Evaluation of Mechanical Properties of Modified 9Cr-1Mo Welds Produced by Narrow Gap Hot Wire and Cold Wire Gas Tungsten Arc Welding Processes for 500MWe PFBR Steam Generators

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ABSTRACT

Modified 9Cr-1Mo material is selected as principal material of construction of Steam Generators (SG) for India's first of its kind 500MWe Prototype Fast Breeder Reactor (PFBR). The fabrication of PFBR Steam Generators involves welding of 12mm, 30mm and 90mm thick modified 9Cr-1Mo components which were carried out by combination of hot wire and cold wire Gas Tungsten Arc Welding processes. Hot wire Gas Tungsten Arc Welding (GTAW) is a relatively new process and limited machines/facilities are available in India for welding with this technique. The most important benefit from the use of a hot wire GTAW system is high weld deposition rate and reduced dilution & porosities from the weld deposits. Eventhough welds were meeting the specification requirements during welding procedure qualification, limited information available on hot wire GTAW process in open literature motivated authors for characterization of welds produced by this specialized technique. During welding procedure qualification, it was found that impact test results of weld metal produced by cold wire GTAW process is superior than weld metal produced by hot wire GTAW process. In light of this, detailed investigation & micro-structural analysis is carried out to find out the root cause for variation in impact properties. This paper details the systematic evaluation and interesting observations during characterization of microstructure & mechanical properties of modified 9Cr-1Mo welds produced by hot wire and cold wire GTAW processes.

Key words: Modified 9Cr-1Mo; Hot wire GTAW; Mechanical Properties; Cold wire GTAW;

1.0 INTRODUCTION

Prototype Fast Breeder Reactor (PFBR) is a first of its kind 500MWe pool type sodium cooled nuclear reactor, which is presently in advanced stage of construction at Kalpakkam, India. The Steam Generator (**Fig. 1**) is a vertical, counter flow, shell and tube type heat exchanger with liquid sodium flowing in shell side and water/steam flowing in the tube side. The choice of Steam Generator design concept is one of the most critical and difficult issues, the designers of LMFBRs (Liquid Metal Cooled Fast Breeder Reactor) are faced with. In case of a crack/failure in tube, high pressure water/steam reacts with shell side sodium and results in exothermic reaction with evolution of hydrogen, corrosive reaction products and intense local heat depending on the leak size. This highly reactive nature of sodium with water/steam requires that the sodium to water/steam boundaries of the steam generators must possess a high degree of reliability against failure. This is achieved by proper designing, correct material selection and stringent manufacturing methods [1]. Ferritic steel of type modified 9Cr-1Mo (grade 91) has been selected for steam generators, as this material has high resistance to stress corrosion cracking in caustic and chloride environment. In addition, this material possesses high resistance to decarburization in the liquid sodium environment and has excellent high temperature mechanical properties. One of the major problems associated with welding of modified 9Cr-1Mo steel is poor toughness of weld metal produced from any of the processes that involves the use of flux. Data available in literature indicates that the toughness of weld metal produced using these processes is far inferior (in the range of 40–100J) while that of the weld metal produced by GTAW process which is comparable to that of the base metal (typically 200J). This problem exists even for the weld metals of more advanced ferritic steels, like grade 92, grade 911 etc. Since, these steels are essentially meant for high temperature application, good toughness at ambient temperature is not a critical requirement for the service. However, toughness is an important consideration during hydro testing of components fabricated using these materials. Accordingly, upper limit for RT_{NDT} (Reference Temperature – Nil Ductility Transition) has been specified to be -15°C for both base metal and welding consumables used for fabrication of PFBR steam generators. This temperature is determined from the results of a combination of impact tests and drop weight tests conducted at different temperatures. The specified upper limit for RT_{NDT} would ensure that there is no risk of fast fracture in the component during hydro test at ambient temperatures.

Gas tungsten arc welding (GTAW) is widely used as a fabrication tool in many industries because of low-distortion, high quality, spatter & slag free welds, clean process, gives precise control of welding heat and allows excellent control of root pass weld penetration. The major disadvantage of this welding process is low deposition rate which makes it uneconomical for welding components with large section thickness. In GTAW process, the filler wire is moved by a feeding mechanism from the wire spool to the contact nozzle. In cold wire GTAW process, the filler wire is fed into the arc at ambient temperature, whereas in hot wire GTAW process, the wire between contact nozzle and molten pool is pre-heated by resistance heating method. A second power source is

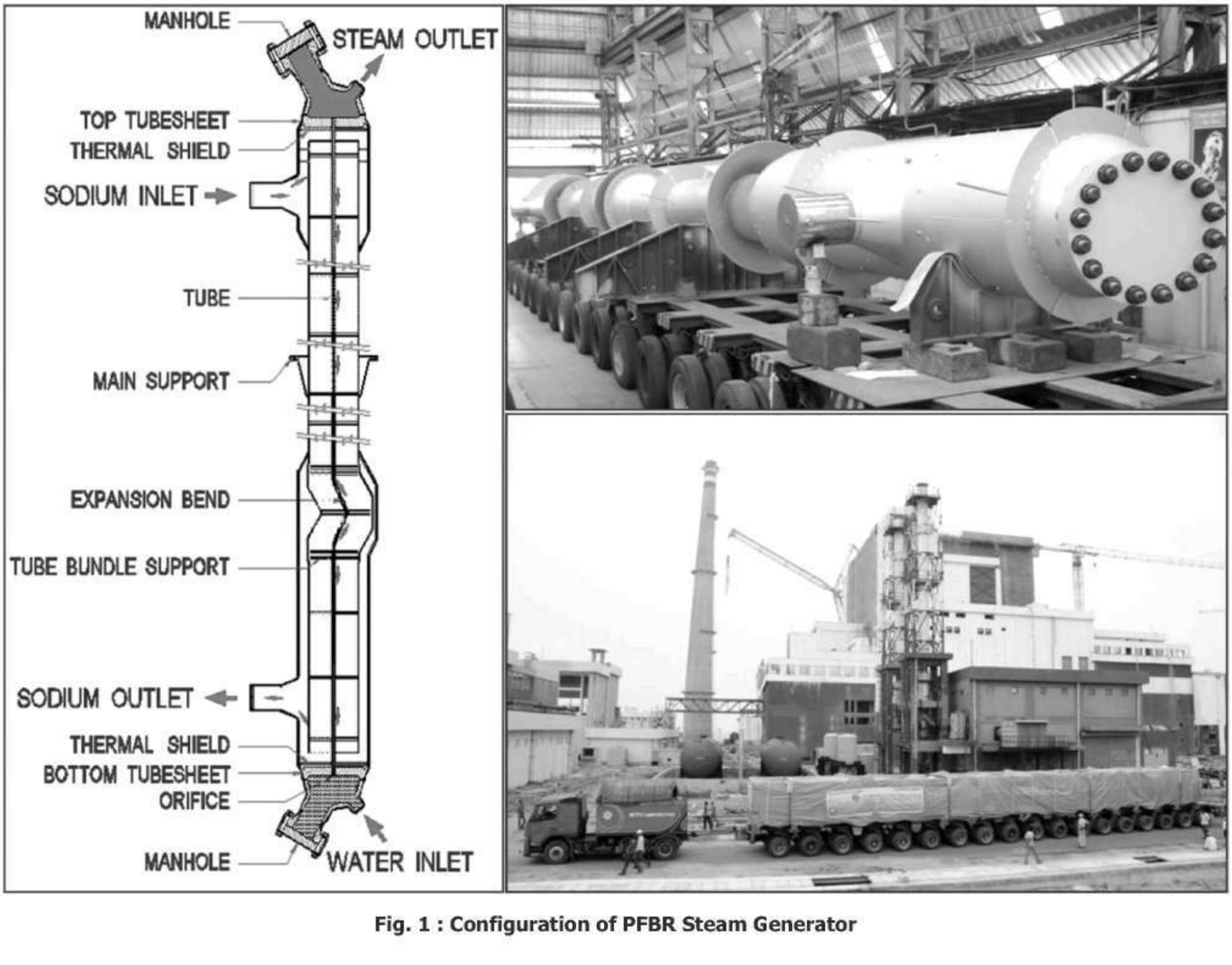

Fig. 1 : Configuration of PFBR Steam Generator

necessary to maintain the resistance heating. The preheating temperature of the wire can be varied within a wide range by controlling the intensity of hot wire current. The energy finally needed to melt the filler wire is decreased by preheating of the wire. As a result, considerable increase in the welding speed can be achieved in hot wire GTAW process that in turn results in increased deposition rate. Hot wire GTAW is a relatively new process and limited information are available in the open literature on affect of various welding parameters.

Following paragraph summarizes the literature survey carried out on various weld properties of Cr-Mo steels and hot wire GTAW process.

2.0 LITERATURE REVIEW ON Cr-Mo STEELS AND HOT WIRE GTAW PROCESS:

2.1 Literature review on Cr-Mo steels :

The various parameters which affect the toughness of modified 9Cr-1Mo welds are Oxygen content in weld metal, weld metal composition, Post Weld Heat Treatment (PWHT), welding parameters and type of electrodes. Toughness can be improved by raising the temperature (below Ac1 temperature of the weld metal) and increasing the duration of PWHT. However, addition of Ni brings down the Ac1 temperature and hence, Ni cannot be increased arbitrarily. In fact an upper limit of 1.5 wt-% for Ni + Mn content is often specified for welding consumables to ensure that Ac1 temperature is above the upper limit of temperature range (730-760°C) employed for PWHT for this class of steels [2].

Welds of modified 9Cr-1Mo steels are highly susceptible for cold cracking because of high alloy content in the steel and predominantly martensitic structure formed both in the weld metal and HAZ. The literature reveals that weld metal cracked within few hours of welding for the welds prepared without preheating. The extent of cracking decreased and the time taken to occur cracking increased with increase in preheat temperature. The critical preheat temperature above which no cracking took place was found to be 200°C (the temperature normally employed preheating of this steel) [3]. It is known that a relatively narrow HAZ, with reduced groove angle in joint preparation improves creep performance of modified 9Cr-1Mo steels [4]. Type IV cracks were observed in the Fine Grain Heat Affected Zone (FGHAZ) in the base metal area of the weldment of Cr-Mo steels during service. In this region, fine grain austenite is produced, which on fast cooling, transforms to martensite if the steel contains 9 to 12 % chromium. Type IV cracking is observed frequently in heat affected zone in 9 to 12 % chromium steels, especially in the presence of inhomogeneous microstructure [4]. Type IV cracking is the life limiting failure mechanism in P91 steels. Creep tests conducted on different zones within the heat affected zone have shown that FGHAZ, where type IV cracking occurs in a weld joint, exhibits the minimum creep strength whereas the coarse HAZ (CGHAZ) shows a creep strength even higher than that of the base metal. Literatures reveals that although the location of type IV fracture in ferritic steel weld joints is the FGHAZ, the creep damage and final fracture behavior of the weld joints are significantly different from those of the simulated FGHAZ having uniform micro structure throughout the specimen. These differences are caused by the tri-axial stress state introduced into the weld joints owing to the presence of different zones that vary significantly in their creep properties. By reducing the HAZ width or the groove angle of the joint, this stress state can be altered to achieve significant improvement in fracture life of the weld joints. However, creep tests at low stress levels were recommended to confirm the benefits of reducing the HAZ width and groove angle in improving the creep life of such weld joints in service [5].

2.2 Literature review on hot wire GTAW process :

The most important benefit from the use of a hot wire system is the virtual reduction/elimination of porosities from the weld deposits. Literature reveals that I^2R heating of the filler metal wire as it approaches the weld puddle drives off most of the volatile surface contamination. Since hydrogen containing compounds present on the filler metal surface, due to various forms of contamination that occur during handling and temporary storage, are a primary cause of porosity in high performance materials, use of hot wire system expected to remove the major source of porosity [6, 7]. The recent advances in the welding power sources and control systems have made it possible to automate the GTAW completely thus considerably improving its deposition rate and efficiency. By using the heated wire as filler material, melting rate of wire can also be increased, thus enhancing the deposition rate further. By proper choice of the welding current and heating current along with wire feed rate, the required deposition rate can be achieved with very little dilution. The deposition rate in hot wire GTAW process was found to be 300% more compared to that of cold wire addition and was equal to that of Metal Inert Gas (MIG) process. Cold wire welds made at a deposition rate of 1.36 kg/h produced the porous weld metal and the same filler metal used with the hot wire technique, at a considerable higher deposition rate produced the sound weld deposit [7, 8].

Fig. 2 : Shell welding of Steam Generator around the tube bundle

The use of hot wire current not only increases the deposition efficiency but also considerably reduces dilution, which depends on hot wire amperage and the amount of filler material melted off. Constant deposition efficiency and constant welding parameters will cause the weld pool temperature to fall, so that dilution will decrease by about 50 % with deposition efficiency ranging between 2 and 3.5 kg/h. If the deposit efficiency rises beyond that value the dilution curves for cold wire as well as hot wire seem to meet. [8]. If wire end energy is kept constant, the hot wire current bears only little influence on the weld shape, that in turn shows its effect mainly in the low deposition efficiency range. With deposition efficiency between 3 and 4.5 kg/h, weld height and width remain virtually constant. As a result, any variation of the welding parameters (such as free current-bearing wire end, arc amperage etc.) hardly affects the weld shape as long as the wire end energy is kept constant. As far as penetration depth and profile are concerned, the hot wire current shows a clear effect. An increase of the hot wire current, while maintaining deposition efficiency and wire end energy at the same value, results in a reduced penetration depth, and the profile will be more even and the dilution is uniform over the entire region of the weld [8].

The hot wire gas tungsten arc welding system makes very efficient use of welding heat input. Techniques have been developed to produce the welds at speeds and deposition rates equal and exceeding common gas metal arc techniques at a lower level of heat input. The process will easily deposit steel at 5.45 kg/h in conjunction with a 450 amp, 13V arc. The same deposition rate with gas metal arc welding requires an arc about 350 amp and 27V. The total energy for the hot wire gas tungsten arc system including the power input to the hot wire is about 80% of the gas metal arc system energy. When the ratios of total energy per pound of metal deposited are compared, the gas tungsten arc hot wire requirement can be less than half that for the gas tungsten arc cold wire [7]. Grain coarsening is perhaps the most serious problem in welding as it results in reduced ductility and toughness. It can be controlled by minimizing heat input during welding [9]. Thus, by minimizing the heat input by adapting hot wire welding process, the desired ductility and toughness of the welds can be achieved.

3.0 FABRICATION OF PFBR STEAM GENERATORS AND WELDING RELATED ISSUES:

About 3% of total weight of the each Steam Generator (SG weight ~42 tones) contains weld metal. All modified 9Cr-1Mo weld joints were preheated at 200-250°C and interpass temperature is maintained at 200-250°C. After welding, post heating is carried out at 200°C for 2 hours. Even though Shielded Metal Arc Welding (SMAW) process is permitted as per PFBR specification, 100% GTAW process alone is adapted during fabrication using ER 90SB9 filler wire to meet the impact properties of welds. Combination of hot wire and cold wire Gas Tungsten Arc Welding (GTAW) process is chosen for fabrication based on the practical possibility and feasibility. The welding of 12mm thick shells around the tube bundle is carried out by 100% cold wire GTAW process (**Fig.2**).

The 30mm thick component welding is carried out by combination of cold and hot wire GTAW process and 90mm thick welding is carried out only by hot wire GTAW process (**Fig. 3**), as the amount of weld metal to be deposited during fabrication is high. The root pass and subsequent pass welding for all 12mm and 30mm thick components were carried out by manual cold wire GTAW process. There is not much added advantage of carrying out hot wire GTAW process on 12mm thick shells, as root and subsequent pass welding is carried out for 4-5 mm thickness by manual GTAW process and remaining weld deposition thickness left would be only around 7-8mm.

As shell assemblies of Steam Generators are insitu welded around the tube bundle in horizontal condition, the welding is carried out only from outside, as there is no access to carry out welding from the tube bundle side. Due to this limitation, the shell joint Weld Edge Preparation (WEP) has only single V or J type. During shell fabrication around the tube bundle, it is not advisable to stop the welding after single pass for examination, as thickness of weld is around 2mm which may not take the shrinkage stresses. There were apprehensions of root pass weld cracking because of high hardness (typically greater than 440 VHN) of deposited weld metal and shrinkage stresses. Therefore, welding is stopped for performing NDE after two layer welding (4-5 mm thickness of weld). After fabrication, entire 26 meters length Steam Generator is subjected to Post Weld Heat Treatment (PWHT) in a single charge at 760±10°C for 4 hours soaking time to relieve the welding stresses and to get homogenous tempered martensite structure.

4.0 WELDING PROCEDURE QUALIFICATION AND TESTING :

The welding procedure qualification is carried out on 12mm, 30mm and 62mm thick test coupons using cold wire and hot wire GTAW process. After welding, qualification test coupons were subjected to Post Weld Heat Treatment (PWHT) at 760±10°C for 4 hours soaking time. The welding procedure is qualified with stringent destructive and non-destructive examinations & testing before executing welding process on the actual job. The qualification test coupons were subjected to all the non-destructive examinations applied in fabrication of actual job. During qualification, weld joints were subjected to thorough visual examination, Liquid Penetrant Examination (LPE), Radiography Examination (RE), longitudinal tensile test at ambient temperature, transverse tensile test at ambient temperature and high temperature, bend tests, RT_{NDT}, Charpy V notch impact test, hardness survey and metallographic examination at 200X magnification for the complete transverse

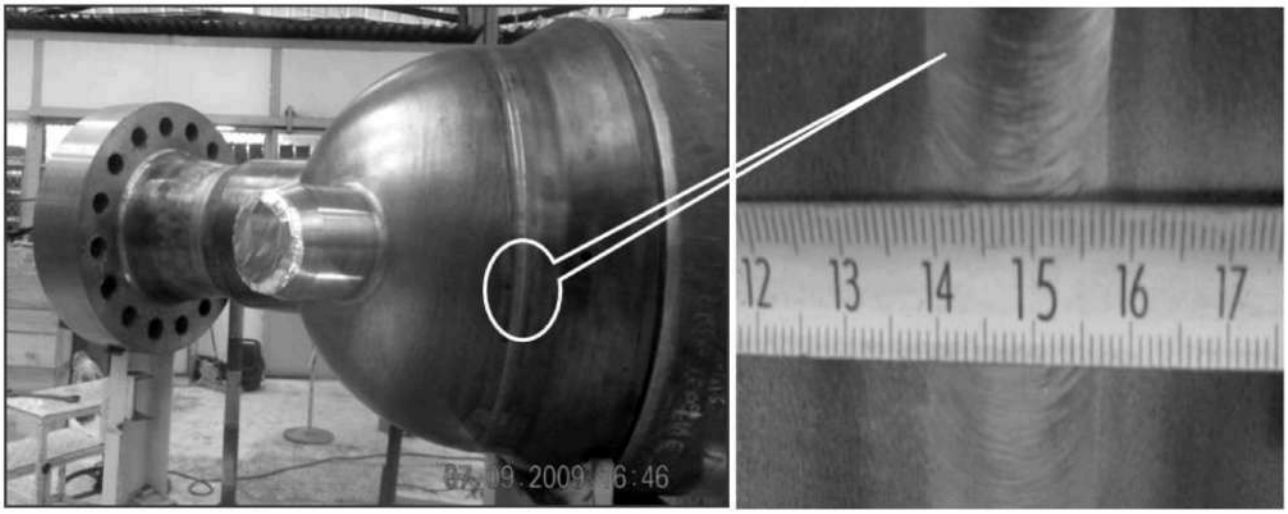

Fig. 3: Weld produced using narrow gap hot wire GTAW process for 90mm thick joint of steam generators

section of the weld. The following paragraph discusses the procedure adapted in brief for testing of qualification test coupons.

4.1 Tensile Test :

After completion of satisfactory non-destructive examinations of the qualification test coupons, the tensile testing of the test coupons were carried out as per the conventional procedure as per ASTM E8 and ASTM E21. The transverse tensile test and longitudinal tensile test is carried out at room temperature as well as at high temperature (525^{0}C). The tensile test specimens from the qualification coupons were taken from the various zones to check the consistency and uniformity of the properties.

4.2 Vickers Hardness Test :

The micro-hardness testing was carried out as per ASTME-384. The load applied was 1kg. Diamond indenter (pyramid) with face angle of 136° was used. For testing, sample was prepared upto mirror finish and etched with Villella's reagent to identify the weld, HAZ and base metal. Micro-hardness test was carried out with interval of 0.5mm in weld. The acceptance criteria was maximum of 280VHN after PWHT and maximum of 505VHN in as welded condition. During testing, load of 1 kg is applied on sample with dwell time of 15 seconds. After putting indentation, both the diagonals of pyramid indenter (d1 and d2) were measured with microscope at magnification of 500X.

4.3 Impact Test :

Charpy-V notch impact test specimens of 10mm x 10mm section having a 2mm deep V notch at an angle of 45°, with a root radius of 0.25 mm is machined. The orientation of specimen for welded joints is transverse to the weld and the base of the notch shall always be perpendicular to the welded surface. One set of three impact specimens representing weld were taken transverse to the weld from top, middle and bottom portion of weld. The top weld specimen is located as close as possible to that surface of the test sample where the last heavy bead has been deposited (but not more than 3 mm from surface). The test specimens were immersed in the liquid bath maintained at test temperature for at least 5 minutes period. Specimens were broken within 5 seconds from the time of removal from the bath. **Fig. 4** shows the Vickers hardness test and V notch impact test on the qualification test coupons.

4.4 Metallographic Examination :

Metallographic examination of weld material was carried out to evaluate the structure by means of a light optical microscope (Model No. OLYMPUS -GX-51 F, Serial No. 7B 18867). The surface to be examined for metallography was prepared initially by milling and grinding. Subsequently sample surface is polished using emery at 120, 220, 320, 400 and 600 grit papers as per ASTM E3. After emery polishing diamond polishing was done to obtain the mirror finished surface which is free from scratches. Prepared sample was etched to reveal the structure

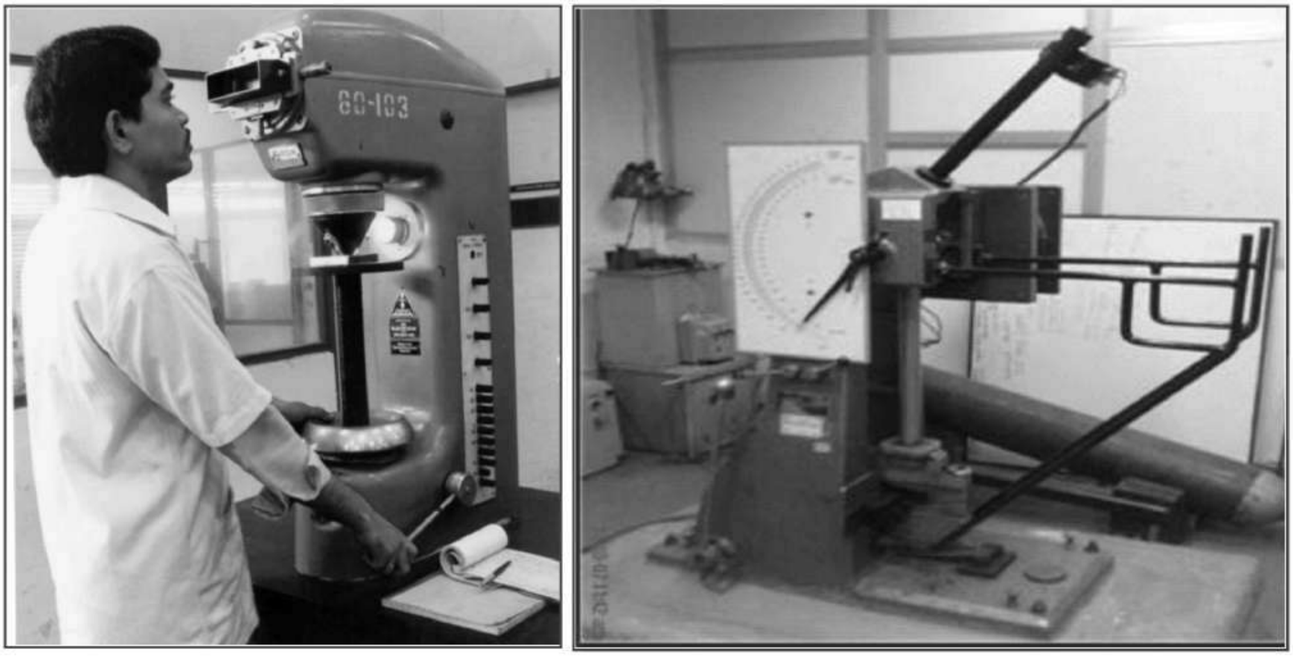

Fig. 4 : Vickers hardness test and V notch impact test on the qualification test coupons

using Vilella's reagent etchant (1gm picric acid+5ml HCl+100ml methanol). After etching, the sample was cleaned in running water and subsequently with acetone and dried. The sample was examined under optical microscope at 500X magnifications.

4.5 Nil Ductility Transition Temperature (NDTT) Test :

The NDTT test was carried out as per ASTM E208, P2 type specimens were selected. Approximately 50mm wide crack-starter weld is deposited on the tension surface of drop weight specimen using 5mm diameter UTP 350 electrodes with minimum 350BHN hardness. At the centre of the bead length, a notch is cut as per ASTM E208. The specimen positioned in the anvil is deflected by a free falling weight with an adequate energy, which is dependent on the yield strength of the material to be tested. During the fall, the weight has to be guided in order to guarantee the specimen being hit in a certain position. The specimen is considered broken if the crack starting from the notch of the weld bead propagates to one or both edges of the tension surface. **Fig. 5** shows NDTT test specimens of the welding procedure qualification test coupons.

5.0 RESULTS AND DISCUSSION :

Systematic evaluation is carried out for microstructure & mechanical properties of 12mm, 30mm and 62mm thick modified 9Cr-1Mo welds produced by hot wire GTAW and cold wire GTAW processes during welding procedure qualification. The test results of various mechanical properties are tabulated in table-1. It is noted that weld metal has qualified all the destructive testing/mechanical properties and non-destructive examinations as per the specification requirements irrespective of welding process. i.e. cold wire GTAW process or hot wire GTAW process.

However, during impact testing at $0^{\circ}C$, it was found that toughness of weld metal produced by cold wire GTAW process

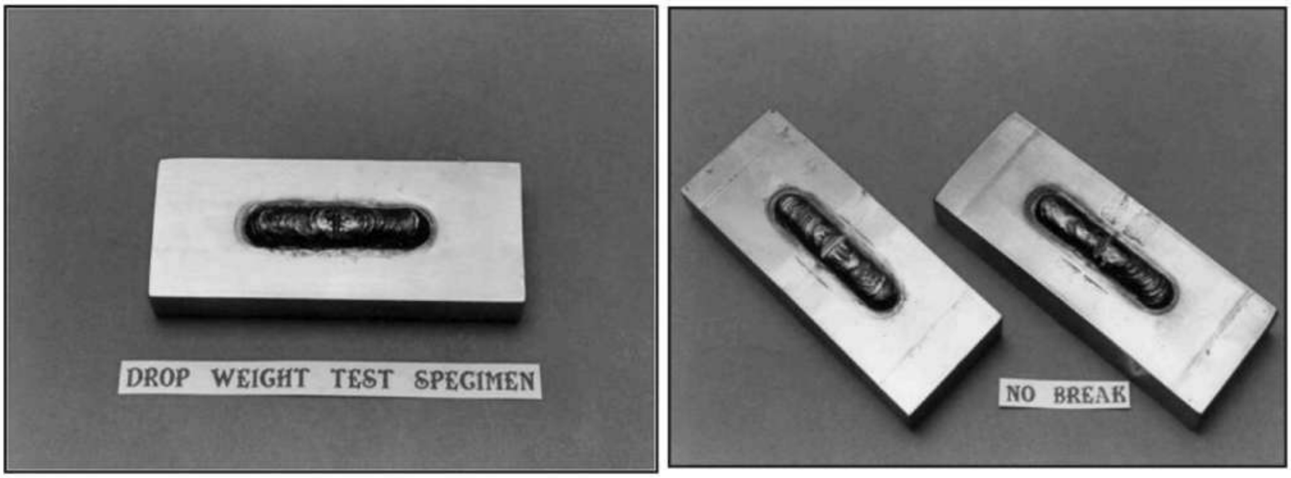

Fig. 5 : NDTT test specimens of the qualification test coupons

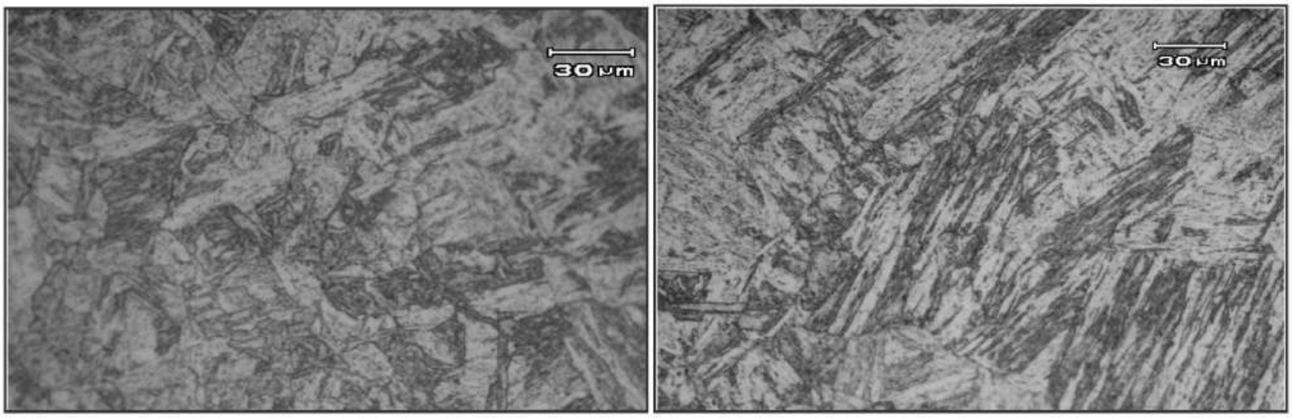

Fig. 6 : Tempered martensite structure of 30mm thick weld produced by cold wire and hot wire GTAW processes respectively

Table 1 : Test results of mechanical properties during various welding procedure qualification

Type of Test	Specification Requirement	12 mm thick, cold wire manual GTAW process, 60°V groove	12 mm thick, cold wire manual GTAW process, 12.5°J groove (pipe)	12 mm thick, cold wire automatic GTAW process, 60°V groove	30 mm thick, cold wire manual+cold wire automatic GTAW process, 8°J groove	30 mm thick, manual cold wire + hot wire automatic GTAW process, 8°J groove	62 mm thick, hot wire automatic GTAW process, 6.4°J groove
Room temperature transverse tensile test	585 MPa (minimum)	696	721	686	684	705	705
High temperature (525°C) transverse tensile test	385 MPa (minimum)	451	457	446	460	452	437
Room temperature longitudinal tensile test	585 MPa (minimum)	NA	NA	NA	753	782	752
High temperature (525°) longitudinal tensile test	to be recorded (in Mpa)	529	NA	NA	584	532	525
Impact test at 0°C	28 Joules (minimum)	164	150	221	205	108	54
Impact test at 18°C after RTNDT determination	68 Joules (minimum)	NA	NA	NA	222	147	163
Hardness test before PWHT	505 VHN (Maximum)	377 to 460	403 to 462	290 to 461	321 to 474	294 to 448	339 to 446
Hardness test after PWHT	280 VHN (maximum)	221 to 253	235 to 252	220 to 268	215 to 266	244 to 264	228 to 260

is superior than weld metal produced by hot wire GTAW process. The hot wire GTAW process has produced higher heat input to the weld, which perhaps one of the reason for reduced impact property. The impact toughness value observed at 0°C for 30mm thick qualification test coupon welded using hot wire GTAW process is 108 joules. Hot wire GTAW process qualification test coupon welded in 62mm thickness has reduced the impact properties to 54 joules. It was found that impact properties have reduced drastically to 50% when the thickness of qualification test coupon has increased to about two times. The repeated thermal cycling during welding on higher thickness might have caused higher heat input to the weld resulting in reduced impact properties.

During welding procedure qualification, higher deposition efficiency is achieved in hot wire GTAW process than cold wire GTAW process. During hot wire GTAW process, reduced welding speed resulted in reduced no. of layers with higher thickness of each layer causing higher heat input to the weld. Higher no. of layers with reduced thickness of each layer in cold wire GTAW process has facilitated effective tempering of weld beads. The hot wire GTAW process is carried out by weaving method, during which each layer is tempered with only one previous weld layer. In cold wire GTAW process, each weld layer is overlapped with two subsequent layers to cover the complete groove width, which might have helped for repeated tempering of previous weld layer for improving the impact properties. However, there were no recordable variations observed in tensile properties at ambient temperature as well as at high temperature (both longitudinal & transverse) for the welds produced using both the processes. As welded hardness and heat treated hardness values were also found almost comparable for both cold wire GTAW and hot wire GTAW processes.

Considering all the above, detailed microstructural analysis is carried out to evaluate the structure at 500X using light optical microscope (Model No. OLYMPUS -GX-51 F, Serial No. 7B 18867). **Fig. 6** shows tempered martensite micro-structure of 30mm thick welds produced by cold wire GTAW and hot wire GTAW processes. Investigations revealed that grain coarsening during hot wire GTAW process perhaps the major cause for poor toughness of welds.

6.0 CONCLUSION :

The impact properties of modified 9Cr-1Mo welds produced by hot wire GTAW process is inferior compared to welds produced by cold wire GTAW process, eventhough toughness is meeting the specification requirements. High toughness value at 0^0C is not a critical requirement for service condition of PFBR Steam Generators. As hydro testing of Steam Generators can be carried out safely with obtained toughness values of modified 9Cr-1Mo welds, hot wire GTAW process is accepted for fabrication. However, Heat input is a key parameter which shall be controlled during welding process to get the desired impact properties. The modified 9Cr-1Mo welds produced by hot wire GTAW process with higher welding speed & many no. of welding layers with reduced thickness of each layer may reduce the heat input which in turn improve the toughness of welds. In addition, welding engineers can explore, analyze and characterize the impact properties of welds by overlapping of layers instead of weaving of welds during hot wire GTAW process.

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