TRENDS IN JOINING TECHNOLOGY DEVELOPMENT FOR PHWR FUEL ASSEMBLIES IN INDIA

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ABSTRACT

Various types of welding/brazing techniques and equipment are used in the production of different kinds of PHWR fuel assemblies. These assemblies are of 19-element, 22-element, 28-element and 37-element type and are unique in joint design. All joints in PHWR fuel assemblies are either welded or brazed without any mechanical joints. Resistance welding, GTAW, Electron Beam welding, brazing and ultrasonic welding are some of the feasible techniques. Resistance welding and brazing are extensively used in fabrication of fuel assemblies involving joining of Zirconium alloys components of different shape and geometry. This paper describes recent advances made and work carried out at Atomic Fuels Division of Bhabha Atomic Research Centre in India in fabrication of different types of PHWR fuel assemblies. Vast experience gained in development of technologies and large-scale production of different core components was utilised to evaluate, develop and assess joining techniques for production. Various joining processes were utilised to achieve improved reliability and economy of products. Several non-conventional processes of joining have been under consideration. Modern Developments in welding power sources, methods of achieving improved weld quality and consistency, advances in weld monitoring etc are described. Efforts made towards better joint quality, ease of production and improved fuel performance is discussed Paper includes work carried out successfully in indigenous fabrication of some equipment, automation of processes and monitoring system.

1.0 INTRODUCTION:

The Indian nuclear power program has given emphasis, from its inception, on indigenous production of fuel assemblies. Therefore, development of fabrication technology including welding and joining of various materials used in different reactors was taken up from the start of the program. As a result of these efforts, important components of our Power Reactors are locally manufactured to highest international standards using modern welding techniques including Electron beam, GTAW and Resistance welding.

There are 8 power reactors of PHWR type working at present and some more are under construction. Fuel assemblies and control rod assemblies are regularly produced for these reactors within the country. They involve different types of welding to stringent specifications.

Fuel assemblies have to operate under severe conditions of high temperature, high pressure, mechanical stress, corrosion, fatigue, creep and irradiation. Integrity of welds is absolutely essential for safe and efficient operation of the reactors. The core components are required to perform with near zero failure during their operating life. Continuous attempts are made to develop newer techniques for improved products. Advanced processes and equipment have been indigenously developed and employed in the production of various components.

2.0 SELECTION OF SUITABLE JOINING TECHNIQUES:

There have been several advancements in welding technologies and many modern methods are now available for fabrication of various nuclear core components. We continuously evaluate the existing processes and search for better alternatives with a view to improve techniques & products. The joining process to be used for fuel fabrication should meet following requirements:

a) sound metallurgical structure, b) adequate strength, c) corrosion resistance, d) reliability and consistency of joint quality, e) adaptability to weld geometry and material, f) adaptability to large scale production, g) adaptability to NDT and h) economy.

In PHWRs, Zirconium alloys are used in fuel and other assemblies. Weldability of these alloys is excellent. Being reactive, they require adequate protection against atmospheric gases during welding. Short weld cycle and low heat input are most desirable for Zirconium alloys. GTAW, Resistance, EB, Laser, Ultrasonic, pulse magnetic and other methods are technically acceptable for welding Zirconium alloys. Some of the techniques are described here:

3. 0 WELDING PROCESSES USED IN NUCLEAR FUEL FABRICATION:

There are three types of joints in PHWR fuel assemblies viz. i) end closure welds, ii) Spacer and bearing pad (appendages) welds, and iii) End plate welds. **Table 1** gives various processes that can be used for these joints.

Processes like GTAW, Resistance, Electron Beam (EB) welding and vacuum brazing have been successfully applied for welding in different types of fuel assemblies. GTAW, Resistance, EB processes have been used in end closure welding of Zircaloy-4. We have evaluated advanced techniques of Laser, Resistance and Ultrasonic welding for clad to appendage welding. For end plate welding, GTAW, Laser and Resistance welding techniques can be applied. In Laser, Resistance and EB welds, heat input is small and weld bead is very narrow, which impart superior integrity to joint. EB welds are performed in vacuum and it offers very good protection to the weld puddle from atmospheric gases in reactive metals during and after welding. There are several attractive features unique to resistance welding such as high rate of production, ease of automation, economy of large scale production, lower heat input, small heat affected zone and fast cooling rate. In PHWRs, fuel assemblies involve large number of welds. Resistance welding is extensively used in their production.

i) End Closure Welding: Clad tubes of fuel elements are welded at both ends with plugs. First end plug may be welded under argon gas. But for second end, welding is done in a chamber under helium atmosphere at specified positive pressure. The gas content (helium) in elements has to be rigidly controlled to maintain a predetermined pressure, which is achieved by standardising the vacuum / gas pressure cycle.

Ends of 0.4 mm thick and 15.3/13.0 mm dia. Zircaloy-4 tubes are closed by welding using thick end plugs in a small chamber under helium after evacuation of clad tubes. Welding is done using resistance welding technique. In end closure welding by resistance welding, quality and consistency are very sensitive to tube and plug geometry and end preparation. Different types of weld geometries have been considered for development.
Power sources: Both types of power sources e.g. direct energy and stored energy types are in use for above welds. End closure welds are made using 100 KVA unit. For direct energy sources, synchronous controls are used with thyristors. Microprocessors are used for programming and data processing. Records of important parameters are kept for all welds. Analysis of data is carried out to assess the performance of welding machines. Inverter technology and D.C. current have also been considered for welding. Other techniques explored for this type of joint are described below:

a. Gas Tungsten Arc Welding (GTAW): This technique is being used widely for BWR fuel and PHWR Control rods. For welding either job is rotated or the torch i.e. by orbital welding. Welds are made by autogenous welding. The heat input is large and temperatures are high, thus a large area gets heated. Components have to be protected adequately by elaborate techniques such as welding in enclosed chamber, providing backing and trailing shields. Variation in power supply, poor tolerance in components and misalignment in rotators etc cause unacceptable variation in the parameters leading to poor welds. Process is slow and automation is essential for large scale production. During mechanisation and automation, many problems are faced causing non-uniform and defective welds. To overcome these problems, arc voltage control (AVC) is employed in which a feed back system is utilised to maintain the gap between the job and welding electrode. Some of the adaptive system incorporated in advanced power sources are short circuit detection, wire feed AVC and frequency AVC. The control should have adequate response to correct any deviation in time. Development of equipment for arc voltage control is carried out in BARC.

TIG welding using modern power sources meets most of the joint requirements. TIG welding of PHWR end plug to clad tube is carried out successfully for experimental assemblies and irradiation tests elements. GTAW is a conventional technique and is simple and economical. However, for large quantity, resistance welding is used in large scale production since it has very short weld cycle.

b. Electron Beam Welding: Historically, first application of EB welding, when it was invented, was in nuclear fuel elements welding. In EB welding, heat input is less and heat affected zone is narrow. The welds are made in vacuum. These are suitable for Zircaloy welding. Welding is done inside chamber. There is depletion of tin and chromium in the weld zone of Zircaloy joint which adversely affects corrosion resistance. The operations are slow and costly. For the second end closure welds, filling plenum gas require special arrangements. Filler material is not normally used.

c. Laser Welding: Laser beam is an attractive source of heat for fusion welding of nuclear components. It does not require vacuum or protective atmosphere. Deeper penetration is achieved and excellent beam maneuverability is available. Laser beam can be focused to a very small spot and energy density can be as high as 1000 MW per sq. cm. Deep penetration, similar to EB, is achieved.

Laser beams can penetrate through transparent windows and so welding can be carried out inside chambers. Components containing plutonium which is toxic and radioactive, can be processed in a glove box by a Laser beam while the Laser gun remains outside. We have studied laser welding for end closure welding application. Welds of acceptable quality have been made by Laser for these joints. Cost is a limiting factor in its use in production. However, it has been used to repair defective resistance welds.

d. Pulsed Magnetic Welding: This process utilizes high frequency high intensity pulsed magnetic fields to produce a joint. It is a cold welding process. The pulsed magnetic fields are produced by switching electrical energy stored in capacitors into specially designed coils. The operating frequency is a few hundred KHz. This process has been used in some countries for end closure welding of Zircaloy cladding tubes for thermal and stainless steel for breeder reactors. High magnetic fields are applied in a very short time to the coil in which the tube end with plug is held. The tube end collapses rapidly on the plug and get closed to form the joint. The process is very rapid. Temperatures are low. Process is feasible for end closure welding of Zircaloy tube. Efforts are being made at BARC to carry out development work in this field.

ii) Spacer to clad tube welds: Thick spacers of varying thickness up to 1.6 mm are to be joined to 0.4 mm thick clad tube at various precise axial and radial locations. The spacers are skewed and require proper fit up. Bearing pads have to withstand drag force and higher joint strength is required. Different possible joining processes are given below:

a. Vacuum Brazing: Vacuum brazing is being employed in most countries for joining Zirconium alloy components for appendage joining of PHWR fuel assemblies. In India, extensive work has been carried out in BARC in this field. Amongst several possible filler materials, a suitable alloy is to be selected which offers adequate wetting properties, gives sufficient strength and forms a corrosion resistant joint. Zr-5% Beryllium alloy is suitable for this application. Brazing is done by induction heating the joints in a vacuum chamber. The components are pre-placed by resistance tack welding. Vacuum deposition and induction brazing processes have been developed and acceptable joints are obtained. However, brazing technique does not find favour with fabricators due to toxicity of beryllium and high cost of process. Brazing cycles adversely affect clad properties in large heat affected zones which is undesirable.

b. Resistance Welding: Resistance welding is a superior technology for appendages welding which we have developed and perfected after extensive trial work. Technique of welding of appendages in loaded fuel elements is already in regular production. Large number of assemblies have been irradiated to required burn-up with excellent performance.

Further work has been carried out to improve technology for welding appendages on empty clad tubes as an alternative technology to brazing, which complex and involve toxic beryllium . The process is developed and equipment designed. The process has been tested by making large number of welds and destructively determining weld strength. Clad I.D. has been checked for any collapse. Corrosion test is also done. Results of the tests are shown in **Table 2** and **Table 3**. Joints were found acceptable in all the tests. Technology is available for production. The technique is very attractive for large scale production. It meets the required strength criteria. Technology is simple. It offers improved recovery and reduced production costs. A metallograph of appendage weld is shown in **Fig. 1**.

c. Laser Welding: Lasers are particularly attractive for beam maneuvering through optics. In conjunction with numerical controlled movements, it is a feasible technique for appendages welding. Possibility of manipulation of the beam using fibre-optics, with remote devices greatly enlarges the scope of Lasers for appendage welding. We have carried out the development and acceptable laser welds of both types (spacer and bearing pads) were obtained. Parameters were optimed and specifications for suitable Laser welding equipment was drawn. Laser welding is a technically feasible and commercial viable process for large production. A laser weld is shown in **Fig. 2.**

d. Ultrasonic Welding: Ultrasonic welding is a solid state welding process and welding is carried out at low temperatures. Zircaloy can be welded by this technique. Normally lap joints can be made by it. Some Zircaloy spacer to clad joints have been made by ultrasonics. The welds are made with very low heat input and application of force is less than that in resistance welding. The heat affected zone is very narrow. We have carried out limited ultrasonic welding trials. The results were incoclusive. A metallograph of weld made in Zircaloy sheet by ultrasonics is shown in **Fig. 3.**

iii) End plug to end plate welds: Elements (19, 22 or 37 elements, depending on fuel assembly design) are joined together, by welding their ends to two 1.6 mm thick end plate at each end to form an assembly. Resistance projection welding is used to weld the elements ends to end plates. Welding can also be done by Laser, GTAW and EB. However, the resistance welding has been found most satisfactory.

Resistance welding Power Source: Recently, considerable work has been done in inverter technology and D.C. power sources. Medium frequency supply offer advantages in specific areas. They are being evaluated for our applications. These systems are not yet standard and are costly. Benefits like compact size, precise feedback control and better performance are useful in our application. For robots, medium frequency units are very attractive as they bring down the cost of robot considerably due to their reduced size and weight.

4.0 EQUIPMENT DEVELOPMENT:

Equipment development has been undertaken simultaneously with process development. Endeavor has been made to select and develop the process in such a way that it is amenable to large scale production. The following equipment have been designed:

4.1 End Plug Welding Equipment based on resistance ring projection welding has been designed. Several improved features have been included in the design.

4.2 Equipment for resistance welding of appendages to loaded fuel elements has been designed based on the development carried out. Equipment is fabricated commissioned and used in regular production.

4.3 Development of welding of appendages to empty clad tubes, similar to brazing route is completed. An equipment has been conceptualised and details worked out for production.

5.0 QUALITY CONTROL AND WELD MONITORING:

GTAW and EB welds are evaluated using standard non destructive tests. But these tests are not readily applicable to resistance welds. Therefore quality control largely depends on destructive tests such as weld strength and metallography on sampling basis. In addition, statistical quality control is applied. Fuel performance over the last few years has been satisfactory and fuel failure rate has been considerably reduced.

5.1 On-line Monitoring and Feedback Control: Types of resistance welds discussed earlier are not amenable to normal non-destructive tests. For end plug welding of fuel elements, 100 % helium leak tests are carried out. This is not adequate for ensuring integrity of welds. Developments have been carried out for ultrasonic testing of this geometry. In addition strict quality control measures are taken to ensure compliance to specifications. Weld defects can be located by using UT of end plug welds. Spacer welds are in very large number and there is no satisfactory technique to ensure their quality through NDT routes. Weld monitoring is developed e.g. displacement measurement during resistance welding and dynamic resistance monitoring.

Considerable work has been carried out in on-line monitoring of resistance welding. We studied several weld monitoring schemes for increasing the reliability of the welds. Initially, attempts were made to control several weld parameters, but they were not found adequate. This led to the requirement of measuring the parameters dynamically . A weld monitor based on dynamic resistance (DR) was connected to the system and DR curves were obtained for a large number of welds. Unlike spot welds, it is difficult to charecterise DR curve for projection welds. Welds were destructively tested and results were correlated with the curves. Very good interpretations were obtained and a DR window was identified for acceptable welds. For a feed back control to be incorporated with DR monitor, data is to be collected for more than half cycle period. A study of weld upset as measured by electrode movement was also made. The work indicated that for effective quality control, multiple monitoring system is essential.

Acoustic emission (AE) technique is being used in many fields for monitoring and it is promising for quality control of spot welds. Work on AE testing is carried out by us for various welds and they have indicated encouraging results. The AE signals have been analysed to distinguish deviation in heat parameters as well as projection geometry in different welds. AE is an advanced and promising technique for weld monitoring.

6.0 SUMMARY:

PHWR fuel assemblies are fully welded structures. Several modern joining techniques are being used in India for welding Zirconium alloys for these assemblies. Many intricate geometries have been successfully welded to a high degree of quality and integrity. Developments are carried out for appendage welding and end closure welding. Modern equipment and techniques are utilised to improve the weld quality, increase production rate, reduce rejection rate and improve reliability. Laser, EB, GTAW and pulse magnetic welding are evaluated in addition to resistance welding. Weld strength, clad collapse, metallography and corrosion tests have been rigorously carried out to comply with specifications. An automatic welding system concept has been designed for spacers welding on empty clad tubes for required production rate.

Advanced techniques in resistance welding, controls and on-line monitoring are being utilised to improve quality and reliability in fuel assemblies. Appropriate quality control plans have been worked out to ensure the weld quality and consistency. Some of the weld monitoring system such as Dynamic Resistance, Weld displacement has been successfully developed to assure, non-destructively, the weld quality. Work on advanced techniques such as Acoustic Emission, ultrasonic tests etc are being pursued for weld monitoring applications. Welding technologies have been developed to meet the requirements of fuel assemblies fabrication for Indian PHWR power program.

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TABLE : 1

EVALUATION OF WELDING PROCESSES FOR PHWR FUEL

JOINT	COMPONENTS	RESISTANCE WELDING	BRAZING	LASER WELDING	EB WELDING	PULSE MAGNATIC WELDING	GTAW
i) End Plug Welding	ø15.3 And 13.0 mm 0.4 mm thick. Clad tube / End Plugs	A	E	C	C	C	B
ii) Appendage Welding	ø15.3 And 13.0 mm 0.4 mm thick. Clad tube / 0.6 to 1.6 mm thick spacers and Bearing pads	A	B	C	D	E	E
iii) End plate Welding	Machined End plugs / 1.6 mm thick End plates	A	E	C	C	E	C

A- EXCELLENT.

B- ACCEPTABLE.

C- FEASIBLE, Commercial viability to be seen.

D- Feasibility is to be checked.

E- NOT CONSIDERED.

TABLE - 2

QUALIFICATION OF APPENDAGE WELDING

ON EMPTY CLAD TUBES

No. of Welds tested : 300 Nos. each.

TESTS CARRIED OUT	BEARING PADS	SPACERS
1. Collapse test by go/no go gauge	OK	OK
2. Collapse test by matallography Shear strength (in kgf)	OK	OK
3. Minimum strength	94.3 (80)	60.7 (60)
4. Mean strength	121.2 (80)	83.7 (60)
5. X- 2œ	99.7 (80)	62.9 (60)
6. Metallography	OK	OK

(Figures in bracket are specified values)

TABLE - 3

CORROSION TEST

	Typical weight gain in mg/dm^2
A) Bearing Pads with circular projection :	19.5
B) Bearing Pads with linear projection :	16.3
	20.7

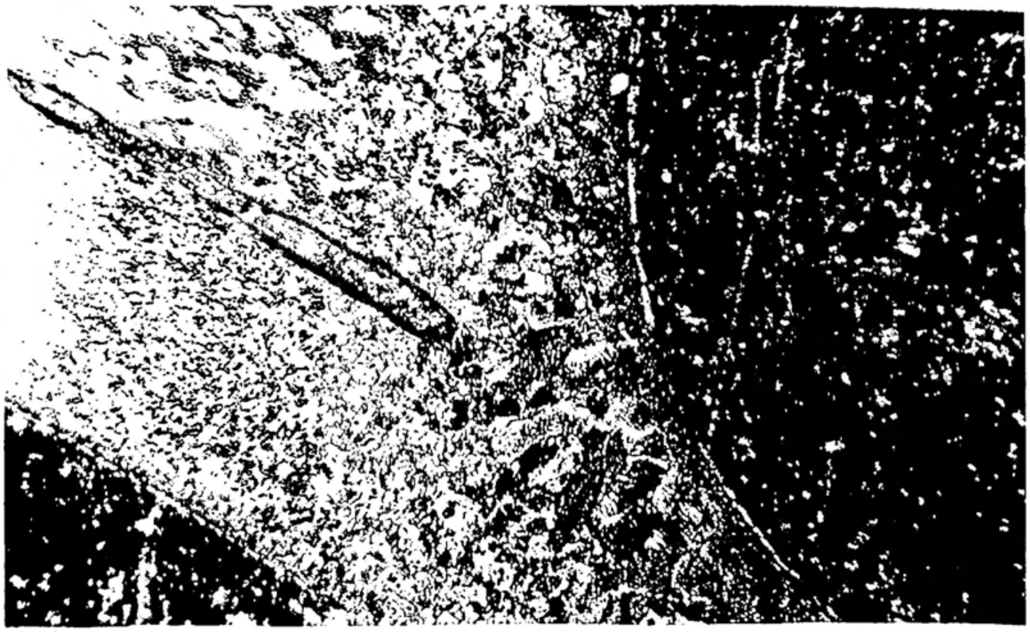

Fig.2. LASER WELDED APPENDAGE JOINT

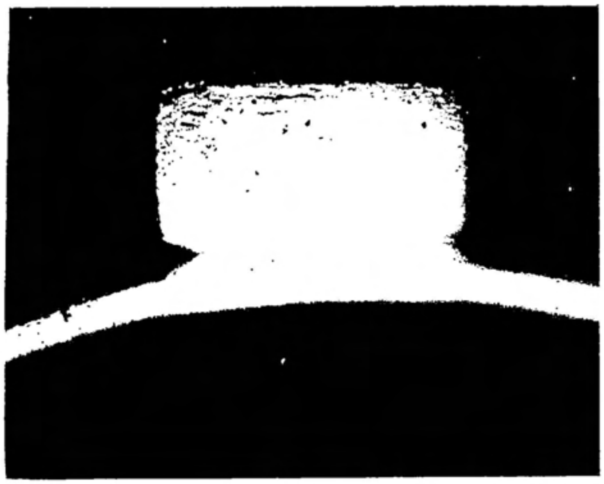

Fig. 1. METALLOGRAPH OF SPACER WELD
MADE ON EMPTY CLAD TUBE

Fig.3. ULTRASONIC WELD