Chapter 7: Summary of the present investigation and suggestions for future work

7.1 Summary of the present work

Three low density steels of austenitic, austenite based in-situ TiC reinforced composite and austenite based duplex steels are designed and successfully produced through vacuum induction melting process using controlled atmosphere of argon. Steels cast in copper mold into plate forms. Results of thermomechanical processing of above steels can be summarized as follows:

Austenite based low-density steel: Addition of 6.2 mass% aluminum reduces density to 6.99 g/cm³. Repeated annealing of cold rolled low-density steel leads to refinement and bimodal grain size distribution. Short annealing twice reduced localized strain, and dislocation density, recrystallizes it and develops recrystallization texture. Strengthening of cold rolled material is dominated by contribution from dislocation but yield strength of annealed material is mainly controlled by grain refinement. Work hardening of cold rolled material exhibits easy glide and rapid steady linear work hardening rate but repeated annealed material displays additional stage of dynamic recovery due to higher elongations and high dislocation storage. Cold rolled steel displays highest yield strength due to high dislocation density and low elongation but repeated annealed one depicts moderate yield strength but high elongation.

Austenite based in-situ TiC reinforced composite:

Addition of Ti in Fe-18%Mn-6.5%Al-1.25%C produces in-situ TiC reinforced austenite matrix composite. Presence of TiC reduced grain size, density but increases Young’s Modulus, yield strength and ultimate tensile strength but reduces elongation.

Strengthening mechanisms in the steel primarily arise from solid solution effects, with enhanced dislocation and grain boundary strengthening due to the presence of TiC; however, precipitation strengthening is limited by the coarse size of the TiC particles. Presence of TiC in PD2-S also displays 3 stages of work hardening i.e., easy glide, steady linear work hardening rate and dynamic recovery. In both stage I and stage II, the work hardening rate decreases much faster than that of base alloy with increasing true strain. Work hardening rate in stage I is much faster than stage II.

Austenite based duplex low-density steel:

The incorporation of 10.5 mass% aluminum in the selected low-density steel (PD1) reduces density to 6.67 g/cc. Homogenization and hot rolling of the selected low density duplex steel precipitates 13% B2. Annealing of the hot rolled steel at 930°C, increases the B2 content to 18%. Ageing of the annealed steel precipitates 8% kappa pearlite which consists of 3% kappa carbide and 5% ferrite. Hot rolled low density steel reports high yield strength due to high amount of solutes, dislocation density and low grain size. Strength decreases in annealed material as a result of reduction in dislocation density. Ageing recovers strength to highest level due to precipitation hardening. Strengthening of homogenized and hot rolled steel/ annealing of it is dominated by solid solution followed by dislocation and grain boundary strengthening. In case of aged low density steel major contribution to yield strength comes from solid solution followed by dislocation and precipitation. The ductility decreases with increasing precipitation of B2/Kappa carbides. Homogenized and hot rolled, annealed steel follows 3 stages of work hardening i.e., easy glide, steady linear work hardening rate and dynamic recovery whereas aged steel with reduced ductility displays first two stages. Coarse grain size and low volume fraction of B2 in hot rolled steel induces lower work hardening which results in low UTS. High volume fraction, wide range of B2 size distribution leads to high amount of work hardening in annealed steel. Aged steel displays highest UTS due to high yield strength and high amount of work hardening resulting from high fraction of B2 and appreciable amount of kappa pearlite.

Electropulsing of annealed and aged austenite based duplex low-density steel:

Electropulsing of annealed duplex low density steel raises the temperature to 346°C, partially dissolves banded, globular and platelets of B2 at this low temperature which is lower than the equilibrium solvus temperature by reducing activation energy. Electropulsing deforms B2 as well as recrystallizes austenite and reduced the intensity of deformation texture. At low current density of later pulse of electropulsing signal, the material is supersaturated due to rapid cooling but the energy is sufficient to accelerate precipitation of B2. Dissolution and precipitation refine the size of B2 and improves its distribution. Electropulsing also spheroidizes the existing B2 precipitates. The improvement in yield strength and work hardening of electropulsed steel is due to refinement, enhancement in uniformity in size distribution and additional B2 precipitation. Improvement in ductility and higher amount of work hardening leads to higher ultimate tensile strength. Annealed as well as electropulsed duplex steel follows the stages of work hardening of easy glide, steady linear work hardening rate and accelerated dynamic recovery, Ludwigson flow behavior. The work hardening rate of annealed steel decreases more rapidly due to more dislocation activities and higher interparticle spacing than that of electropulsed sample and material quickly goes to accelerated dynamic recovery. Steady linear hardening rate is prolonged for electropulsed duplex low-density steel due to higher ductility. Electropulsing of aged duplex steel breaks kappa carbide partially and spherodizes it due to reduction in barrier energy of dissolution and diffusion, respectively. Refinement of B2, dissolution of kappa carbide decreases the YS and UTS but recovers tensile toughness due to increased ductility. The work hardening rate of aged and electropulse aged materials are similar to those of annealed and electropulse annealed ones but with only two stages of easy glide and steady linear hardening stage.

7.2 Suggestions for future work

The following suggestions are made for the future work based on the present investigation

- Addition of limited amount of TiC increases the strength, elastic modulus and specific stiffness of austenitic low-density steel. Addition of higher amount of TiC through in-situ reinforcement needs to be done to further increase the specific stiffness to successfully incorporate these steels into applications.
- Even though strength of low-density steel is significantly higher than austenitic stainless steel, ductility is a concern, needs further improvement.
- The tensile test of duplex steel in present investigation is performed at strain rate of 10^{-3}/s. Austenitic steels are used at low temperatures for cryogenic applications. The transformation behavior and mechanical properties needs to be studied at low as well as cryogenic temperature at various strain rates.
- Conventionally, austenitic stainless steels are used for hydrogen storage tanks due to its higher hydrogen solubility and low diffusion rate. The presence of Ni, Cr increases the cost of stainless steels. As the present materials are containing austenitic matrix with lesser cost alloying elements, and higher strength compared to stainless steels, their suitability to hydrogen storage tanks needs to be evaluated.
- The density is reduced up to 6.67 g/cc with 10.5% presence of Al. Addition of higher Al contents with optimizing remaining alloying elements may be done to further reduce the density by maintaining higher strength levels.