Abstract

Quenched and tempered low alloy abrasion resistant steels, also referred to as low alloy martensitic steels, are the family of weldable high strength steels which have been designed and developed to serve as good structural materials in view of improved performance with good economy. Owing to these reasons, the utilization of Q&T grades for engineering applications has grown to a significant extent and thus has resulted in reduced metal consumption by up to 40 percent, since the thickness of the walls of structures made from these alloys can be made thinner as compared to conventional steels. Based upon their typical strength characteristics these grades have been industrially used exclusively in the areas requiring high resistance to abrasion and such applications include areas like mining, mineral processing, earthmoving and other severe abrasive wear condition applications. Some important fabrications made from these steels include chutes, hoppers, dump truck beds, cutter bars, scraper blades, liner plates, tipper bodies, containers, crushing mills, mills, excavator buckets and loading buckets etc. The current status of their usage shows that these grades of quenched & tempered steels are considered as the best choice and replacement in the high strength and high toughness requirement conditions especially those involving wear.

Welded fabrications comprising of these steels and serving in different environments show certain weldability related problems which affect their mechanical and metallurgical behaviour significantly. Some of these problems include; cracking susceptibility of these welds, widely formed heat affected zones (HAZs) besides significant loss of hardness in their HAZs. These problems, individually as well as jointly become the cause of premature failures of the welded structures/fabrications. The relevant literature reviewed in this area shows that few research attempts have been made to overcome these problems, such that the service performance characteristics of
these steels could be improved. Owing to commercial reasons, much literature is not available on these steels which could help in understanding the exact nature and cause of weldability related problems, and thus aid the fabrication industry directly in designing and using improved welding procedures which can lead to structures with reasonable strength, good reliability as well as dependability. Under this category of steels, different manufacturers manufacture specific grades under different trade names for which the fabrication related information is only indicative. So as such, very scanty information is available which leaves a scope for researching into this important alloy which would help in strengthening the data base related to various weldability issues, such that the engineering potential of these steels is extracted to the maximum possible extent.

Out of many grades, in the present work the grade JFE-EH400 was selected and investigated for studying various aspects related to it, aiming that researching on this material would help in understanding largely the engineering behaviour of quenched and tempered (Q&T) steels. Keeping in mind the various problems encountered with welded fabrications made from this material, it was decided to formulate problem with clearly stated objectives with an aim of improving mechanical and metallurgical properties without any undue loss of wear performance for JFE-EH400 welds.

Experimental studies were carried out by fabricating different welded joints by incorporating firstly, the concept of variable joint design and secondly, using different filler combinations for welding this grade of steel using SMAW process (for giving main weld passes) and GTAW process (for giving root weld passes). As a part of the first objective of this work, three different joint designs namely JV, JU and JC were used for accomplishing welded joints in 15 mm thick JFE-EH400 steel. The aim of studying this aspect of the work was to understand how the joint design variations affect
the overall heat dissipation characteristics and hence cooling rates of these welds, which consequently would influence the mechanical as well as metallurgical properties of these joints. The results from this part of the work revealed that among all the joints studied, the joint JV possessed relatively higher heat dissipation characteristics as compared to the joints JU and JC owing to which its weld metal microstructure possessed fine acicular ferrite which accounted for mutually variable strength among these welds. Further, it was observed from the HAZ microstructural studies of these joints that the JV joint by virtue of offering relatively higher cooling rate resulted into a greater extent of grain coarsening in the coarse grain heat affected zone (CGHAZ), whereas, subcritical heat affected zone (SCHAZ) underwent a lesser degree of tempering effect due to which its grain structure got more refined as compared to the HAZ of the JU and JC joints. Tensile studies of these joints showed that the JV joint by virtue of its relatively high hardness within the weld metal resulted into maximum yield strength of 623 MPa followed by the JU joint (528 MPa) and JC joint (512 MPa), whereas, the ductility of these joints decreased with increased hardness of these welds. Impact toughness studies of these joints showed that the JC joint possessed maximum CVN value for the cover pass as well as the root pass, both at room temperature and 0 °C, followed by the CVN values possessed by the JU and JV joints respectively.

The next part of the work comprised of fabricating joints using five different filler combinations that helped in comparing mechanical, metallurgical and wear performance of these welds quantitatively. This aspect of the work was aimed to find out the most suitable filler combination that would help in designing welding procedures capable of delivering improved performance by these welds. Three ferritic grades (E7018-G filler used for joint named WJM, E9018-G filler used for joint named WJG and E9018-B9 filler used for joint named WJX), one austenitic grade (E309L
filler used for joint named WJA) and one austenitic-ferritic grade combination (E309L+E7018-G filler combination used for joint named WJMA) steels were used as filler material combinations for accomplishing joints which were subjected to mechanical as well as metallurgical testing. The main results from this part of the experimental work revealed that due to metallurgical mismatch, significant microhardness as well as microstructural variations were observed across different zones of these welds. Microhardness studies made along weld centre line (WCL) showed that for the joint WJX, the weld metal of the cover pass region comprised of tempered martensitic structure that possessed highest microhardness of 413.3 VHN, followed by the joints WJG and WJM showed microhardness of 265.7 VHN and 235.9 VHN respectively. The root regions of the joints WJA and WJMA by virtue of possessing martensitic structure resulted in relatively high microhardness of 384.7 VHN and 424.1 VHN respectively. Tensile studies of these welds showed that the joint WJX possessed maximum yield strength of 789 MPa and UTS of 832 MPa, whereas joints WJM and WJG possessed yield strength of 623 MPa and 639 MPa, and UTS of 694 MPa and 725 MPa respectively. Impact toughness studies showed that among three ferritic filler combinations used, the joint WJX possessed the highest CVN value of 237 J followed by the joints WJG and WJM which showed CVN value of 204 J and 189 J respectively. The joints made using austenitic filler combinations performed worst, as joints WJA and WJMA could possess a CVN value of 128 J and 110 J only respectively. The outcome after accomplishing this objective helped in establishing that the filler E9018-B9 was most suitable as it resulted into improved tensile strength, ductility as well as impact toughness of these welds.

After studying the mechanical as well as metallurgical aspects of these welds, it was important to assess any loss of wear performance of these welds (keeping in mind
the metallurgical mismatch between different fillers and the base material) due to welding, such that the most suitable welding procedures could be established in terms of improved overall performance of these joints. So, with an aim of gaining insight into the wear behaviour of these weldments and covering broader aspects of wear conditions, two different wear testing techniques viz. two-body abrasion wear test (using pin-on-disc tribometer) and three-body abrasion wear test (using dry sand rubber wheel test) were employed for generating data through wear modeling. Mathematical models were developed using response surface methodology with central composite rotatable design and various factors contributing to wear, along with their interactive effects were analyzed using standard statistical techniques. Wear modeling carried out in this way was used for making quantitative comparisons regarding the extent of wear loss that occurred in these welds w.r.t. the base metal, when subjected to different conditions of wear. This wear characterization of the welds was further supplemented by studying their correlations with the metallurgical aspects including microhardness and microstructures of different zones of these weldments. Mathematical models developed for studying the wear performance of the base metal on the basis of two-body abrasion wear studies helped in finding the quantitative influence of various wear variables such as load, revolutions and abrasive grit size on the abrasive wear characteristics of the base metal. The maximum wear rate/mass loss of the base metal was found to be 102.158 mg corresponding to the wear condition when load of 20 N with abrasive grain size of 80 mesh and rotational speed of disc being 300 revolutions was used, whereas, the minimum wear rate was found to be 14.098 mg at 10 N load when disc loaded with 180 mesh abrasive paper was rotated for 100 revolutions. For three-body abrasive wear, condition of 100 N load with the disc speed of 2 m/s abraded using SiC abrasives with the flow rate of 300 gm/min, when the surface under test was
held for 2000 revolutions, the maximum wear rate of the base metal was found to be 2.217 grams. However, when this surface was abraded against a load of 60 N applied using a disc rotating at a speed of 4 m/s with SiC abrasives flowing at the rate of 200 gm/min for 1000 revolutions, a minimum mass loss of 0.472 grams was observed.

Wear studies as carried out on these joints showed that for the two-body abrasion wear conditions, the wear performance of the joints WJA and WJMA was found to lie between the joint WJX and WJM, whereas, wear performance of the HAZ of these joints was found to be in a closer range to each other besides which it was also found that the wear rate of all the HAZs was greater than their respective weld metals. Under three-body wear conditions the wear performance of the joint WJX showed the least wear rate as compared to the other joints owing to its extremely fine tempered martensitic structure (possessing high microhardness of greater than 400 VHN) which indicated that microstructural features that affected the toughness characteristics of these joints also significantly influenced the wear performance of these joints.

So based upon the present work, it could be concluded that grade JFE-EH400 in particular, and quenched and tempered low alloy abrasion resistant steels in general, if welded using double V groove design with E9018-B9 as the filler choice can result into improved mechanical, metallurgical and wear performance. The data generated through this work being of industrial relevance is expected to cater to the needs of welding industry involved in JFE-EH400 grade quenched and tempered low alloy abrasion resistant steels fabrications, besides being useful for the alloy designers as well as for the filler/consumable development related to these steels.

**Keywords:** Quenched and tempered low alloy abrasion resistant steel (JFE-EH400); SMAW (Shielded metal arc welding); GTAW (Gas tungsten arc welding); Joint design; Microhardness; Microstructure; Tensile properties; Impact properties;
Fractography; DOE (Design of experiments); Wear; Two-body and three-body abrasion.