Chapter 30

Qualification of Magnetic Pulse Welding Joints

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This article discusses the different techniques adopted to qualify the joints developed by Magnetic Pulse Forming and Welding [1]. In Magnetic Pulse Forming and Welding transient magnetic field is generated and this field interact with thin metallic sheet job kept close to the magnetic field. When stress generated by the difference of the pressure gradient across the conductor exceeds the von Mises stress of the job (tube or sheet), it gets deformed. This process can be utilised to form and weld hollow tubes by implosion or explosion and also thin metallic sheets of high conductive material like aluminium, copper and mild steel and its alloys. The ductility and high conductivity are the prerequisite for this kind of joints for better performance. The resistivity of mild steel (15 μΩ-cm) has been found experimental transition point above that conductive drivers to improve the efficacy of the magnetic field is usually adopted. The joints formed by this technique depends upon several physical, geometrical parameters of job and also machine operational parameters. The machine operational parameter can be finally translated into two parameters, i.e., field and rate of change of field across the work piece (job) which is the machine current and operation frequency coupled with the tool coil. Spatial and temporal field is generated by the tool coil across the workpiece when pulsed current in injected in the coil. Magnetic Pulse Joints are particularly suitable for mass production and automated feeding system. Once the geometrical parameter of the joint configuration and operational parameters of the machine are established same has to be repeated.

30.1. Introduction

Joints developed by pulsed magnetic field are based on the principal of “Joining by Deforming”, means only lap joints are formed and either one or both mating sheet components may deform before joining takes place. Three types of joints can be made with this technique: form-fit joint, interference fit joint and welded joint depending upon the application. The qualification criteria made by three different type of joints are different depending upon the applications.

The form fit joints are achieved by having under cuts (groves) azimuthally or axially depending upon the type of load to be carried by the joint. In this type joint tool coil is placed coaxially in expansion or compression mode. The elastic-plastic bracing of the mating partners is achieved based on interface fit joint called crimping. In magnetic welding mating surfaces come closer in microstructural level and metallurgical bonding takes place without adding heat energy within fraction of a second.

30.2. Joint Evaluation

Magnetic pulse joints are evaluated both Non-Destructive Test (NDT) and Destructive Testing (DT) methods [2]. Measurement of the weld quality is done using destructive test but the workpiece is destroyed during the evaluation. The joints are qualified depending upon the configuration, application and acceptance criteria set by end user of the product. The method adopted in Accelerator and Pulse Power Division (APPD), BARC and IGCAR [3] are enlisted below in pertinent to tube sealing by Magnetic Pulse Welding:

- Helium leak detection
- Computerized Tomography
- Dimensional measurements
- Profilometry study
- Non-destructive evaluation by immersion ultrasonic testing
- Thermal Cycle test
- Hydraulic Burst Test
- Metallographic study by optical microscopy and SEM.
- Hardness profile
- Pressure burst test at elevated temperature.
- Dye penetrant testing, radiography and optical microscopy of the samples failed in pressure burst test.

Following tests are also reported in literature for some magnetic pulse joints:

- Torsion test
- Peel test.
- Push/Pull test.
- Pressure cycle tests.

Some tests are the directly adopted that are being used in qualifying explosive welding akin to Magnetic Pulse Welding [4]. In this article the weld qualification adopted for joining Indian Prototype Fast Breeder Reactor (PFBR) fuel clad to end plug by magnetic pulse welding is articulated. The cladding materials are D9 austenitic steel, Ferretic-Martensetic T91 and Oxide Dispersion Strengthen steel having outer and inner dimeter of 6.6 mm and 5.7 mm respectively. The mechanical, electrical and thermal properties of all cladding material are differ each other, that also matters while developing magnetic pulse bonded joint.

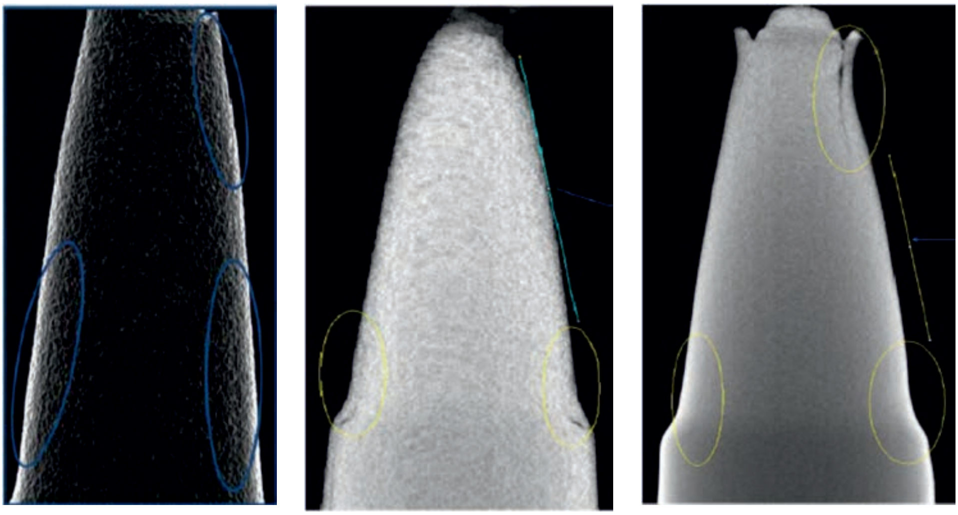
Figure 30.1. Indicative MP Welded fuel clad to end plug samples (OD 6.6 x 0.45 mm thick).

30.2.1. Helium Leak Detection

Helium due to its inertness, non-condensability, high diffusivity, scarcity in atmosphere and non-toxic characteristics is the best choice to identify leak and is used in MPW tube to end plug joint. It escapes through leaks easily due to its small atomic size. The test is based on the principle of field mass spectrometer. The Helium Leak test was conducted on all joints at room temperature with the help of MSLD “Smart Test ”PFLIFFER VACUUM, available with APPD. All joints passed the criteria set by end user IGCAR, i.e. $< 10^{-8}$ mbar.l/sec or 10^{-15} MPa.M^3/s. Usually HLD is done at room temperature but clad of low thickness can undergo severe structural changes in reactor conditions, which necessitate also high temperature leak testing of welded joints. Two numbers of 500 mm long D9 steel clad tube welded at one end with SS316LN end plug were tested for HL detection at 673 K and 4 Bar He pressure for two hours at IF3, BARC and no change in any back ground leak reading i.e., 5×10^{-10} mbar.l/s was observed.

30.2.2. Computerized Tomography

Computerized Tomography is a non-destructive evaluation technique that can produce 2D and 3D cross-sectional images of the work piece. The X-ray Micro-tomography conducted on three D9 clad-SS316LN plug MP welded samples at NXPS, TPD, Purnima Labs are shown in Figure 30.2(a) to Figure 30.2(c). In this test one can ascertain any opening in the joint, uniformity in the forming, under cut or any deposition. The lowest possible resolution of the system was 13 μm so only with tomography, it was not possible to find the extent of weld lengths.



(a) (b) (c)

Figure 30.2. Computerized X-ray Micro-Tomography of three magnetic welded samples (D9 steel clad to SS316LN Plug).

30.2.3. Dimensional Measurements

Diameter of the weld junction towards the open end of the tube is measured by a Vernier caliper and no change in dimensions was confirmed. This test is very much essential where in field shaper with Bitter coil type of tool is used for welding. The profile of the field generated across whole cross section is not uniform and creates unsymmetrical loading of the work-piece (tube). No deformation of the tube was also observed by visual inspection. Table 30.1 shows the dimensional measurement results of seven samples conducted at IGCAR.

Table 30.1. Dimensional measurements across the tube.

	Distance towards the tube from tube to plug junction (mm)					
Sample No	0	10	20	30	40	50
L1	6.41	6.63	6.63	6.62	6.63	6.62
L2	6.45	6.6	6.61	6.65	6.61	6.63
L3	6.57	6.62	6.64	6.55	6.55	6.56
L4	6.41	6.59	6.6	6.59	6.59	6.64
C1	6.51	6.57	6.61	6.61	6.56	6.57
C2	6.55	6.61	6.61	6.56	6.6	6.58
C3	6.66	6.59	6.58	6.57	6.57	6.58

30.2.4. Profilometry Study

In profilometry study surface roughness variation in the weld and the tube was analysed and was found to be with acceptable limit for all joints. In welding process all the energy coupled to work piece is by inductive and not by conduction, surface of the work piece (clad tube) is not getting affected. If insulation between work piece and tool coil fails even partially, the surface roughness would be affected. Seven welded samples have been tested for surface roughness at four position (at 0, 90, 180 & 270 degrees). In all measurements parameters calculated as average value of all sampling lengths and a micro-roughness filtering is used, with a ratio of 2.5 μm. The maximum height of roughness profile was in the range of 10 to 35 μm and found to be qualified for deployment in reactor applications. This measurement was carried out at metal forming & tribology section, IGCAR. Figure 30.3 shows one typical Profilometry results.

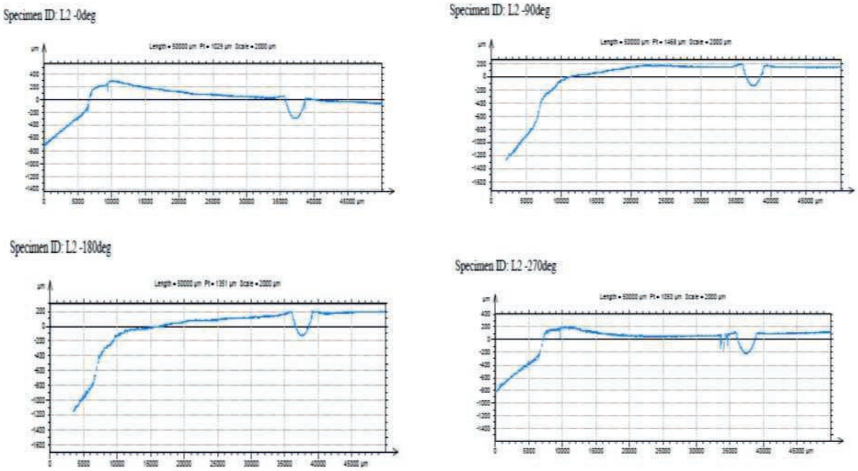


Figure 30.3. Profilometry studies for MPW joint L2 at different locations.

30.2.5. Ultrasonic Testing

In the case of the conventional end cap weld joints (GTAW or Laser), the weld interface to be inspected is across the thickness of the fuel pin, as shown in Figure 30.4.(a) but in MPW joint, the weld interface is parallel to the top surface of the fuel pin in MPW joint, as shown in Figure 30.4 (b).

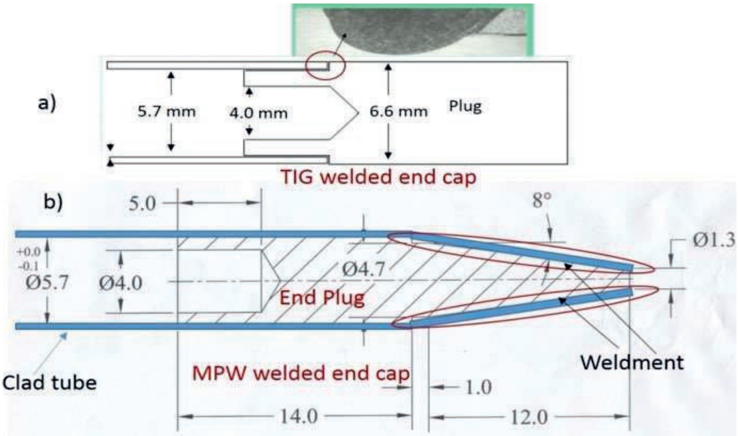


Figure 30.4(a). TIG weld of fuel pin to end cap and (b). MP weld of fuel pin to end plug.

Necessity was arisen to develop a new ultrasonic nondestructive evaluation methodology to inspect and qualify the MPW fuel pinsas conventional immersion based angle beam ultrasonic inspection technique cannot be used in MP welded sample. The total weld length between the fuel pin and the end plug can be divided into three regions (zones) of approximately 3 mm, 7 mm and 2 mm, respectively, as shown in Figure 30.6.a. In Region-I, i.e.in the lower side of the end plug weld, multiple back wall (MBW) echoes corresponding to the fuel pin thickness are observed in the B-scan image (Figure 30.5. (a) & (b)), which indicates un-bonded region between the fuel pin and the end plug in this region. For a similar MPW weld location, the optical micrograph of the cross-section has clearly shown no bonding between the fuel pin and the end plug. In Region-II, the back wall echo corresponding to the thickness of the end plug is observed for about 7 mm length and is shown with an ellipse in Figure 30.6.(a) i.e. at this region the fuel pin and the end plug are bonded properly. The optical micrograph in a similar region has shown a good bond between the fuel pin and the end plug. In Region-III, the back-wall echo corresponding to the thickness of the end plug is absent, indicating the lack of bond between the fuel pin and the end plug for about 2 mm length at the end of the weld. The same has been confirmed by the optical micrograph, where a gap between the clad tube and end plug is visible. Hence, the B-scan obtained from ultrasonic inspection has been very well correlated with the optical micrograph obtained from the cross section of the MP welded sample.

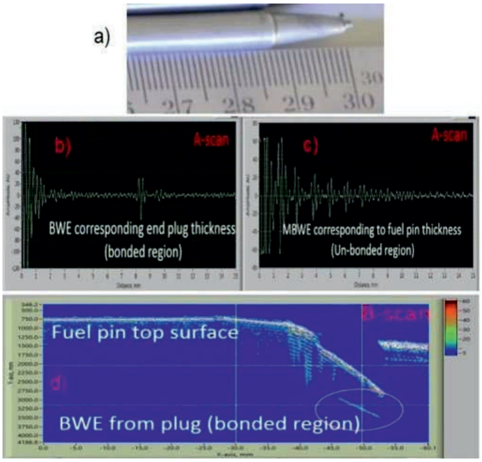


Figure 30.5(a). Ultrasonic inspected region of fuel pin, typical A-scans from (b). bonded and (c). un-bonded regions and (d). typical B-scan scan showing the length of the bonded region.

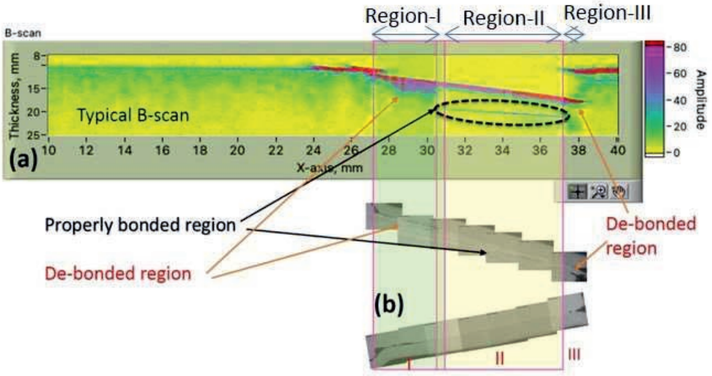


Figure 30.6. Comparison of a typical ultrasonic B-scan image with an optical micrograph of the longitudinal section of MP welded sample.

Hence the ultrasonic testing has to be developed specific to the weld configuration and later it should be ascertained with optical microscopy while developing the procedure. Once the method is developed procedure can be one of the important NDT method to qualify the magnetic pulse welding

30.2.6. Thermal Cycling

Thermal cycle test is performed to determine the resistance of the components/parts to withstand the thermal fatigue resulted/generated due to the repeated temperature variations. This test can be performed by cycling the component between high and low temperatures that exceed its normal use temperatures. So, to check the integrity of the joint, tests were performed by choosing higher and lower cycling temperatures as 823 K and 300 K, respectively for 30 min dwell time. Four samples were subjected to 5 cycles each in a CARBOLITE make furnace (Model No. CWF1300) in normal atmosphere. After performing the test, all samples were subjected to helium leak test. No degradation in the leak tightness of the samples was observed. Figure 30.7 shows the four MP welded samples (~65 mm long, D9-SS316LN) after subjecting the thermalcycles. It is seen from the photo that surface colour of the samples have changed due to oxidation under elevated temperature due to the presence of air.

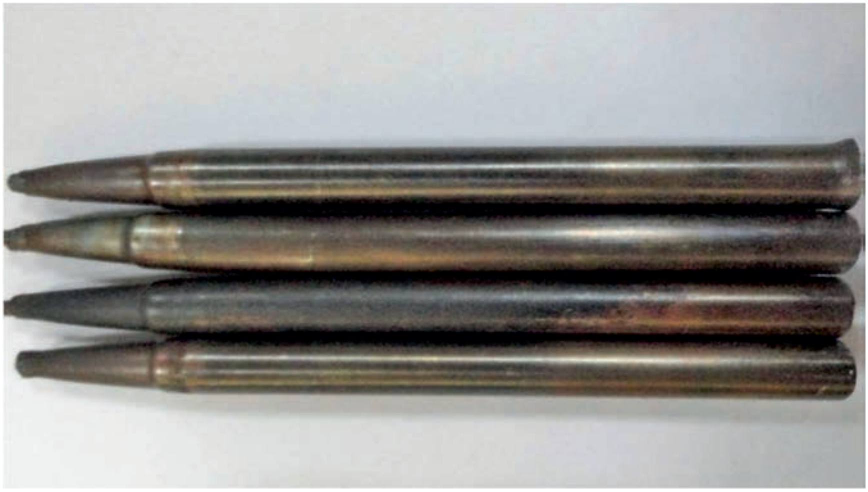


Figure 30.7. EM Welded samples after five thermal cycle (823K, 1800sec-300K, 1800sec) in air furnace.

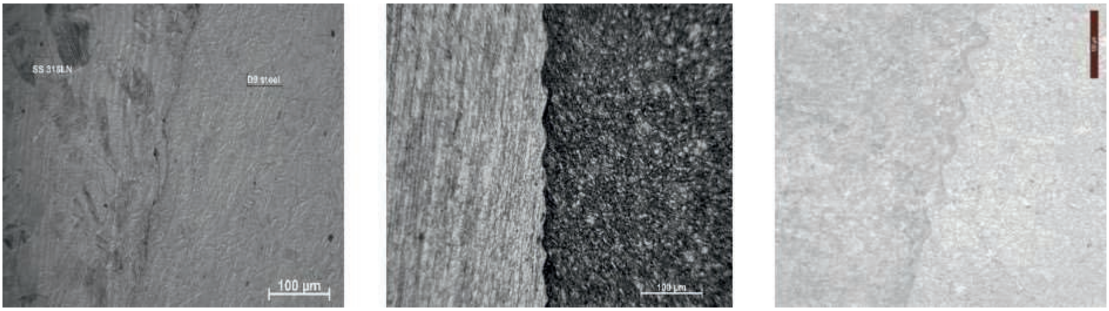
Similarly, two magnetic pulse joints developed between AA5052 tube (of 65 mm OD x 2 mm thick) to SS304 end sheet was subject thermal cycling in hot water bath (~373 K) for 1800 sec and 273 K for 1800 sec. One such joint has completed the 400 cycle and there is absolutely no change in the Helium leak parameter. The joint qualified HLD better than for 1.5 x 10^{-9} mbar.l/sec. This joint is being developed at APPD for research reactor tube to end sheet in collaboration with Reactor Engineering Division, BARC.

30.3. Destructive Test

Destructive tests like proton irradiation and Vickers hardness measurement across joint, pull out, metallographic study, hydraulic burst test of joint have been performed on different samples. Some of the results have been discussed below.

30.3.1. Metallographic Study by OM and SEM

To check the integrity of all the joints and extent of bonding is clearly ascertained by the optical microscopy. The Scanning Electron Microscopy with EDS attachment gives the chemical composition across the bond zone. More than sixty-five MP welded sample (D9-SS316LN, T91-T91 and ODS-T91) were sectioned in both axial transverse direction using electric discharge wire cut machine. Microstructural and scan electron microscopy analysis is performed in the transverse and longitudinal direction. To avoid any microstructural changes, proper coolant need to be used during the cutting process.



(a) D9 clad-SS316LN Plug. (b) T91 clad-SS304 Plug. (c) ODS Clad-T91 plug.

Figure 30.8 Optical Microscopic snap of different clad-plug (in axial direction)

The optical micrographs of the D9-SS316LN, T91-SS304 and ODS-T91 interface shown in Figure 30.8. In MPW, welds may show a wavy pattern or not at the weld interface. These waviness patterns are formed due to the penetration of the jet from the flyer tubeon solid end plug surface at the point of collision. Plastic deformation at the point of collision of two metalsto be joined leads to high-velocity impact, which causes the grains at the interface to become semisolid, and hence, they show a metallographic examination carried out by SEM (Figure 30.9a & b) verifying the quality of the weld. It is found that no intermetallic formation was found but radial micro-cracks were observed in transverse direction.

30.3.2. Hydraulic Burst Test

To ascertain the strength of the joint is better than parent material and also get the ranges of pressure at which the structure fails, hydraulic bust test was conducted at 300 K on three samples close to 65 mm long D9 clad to SS316LN plug joints. Proper interface fixture was welded opposite end of the joint where hydraulic pressure is applied.

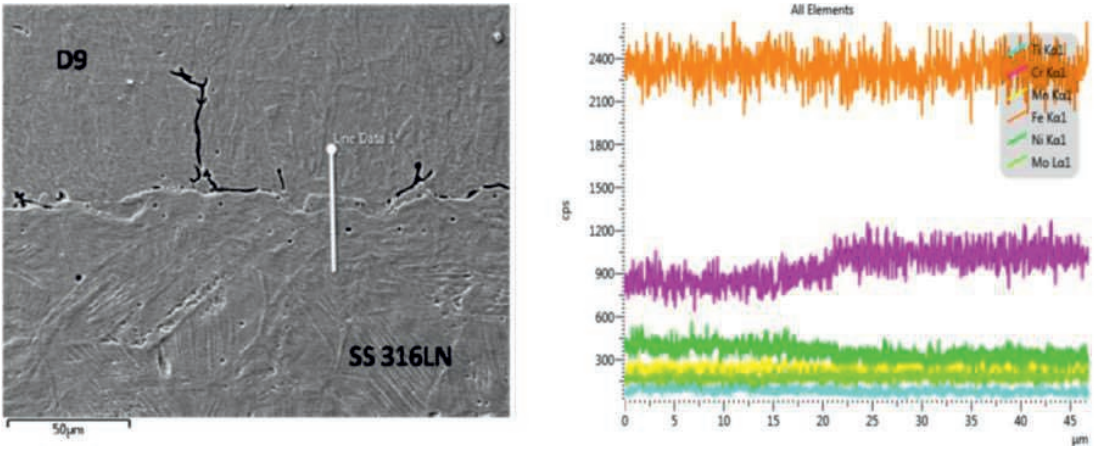


Figure 30.9(a) Secondary Electron Micrograph and (b). Composition profile at Interface.

Figure 30.10(a). Sample 1 & 2, failed at 1096.6 Bar (Fitting- Pitch: 19/20G1/4", Dia. 14.3 mm x 11 mm length), (b). Sample 3, failed at 1101.5 Bar, (Fitting: Sweglok 3/8”) (c). Interface fitting with sample-1 and pressuriser and (d). Tube failed at 108.28 MPa (sample No.3).

Based on first principle calculation pressure required to fail the D9 steel tube was greater than 105MPa as shown in Figure 30.10.(a), 30.10(b), 30.10(c) and 30.10(d) and all sample met this criterion. These test are conducted at "Maximator Ltd" at Navi Mumbai.

30.3.3. Hardness profile at weld interface

The hardness variation across the joint interface is recorded using a micro-hardness tester. The test is performed at a load of 0.025 kg. The micro-hardness value is observed to be 309 VHN and 280 VHN at the D9 side and SS 316LN side, respectively. An increment in hardness by 2–5% is observed near the interface on both sides, which can be attributed to the strain hardening during the MPW process.

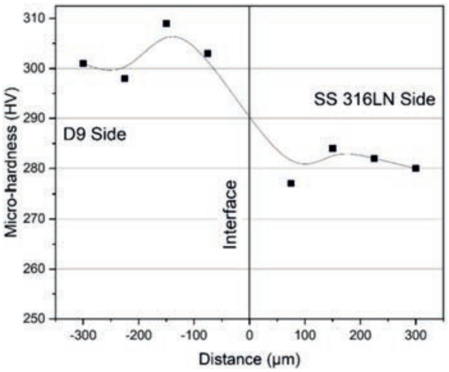


Figure 30.11. Pattern of micro-hardness near the bonding interface for the MP welded sample.

Figure 30.11. shows more percentage increase in hardness could be attributed to tending towards brittleness and structure may lead to failure.

30.3.4. Pressure Burst test at Elevated Temperature

APPD, BARC and IGCAR [5] are jointly working on the developmental programme to qualify the magnetic pulse welded (MPW) technique for joining the fuel pin clad tube of future fast breeder reactor (FBR).

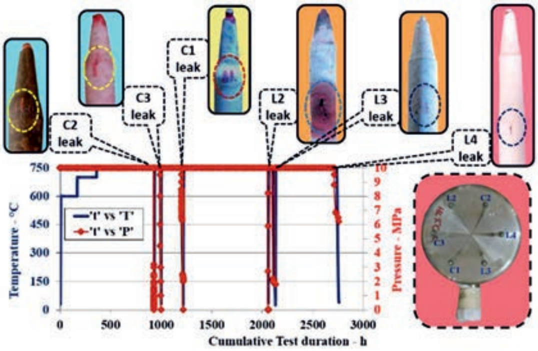


Figure 30.12. Out-pile test results.

Six MPW samples were subjected to Out-Pile test with two kinds of end plug (both Type-L and Type-C) three each. The” L Type” does not have cavity towards other end of the plug where as “C-Type” have a cavity. The minimum and average rupture time for the Type-L specimens are 1672 h and 1884 h for an effective accelerated test temperature of 750 C and 10 MPa argon gas pressure. This test qualifies the magnetic Pulse Welding for high temperature and pressure test for D9-SS316LN pair. The results are showcased in Figure 30.12.

30.3.5. Pull/Push Test

One D9 clad to SS316LN end plug joint having design feasible to conduct pull out test was prepared. The specimen was held firmly one end at plug and other end at tube with solid rod inside. This joint is development for finding the pull out strrength of sealing the fuel clad of D9 steel clad to specially designed end plug in fast breeder reactor program. The tensile stress time graph shows that the tube stated yielding in between 550 to 600 MPa and ultimate stress that sustained by the tube is 880 MPa.

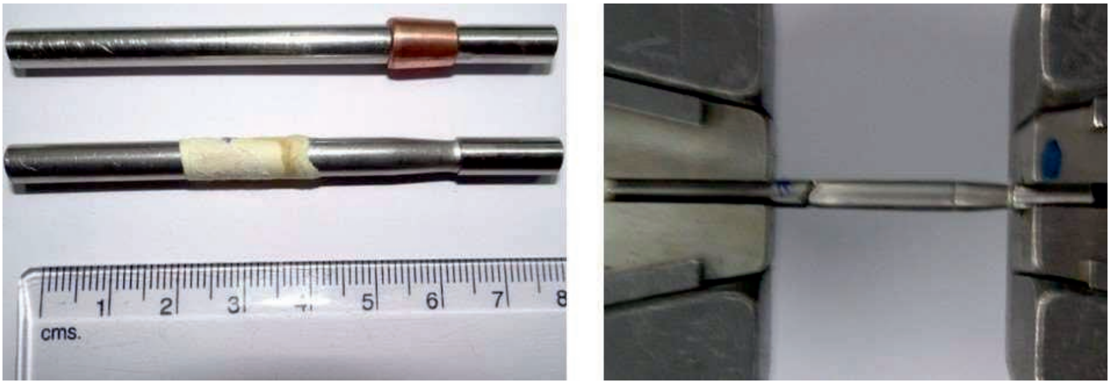


Figure 30.13(a). MP Welded Joint have special plug design for Pull Out test enable and (b) Tube failed at penetrant material at 880 MPa and joint is intact.

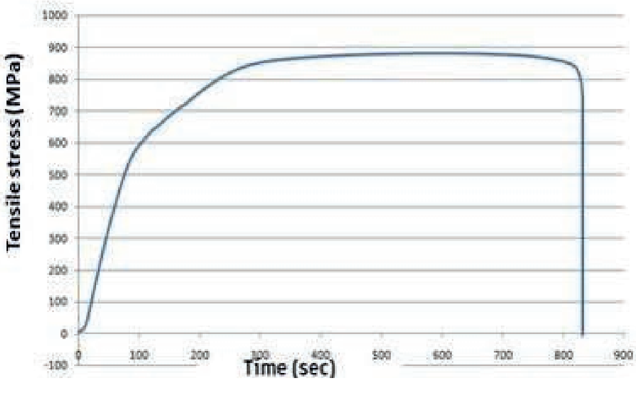


Figure 30.14. 6.6 mm OD x 0.45 mm thick D9 steel to SS316LN end plug MPW joint.

This result is very much evident that the joint is stronger than the parent material as the process is high strain and strain rate features. In PFBR fuel pin, a 70 cm gas plenum is separated from MOX fuel and breeding material by a hollow SS316LN plug. Presently D9 steel clad is rolled on SS316LN hollow plug with conventional rollers. It has been observed that due to spring back effect some air gap creates between plug and tube. In APPD, BARC we have developed tool coil and field shaper for magnetic crimping. A push test was conducted on conventionally rolled and magnetic crimped joints. Figure 30.15 shows the load bearing capacity of the both joints. Magnetic crimping joint sustained more load in comparison with the rolled joint. Both pull and push tests were conducted at Material Science Division, BARC.

Figure 30.15. Graphs shows Electro-magnetic crimped and conventional rolled joint between D9 steel to SS316LN Plug.

30.4. Conclusion

The Magnetic Pulse Weld qualification adopted at BARC-IGCAR for qualifying fuel pin end sealing is covered in this article. The torsion test, cyclic pressure test and peel tests are also conducted to qualify the MP joint but APPD we have not conducted these tests on fuel pin end cap application as the test conducted so far confirm the good quality of the joint. The torsion test can determine if the shear strength of a weld is stronger than the base material. Only if the weld strength is lower, a value for the ultimate shear strength of the weld can be obtained with torsional test. Further pressure capsule test and in pile test and are planned in near future. Magnetic pulse welded joints were exposed to proton irradiation close to 2dpa and stress induced was also analyzed. No change in stress level after irradiation between parent material and joints was observed. Dye penetration test and radiography conducted after out pile test also indicate there was no defects in the joints. In a nut shell in DAE several destructive and non-destructive techniques are developed to evaluate the quality of MP welded joint between fuel clad tube to specially designed end plug.

References

[1] V. Psyk, D. Risch, B.L. Kinsey, A.E. Tekkaya, M. Kleiner. “Electromagnetic forming—A review”, Journal of Materials Processing Technology, 211, 787–829, 2011.

[2] M.R. Kulkarni, Tanmay Kolge, Archana Sharma, Voona Srikanth, Arjit Laik, Shaju Albert and Sachin Kore, “Joining of D9 cladding Material to SS316LN End Plug Using Electromagnetic Pulse Technology” BARC Report,BARC/2018/I/026

[3] Gopa Chakraborty, M.R. Kulkarni et.al, Magnetic pulse welding and characterization of D9 clad tube to SS316LN plug joint, FBTR 1&2, IGCAR, 31110, TR, 1007. 2021

[4] International Organization for Standardization. ISO 15620. “Welding – Friction welding of metallic materials”, https://www.iso.org/standard/72734.html Switzerland: ISO, 2000.

[5] R. Suresh Kumar, R. Manu, K. Mohan, G. Venkataih, B.E.Bhaskar, M.Aravind, “Out Pile Qualification of FBR Fuel Pin Clad Tube Joint Using magnetic Pulse Welding; Test Series-2”, FBTR 1&2, IGCAR, 31110,TR, 1005. 202