Abstract

The present study demonstrates the evolution of precipitates and texture during the recrystallization of different grades of single phase ferritic steels. Single phase ferritic steel has been chosen for the investigation in order to eliminate the effects arising from the complex multiphase system and to focus on the role of alloying elements, initial as-cast structure and different processing thermomechanical parameters on the development of final structure and their effect on mechanical properties. Most of the investigated steels are as received industrial grades except one where suitable alloy design and casting were carried out on a laboratory scale intended to achieve significant nanoprecipitation strengthening. All the steel samples were thermomechanically processed, characterized and tested for the evaluation of mechanical properties. The evolution of clusters and nano-sized precipitates during the course of hot rolling, annealing, or ageing treatment was studied extensively through scanning electron microscopy, transmission electron microscopy and atom probe tomography. The evolution of grain structure, texture and recrystallization process was studied through scanning electron microscopy, electron back-scattered diffraction technique and hardness measurements.

The thesis is majorly divided into two sections. In section A, to investigate the effect of atom clusters/fine scale precipitates on the evolution of ferrite grain structure during annealing of the deformed sheet, two precipitation-strengthened steels were chosen. The first study under this section reveals remarkable retardation of recrystallization and grain growth during sub-critical annealing of 60% cold-rolled ferritic steel containing Ti and Mo. The steel exhibited just a partially recrystallized (60%) fine ferrite grain structure (~8.8 μm) even after annealing for 24 h at 600°C. An intriguing aspect was the emergence of tiny partially coherent (Ti, Mo)C precipitates in Ti-Mo steel after 8 h of annealing. Those precipitates effectively pinned down the dislocations and migrating ferrite boundaries, significantly retarding the recrystallization and grain growth, respectively. Grain refinement and substantial precipitation strengthening from the partially coherent (Ti, Mo)C nano-sized precipitates ensured a decent combination of strength (UTS ~ 821 MPa) and ductility

(~ 16.5% total elongation) in the 8 h annealed sample. Extensive yield point elongation (~ 4%) observed in that sample (undesired for automotive-body application) can be attributed to the combined effect of shearing of nano-sized partially-coherent precipitates by the dislocations along with Cottrell locking of dislocations by the solute atoms.

The second study under section A elaborates on the age-hardening behavior of Cu, Ni, and Al added steel by the formation of stable copper-aluminide intermetallic precipitates as well as B2-NiAl and Cu-rich nanoprecipitates. After solutionizing treatment, during ageing at 400°C, interestingly, the hardness plot reveals two peaks, 1st at 4 h (380±8 Hv) and 2nd at 22 h (480±10 Hv). There is a diminutive drop in the hardness to 369±7 Hv in between i.e., at 14 h of ageing. Cu lean intermetallic precipitates (e.g. CuAl) form during the early stages of ageing owing to the lower diffusion coefficient of Cu in the matrix and small free energy of formation. Apart from that, the lower diffusion coefficient of Cu and Ni segregation at the interface retards the coarsening kinetics of the precipitates. At the later stage, ordered B2-NiAl and Cu-rich BCC precipitates, in combination, further enhance the age-hardening behavior until coarsening takes place and the BCC Cu precipitates transform into elongated FCC precipitates through the 9R structure.

The second section of the thesis comprises the role of grain structure, texture and precipitates on the recrystallization and mechanical properties in two different grades of ferritic stainless steels, one Ti stabilized and another dual stabilized ferritic stainless steel with Ti and Nb. In Ti stabilized, 409L grade ferritic stainless steel, the effect of the initial as-cast structure on the microstructure-texture evolution during thermomechanical processing was studied. Samples from the regions of cast slab having ‘columnar’, ‘equiaxed’ and a mixture of ‘columnar’ and ‘equiaxed’ grains were subjected to two different processing schedules, one with intermediate hot-band annealing before cold-rolling followed by final annealing, and another without any hot-band annealing. Electron back-scattered diffraction study reveals that large columnar crystals with cube orientation are very difficult to deform and recrystallize uniformly. Resultant variations in ferrite grain structure and retention of the cubetextured band in cold-rolled and annealed sheet contribute to ridging behavior during stretch forming. An initial equiaxed grain structure is certainly beneficial to reduce or even eliminate ridging defects by producing a uniform ferrite grain structure, free from any texture banding. The application of hot-band annealing treatment is also advantageous as it can maximize the evolution of beneficial gamma-fiber texture and eliminate the ridging defect in the case of a completely 'equiaxed' starting structure. Such treatment reduces the severity of ridging even if the initial structure contains typically mixed 'columnar-equiaxed' grains.

The final study focuses on the processing of a thick plate (≥12 mm) and strip (3-4 mm) of a Ti-Nb dual stabilized ferritic stainless steel, where hot rolling reduction is comparatively less. The recrystallization kinetics of hot rolled plate was studied with detailed microstructural and texture evolution during annealing. The investigation was further extended to cold rolling and annealing considering the industrial application in thicker strip production. Mechanical properties were correlated with the processing schedule and microstructural parameters. The fine and recrystallized hot band structure is required to get the desired fine microstructure in cold-rolled and annealed conditions. Higher hot band annealing time facilitated significant precipitation providing enhanced strengthening after cold-rolling and annealing treatment despite having a coarser grain size. Mechanical properties were directly correlated to the high-angle, and low-angle grain boundaries and geometrically necessary dislocations in the investigated steel.

Keywords: High strength ferritic steels; Ferritic stainless steels; Sub-critical annealing; Hot-band annealing; Age-hardening; Recrystallization kinetics; Atom Probe Tomography; Nanoprecipitates; Texture banding; Ridging; Structure-property correlation.