Chapter 29

Deployment of Magnetic Welding and Forming In Indian Prototype Fast Breeder Reactor

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This article discusses the two applications of magnetic pulse forming developed at Accelerator & Pulse Power Division for Indian PFBR fuel applications. The magnetic pulse forming is a high energy rate forming (HERF) technique most widely used in industry. In this process electrical energy is converted into mechanical energy by exploring the Lorentz's force. The end plug joining of fuel pin cladding tubes made of D9 alloy steel (austenitic), ferritic-martensitic steel (mod. 9Cr-1Mo) and 9Cr-1Mo oxide -dispersion strengthened (ODS) steel can be welded using this technique. The magnetic pulse crimping of D9 alloy steel over SS316LN hollow plug was also been demonstrated for prototype fast breeder reactor fuel pin application. MP weld was qualified for various destructive and non-destructive tests and three pin tested for out-pile test qualified for useful resident time in reactor. Initial trials of magnetic crimping showed promising results. More detailed trials and testing are planned in near future.

29.1. Introduction

Austenitic stainless steels type 304LN and SS316LN, modified 9Cr-1Mo steel and alloy D9 are the major material used in construction of Prototype Fast Breeder Reactor (PFBR). Materials resistant to void swelling, irradiation creep and irradiation embrittlement as well as satisfying the high temperature properties and target burn-up required in FBRs are large ($>$ 200,000 MWD/ton), for economic viability. The core components such as clad tubes and wrappers are made up of alloy D9. Research is underway to improve the existing alloys to extend the life of the reactor and enhance the fuel burnup by improving the core material resident time. Alloy variants of SS316LN SS, alloy D9, mod. 9Cr-1Mo steel and ODS have been developed in DAE and alloy have been evaluated for their mechanical properties, workability and weldability. The mod 9Cr-1Mo-Martensitic steels have proven as a long life fuel pin cladding material for advanced fast reactors due to their high dpa dose sustenance, excellent swelling resistance, good thermal conductivity, low thermal expansion. But their application is restricted to metallic fuel as operating temperature is limited to 550 °C, hence oxide dispersed ferritic-martensetic steels are evolved to increase the working temperature of the material above 650 °C. Joining of alloy D9 by fusion welding is admissible but mod.9Cr-1Mo and ODS steel fusion welding such as TIG/LASER diminishes the strength of the welded joint. The heat treatment of the grade 9Cr-1Mo steel or particle disperse consistency of ODS steel is not affected by the magnetic pulse welding, hence eradicating the problems related to Heat Affected Zones [HAZ]. As in the magnetic forming process there is no or very low spring back effect due to loading in plastic region, this advantage is explored in magnetic crimping process.

29.2. End Plug Welding and Crimping

The present D9 alloy cladded fuel pin for PFBR is shown in Figure 29.1. The fuel pin is sealed with SS316LN end plug both sides. The central one metre length contains MOX fuel followed by 30 cm long UO_2 blankets both sides. The whole column of fuel and blankets are held against hollow SS316LN plug of 10 mm long at bottom side and with the help of spring in the upper side. The gas plenum is provided at bottom side of the pin to contain the released fission gases and limit the internal pressure below 50 bar during useful life of the fuel pin. The clad tube is crimped over the hollow plug by rolling method in present design.

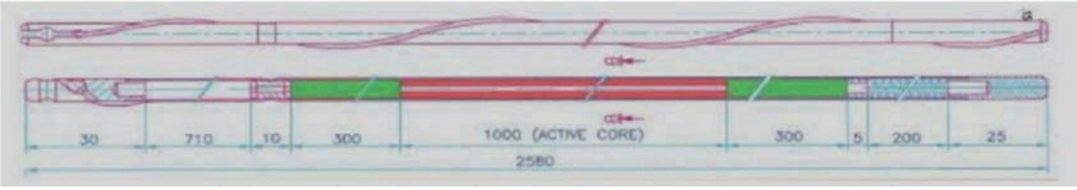

Figure 29.1. PFBR fuel pin configuration (Left to Right indicate bottom to top position in in-situ).

29.2.1. Magnetic End Plug Welding

Presently adopted SS316LN end plugs design for LASER/ TIG welding is shown in Figure 29.2(a) with dimensions (6.6 mm OD x 0.45 mm thickness). Figure 29.2(b) shows the radiograph of the end cap-tube assembly before welding.

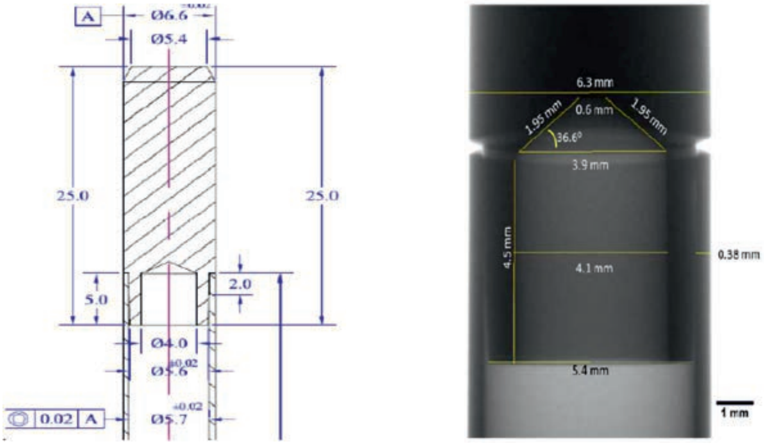

Figure 29.2(a). Plug-Tube assembly for TIG/LASER welding (left) and (b). Radiograph of the D9 steel tube and SS316LN plug (right).

The geometry of the plug depends upon the type of process adopted for joining. The geometry adopted for TIG/LASER is not suitable for magnetic pulse welding. The magnetic pulse welding uses Lorentz's for joining the end plug to fuel clad tube. Since the electrical conductivity of D9 steel tube is poor (<2% IACS), a conductive disposable sleeve called "Driver" was adopted to translate the force on the poor conductive material. The copper was deployed as a driver material in all magnetic pulse welding owing to its high conductivity, density and melting point. The plug-tube assembly was modified to suit the "Welding by Forming" principle. In this process transient high pressure in the range of 700 to 800 MPa was applied on the clad and clad collide with very high (350-400 m/s) velocity over specially designed end plug as shown in Figure 29.3. The cylindrical clad tube deformed to conical shape while getting welded with plug. Welded joints (D9-SS316LN) were qualified [2] for helium leak rate (< 5 x 10^{-9} mbar.l/sec), dimensional stability, profilometry, computed tomography, thermal cycling, hydraulic bust test at room temperature (>1000 bar), computed tomography, optical microscopy for confirmation of waviness, SEM to confirm no HAZ, out-pile test (100 bar, 750 ºC) for resident time in reactor [3]. Similarly, T91-T91 and ODS-T91 were qualified for HLD, OM, SEM, CT. The out-pile and in-pile tests for ODS clad to T91 end plug are the immediate future targets. Joining of plug to the tube has been carried out in a 70 kJ, 25 kV proto type MPW machine with remote operation features and computer interface, developed at APPD. Later welding has been re-established on tailor made 30 kJ, 15 kV machine also. Table 29.1 gives the detailed specification of both machines.

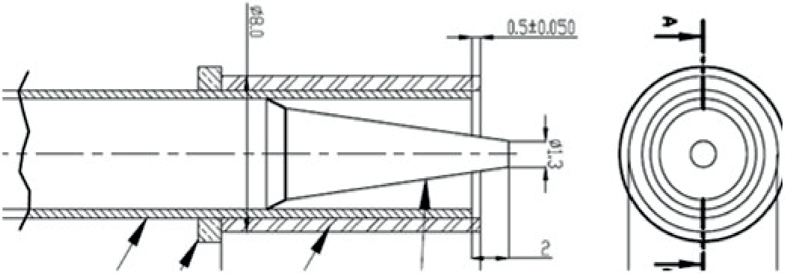

Figure 29.3. End plug (SS316LN/T91)-Clad tube (D9/T91/ODS)-Driver (Copper)-Ring (Delrin) assembly adopted in magnetic pulse end cap sealing.

Figure 29.4. Magnetic pulse welded samples.

Table 29.1. Specifications of Magnetic Pulse Welding machine.

Parameters	Machine I	Machine II
Capacitance	224 µF	300 µF
No of Sub-banks	2	1
Voltage	25 kV	15 kV
Switches	Trigetron Spark Gap	Trigetron Spark Gap
Power Supply	Constant Current	Constant Voltage
System Inductance	~240 nH	~140 nH
System Inductance	~5 mΩ	~3.8 mΩ
Short Circuit Current	> 400 kA @25 kV	> 700 kA @15 kV
Shot Circuit Frequency	~22 kHz	~30 kHz
Tool Coil	Bitter coil with field shaper (106 mm Dia X 80 mm)	Bitter coil with field shaper (60 mm Dia X 60 mm)

Figure 29.5(a). Photograph of Machine and (b). Photograph of Machine-II.

29.2.2. Magnetic Crimping

As the process is high strain and strain rate forming and loading is done in plastic zone by controlling the applied stress, spring back can be totally mitigated. Figure 29.6(a) and Figure 29.6(b) shows the crimping of D9 alloy clad over SS316LN hollow plug by conventional rollers and magnetic pulsed crimping process respectively. The magnetic crimping was carried out on the 70 kJ, 25 kV machine with only one sub-bank. It was necessary to adopt copper driver even at 21 kHz (Ref. Appendix-A) as most of the field generated was diffused inside the clad without exerting the net radial deforming stress on the clad. The system operating parameters were 8.45 kJ at 13 kV. The first peak current carried in the four-disc Bitter coil was 182 kA at 21 kHz ringing frequency as shown in Figure 29.6(c). This current created a field close to 30 T across the driver with the help of copper field shaper. The driver was removed subsequently and radiography was taken at Technical Physics Division. It is evident from the radiography that clad tube has flown better inside the groove (dimple) in case of magnetic crimping process compared to conventional rolled process. The process qualifications would be done in consultation with all concerned user (IGCAR, Kalpakkam)/developer (NFC, Hyderabad) and fabricator (IF3 Tarapur).

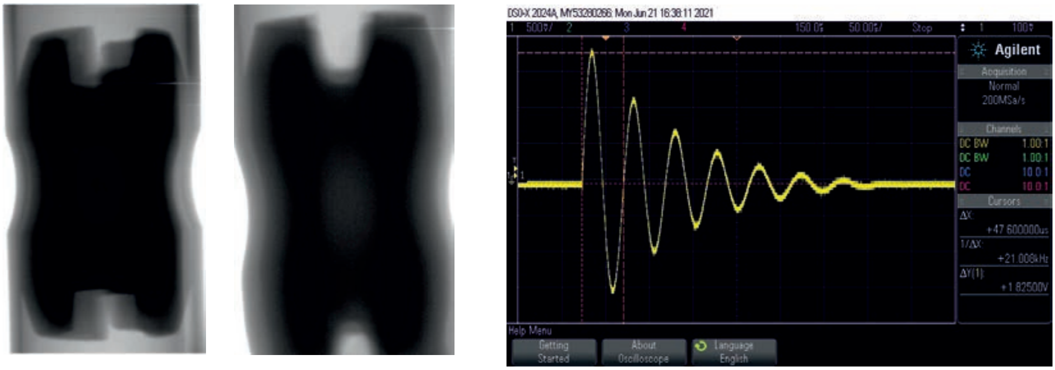

Figure 29.6(a). Conventional Crimping, (b). Magnetic Crimping and (c). Current wave form of magnetic crimping, peak current: 182 kA, frequency: 21 kHz, Copper driver (10 mm x 0.5 mm thick, yield strength 70 MPa).

29.3. Conclusion

Magnetic pulse forming and welding has matured to large extend in APPD, BARC in last two decades. APPD is capable of make machines, developed the tool coils and process. In last one decade, MPW of clad tube to plug for PFBR application has been demonstrated to the end user satisfaction. APPD is in a position to give complete solution to crimping application for PFBR fuel clad to hollow plug also. It is also involved in the development of different welding joints, difficult to join by fusion technique for departmental applications.

29.4. Appendix-A

Magnetic pressure required to be generated to overcome circumferential stiffness P of the work piece is given by the relation.

$$P=N(\sum ys\ 2\Delta)/Dow \tag{29.1}$$

Where $\sum ys$ is the yield strength, Δ is the thickness and Dow outer diameter of the job piece. The factor $N \epsilon$ (1, 10), considering of inertia, strain and strain rate hardening, through thickness stress, job length because the workpiece is not thin walled ($i.e. 2\Delta/Dow > 1/10$) tube.

For efficient generation of Lorenz force on the work piece skin depth δ should be at least equal to workpiece thickness.

$$\delta = \frac{1}{\sqrt{\sigma \pi \mu f}} \tag{29.2}$$

Where σ and f are the conductivity of work piece in S/m and operating frequency in Hz respectively. For D9 steel clad σ and $\sum ys$ are 1.35 MS/m and 550 MPa respectively. For operating frequency of 21 kHz, the skin depth is 2.99 mm. When skin depth equals the thickness of the tube, 86% of the magnetic field is shielded. If skin depth is half of the thickness 98% of field is utilized.

The net magnetic pressure P_{mag} acting on the surface of the work piece is given by the relation

$$P_{mag} = (B^2_{out} - B^2_{in})/2\mu_0\ Pa \tag{29.3}$$

Where B_{out} is the field acting on outer surface and B_{in} is the diffused field inside the work piece in Tesla. In all calculation relative permeability is considered unity as operating field saturate all the magnetic material if exists.

$$B_{in} = B_{out}\ e^{-\Delta/\delta} \tag{29.4}$$

For 30 T impinged field on clad, diffused out field is 25.8 T. Hence net pressure acting on clad is close to 90 MPa which is not enough to deform. This is also practically observed. This necessitates the high conductive driver like copper. With 0.6 mm thick driver the effective pressure translated on clad is close to 335 MPa. This pressure enough to crimp the clad without spring back effect. For creating welding profile of the hollow plug need modification and field intensity should be more than 42 T.

References

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