charpy V-notched impact energy of 20-30 J which are far superior in comparison with conventional 880 grade pearlitic rail steels and other bainitic rail steels reported in literature. The bainitic ferrite in the hot rolled and continuously cooled steels was estimated to possess 0.07-0.11 wt.% carbon, which is higher than conventionally considered value of 0.03 wt.%.

The kinetics and extent of bainite transformation have been studied extensively and effects of different processing parameters (*viz.* austenite grain size, strain, deformation temperature, prior bainite/martensite) were investigated. Sheaves of bainite grow to a larger size with increasing prior austenite grain size which results in an acceleration in the overall bainite transformation kinetics and also an increase in the total bainite fraction. Although the nucleation site density of bainite increases in plastically deformed austenite, each nucleus transforms a smaller volume of austenite because the defects introduced by deformation obstruct the motion of the glissile austenite/bainite interface. As a result, the total amount of bainite that can be obtained at any isothermal transformation temperature is reduced relative to that in the undeformed austenite.

Experiments involving two-step isothermal transformation to bainite showed thermal stabilization of austenite, where the amount of bainite in the two-step treatment was less than that in a single-step isothermal treatment. A decrease in the bainitic ferrite plate volume due to higher strength of parent austenite at lower temperature and higher nucleation rate, together with limited number of nucleation sites are believed to be responsible for this stabilization. It is thus inferred that the ‘additivity principle’ does not apply to bainite transformation in continuous cooling condition.

The work hardening characteristics and prevalent damage mechanisms of carbide-free bainitic steels were examined with special emphasis on the stability of retained austenite against deformation induced martensite (DIM) transformation. Due to greater sensitivity to microstructural details, modified Crussard-Jaoul (C-J) analysis is found to best describe the work hardening characteristics of carbide-free bainitic steel in comparison with the Hollomon and differential C-J analyses. Preferential deformation of retained austenite, followed by DIM transformation of retained austenite and finally simultaneous deformation of all the microstructural constituents, in association with dynamic recovery in bainitic ferrite are believed to be the three main deformation mechanisms in such steels. Furthermore, films of retained austenite were found to be more stable than blocks of retained austenite. Improved load transfer due to enhanced specific surface area and higher critical stress required to nucleate deformation induced martensite are believed to be the main reasons for higher stability of retained austenite films.

Orientation dependence of deformation induced martensite on retained austenite during uni-axial tensile deformation of carbide-free bainitic steel has been studied in detail using combined crystal plasticity modelling and experimental macrotexture analysis. The results indicate that the P {110}<122> component of retained austenite predominantly undergoes DIM transformation. Experimental evidence in a reference material (AISI 316L stainless steel) further confirms this. Analytical calculations in 316L stainless steel using a model based on phenomenological theory of martensite crystallography (PTMC) conjoined with interaction energy and prior austenite reconstruction from EBSD data indicate that the orientation dependence of DIM could not be explained completely by Patel-Cohen model. However, variant selection according to Patel-Cohen model was observed when deformation induced martensite transformation of P component austenite was considered.

Keywords: Carbide-free bainite; Transformation kinetics; Thermomechanical processing; Mechanical properties; Deformation induced martensite; Variant selection.