Abstract

High manganese steels have recently drawn much interest in steel industries in an attempt to reduce the production cost by replacing expensive alloying elements like Ni and Cr, etc. High manganese steels can be categorized as Hadfield steel, high Mn TRIP steel, TWIP steel and TWIP/TRIP steel. The production of TRIP and TWIP steels always involves thermo-mechanical processing such as hot rolling, cold rolling and annealing. In all these stages, the steel goes through thermal cycles involving both heating and cooling. Therefore, martensite formation is likely to take place in these steels. Martensite formation generally takes place during thermal, thermo-mechanical and deformation processes. Mechanical properties of steels subjected to rolling and annealing are determined by the presence of different phases and their morphology. Thus, understanding the thermally induced and deformation induced martensite in these alloys is extremely important because it determines the mechanical properties that make them suited for applications.

Stacking fault energy (SFE) is considered as the main criterion to design high manganese steels (TWIP and TRIP). Several direct and indirect methods such as TEM node method, X-Ray method and thermodynamic model are generally used for the estimation of stacking fault energy. For low SFE high manganese steels, it is difficult to measure their SFE by TEM method because their SFE is so low that extended dislocation can barely be constricted.

To study martensite formation, different high manganese steels with varying carbon content were selected and cast and hot-forged in laboratory. Different thermodynamic models available in literature were used to calculate the driving force ($\Delta G^{\gamma \to \varepsilon}$) for $\gamma \to \varepsilon$ martensite transformation then estimate the Ms temperature for the formation of ε-martensite in these steels. The models proposed by Olson and Cohen and X-ray analysis were then used to calculate the SFE of these steels. The steels were subjected to cooling and deformation test. Optical micrograph, SEM, TEM and XRD analysis was done for microstructure observation and phase identification. The Ms temperatures of ε-martensite in low carbon-manganese steels used in this work were estimated to be higher than room temperature and SFE value was in the range of martensite formation.

Therefore, high fraction of martensite was formed in these steels during cooling from 1000ºC. Slow cooling (in furnace) was found to give higher fraction of martensite in comparison to water and ice quenching. Samples quenched in liquid nitrogen however gave higher fraction of martensite because of larger degree of super cooling below the Ms temperature. It has been argued that isothermal martensite forms in these cases. The Ms temperatures of ε-martensite in other steels with higher carbon and with 1.5 to 4 wt% Al were less than room temperature and the SFE values were in the range of twinning. No martensite was observed in these steels. Increase in holding time from 10 to 30 and 60 minutes at 1000°C leads to slight increase in martensite fraction presumably because of release of stress and larger austenite grain size. To confirm the formation of isothermal martensite, steel samples were held 10°C below the Ms temperature for 900 and 3600 seconds followed by water quenching. Martensite fraction was found to increase in comparison with the samples quenched directly from 1000°C in water at room temperature. The value of stacking fault probability (Psf) of the samples cooled at different rates / media was found to decrease in comparison with forged sample. Decrease in Psf value indicates the consumption of stacking faults due to martensite formation during cooling of samples. Martensite fraction increases with increase in grain size after quenching. Apparent SFE has negligible variation with increase in grain size.

The as-forged samples were deformed at room temperature in tension, compression and by rolling. The amount of martensite was found to increase with strain in all the cases. The stability of austenite to strain induced transformation was found be higher for cold rolling and compression. By comparison, the stability of austenite was lower in case of deformation in tension.

Among high manganese steels, TWIP steel offers good combination of strength and ductility because of extensive formation of twins during deformation. One of the drawbacks of these steels is lower yield strength. Therefore, work is being done by various researchers to improve the yield strength and other tensile properties by decreasing the austenite grain size through recrystallization process. Therefore, the effect of cold rolling and annealing on recrystallization behavior was studied in the present study. TWIP steel samples in the as forged condition were cold rolled giving different reductions (40-80%) and annealed at different temperatures (700°C -900°C). During cold rolling of steel,

deformation twins are formed within austenite grains and its fraction increases with cold reduction. Recrystallization does not take place during annealing at 600°C for 180 minutes and twin structure is maintained. Recrystallization starts after 10 minutes for all the cold rolled samples at 700°C and the time decreases with increase in deformation and annealing temperature (800°C and 900°C). Recrystallization takes place rapidly at 900°C and it takes 1-2 minute for complete recrystallization of 70% and 80% cold rolled samples while 5 to 8 minute are required for 40%, 50% and 60% cold rolled samples . JMAK exponent value was found to be in the range of 0.2 to 1.40. JMAK exponent below unity may imply that (i) the nucleation rate decreases with time and (ii) heterogeneous nucleation takes place. Presence of deformation twins after cold rolling helps to speed up the recrystallization kinetics at high temperature as 800°C and 900°C. Activation energy (Q) of recrystallization is found to decrease with increase in cold reduction. Activation energy is found to be in the range of 108 kJ/mol to 273 kJ/mol. Cahn-Hagel growth rate (G) measurements indicated that the growth rate decreases throughout the recrystallization for 700°C, 800°C and 900°C.

The effect of twinning and (ε and α') martensite on mechanical properties has been studied in high manganese steels. Hollomon analysis shows multi-stage deformation in the forged and quenched steels. Different strain hardening exponent (n) values were obtained in different stages of deformation. Low carbon steels (C=0.15 and C=0.2 wt%) having relatively higher fraction of martensite in the initial as-forged samples show single stage deformation and have single n value whereas steels with medium (0.35 wt%) and high (0.5wt%) C having no martensite in the initial condition shows three stages of deformation having three different n values. n value increases from stage I to stage III. Higher n value is obtained in the last stage where strain hardening is higher due to the rapid formation of martensite or twinning. Samples quenched from 800ºC and 1200ºC to room temperature which have high fraction of martensite offer poor mechanical properties. Sample quenched from 1000ºC which has martensite and twinning together after tensile test offers better mechanical properties.

Keyword: Stacking fault energy, Martensite formation, Recrystallization and Mechanical Properties