Abstract

Welding has been one of the widely used fabrication processes even for critical engineering components in aerospace or nuclear industry. With growing demand for the safety of welded structures, integrity assessment has become an essential aspect of production welding. The heterogeneous nature of the weldment, comprising weld metal, heat affected zone (HAZ) and base metal, makes it very difficult to obtain a representative property data for the welded joint which can be employed for integrity assessment. Moreover, the HAZ itself comprises a range of microstructures leading to a wide variation in the mechanical properties within the HAZ thus complicating the establishment of representative property data for welded joints. However, a closer look at the causes of weld related failures reveals that most of the failures have been attributed to the HAZ. As HAZ forms the weakest link in a welded joint, it is generally treated as a metallurgical notch and evaluated. The metallurgical notch arises out of brittle microstructural regions, within the HAZ, often referred to as local brittle zones (LBZ) where the stress amplitude would be much higher than in the surrounding areas. Present day practices suggest the application of fracture mechanics (FM) based concepts, such as, crack tip opening displacement (CTOD), δ_c, for the assessment of integrity or calculate the criticality of an existing flaw in a welded joint.

In view of the microstructural heterogeneity within the narrow region of HAZ and the difficulties associated with testing the same, two methods are being explored to evaluate the toughness of different microstructural regions of HAZ. They are:

- composite HAZ specimen testing and
- simulated HAZ specimen testing.

Composite HAZ specimen is evaluated for toughness by careful location of the notch close to the fusion boundary. After testing, post metallographic examination is carried out to assess whether the specimen has sampled the desired region. Two types of criteria have been reported to validate HAZ composite test data. The propositions made in these criteria are very stringent and a large number of tests are needed to be conducted to fulfil

the criteria. None of these criteria cover the wide range of properties exhibited by the HAZ.

Simulation technique is an established method of evaluating individual microstructural regions of HAZ. Especially, localised brittle microstructural regions can be routinely analysed as the microstructure of interest is generated uniformly throughout the thickness. In spite of a high level of sophisticated and expensive instrumentation, the technique is still short of accurately reproducing the HAZ microstructures for a given peak temperature obtained during welding. In addition, commercial simulators have limitations on specimen size, usually restricted to $10x10x100mm^3$, which has a significant role in determining the fracture toughness for FM based integrity assessment. On the other hand, a possible method to simulate HAZ microstructures through conventional heat treatment has not been investigated thoroughly. Importantly, in this method, the specimen size would not become a limitation. However, there is no systematic study available verifying to what extent the heat treatment route would simulate HAZ microstructural conditions. Moreover, such a study can also reveal the fracture behaviour of the steel at high austenitising temperatures.

Although simulation technique is still widely used to assess toughness of individual microstructural regions, it is found that there is no suitable methodology available to convert the simulation data to composite HAZ toughness. Hence, it is essential that a suitable methodology is available to convert the simulation data to arrive at composite HAZ toughness.

It was observed that empirical models to predict mechanical properties provide initial estimates to the designers to validate their designs. Although several established models are available for predicting the hardness and the tensile properties, models for predicting the impact toughness and fracture toughness are scanty and limited to expressing the toughness as a function of carbon equivalent in a nomogram. It was found that, when such models are applied for simple carbon steels and carbon manganese steels, they either overestimate or underestimate the critical cooling rates and thus lead to errors in calculating the properties. Hence it is needed to develop a separate set of empirical models suitable for typical C-Mn and C-Mn micro alloyed steels.

The objectives of this investigation thus encompass comparative studies on weld HAZ and heat treated conditions, explore a suitable criteria to convert data obtained from individual microstructural regions of HAZ to a composite HAZ toughness, and to develop empirical models for prediction of mechanical properties of typical structural steels.

The investigations have been carried out on a niobium micro alloyed steel plate of 12mm thickness in hot rolled and normalised condition. The investigation is broadly categorised into four modules to meet the objectives.

Module I consists of characterisation of microstructure and mechanical properties of the selected Nb micro alloyed steel in the as received condition, preparation of bead on plate welds with different welding processes *viz.*, (a) manual metal arc welding (MMAW), (b) submerged arc welding (SAW) and (c) gas metal arc welding (GMAW), with data acquisition for characterising cooling rates, microstructure and hardness of the heat affected zones in these three welding conditions. ***Module II*** comprises studies on the experimental material austenitised to various temperatures and subsequently quenched to varying rates by quenching in air, oil and water. The thermal profiles collected during quenching were examined to verify the microstructures obtained in the specimens. The constituents of ***Module III*** are (a) preparation of weld HAZ and simulation heat treated test specimens, (b) tensile tests, impact tests and fracture toughness tests on heat treated specimens and composite HAZ specimens, (c) analysis of the fracture behaviour of C-Mn-Nb micro alloyed steel at high austenitising temperatures, (d) assignment of toughness index to each of the microstructural regions of the weld HAZ obtained from simulation data and (e) proposing a model to convert the toughness index of each of the microstructural regions to composite HAZ toughness. ***Module IV*** is an attempt at developing (a) property database for various microstructural conditions of the material and (b) empirical modelling, through multiple regression, of welded and heat treated conditions for obtaining hardness, tensile strength, CVN impact energy and fracture toughness, with a given set of peak temperatures and the cooling rates.

The three welding processes for the chosen welding conditions have resulted in three distinct cooling conditions with GMAW showing higher cooling rates compared to others. Significant grain coarsening was observed in the SAW process, while GMAW process showed less pronounced effect of coarsening characteristics because of higher heat input employed during welding. The HAZ in all the three welding processes have shown, typically, presence of ferrite-ferrite carbide aggregates, upper bainite/ferrite side plate morphology and/or martensite in the region close to the fusion boundary ($\leqslant$1mm). As expected, this region also showed inferior properties compared to other regions of the welded joint. However, significant difference in the volume fraction of these microstructural constituents has been observed between GMAW process and the other two welding processes *viz.*, MMAW and SAW. Similarly, significant morphological changes were also observed in the grain refined region (at around 1.5 to 2.5mm from the fusion boundary) and in the intercritical region (at around 2 to 3.5mm from the fusion boundary). These observed changes are believed to be a result of the faster cooling conditions experienced in the HAZ of GMAW process in the present study. In spite of testing a number of identical samples, it is difficult to arrive at a representative data for either impact toughness or fracture toughness of the HAZ. Some of the fracture toughness specimens showed pop-in behaviour indicating presence of brittle microstructural regions which resulted in lower fracture toughness. Although fatigue precrack ended in the grain coarsened zone of the HAZ, the crack path, during CTOD testing, deviated into adjacent softer microstructural regions due to the movement of plastic hinge away from the brittle microstructural regions. Examination of fracture surfaces showed evidence of brittle failure regions in the impact toughness tests although the data did not reflect the same possibly due to the imprecise sampling associated with the location of the notch.

Heat treatments at austenitising temperatures above 1000°C result in coarse prior austenite grain size. The three quench media that have been employed resulted in three distinctly different microstructural conditions: a mixed microstructural condition of ferrite carbide aggregates and ferrite/martensite with oil quench conditions showing significant amount of martensitic phase while air quench resulting in ferrite phase. Water quenching has resulted in predominantly martensitic microstructural condition at all austenitising temperatures. Significant presence of martensitic phase resulted in dramatic increase in the tensile strength accompanied by reduction in % elongation. On the other hand, CVN impact and fracture toughness tests reflected reduction in toughness proportional to the volume fraction of brittle phases. Among the various quench media, air quenching showed better mechanical properties. The toughness of low temperature austenitisation (<1000°C) followed by air quenching (LTA) was found to be better than both the high temperature austenitisation followed by air quenching (HTA) and the base material, due to the presence of finer prior austenite grain size in LTA heat treatments. The C-Mn-Nb micro alloyed steel employed in the present investigation showed conventional decrease in the fracture toughness at higher austenitising temperatures, as against the reported trends of results in some HSLA steels, which is attributable to grain boundary embrittlement due to the segregation of P to the grain boundaries.

A systematic comparison of properties was made between weld HAZ in MMAW, SAW and GMAW with the same in heat treated conditions. Based on a detailed evaluation of microstructure and mechanical properties, it may be said that it is possible to study the HAZ behaviour of weldments through standard heat treatment techniques and to generate conservative mechanical property data for design evaluations. In the present investigation, the microstructural observations and hardness survey revealed a close resemblance between MMAW and SAW with that of air quenching and GMAW displaying features similar to oil quenching. Application of rule of mixtures, generally applied to convert individual phase hardnesses to an absolute hardness of a given region, appears to yield reasonably good estimates of fracture toughness as well. This may be due to the fact that fracture toughness is affected by the microstructure ahead of the crack tip in a way similar to that of hardness. Hence it should be possible to convert the fracture toughness determined through simulation route for each of the microstructural regions of HAZ to a representative fracture toughness of the overall HAZ.

A look at the database generated, for the purpose of developing empirical relations for predicting mechanical properties, reveals a wide ranging mechanical and fracture properties for C-Mn-Nb micro alloyed steel. Presence of even smaller volume fraction of brittle phase resulted in substantial reduction in the fracture toughness although tempering restores the property to a certain extent. There exists a relationship between hardness and other mechanical properties *viz.*, tensile strength, impact toughness and fracture toughness of the steel under investigation. Empirical models have been proposed to predict mechanical and fracture properties of C-Mn-Nb micro alloyed steel as a function of peak temperature, T_p and cooling rate at 700°C, V_{r700}, or the time to cool between 800-500°C, $\Delta t_{8/5}$. A significant outcome of this study is that a methodology is proposed to predict conservative mechanical properties of critical components fabricated by welding if thermal cycles experienced by the joint could be measured during fabrication.