Abstract

High Strength Low Alloy (HSLA) steels are of particular interest for large submarines, offshore structures, line-pipes and other structural applications, that require a combination of strength, toughness and weldability. The present study focuses on the structure - property correlation in one HSLA-80 and two HSLA-100 steels supplied by the Naval Research Laboratory of U.S.A; these steels contain several alloying elements such as Cu, Ni, Mo, Mn, Nb, Al, etc.

In the present work, a simple analytical approach has been presented to predict the equilibrium solubility of stoichiometric, as well as, non-stoichiometric carbonitrides in the HSLA steels. Formation of AlN precipitates has also been considered to examine the extent of its influence on the solubility of carbonitrides. In addition, to investigate the effect of titanium addition on the solubility of complex carbonitrides such as Nb-Ti(C,N), a sub-lattice regular solution approach, similar to that of Zou *et al.* [ZK92], has been adopted here with some modifications. The solubility of niobium carbonitride predicted by the present analysis is in agreement with that reported in the literature. The dissolution temperatures of AlN and niobium carbonitride in the present steels were estimated and these were found to be a function of the alloy chemistry. The presence of AlN precipitates is observed to have an appreciable influence on the solubility of Nb, N and C, and consequently on the solubility of carbonitrides. An increase in Ti content was also found to decrease the solubility of Nb and N, while the solubility of C was insensitive to Ti addition. The solubility of Nb and nitrogen in case of non-stoichiometric precipitates is predicted to be higher than that of stoichiometric precipitates; but the solubility of C does not appear to depend on the stoichiometry of the precipitate. The calculated solubility of Nb in ferrite is higher, whereas the C and nitrogen solubility is lower than those predicted in the literature.

In order to study the phase transformation behaviour in the present HSLA steels, several experimental techniques, such as dilatometry, optical microscopy, transmission electron microscopy (TEM), scanning electron microscopy (SEM), electrical resistivity, hardness and impact property measurements, were extensively used in the present investigation.

Microstructure of the HSLA steels in as-quenched condition showed a predominantly lath martensite structure with high dislocation density. Grain coarsening behaviour of these steels was assessed by optical microscopy. An abrupt rise in prior austenitic grain size (PAGS) following quenching from Tq = 1050-1100 °C was observed, which seems to be related with the coarsening of precipitates [AlN/Nb(CN)] beyond a critical size [GP67]. The hardness of the samples quenched from various austenitizing temperatures (800-1200 °C) was measured and found to be highest for austenitizing at 800 °C. This may be partly attributed to the finer laths / packets and the presence of some copper / Nb(C,N) precipitates. The dissolution of copper precipitates and coarsening of the AlN / Nb(C,N) at higher Tq result in a drop in hardness.

The transformation of austenite and the precipitation characteristics during continuous heating and cooling have been studied by dilatometry and resistivity technique. The bainite start (B_s) and bainite finish (B_f) transformation temperatures were determined by the resistivity method, which compare well with those determined by dilatation experiments. Optical and scanning electron microscopy studies endorsed the formation of bainite and / or martensite during continuous cooling. Continuous Cooling Transformation (CCT) diagrams for both HSLA-80 and HSLA-100 steels were constructed from the dilatation data. Non-isothermal kinetic analysis of CCT data yields two activation energies, i.e. 145-200 kJ/mol and 40-50 kJ/mol. The former possibly corresponds to the defect assisted diffusion of Cu in acicular ferrite / bainite matrix leading to fine copper precipitates, whereas the latter may be associated predominantly with the diffusion of carbon in ferrite [JC92].

The kinetics of copper precipitation during isothermal aging was also assessed by measuring the resistivity continuously as a function of aging time at T_A = 450-550 °C. A kinetic analysis using Johnson-Mehl-Avrami equation indicates that the precipitation occurs in two stages. The first stage, presumably associated with copper precipitation, has an activation energy of 114-126 kJ/mol, which is much lower than that for diffusion of copper in ferrite (284 kJ/mol), apparently indicating the dominant influence of high density of dislocations in the quenched martensite matrix on the diffusive mass transfer during aging. In the second stage, a lower activation energy (64-77 kJ/mol) may be ascribed to the diffusion of carbon in ferrite during tempering of the HSLA steel in presence of the lattice defects. From the resistivity data noted in course of heating to 500 and 550 °C (rate of heating = 0.33 °C/s), the amount of copper precipitation could be estimated as 1.2 and 1.6 wt.%, which matches well with those derived from isothermal resistivity experiment.

A peak in the hardness during isochronal (1 h) aging was observed at T_A = 500-550 °C, whereas Charpy impact toughness was lowest at T_A = 450 °C. Aging at higher temperatures manifested a fall in the hardness and a rise in the impact strength possibly due to the formation of coarser copper precipitates. The fractographs of the Charpy specimens were in good agreement with the impact strength measurements, apparently indicating an adverse effect of the coherent copper precipitates on the impact properties.