DEVELOPMENT OF SCIENCE BASED TECHNOLOGY OF WELDING AND HARDFACING FOR INDIAN FAST REACTOR PROGRAMME

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Abstract:

Establishing science and technology of Fast Breeder Reactors (FBRs) in India for power generation is essential for meeting growing energy demand in a sustainable manner. The development of FBRs necessitates extensive research and development in domains of materials and manufacturing technologies in association with a wide spectrum of disciplines and their inter-twining to meet the challenging technology. The paper highlight the work and the approaches adopted for the successful deployment of welding and hardfacing technologies for the structural components of current and future Indian Fast Breeder Reactor Programme. Robust welding technology has been established for manufacturing of various components of 500 MWe Prototype Fast Breeder Reactor (PFBR) such as reactor vessels, piping, steam generators, fuel sub-assemblies etc. through 'science-based technology' approach. The indigenous manufacture of the large components of the PFBR has been successful in meeting the specifications and indeed improving on the design requirements. The technology for the Hardfacing of the grid plate has also been successfully developed.

Key Words: Fast Breeder Reactor, Austenitic Stainless steels, Mod. 9Cr-1Mo steels, Welding and Hardfacing

1. Introduction:

India's energy requirements are large and nuclear is a viable robust option for meeting the growing demands to achieve high pace of economy and providing better quality of life. The demands shall be approximately three fold in 2030 and six fold by 2050. Alternate energy resources like coal, gas, oil, wind, solar, bio-mass and bio-waste shall continue to be enhanced based on improved science based technologies. The nuclear energy program in India is being implemented in three stages. In the first stage, natural uranium fuelled Pressurized Heavy Water Reactors (PHWR) are in operation and under construction. Plutonium generated from PHWRs will by utilized in Fast Breeder Reactors (FBR) in the second stage. Successful operation of FBRs will facilitate launching of a large scale Th-232 - U-233 fuel cycle in the third stage. FBRs also utilize natural uranium fuel effectively through breeding and thus provide a rapid energy growth potential. Thus, FBRs provide long term energy security utilizing the indigenous uranium and thorium reserves. Indira Gandhi Centre for Atomic Research, Kalpakkam is responsible for the establishment of fast breeder technology in the country. Advanced research facilities have been established and extensive studies have been carried out in the areas of materials and manufacturing technology development [1], This has laid the foundation for the design and development of 500 MWe Prototype Fast Breeder Reactor (PFBR). The construction of the PFBR has begun with the first pour of concrete in October, 2004 and is expected to be completed in 2012. India envisages to build six 500 MWe commercial fast breeder reactors after successful commissioning of PFBR.

Fast Breeder Reactor components operate under hostile and demanding environment of high neutron flux, liquid sodium and elevated temperatures. Resistance to void swelling, irradiation creep, and irradiation embrittlement are the major considerations in the choice of materials for core components. Structural materials should have good resistance to creep, low cycle fatigue, creep-fatigue interaction and sodium corrosion. The schematic sketch of the reactor assembly is shown in fig. 1. Austenitic stainless steels are chosen as major structural materials in view of their adequate high temperature mechanical properties, compatibility with liquid sodium, good weldability, availability of design data and vast experience in then use of these steels for high temperature service. Irradiation effects are not important for the structural components such as reactor vessel, grid plate, pumps and intermediate heat exchanger. Stabilized steels 321 and 347 are not chosen since their welds are prone to cracking during welding, during reheating and also in service. Nitrogen alloyed low carbon austenitic stainless steel types 304 L(N) and 316 L(N) have been selected for structural components of PFBR. Modified 9Cr-1Mo steel has been chosen as the steam generator structural material for PFBR because of their superior high temperature strength, microstructure stability, compatibility with liquid sodium and steam at high operating temperatures. Specifications for these materials are more stringent than the ASME standards. The chemical composition is controlled within close limits to avoid scatter in mechanical properties. Lower limits on sulphur, phosphorous and silicon to improve weldability and on the inclusion content to ensure high degree of cleanliness [2] .

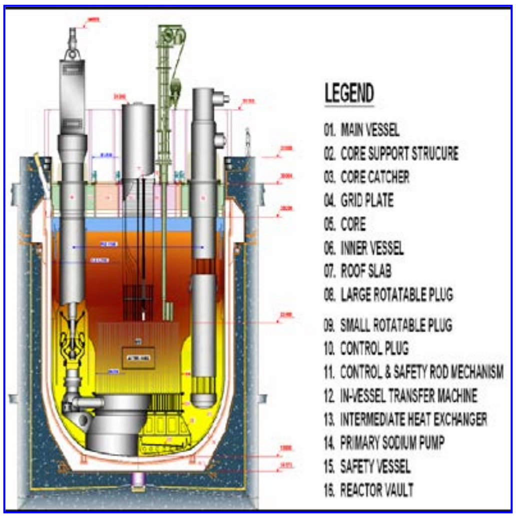

Fig. 1 Schematic sketch of PFBR Assembly

2. Welding Technology:

Welding is extensively employed in the fabrication of reactor and steam generator structural components. Weld metal cracking and heat affected zone (HAZ) cracking are major issues in welding austenitic stainless steels. Weld metal cracking has been controlled by optimizing the chemical composition of the welding consumables. Carbon in the range of 0.045-0.055 wt% and nitrogen in the range of 0.06 – 0.1 wt% are specified to provide weld joints with improved creep strength and freedom from sensitization in the as welded state. In addition ferrite in the weld metal is controlled within 3 – 7 FN by optimizing the composition of the welding consumable to promote primary ferritic solidification mode. A minimum of 3 FN is specified to ensure freedom from hot cracking in the weld metal. As δ - ferrite undergoes phase changes to carbides and intermetallic phases at high temperatures reducing the creep rupture life, an upper limit of 7 FN has been specified. HAZ cracking is avoided by specifying lower permissible limits for P,S, Si, B, Ti and Nb.

Two major issues with welding of modified 9Cr-1Mo steel are hydrogen assisted cracking and improving the impact toughness of the weld metal. Hydrogen assisted cracking is avoided by carefully controlling the diffusible hydrogen content in the weld deposit and HAZ microstructure. Methodology has been developed for evaluation of Hydrogen assisted cracking susceptibility of the base and weld metal. Post weld heat treatment cycle has been optimized to improve the impact toughness in mod. 9Cr-1Mo weld metal. Mod. 9Cr-1Mo steel weld joint showed the lowest creep rupture strength in comparison to that of weld metal because of type IV cracking. The characteristic feature of type IV cracking is that the creep cavitation and fracture occurs in fine grained/inter-critical heat affected zone (FGHAZ/ICHAZ) of the weld joints. Although it is difficult to avoid this type of cracking, several methods such as modifications to the base metal composition with small additions of boron, design of weld consumables, weld design and process optimisation are being adapted to improve the resistance to type IV cracking.

The welding consumables as per PFBR specifications have been successfully developed and the structural components of PFBR have been fabricated indigenously. For future FBRs, employing automated welding processes for enhanced quality and higher productivity will be a priority and Flux Cored Arc Welding (FCAW) process is under development.

2.1 A-TIG Welding

2.1.1 Enhancing the performance of TIG welding process using activated fluxes

TIG welding process is one of the candidate process for fabrication of various components in the nuclear industry. The principal disadvantages of TIG welding lie in the limited thickness of material which can be welded in a single pass, poor tolerance to some material composition (cast to cast variations) and the low productivity. A-TIG welding process has been successfully developed for welding of austenitic stainless steels and mod. 9Cr-1Mo steel. This innovative technology allow faster welding speed, require reduced joint preparation, consumes less filler wire and involve reduced distortion correction through lower heat input and higher joint penetration. Residual stresses were found to be reduced considerably in A-TIG weld joints. Figure 2 shows the variation in the depth of penetration as a function of current for type 316 LN stainless steel during A-TIG welding. Up to 10 mm depth of penetration could be achieved in single pass welding using A-TIG welding.

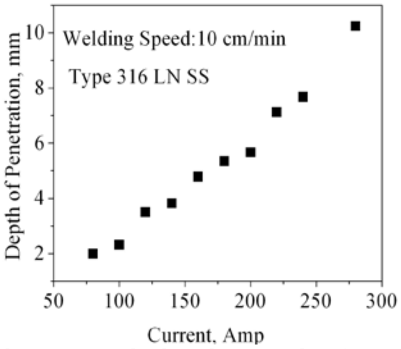

Fig. 2 Variation in Depth of penetration as a function of Current [3]

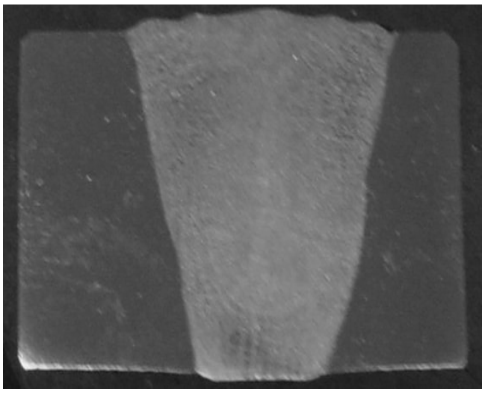

Fig. 3 Macrostructure of type 304 LN SS A-TIG weld joint [3]

Figure 3 shows the macrostructure of the type 304 LN stainless steel weld joint made by A-TIG welding process in single pass.

2.1.2 Mitigating Variable Weld Penetration during Autogenous TIG welding

The variable weld penetration i.e inconsistency in weld penetration with increasing welding current was observed (fig. 4) when the 316LN stainless steel welds were produced without flux due to low sulphur content below 50 ppm. It can be seen from the figure 4 that the depth of penetration decreased with increasing current when welded without using activated flux. The same welds when produced with activated flux, exhibited consistent variation in the depth of penetration with increasing current (fig. 4). This observation implies that the use of activated flux has mitigated the variable weld penetration caused by low sulphur content in 316LN stainless steel. Overcoming the variable weld penetration using activated flux during autogenous TIG welding of austenitic stainless steels is considered as significant achievement.

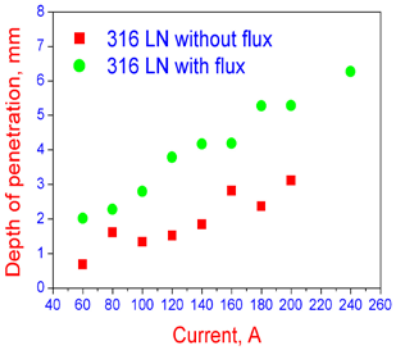

Fig. 4 Comparison in the variation in depth of penetration as a function of current with and without flux for type 316 LN stainless steel [3]

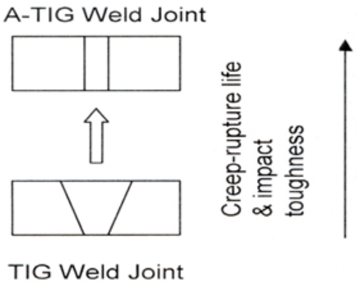

Fig. 5 Schematic sketch showing improvement in mechanical properties for type 316 LN Stainless steel weld joint

2.1.3 Improvement in the Creep rupture behaviour of type 316 LN Stainless Steel Weld Joint made by A-TIG welding

Improvement in mechanical properties such as Creep-rupture life and impact toughness have been observed in type 316 LN Stainless steel weld joints made by A-TIG welding process (fig. 5). Figure 6 shows the creep curves for the base metal and the weld joints. A-TIG weld joint exhibited better creep rupture life compared to that of the multipass TIG weld joint. Stress-rupture tests revealed that the creep rupture life of 316 LN A-TIG weld joints enhanced by 75% compared to that of the conventional TIG weld joints (fig. 7). This is a significant achievement. The mechanism for enhancement in creep rupture life is discussed in detail by sakthivel et al [4]. Improvement in mechanical properties in A-TIG weld joints has been demonstrated and the process will be employed for fabrication of stainless steel pipes in future FBRs.

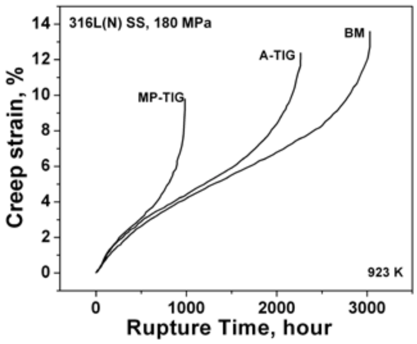

Fig. 6 Typical creep curves for type 316 LN SS base metal and weld joints[4]

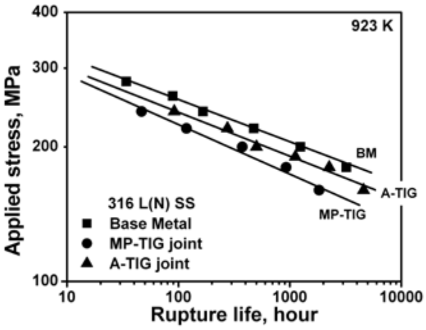

Fig. 7 Comparison of stress-rupture plots For type 316 LN SS base metal and weld joints [4]

2.2 Soft Computing in Welding

Soft Computing is causing a paradigm shift in welding science and technology as it can solve problems that have not been able to be solved by traditional analytical methods. Welding is complex technology because the quality of the weldment is a function of the interaction of the large number of variables and microstructural changes during welding. These interactions need to be understood and controlled to produce good quality welds.

2.2.1 Stainless Steel Welding

Soft computing techniques have been used to predict stainless steel weld microstructure, prediction of weld bead shape parameters as a function of process variables, for predicting weld bead width and depth of penetration from Infra red Thermal image of the weld pool, and optimization of welding processes. Solidification cracking in stainless steel welds is a major fabrication issue during the welding of structural components of nuclear reactors. Two microstructural features which influence the solidification cracking in stainless steel welds are the solidification mode and ferrite content. In our Materials Joining research group, Advanced Neural network techniques have been employed for accurately predicting the solidification mode and ferrite number as a function of weld metal composition in stainless steel welds [3].

Bayesian classification neural network model for predicting the solidification mode in austenitic stainless steel welds has been developed. The developed model is first of its kind. Nickel was found to exhibit a clear pattern in influencing the solidification mode in austenitic stainless steel welds (fig. 8a). Analysis of combined effect of nickel and other alloying elements showed that in addition to nickel, chromium, manganese and nitrogen were the other alloying elements whose concentrations determine the solidification mode in austenitic stainless steel welds. Combined analysis of nickel and other alloying elements on the probability of ferritic solidification mode showed that increase in chromium, molybdenum and silicon content promoted primary ferritic solidification mode while increase in nitrogen content promoted primary austenitic solidification mode. Combined effect of Cr_{eq}/Ni_{eq} ratio and the nickel content on the solidification mode is shown in fig. 8b. The predictions of the model were in good agreement with the experimental results and the model predicted the real behaviour of austenitic stainless steel welds very well. With close control of nickel, chromium, manganese and nitrogen, it is possible to obtain primary ferritic solidification mode and hence reduce the tendency for solidification cracking.

The most accurate composition only dependent Bayesian neural network model on Ferrite Number has been developed using the data which was used for generating the WRC – 1992 diagram and our laboratory data[3].

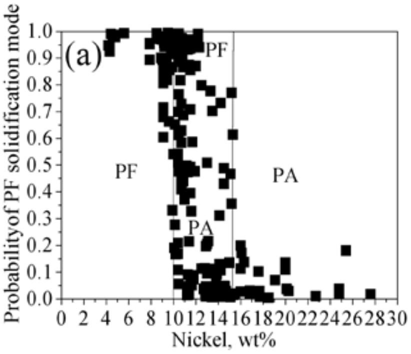

Fig. 8a Effect of Ni content on the Primary solidification mode [3]

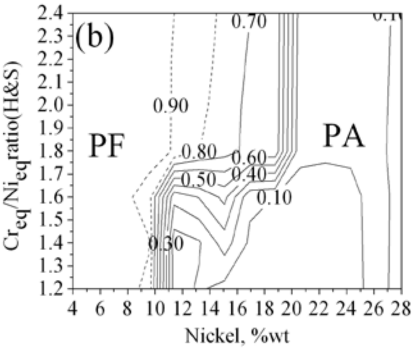

Fig. 8b Combined effect of Ni and Cr_{eq}/Ni_{eq} ratio on the primary solidification mode [3]

The accuracy of Ferrite Number prediction using the Bayesian neural network model has been found to be 63% more accurate than the WRC – 1992 diagram and 40% more accurate than the FNN – 1999 model. This is certainly a significant improvement over the existing methods currently available for Ferrite Number prediction. Model perceived significance of the individual elements showed that Mn and Nb are insignificant in influencing the ferrite number. This was a new observation and reported for first time. The role of the alloying elements in influencing the Ferrite Number was found to change when the base composition was changed. Figure 9 & 10 shows the comparison between the predicted and measured FN for the data used during training and testing respectively. There was excellent agreement between the predicted and measured FN values. The generalized Bayesian neural network model on Ferrite Number has been tested with data from different sources which were not used during the training. The RMS error determined for all test datasets has been less than 2.0. It implies that the model developed in the present work is robust and best suited for accurately predicting the Ferrite Number in stainless steel welds. Interaction between the elements such

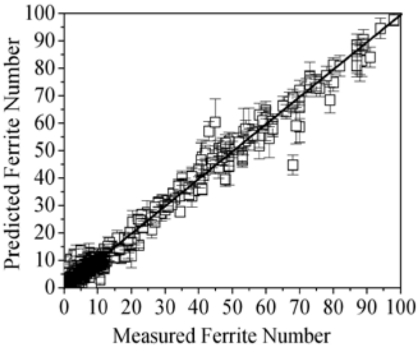

Fig. 9 Comparison between the Predicted and Measured FN for the entire dataset [3]

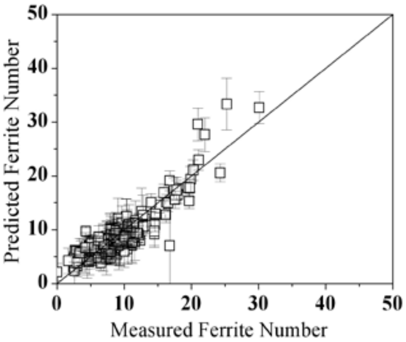

Fig. 10 Comparison between the predicted and Measured FN for test data [3]

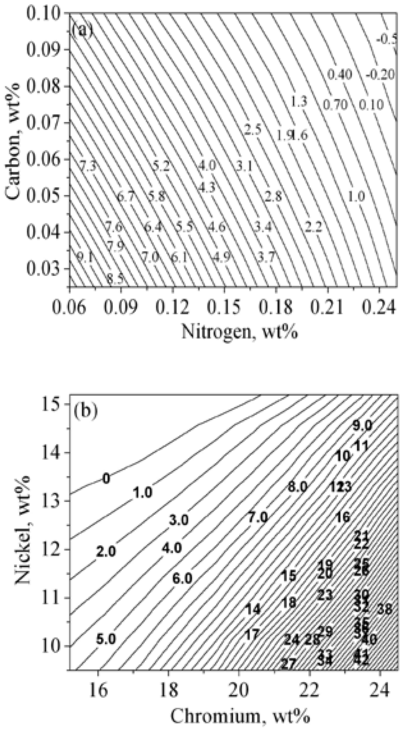

Fig. 11 (a) Combined effect of C and N (b) Combined effect of Cr and Ni on the predicted FN [3]

as C and Ti in influencing the Ferrite Number could be studied from the analysis of combined effect of alloying elements. Figure 11a shows the combined effect Cand N on the predicted FN while fig. 11b shows the combined effect of Cr and Ni on the predicted FN values. These plots are finding application during the selection of welding consumables for controlling the FN in stainless steel welds. The development of the most accurate composition only dependent neural network model is a significant improvement over conventional constitution diagrams such as WRC-92 diagram and the other models that are currently available. The trends identified by the model for the role of various alloying elements such as nickel, chromium, carbon, nitrogen, molybdenum, vanadium on the Ferrite Number was consistent with the role of these elements expected metallurgically. The above knowledge gained through this study for various austenitic stainless steel alloys is quite useful during the alloy design of the welding consumables for obtaining the desired Ferrite Number in stainless steel welds. The models developed for predicting stainless steel weld microstructure are finding application during the selection of welding consumables.

2.2.2 Remote repair welding using vision sensor

The GTAW process has been difficult to model analytically due to the complex, highly coupled non-linear system control parameters inherent in fusion welding processes. Remote welding techniques are required to repair nuclear reactor components. In our materials joining laboratory, efforts are on to develop intelligent GTAW system employing soft computing techniques for carrying out remote repair welding of nuclear reactor components. Computational Intelligence based models employing adaptive neuro-fuzzy Inference system have been developed correlating the process variables such as current and the image features extracted from Infra red thermal images of weld pool with weld bead shape parameters such as depth of penetration during A-TIG welding of 6 mm thick type 316 LN stainless steel plates. Figure 12 & 13 shows the comparison between the predicted and measured weld bead width and depth of penetration respectively. There was excellent agreement between the predicted and measured values. These models have potential for monitoring the depth of penetration and will find application during on-line monitoring and control of welding process. These research efforts indicate the growing interest world wide in the development of intelligent, closed loop automatic control systems for realizing high performance welding technology. Soft computing techniques have been used to develop models for adoptive control of A-TIG welding process which will find application during remore repair welding of reactor components.

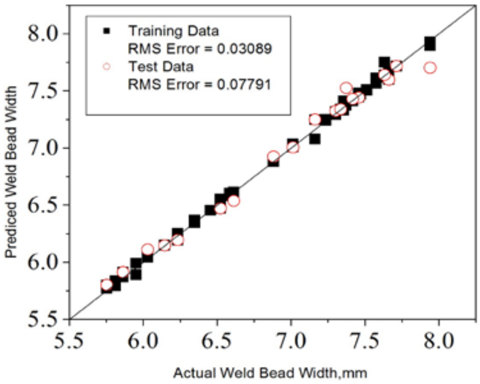

Fig. 12 Comparison between the predicted and measured weld bead width [5]

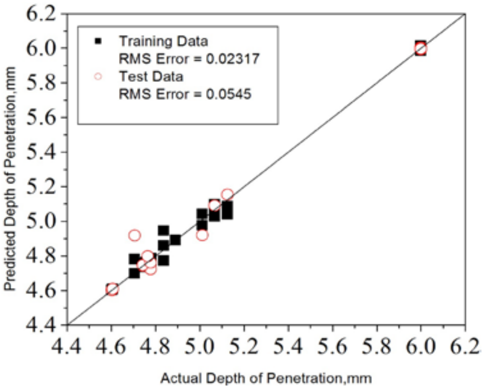

Fig. 13 Comparison between the predicted and measured depth of penetration [5]

2.2. 3 Optimization of Welding Process

An intelligent model combining artificial neural network and genetic algorithm has been developed for determining the optimum process parameters for achieving the desired depth of penetration and weld bead width during A-TIG welding of type 316LN and 304LN stainless steels. First ANN models correlating process parameters with depth of penetration and weld bead width have been developed. There was good correlation between the measured and models predicted depth of penetration as well as the weld bead width for both training and test data. A genetic algorithm code was developed in which the objective function was evaluated using the artificial neural network models. The optimized values for genetic algorithm parameters such as cross-over rate, population size and mutation probability were identified. The developed genetic algorithm model produced multiple outputs such as current, torch speed, voltage and arc gap for same target depth of penetration and bead width, and validation was carried out by experiments. There was good agreement between the target values and the actual values of depth of penetration and weld bead width obtained for both the stainless steels.

Tungsten Inert Gas (TIG) welding is preferred for welding of mod. 9Cr-1Mo steel in which the depth of penetration achievable during autogenous welding is very limited. Therefore, Activated flux Tungsten Inert Gas (A-TIG) welding, a novel welding technique has been developed in-house to increase the depth of penetration. In modified 9Cr-1Mo steel joints produced by A-TIG welding process, weld bead width, depth of penetration and Heat Affected Zone (HAZ) width play an important role in determining the mechanical properties and also the performance of the weld joints during service. To obtain the desired weld bead geometry, and HAZ width it becomes important to optimize the welding process parameters. In this work, Adaptive Neuro Fuzzy Inference System (ANFIS) is used to develop independent models correlating the welding process parameters like current, voltage and torch speed with weld bead shape parameters like depth of penetration, bead width and HAZ width. Figure 14 & 15 shows the comparison between the predicted and measured values of depth of penetration and HAZ width respectively. Then Genetic Algorithm (GA) is employed to determine the optimum A-TIG welding process parameters in order to obtain the desired weld bead shape parameters and HAZ width. Thus, the present work shows that Genetic Algorithm has the capability to optimize and produce multiple sets of welding process parameters that can lead to the desired weld bead profile and HAZ width accurately in austenitic stainless steels and mod. 9Cr-1Mo steel. The above methodology for process optimization can be extended to other welding processes as well.

3.0 Hardfacing:

3.1 Hardfacing of reactor components

Nickel based colmonoy alloys have been selected for replacement of the cobalt based stellite alloys as the hard facing material for the nuclear steam supply system (NSSS) components of PFBR. Colmonoy was chosen to keep induced radioactivity to the minimum for maintenance and decommissioning purpose. Many challenges have been undertaken at IGCAR to evolve a robust hardfacing strategy for the components of PFBR. The choice of appropriate deposition process is a must for success. Metallurgical studies revealed that the hardness and microstructure of the gas tungsten arc welding (GTAW) deposit of the Ni-base hardfacing alloy is significantly affected by dilution from the base metal with the width of the softer dilution zone (of up to 2 mm) often exceeding the final desired hardface deposit thickness. Also, certain components like grid plate sleeves of about 80 mm ID, that required hardfacing deep inside the inner surface of the sleeve were not amenable for hardfacing by conventional processes like GTAW process unless major design concessions were permitted. Hence, the more versatile plasma transferred arc welding (PTAW) process was chosen so that the width of the dilution zone could be controlled to as low as 0.2 mm (Fig. 16), by optimising the deposition parameters.

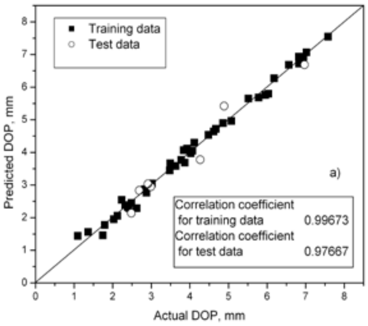

Fig. 14 Comparison between the Predicted and actual depth of penetration [6]

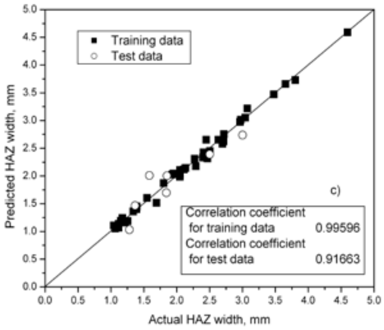

Fig. 15 Comparison between the predicted and actual HAZ width[6]

3.2 Hardfacing of Bottom Plate of Grid Plate Assembly

Grid plate of PFBR is a massive structure consisting of two plates (top and bottom of ~6.5 m in diameter). Grid plate houses a large number of sleeves in which foot of the sub assemblies rest. The grid plate assembly in turn rests on core support structure that also acts as boundary between cold and hot sodium in the reactor. Both the grid plate assembly and the core support structure are made of AISI 316L(N) stainless steel and immersed in flowing sodium and remain in contact throughout the reactor life (60 years). Hence, there should not be any self welding between these two components at their contact location. Hardfacing is carried out on two annular grooves machined on the bottom plate of the grid plate. These grooves are located towards the periphery of the grid plate and hence, diameters of these groves are close to that of the grid plate itself and total length (circumference) of single hardfaced deposit was close to 21 m.

During technology development of the grid plate, extensive cracking of the deposit is observed when deposition was carried out as per the procedure finalized initially based on trials carried out on 80 mm thick 1000 mm diameter plate. Subsequently, a detailed review of the design of the groove, welding process, procedure, heat treatment etc. was taken up in which designers, materials engineers, hardfacing agency and manufacturer of the grid plate participated. The groove width was reduced from 45 to 20 mm and the groove angle increased from 30° to 60°. This enabled us to carry out hardfacing in single layer and single pass of deposition. Preheat temperature for deposition was increased from 773K to 923K and the furnace for preheating and stress relieving heat treatment was modified to ensure that the temperature variation across the component during heating or cooling is reduced considerably. It was also decided to carry out hardfacing continuously using four Plasma Transferred Arc Welding (PTAW) machines positioned on a circular track which was concentric to the bottom plate. Machine controls were suitably modified to have smooth deposition between starting and ending locations of the deposit, which is found to be more prone to cracking than the other locations of the deposit. The process has been successfully employed for the bottom plate of the grid plate assembles of PFBR. After bottom plate reached preheat temperature, the entire operation of hardfacing of the two grooves of ~6.5 m dia. each took only a few hours. Fig. 17 shows the grid plate mounted on the furnace bed with hardfacing operation in progress. Neither cracks, nor de-bonding nor surface porosities were observed on the deposits.

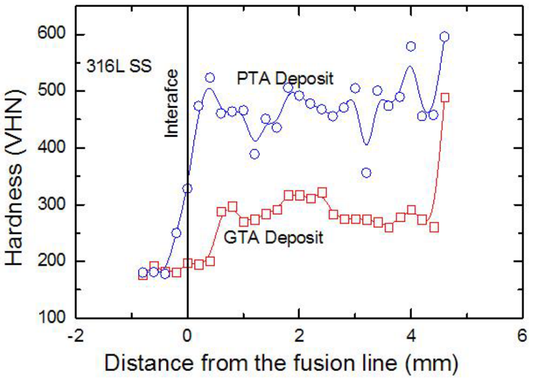

Fig. 16 Hardness profiles for Colmonoy deposits made by by GTAW and PTAW welding processes

Fig. 17 Hardfacing of the Grid Plate

3.3 Correlating hardness with Ferritescope measurements for hardface deposit

Recent study on hardfacing [7] revealed that dilution of the deposit by the base metal affects hardness as well as magnetic properties of the deposit. Dilution of the deposit is highest in the first layer and negligible from the third layer onwards. Accordingly, the variation in hardness and magnetic properties are significant only in the first two deposit layers. Variation in magnetic properties as determined from Ferritescope and Magnegage readings for hardface deposits as well as twin deposits showed a fair correlation with dilution level of the matrix. Good correlation was also obtained for both Ferritescope and Magnegage reading with Ni/Fe ratio indicating that Ferritescope and Magnegage, instruments normally used for measurement of delta ferrite content in stainless steel can be used for estimating dilution of the deposit. Similar to magnetic properties, hardness of the hardface and twin deposits also follow a fair correlation with dilution represented by Ni/Fe of matrix. As both the magnetic property and hardness are affected by dilution and hence an indirect correlation exists between hardness and magnetic properties (Fig. 18). Hence, one of the potential applications of the results presented here can be the use of magnetic measurement as a non-destructive tool to estimate the surface hardness of the Ni-base hardfaced coatings on austenitic stainless steels. Hence, it could be possible to predict the hardness of the deposit simply by measuring the magnetic property of the deposit by Ferritescope and Magnegage, equipments widely used in the field for measuring delta-ferrite content in stainless steel welds. The importance of such measurements is significant in hardfacing of actual components for various applications, which are not amenable for in-situ hardness measurements.

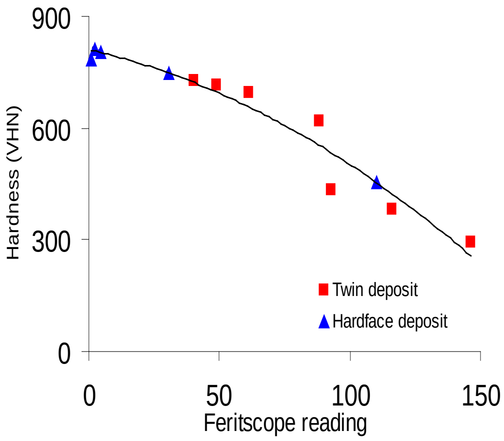

Fig. 18 Variation of hardness with Ferritescope Readings of hardface deposits

4. Concluding Remarks:

A few illustrative exemplary approaches followed for successful deployment of welding and hardfacing technologies for the current and future Indian Fast Breeder Reactor Programme have been described. Research and development and deployment of welding and hardfacing technologies has been enabled by innovative modelling, characterisation, testing and evaluation of weld joints, successful implementation in manufacturing processes and validation of technologies by demonstration with real-life structures and components. The extensive collaborations among academic, research and industrial organisations with 'science-based technology' approach are the guiding principle for the successful development of welding and Hardfacing technologies for the Indian Fast Breeder Reactor Programme.

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