# Abstract

A comparative study has been carried out on the development of ultrafine grained ferrite-carbide and ferrite-martensite dual phase (DP) structures in a low carbon microalloyed steel processed using two different thermomechanical processing routes, (i) inter-critical deformation and (ii) warm deformation and inter-critical annealing. The samples were deformed using Gleeble3500® simulator, maintaining a constant total strain ($\varepsilon = 1$) and strain rate ($\acute{\varepsilon} = 1/s$). Ultrafine grained DP structures could be formed by careful selection of deformation temperature ($T_{def}$) for inter-critical deformation and annealing temperature ($T_{anneal}$) for warm deformation and annealing treatment. The ferrite-martensite microstructures developed in this study have ferrite grain sizes in the range of 1.5 to 4.0 µm, the sizes and fractions of fine martensitic islands ranged from 1.5 to 3.0 µm and 15 to 45 percent, respectively. Dynamic strain induced austenite to ferrite transformation followed by continuous (dynamic) recrystallization of the deformed ferrite grains dictated the grain refinement during inter-critical deformation, while, continuous (static) recrystallization by pronounced recovery dictated the grain refinement during warm deformation and inter-critical annealing. The fraction of high angle boundaries (with >15 degree misorientation) increased with the increase in $T_{def}$ or $T_{anneal}$, depending on the processing schedule. The effect of different starting microstructures, i.e. ferrite-pearlite (F+P) and ferrite-martensite (F+M) with varying martensitic morphologies namely blocky martensite ($F+M_b$) and fibrous martensite ($F+M_f$) and heating rates (1 - 200 °C/s) on the formation of ultrafine DP steels after cold rolling and inter-critical annealing have been investigated. Grain refinement after annealing of cold rolled samples depends on the rate of recovery, recrystallization, transformation, and grain growth. Strong recrystallization-transformation interaction and suppression of ferrite grain growth by uniform distribution of fine austenite islands, formed around the carbide particles, offered finest ferrite grain size and best combination of strength and ductility in $F+M_f$ sample compared to other samples. Mixed ferrite grain structures, comprised of fine and coarse grain regions and showing 'bimodal' grain size distribution along with carbide and martensite phases have also been produced by rapid inter-critical annealing of warm rolled (or cold rolled) samples. The tensile response of the ferrite-carbide and ferrite-martensite steels with unimodal (fine or coarse) and bimodal distribution of ferrite grains have been compared. Ultrafine grained dual phase structure offered the best combination of tensile strength and ductility among all the samples. Finally the effect of microalloying elements i.e. niobium and vanadium with varying carbon and nitrogen contents on different thermomechanical processing (continuous or natural cooling and coiling study) have been investigated. Multiple light deformation passes in continuous cooling schedule, along with low C (~0.03 wt. %) chemistry, have been found to be superior over single pass, heavy deformation schedule in terms of precipitate size and hardness in Nb-microalloyed steels. High C, low N chemistry with an intermediate cooling rate (~1.4 °C/s) and low C, high N chemistry with an intermediate coiling temperature (~600-650 °C) are found to be superior in terms of precipitation and tensile properties in V-microalloyed steels.