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PROF. PLACID RODRIGUEZ MEMORIAL LECTURE 2020

Development of Welding Procedures for Critical Applications in Nuclear and Fossil Power Plants

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Abstract

I am involved in the several projects for development of materials, welding procedures and welding consumables for nuclear and Advanced Ultra Super Critical (AUSC) coal-fired power plants. As it is difficult to cover the entire work, I am presenting here some of the important and unique welding activities in this prestigious Prof. Placid Rodriguez Memorial lecture.

As a national mission program, research organizations and industries are working together for the development of new materials, fabrication technology, designing and construction of Indian Advanced Ultra Super Critical (AUSC) thermal power plant of 800 MWe capacity with steam parameters 710°C/720°C/310 bar. Indigenously developed Alloy 617M (a chemistry control variant of Alloy 617) and 304HCu SS are materials of choice for AUSC boiler tubes. Welding procedure has been developed and qualified for similar and dissimilar metal welding of Alloy 617M and 304HCu SS boiler tubes. Repair welding procedure for service exposed Alloy 617M has also been established. The dissimilar metal welding between 10Cr ferritic martensitic steel and nickel-base Alloy 617M rotor forgings for AUSC high pressure (HP) and intermediate pressure (IP) steam turbines is unique and first of its kind. For this, welding procedure, weld groove design and post weld heat treatment has been optimized using hot-wire narrow-gap TIG welding process, and mock-up weld joints are qualified as per ASME Section IX requirements. Root pass argon gas purging methodology in the localized cavity of solid welded rotor has also been established and qualified. Both NG-TIG welding procedure and root pass argon gas purging methodology has been successfully implemented in the fabrication of full-size welded rotor for AUSC project.

Similar and dissimilar welding of commercially pure titanium and 304L SS are required for the reprocessing of Fast Breeder Reactor nuclear spent fuel. The dissimilar metal joint between titanium and 304L stainless steel (SS) was carried out by explosive cladding process. The explosive cladded plates were qualified by ultrasonic examination, shear test, bend test and three phase (liquid, vapour, and condensate phase) corrosion test in 11.5M boiling nitric acid. The activated flux has been formulated in-house for autogenous TIG welding of titanium. The activated flux TIG weld joint fabricated using 6 mm thick titanium plate passed as per ASME section IX requirements and 11.5M boiling nitric acid test. This paper highlights some of the critical welding procedures developed for AUSC and nuclear power plants.

Keywords: 10Cr steel; Alloy 617M; Titanium; 304L SS; 304HCu SS; Welding; ATIG; Narrow-Gap TIG; Welded rotor.

1.0 Introduction

I would like to thank The Indian Institute of Welding (IIW-India) for giving me this honour of delivering Prof. Placid Rodriguez Memorial lecture at the National Welding Seminar (NWS 2020-21). Prof. Placid Rodriguez was the Director of IGCAR, Kalpakkam from December 1992 till October 2000. Dr. Rodriguez is Internationally well-known for his R&D contributions in Mechanical Metallurgy, Welding Metallurgy and Nuclear Materials. He has guided and nurtured several of our senior colleagues in the multidisciplinary fields of Science and Engineering for the advancement of fast breeder reactor technology in India. I consider this as a great honour that I am selected to deliver this lecture for the year 2020 instituted in his memory by IIW-India.

Research and Development on coal-fired thermal power plants with higher thermal efficiency has been taken up by advanced countries for meeting the large requirement of electricity and to reduce the emission of CO_2, SO_x and other environmentally hazardous gases [1]. Towards this, India is aiming to indigenously develop materials and fabrication technologies, and to design and build an 800 MWe capacity Advanced Ultra Supercritical (AUSC) coal-fired thermal power plant with steam parameters of 710°C/720°C/310 bar to achieve high efficiency (~ 46%). With the promotion of steam parameters to AUSC level, high temperature materials with improved creep strength, steam corrosion and oxidation resistance such as advanced austenitic heat resistant steels and Ni-base superalloys are required. Austenitic stainless steel (SS) 304HCu and nickel-base Alloy 617M (a chemistry control variant of Alloy 617) are the candidate boiler tube materials for AUSC plants. For the first time in India, the indigenous development of 304HCu SS seamless tubes (52 mm OD, 9.5 mm WT) and Alloy 617M seamless tubes (52 mm OD, 11.9 mm WT) has been successfully developed by IGCAR Kalpakkam in collaboration with industrial partners MIDHANI Hyderabad and NFC Hyderabad meeting the international standards [2].

Alloy 617M and 10%Cr ferritic martensitic steel are candidate rotor materials under consideration for steam turbine of India Advanced Ultra Super Critical (AUSC) coal fired power plants [3-4]. 10% Cr steel is used for section of the rotor subjected to maximum temperature up to 540°C. While, Alloy 617M is considered for high temperature section of the rotor above 540C and maximum up to 720°C [4]. Hence, there is a dissimilar metal welding (DMW) between 10% Cr steel rotor parts to Alloy 617M rotor parts [4-5]. This DMW will be executed by hot-wire narrow-gap TIG (NG-TIG) welding process using Alloy 617 filler wire (ERNiCrCoMo-1).

Narrow-Gap welding also known as narrow-groove welding is an advanced technique for higher productivity in the manufacture of thick-walled components. This welding technique uses joint preparation with small included angle (typically 2-20) which requires less volume of weld metal and hence less welding time and is economical. Narrow-Gap technique have been used for various welding processes such as Submerged Arc Welding (SAW), Gas Metal Arc Welding (GMAW), Tungsten Inert Gas (TIG) welding. Because of narrow-groove and limited accessibility to the joint root, specialized equipment is required to carry out the welding. The narrow-gap TIG (NG-TIG) welding is carried out using narrow-groove joint design which is a radical departure from conventional manual welding joint preparation. NG-TIG welding process is used in thick section welding of nuclear and thermal power plant components [6-7]. One of the critical applications of NG-TIG welding process is in joining of turbine rotor in Advanced Ultra Super Critical thermal power plant. The HP and IP rotors are solid rotors with localized cavity beneath the 10Cr steel/Alloy617M dissimilar weld. Therefore, in addition to the of NG-TIG welding procedure development, there was a requirement to develop a methodology for root pass argon gas purging procedure in the localized cavity (called as weld cavity) during root pass welding to protect the weld root from atmospheric contamination. To develop the welding procedure for DMW between 10%Cr steel and Alloy 617M rotor parts, a systematic study on welding of rotors of Alloy 617M with rotors 10%Cr steel was taken up at IGCAR, Kalpakkam under AUSC pre-project R&D project.

In nuclear industries, commercially pure titanium (ASTM Grade-1 and Grade-2) is used as a structural material (dissolver vessel) for the reprocessing of spent fuel where highly concentrated nitric acid (11.5 molar) in boiling condition is used for the dissolution of spent fuel. However, for cost effectiveness the rest of the plant piping/equipment, which are either exposed to low concentration nitric acid or are not at all exposed, are made of 304L SS. This requires the development of dissimilar metal joint between Ti and 304L SS. These dissimilar joints are required in pipe geometry of various sizes (8NB to 100 NB SCH 40 pipe). The integrity of this transition joints is very critical for the safe operation of reprocessing plant. The limited mutual solubility of Ti in Fe and vice versa, easy formation of brittle intermetallic compounds like FeTi and Fe2Ti has ruled out the fusion welding option in joining of Ti to Fe-base alloys like 304L SS. Solid state welding processes that limit the extent of inter-mixing are generally employed for joining Ti to 304L SS and many such dissimilar metal combination [8]. It has been reported that the explosive welded Ti/304L SS joints shown better properties than of friction welded joints [9, 10]. For this reason, the explosive cladding was carried out for joining Ti to 304L SS required for the Demonstration Fast Reactor Fuel Reprocessing (DFRP) plant which is being commissioned now at IGCAR, Kalpakkam. As the explosive cladding is possible in plate geometry, it was decided to carry out explosive cladding in plate geometry and subsequently machine out couples (in pipe form) from the cladded plates. Subsequently 304L SS and Ti sides of the dissimilar couples can be welded to 304L SS and Ti pipes, respectively for making joining inserts which are welded again to the respective end using fusion welding on-site.

The use of activated flux in TIG welding is found to be a promising technique to improve the productivity and reduce the overall welding cost.Activated Flux TIG (ATIG) welding fluxes are now available for welding a wide range of materials including carbon steels, low alloy steels and stainless steels. However, all the flux formulations are protected by patents. Further, there is a limited study and information available about the ATIG fluxes for welding of Ti and its alloys. Therefore, activated flux has been optimized and qualified for ATIG welding of commercially pure titanium required for fabrication and repair welding of titanium equipment in nuclear reprocessing plant [11].

The following sections highlights the systematic study carried out for the development and implementation of some of the critical welding technologies work carried out for Indian AUSC mission program and nuclear application.

2.0 Development of NG-TIG welding procedure for 10Cr steel/Alloy 617M welded rotor

The chemical composition and mechanical properties of 10Cr steel and Alloy 617M forgings, and Alloy 617 filler wire used are given in **Table 1**. **Figure 1** shows the hot wire NG-TIG welding facility at IGCAR with column and boom arrangement and Tilt Table Positioner (Rotator) of 1 ton and 10 ton capacity for circular welding of pipe. The NG-TIG welding procedure for rotor welding has been successfully developed at IGCAR by the execution of following activities in a very systematic manner: (i) NG-TIG facility set-up at IGCAR for thick section rotor forging welding, (ii) procurement of forgings, (iii) welding parameters optimization by first doing welding trials on 304 SS hollow bar, (iv) DMW trials using 200 mm diameter hollow forging with weld thickness of 50 mm by two methodologies (direct welding and buttering method), and (v) DMW trial using 400 mm diameter hollow forging with weld thickness of 95 mm by buttering method, (vi) NDT and mechanical testing qualification as per ASME requirements.

The first method is by direct welding between 10Cr steel and Alloy 617M using ERNiCrCoMo-1 filler metal followed by PWHT at 670°C/10h. The second method is by buttering/weld overlaying of 10Cr steel by ERNiCrCoMo-1 filler metal followed by PWHT at 670°C/10h and subsequent welding of overlay deposit with Alloy 617M rotor part. Both the 200 mm diameter NG-TIG weld joints having weld thickness of 50 produced by two different methodologies passed in radiography, tension and bend tests. **Fig. 2** shows the buttering of 400 mm diameter 10Cr forging and subsequent NG-TIG welding with 400 mm diameter Alloy 617M part. Weld overlaying/buttering of 10Cr steel was carried out using ERNiCrCoMo-1 filler and conventional TIG torch mounted on column and boom arrangement with job fixed on tilt table positioner. The deposition of ERNiCrCoMo-1 weld metal on 10Cr steel forging was successfully done using computer-controlled program for a required height of 33 mm towards job center (**Fig. 2b**). The welding torch shifted automatically after every 360 of job rotation (**Fig. 2a**). Preheating and inter-pass temperature of around 200°C was maintained during buttering operation using induction heating system. The weld overlaying was qualified by liquid penetrant test after the final pass and found to be free from surface defects. The 10Cr steel buttering piece was subjected to PWHT at 670°C for 10h to temper the HAZ of 10Cr steel. For rotor welding, 10Cr steel buttering piece and Alloy 617M solid forging were machine fabricated into hollow forging (400 mm OD x 95 mm wall thickness) and narrow groove edge prepared with groove angle of 5° for NG-TIG welding. NG-TIG welding was carried out between Alloy 617 buttering layer and Alloy 617M part in 1G position using ERNiCrCoMo-1 filler (Fig. 2c). During welding, inter-pass temperature was maintained below 150°C. The welding parameters were optimized to ensure good side wall fusion in the narrow weld groove. The 95 mm thick DMW was completed in 50 weld passes which passed in Phased array UT as per the rotor specification, and cross-weld tension and side bend tests as per ASME section IX. Three samples (weld root, middle and top/face) were fabricated for covering the 95 mm thick joint. Four sets of side bend and two sets tension test specimens were tested as per ASME section IX requirement. The cross-weld tension tests showed tensile strength in the range of 768-792 MPa in comparison to minimum specified tensile strength of 655 MPa for Alloy 617M forging (weakest of the two materials used) and are acceptable as per standard. The microscopic examination of metallographically polished and etched welded samples showed good metallurgical bonding across the fusion line. Further analysis of metallography samples by SEM-EDS for dilution zone and precipitate characterization are completed. Based on the present investigations on narrow-gap TIG welding process, it was found that the narrow-gap TIG welding process can be used successfully for thick section joining. The weld joints were found to be defect free and showed acceptable mechanical properties. Welding procedure specification including weld groove design and PWHT was finalised for fabrication of welded turbine rotors for AUSC project.

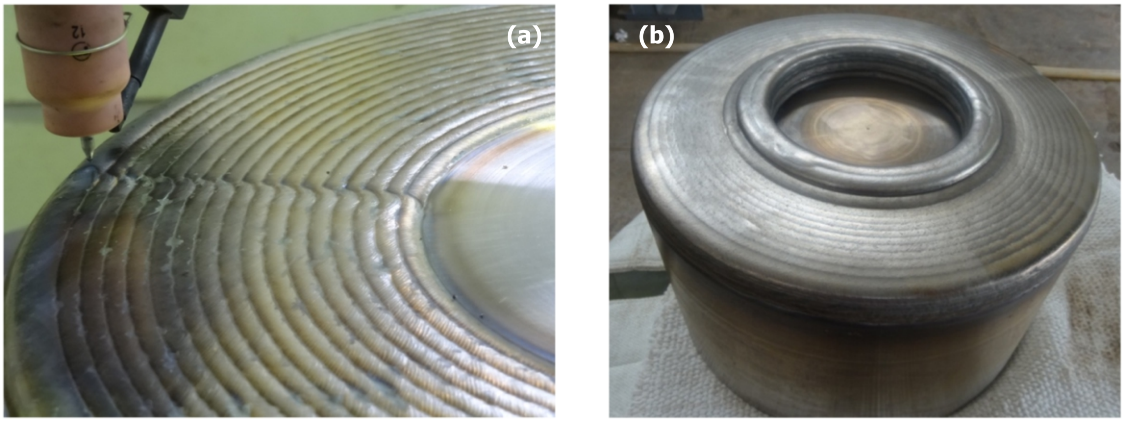
The AUSC welded rotors are solid forgings designed with a localized hollow cavity (referred as weld cavity) beneath the weld as shown in **Fig. 3 (a)**. Due to the absence of through hole, it was not feasible to adopt the conventional method of argon gas purging on the ID side to protect the weld root from atmospheric contamination / oxidation during root pass welding. The root pass purging procedure has been successfully developed at IGCAR. The methodology adopted for root pass purging involves making small holes across 360 periphery adjacent to joint fit-up/land location for the argon gas to enter inside the weld cavity while root pass welding and protect the weld root from oxidation and closing of holes by the molten weld pool during root pass itself. Welding trials were carried out on 90 mm diameter solid 316 SS round bar with localized weld cavity using 308L filler wire and NG-TIG welding machine. Initial welding trials showed lack of shielding of weld root and weld metal puncture/hole created during 2nd weld-pass due to internal gas pressure and low strength hot molten zone. Subsequently, the welding parameters and welding sequence were optimized and the 316 SS mock-up weld joint with 10 mm joint thickness was completed successfully (**Fig. 3b**). The weld joint passed in X-ray radiography. The completed weld joint was cut adjacent to the weld for visual inspection. **Fig. 3(b)** shows photograph of cut section of mock-up weld joint with localized cavity revealing consistent weld root penetration and effective argon gas shielding from root side. The repeatability of the results and welding parameters were verified by doing more mock-up weld joint. Both the NG-TIG welding and root pass purging technologies are successfully implemented for the manufacturing of full size welded rotor for AUSC project (**Fig. 4**).

Table 1 : Chemical composition and mechanical properties (at RT) of 10Cr steel forging, Alloy 617M forging and Alloy 617 filler wire

Cr	Mo	W	V	Nb	Ni	C	N	Mn	Si	P	S	Al	Fe
10.56	1.07	0.98	0.2	0.02	0.77	0.123	0.046	0.42	0.024	0.005	0.002	0.005	Bal.
0.2% YS (MPa)		**UTS (MPa)**		**% Elongation (5d)**			**% Reduction in Area**				**Impact Strength (J)**		
770-779		894-902		17-18			59-62				56-61		
Alloy 617M Forging													
Cr	**Fe**	**Mn**	**Mo**	**Co**	**Al**	**C**	**Cu**	**B**	**Si**	**S**	**N**	**Ti**	**Ni**
22.9	0.38	0.001	8.39	12.32	0.81	0.062	0.019	0.003	0.11	0.002	0.0046	0.428	Bal.
0.2% YS (MPa)				**UTS (MPa)**					**% Elongation (5d)**				
414				726					52.6				
Alloy 617 Filler Wire													
Cr	**Fe**	**Mn**	**Mo**	**Co**	**Al**	**C**	**Cu**	**B**	**Si**	**S**	**N**	**Ti**	**Ni**
22.30	0.8	0.42	8.7	11.30	1.3	0.1	0.1	-	0.32	0.002	-	0.42	Bal.

(a) NG-TIG Welding Machine (b) NG-TIG Torch

Fig. 1 : (a) Hot Wire Narrow-Gap TIG welding machine with column and boom arrangement and (b) NG-TIG Torch.



(a) & (b) 10Cr steel forging buttering with ERNiCrCoMo-1,

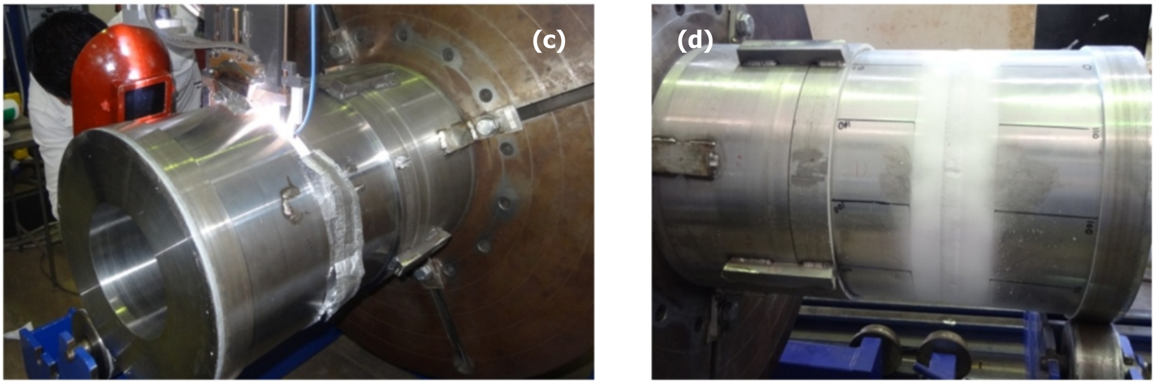
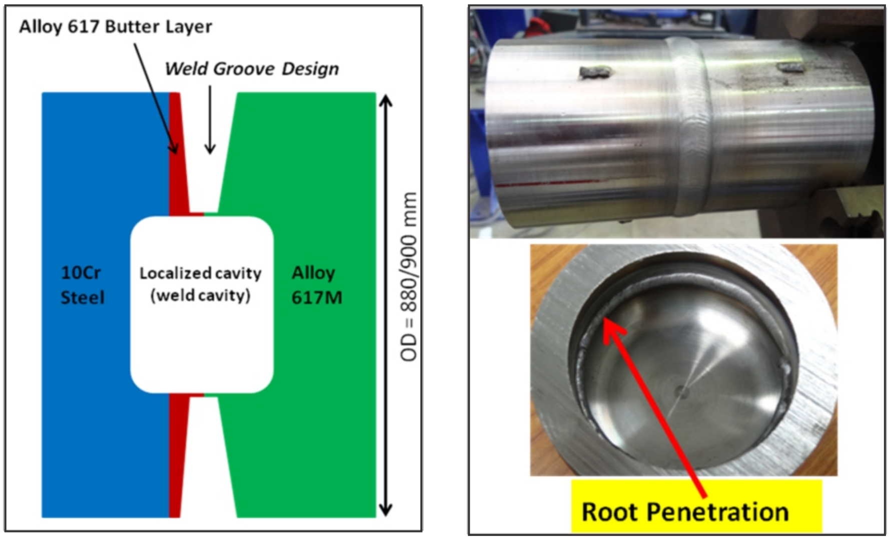


Fig. 2 : (a)&(b) 10Cr steel forging buttering with ERNiCrCoMo-1, (c) NG-TIG welding in progress and (d) LPT after final weld pass of 400 mm diameter 10Cr steel/Alloy 617M weld joint.



(a) Schematic of weld groove design

(b) Mock-up weld joint

Fig. 3: (a) Schematic of weld groove and localized hollow cavity (weld cavity) in the welded steam turbine rotor, (b) mock-up weld joint for root pass argon purging and cut section.

Fig. 4 : Photograph of Full Size AUSC Welded Rotor

3.0 Similar and Dissimilar Welding of 304HCu SS and Alloy 617M Boiler Tubes

Welding procedures are developed for similar and dissimilar weld joints of 304HCu SS tube (θ 52 mm x 9.5 mm wall thickness) and Alloy 617M tube (θ 52 mm x 11.9 mm wall thickness). Welding of 304HCu SS tube was carried out using matching filler wire ER304HCu SS.The ER304HCu was with higher Ni and Mn compared to 304HCu SS base material. Similar welding of Alloy 617M and dissimilar metal welding of Alloy 617M/304HCu SS was carried out using ERNiCrCoMo-1 (Inconel 617). The chemical composition of 304HCu SS and Alloy 617M tube materials and welding consumables is given in **Table-2**. Multi-pass TIG welding was carried out using single-V joint geometry by a qualified welder in a systematic way and procedures were qualified by carrying out X-ray radiography and mechanical tests (tension and bend) of the weld joints as per ASME Section IX. Lack of fluidity of nickel base filler wires was a challenge to obtain full penetration and crack free joints. Welding parameters and groove angle was optimized by doing few welding trials on mock-up pieces to obtain radiographically qualified joints. **Figures 5 & 6** show photograph of Alloy 617M boiler tube weld joint and its bend tested specimens respectively. **Table 3** shows cross-weld tensile properties of similar and dissimilar weld joints of 304HCu SS and Alloy 617M tube joints. All the three type of welded tube joints passed bend test and tension test as per ASME Section IX requirements. Based on this approved welding procedures, subsequently, total 125 numbers of similar and dissimilar weld joints (100 nos. similar and 25 nos. dissimilar) were fabricated. All the weld joints were qualified by liquid penetrant examination, X-ray radiography.

Alternately, Orbital TIG welding procedures are also developed for joining of 304HCu SS and Alloy 617M tubes using newly established Orbital TIG welding facility at IGCAR (**Fig. 7**). The weld groove design, welding sequence and welding parameters are optimized to avoid concavity in 5-7 o'clock position due to gravity effect and to get the consistent weld root penetration and radiography quality weld joints.

Table 2 : Chemical composition of 304HCu SS and Alloy 617M tube materials, and welding filler wires (wt. %)

Elements	**Base Metal Tubes**		**Welding Consumables**	
	304HCu	**Alloy 617M**	**ER304HCu**	**ERNiCrCoMo-1**
Carbon	0.07-0.13	0.05-0.08	0.04-0.08	0.05-0.15
Chromium	17.0 -19.0	21.0-23.0	19.5-22.0	20.0-24.0
Nickel	8.0-10.0	balance	9.0-11.0	balance
Molybdenum	-	8.0-10.0	0.5 max	8.0-10.0
Manganese	1.0 max	0.3 max	3.0 max	1.0 max
Silicon	0.3 max	0.3 max	0.3-0.65	1.0 max
Sulphur	0.01 max	0.008 max	0.03 max	0.015 max
Phosphorous	0.03 max	-	0.03 max	0.03 max
Nitrogen	0.07-0.12	0.05 max	0.1-0.16	-
Cobalt	-	11.0-13.0	-	10.0-15.0
Copper	2.5-3.5	0.5 max	3.01	0.5 max
Niobium	0.3-0.6	-	0.4 max	-
Titanium	-	0.3-0.5	-	0.6 max
Aluminium	0.003-0.03	0.8-1.3	0.03 max	0.8-1.5
Boron	0.002-0.006	0.002-0.005	0.01 max	-
Iron	balance	1.5 max	balance	3.0 max

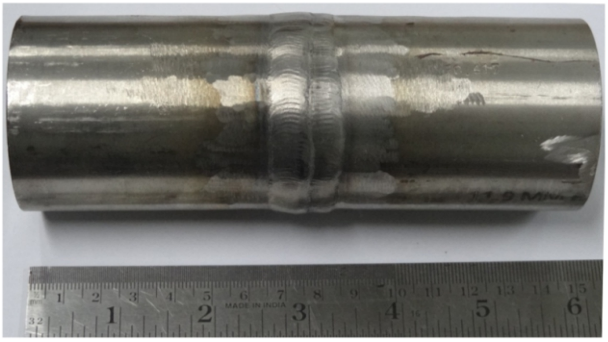


Fig. 5 : Photograph of a typical Alloy 617M welded tube

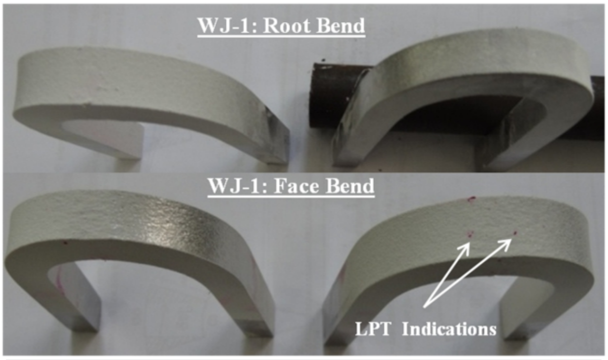


Fig.6 : Photograph of bend tested specimens of Alloy 617M welded tube

Table 3 : Tensile properties cross-weld similar and dissimilar tube joints

Tensile Properties of 304HCu SS & Alloy 617M Weld Joints				
Weld Joints	**Filler wire**	**UTS (MPa)**	**Failure Location**	**Remarks**
304HCu SS Weld Joint	ER304HCu	694	Weld	Met ASME section IX and are Acceptable
Alloy 617M Weld Joint	ERNiCrCoMo-1	798	BM/WM	
304HCu/Alloy 617M DMW	ERNiCrCoMo-1	706	304HCu Base Metal	

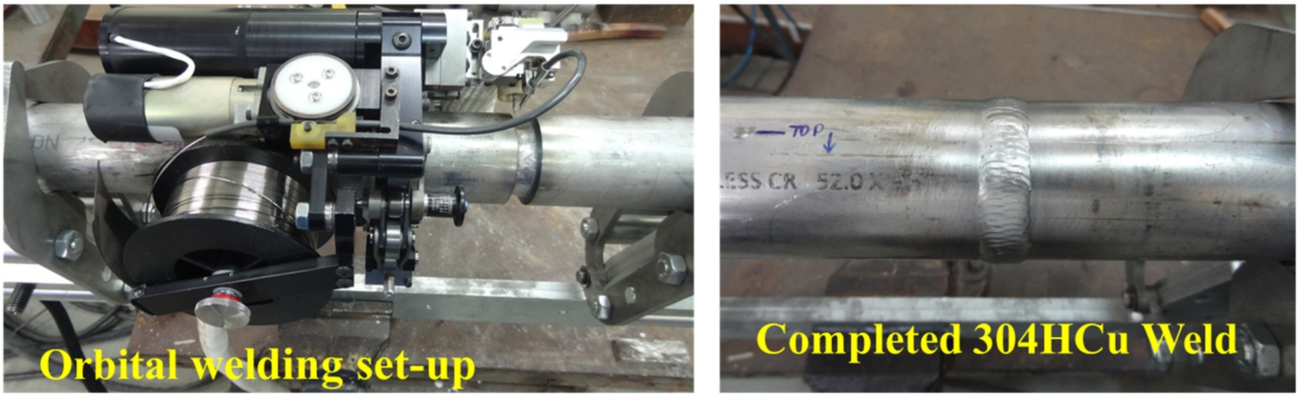


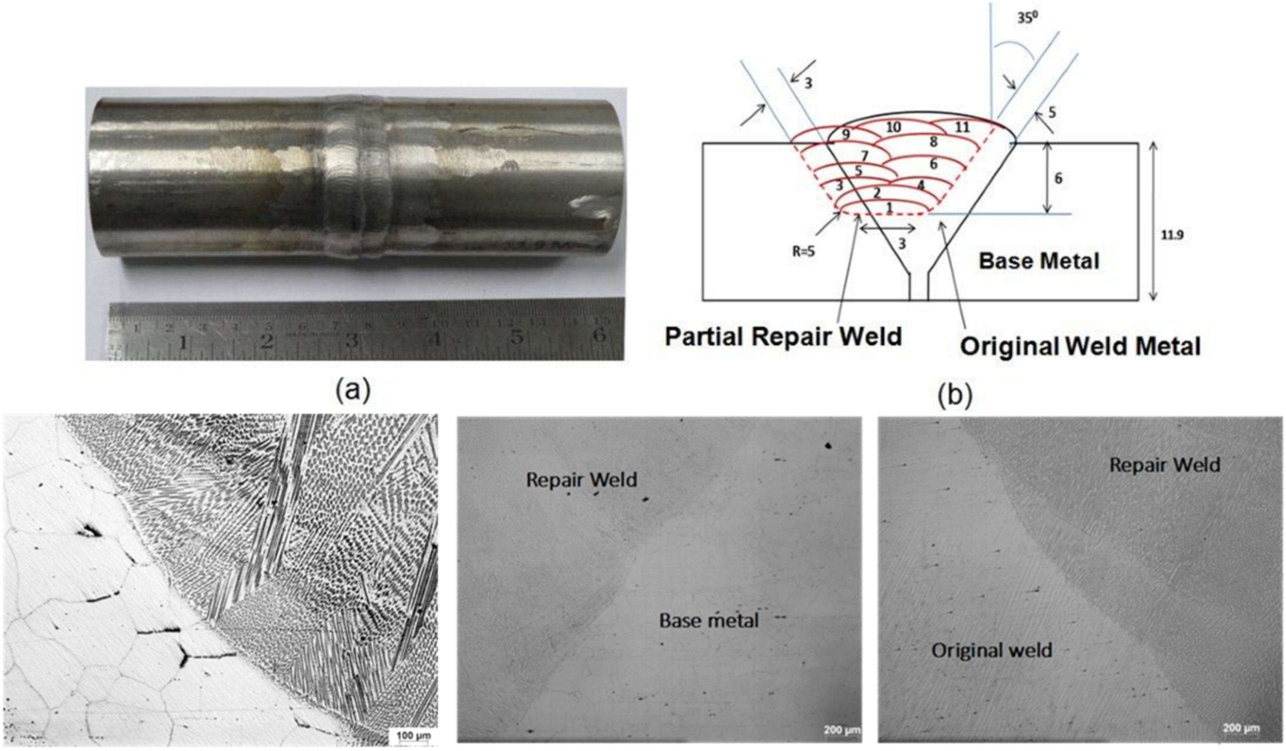
Fig. 7 : Orbital TIG welding of 304HCu and Alloy 617M tubes

4.0 Repair welding procedure development for service exposed Alloy 617M welded tube

Alloy 617M base metal and welded tubes possess sufficient ductility and toughness in the as-received solution annealed and as-welded condition respectively. However, during high temperature service (675-750^{o}C in the AUSC plant), the precipitation of secondary carbide precipitates (mostly Cr-rich $M_{23}C_6$ along grain boundary) and γ-Ni_3(Al, Ti) within the grain significantly increases the strength of the material with reduction in ductility and toughness. This may result in cracking of the Alloy 617M components during prolong service. Therefore it is crucial to develop the repair welding procedure for Alloy 617M components to make the AUSC plant economically viable.

The repair welding behavior of service exposed Alloy 617M welded tube was studied by subjecting the base metal tube and multi-pass manual TIG welded tube (**Fig. 8a**) to simulated ageing heat treatment in the furnace (at 700 ^{o}C and 750 ^{o}C for 1000h & 4000h). Extensive carbide precipitation along the grain boundaries, and γ' within the grains were observed in the aged base metal and weld metal. The yield strength and tensile strength of Alloy 617M base metal and weld metal after ageing heat treatment increased by 150-200 MPa in comparison to as-received/as-welded condition. In contrast, the Charpy V-notch toughness showed significant reduction after ageing viz. weld metal toughness reduced from 125J in the as-welded condition to 50J after ageing.

Partial penetration repair welds (**Fig. 8b**) were made on weld joints of Alloy 617M tubes by manual TIG welding process using Alloy 617 filler wire (ERNiCrCoMo-1). Repair welding of welded tube joints was carried out in the following conditions: (i) as-welded tube (without ageing heat treatment), (ii) aged welded tubes (700 ^{o}C/1000h and 700 ^{o}C/4000h), and (iii) aged welded tube (700 ^{o}C/4000h) followed by solution annealing heat treatment at 1160 ^{o}C/1h. There are no anomalies observed in microstructure of repair weld fabricated in as-welded tube. The microstructural analysis revealed the presence of micro-fissures in repair welds fabricated in aged welded tubes (**Fig. 8c**). These micro-fissures formed in the heat affected zone (HAZ) are intergranular in nature, i.e. cracks are formed along the grain boundaries. During aging the grains are strengthened by γ' precipitation; and the grain boundaries are weakened by formation of continuous network of Cr-rich $M_{23}C_6$ carbides along grain boundary. Inability of the stronger aged material to deform and localized stress concentration at grain boundaries owing to the presence of incoherent carbides resulted in de-cohesion of grain boundaries due to shrinkage stresses generated during repair welding. This de-cohesion resulted in micro-fissures in the HAZ. However, the application of solution annealing heat treatment at 1160 °C for 1h to aged Alloy 617M before repair welding could help in producing repair welds without micro-fissures (**Fig. 8d**). This is due to dissolution of precipitates formed during ageing at high temperature solution annealing and hence restoration of ductility and toughness. The repair weld joints passed in LPT, radiography and cross weld tensile test as per ASME Section IX. Thus, the present study reveals that solution annealing heat treatment of service exposed material before repair can minimize this risk and results in repair welds of acceptable quality and required properties.



(c) Micro-fissures in aged repair weld

(d) Acceptable repair weld microstructure

Fig. 8: (a) photograph of manual multi-pass TIG Alloy 617M welded tube, (b) Schematic of partial repair weld groove design in overlap with original weld and base metal, (c) micro-fissures in the weld HAZ of repair weld carried out in aged condition, and (d) repair weld free from micro-fissures carried after the aged weld tube subjected to solution annealing heat treatment (1160^{o}C/1h).

5.0 Fabrication of Ti/304L SS Explosive cladded couples for nuclear spent fuel re-processing plant

The dissimilar joint between titanium and 304L SS are required in pipe configurations of various sizes (8NB to 100 NB SCH 40 pipes) for connecting the titanium dissolver vessel to 304L SS plant piping. For this, the surface finished Ti Garde-1 plate of 12 mm thick was explosive cladded on 25 mm thick 304L SS plate. Two numbers of cladded plates (named as A and B) of size 450 mm × 450 mm × (12 mm Ti + 25 mm 304L SS) were fabricated at an Indian industry. Explosive cladded plates were given a stress-relieving heat treatment at 813K (540^{o}C) to release the residual stresses and soften the bond zone. The soundness of the joint was evaluated by ultrasonic examination to find out lack of bonding or any cracking etc. The ultrasonic qualified Ti/304L SS explosive cladded plates were qualified by mechanical tests and corrosion test.

Shear test was carried out as per ASTM B898 and one sample was tested for each cladded plate (**Fig. 9a**). The shear strength of the cladded plates A and B are 210 and 278 MPa respectively and both the cladded plates met the minimum specified shear strength of 137.9 MPa as per ASTM B898, which indicate good bonding between Ti and 304L SS.

Bend test of the cladded plates was carried out as per ASTM B898. For each cladded plate, two face-bend tests were carried out with bend radius of 2T, where T is the thickness of the bend test sample. Out of two face bend tests, one sample was tested with the cladding metal (Ti) in tension and the other with the cladding metal (Ti) in compression. For both cladded plates, face bend samples showed bend ductility of 180^{o} with no crack in the bend surface as well as no de-bonding in the explosive joint interface (**Fig. 9b**). This reveals that the joints have good metallurgical bonding at the joint interface.

To carry out the tensile test in pipe geometry, Ti/304L SS couples (8NB SCH40) were machined out from two cladded plates. The Ti/304L SS couples were butt-welded to titanium pipe on Ti side and to 304L SS pipe on 304L SS side. Fusion welding of titanium pipe was carried out by TIG welding process using 1.6 mm diameter titanium filler wire (ERTi-1) and high purity argon for shielding. Welding was completed in two passes, and low heat input, sequential welding and intermediate cooling were employed to avoid overheating of the explosive cladded region. Similarly, welding of 304L SS pipes to the 304L SS end of the dissimilar couples were carried out by TIG welding process using 1.6 mm diameter ER308L filler wire and welding was completed in two passes. The weld joints were qualified by LPT and radiography. Tensile test of the full section welded pipes (**Fig. 10**) were carried out as per ASME Section IX, and 2 samples were tested for each cladded plate. All the four samples fractured at the Ti/304L SS explosive welded joint interface with UTS in the range of 289–306 MPa compared to UTS of 326 MPa for Ti base material (weakest of the two materials used, viz. Ti and 304L SS). However, the tensile strength of the weld joints is more than the minimum specified tensile strength for grade-1 Ti material (240 MPa) and is acceptable as per ASME section IX.

Fig. 9: (a) Shear tested, and (b) face-bend tested specimens of Ti/304L SS explosive cladded plates

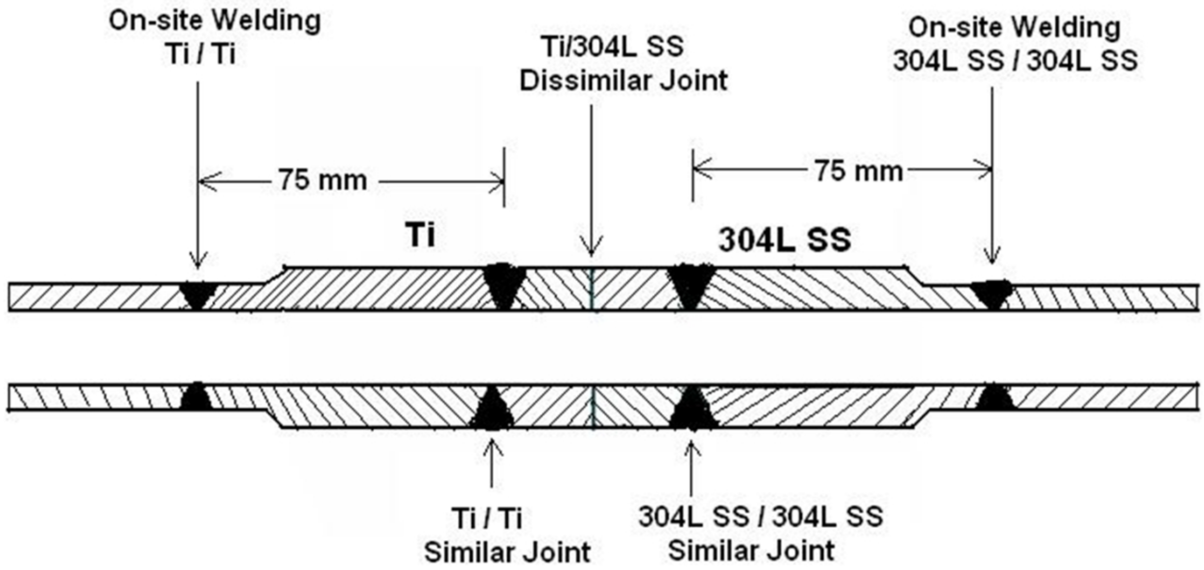
Fig.10 : Photograph of tensile test specimen of Ti/304L SS couple after TIG welding to Ti and 304L SS pipe

The Ti/304L SS explosive cladded samples were subjected to three phase corrosion tests (liquid, vapour, and condensate phase) in nitric acid bath of 11.5 M concentration. The concentration of the acid was selected as 11.5 M to simulate the acid concentration used in the spent fuel reprocessing plant. **Table 4** shows the average corrosion rates for 240 h for the cladded plates A and B, and Ti base material in liquid, vapour and condensate phases of boiling 11.5 M nitric acid. The corrosion rates of Ti/304L SS explosive welded samples are found to be comparable to the Ti base material and are acceptable. The corrosion rates are high in liquid phase compared to vapour and condensate phases due to higher concentration of nitric acid in liquid phase.

Detailed microstructural characterization of the Ti/304L SS joint interface was also carried out to identify the intermetallic compounds formed at the interface during explosive cladding. After the successful qualification of the explosive cladded plates, Ti/304L SS couples in pipe geometry (8NB to 100NB SCH40) required for reprocessing plant were machine fabricated from the cladded plates. New pipe-to-pipe joint design with higher wall thickness in the Ti/304L SS joint region proposed is implemented in the plant to ensure integrity of the joints in service (**Fig. 11a**). Welding procedure with use of copper sleeve at the explosive cladded interface to act as a heat sink was qualified for joining Titanium and 304L SS pipes to respective ends of Ti/304L SS dissimilar couples for fabrication of the intermediate pieces for connecting the Titanium dissolver to the 304L SS pipelines in the site (**Fig. 11b**). This qualified procedure for the Titanium/304L SS intermediate pieces has been adopted in the fabrication of pipelines in the reprocessing plant at IGCAR.

Table 4 : Average corrosion rate (in mpy) in liquid, vapour and condensate phases of boiling 11.5 M nitric acid after 240 h for cladded plates and Ti base metal

Phase	**Cladded Plate A**		**Cladded Plate B**		**Ti Base Metal**
	Test 1	**Test 2**	**Test 1**	**Test 2**	**Test 1**
Liquid	18.0	18.62	19.44	20.15	20.09
Vapour	1.6	1.8	2.372	1.744	0.62
Condensate	1.29	2.22	1.466	1.686	2.03



(a) Schematic of Ti/304L SS couple design

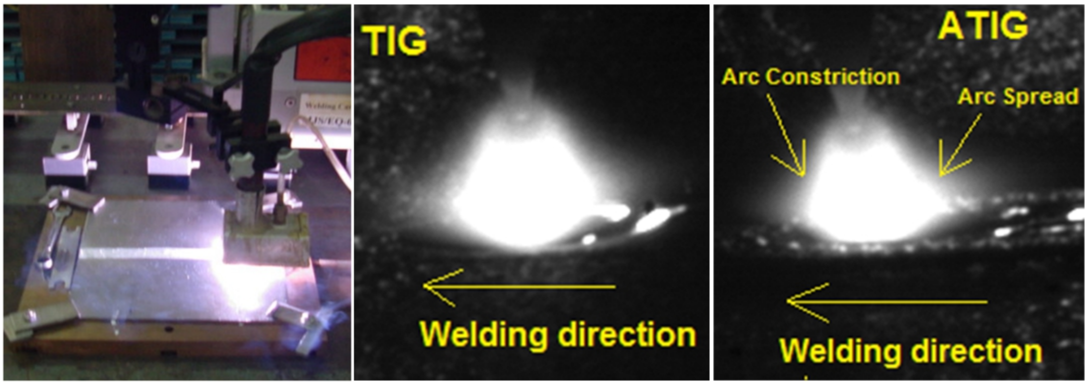
(b)Welding set-up with copper-sleeve as heat sink for fabrication of intermediate piece

Fig.11 : Fabrication of Ti/304L SS pipes from the explosive cladded plate for onsite welding.

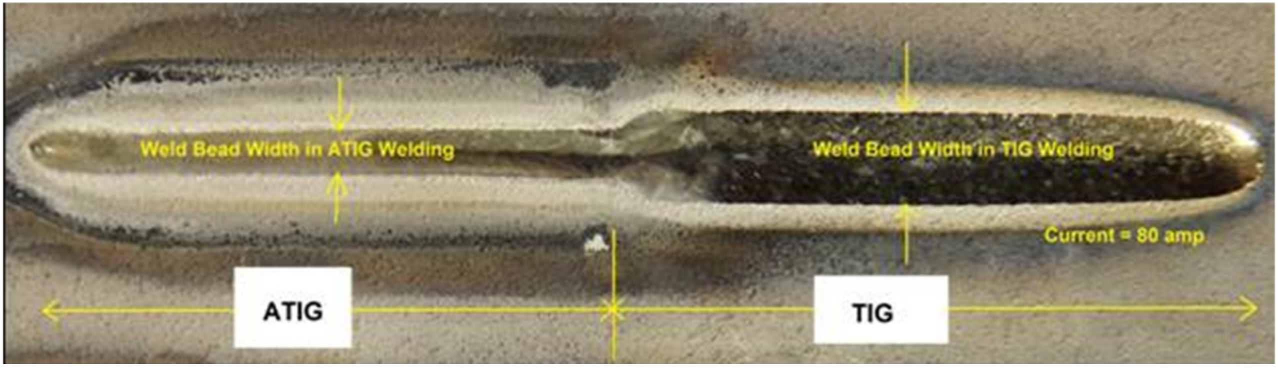
6.0 Development of Activated Flux for TIG welding of Titanium

Titanium and its alloys are used primarily in corrosion resistance service and specific strength efficient structures. Commercially pure (CP) titanium is used for corrosion resistance applications fabricated into tanks, heat exchangers, chemical processing vessels, power generation plants, etc. However, titanium alloys are mostly used in high-performance service requirement like aerospace applications. In nuclear industries, CP titanium (ASTM grades 1 and 2) is used as a structural material for the reprocessing of spent fuel where highly concentrated nitric acid in boiling condition is used for the dissolution of spent fuel.

The activating flux has been developed and qualified for activated flux TIG (ATIG) welding of commercially pure titanium required for fabrication and repair of titanium components in nuclear fuel reprocessing plant. The flux formulation was optimized after carrying out trials with different sets of flux powders and subsequent metallographic observation of weld bead profile. ATIG welding of titanium using this flux, with optimized welding parameters, produces



(a) ATIG Welding (b) TIG Arc (c) ATIG Arc



(d) Weld Bead profile comparison between TIG and ATIG

Fig. 12 : (a) ATIG welding of titanium in progress, (b) & (c) TIG and ATIG Arc images captured using high speed camera, and (d) weld bead comparison between TIG and ATIG welding.

full penetration welds in 6-mm-thick plates having weld bead depth-to-width ratio of 1.25 compared to 0.25 of conventional TIG welds.The welding arcs captured using high speed camera shown arc constriction and overall arc size reduction in ATIG compared to TIG is a proof of mechanism of arc constriction by the used flux which increases the arc energy density and therefore welding penetration (**Fig. 12**). ATIG weld joints were prepared using 6-mm-thick titanium plates using square-butt joint geometry and these joints were qualified by radiography. Root and face bend tests passed 4T bend radius as per American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code-Section IX requirements with bend angle of 180°. Transverse tensile testing of weld joints showed fracture in the weld metal with sufficient ductility and tensile strength of 398 MPa, which was close to the base material tensile strength of 402 MPa thereby meeting ASME Section IX requirements. Uniform hardness across the weld confirmed that the weld was not contaminated by components of flux or atmospheric gases, which can result in increased hardness of the weld metal leading to embrittlement. The corrosion test of the weld joints in 11.5 M boiling nitric acid showed improved corrosion resistance compared to base material.

7.0 Conclusions

Development of NG-TIG welding procedure and especially root pass argon gas purging procedure in the localized cavity required for AUSC welded steam rotors has been a great challenge. Based on the systematic planning and execution, the procedures were qualified with repeatability and successfully implemented for the fabrication of full-size IP welded rotor for AUSC project. Welding procedure and consumables are also qualified for similar and dissimilar welding of AUSC boiler tube materials. Ageing induced microstructure and mechanical properties changes in Alloy 617M base metal and weld are found to be significant and has adverse effect on repair welding which is unavoidable during prolonged service. Solution annealing heat treatment of service exposed Alloy 617M base metal/weld prior to repair welding is recommended. Titanium/304L SS dissimilar welded couples required for nuclear spent fuel reprocessing plant was successfully qualified including nitric acid test and implanted in the nuclear spent fuel reprocessing plant. Activating flux has been developed and qualified successfully for autogenous TIG welding of 6 mm thick titanium and the weld qualified all the tests required for intended application in reprocessing plant.

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