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Design of high field tool coil for magnetic pulse welding

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The Accelerator and Pulse Power Division (APPD), BARC has developed strong Bitter coil with field shaper and 70 kJ, 25 kV electromagnetic manufacturing machine, for forming and welding applications. They conducted investigations into possibility of using Electromagnetic Pulsed Technology (EMPT) in joining austenitic –austenitic stainless steels, using samples fabricated to simulate tube and caps with coil developed at laboratory. The coil has been designed for industrial mass production that consists of four numbers of copper discs axially reinforced with non-magnetic steel studs. The polyamide films are used as coil and stud liner whereas Fibre Reinforced Plastic (FRP) is used as inter disc insulation. This paper discusses the design details of the 20kV, 250kA, 10 kHz Bitter coil, field shaper with replaceable inserts. This designed coil has been regularly used at rated value and generating the field of 35-40T in volume of Ø8.8mmX13mm. The steel tube to plug joints developed by this tool qualified helium leak better than 1.2x10^{-9} *mBar.litre.s*$^{-1}$ *and parent tube failed under pull out test but joint was intact.*

Keywords: *Bitter coil, field shaper, magnetic welding, tool design.*

1.0 INTRODUCTION

MAGNETIC pulse welding is a special case of electromagnetic forming [1]. Electromagnetic forming is an impulse or high speed forming process, using pulsed alternating magnetic fields to apply forces on conductive workpiece without mechanical contact or working media. The pulse magnetic force is generated by transient magnetic field between a current carrying tool coil and work piece. Transient high current is obtained by discharging the energy stored in the capacitor bank. For forming, coil design can vary widely depending upon the geometry of the parts. This flexibility in the coil design is a major advantage of the forming process. This joining technique is primarily applied to tube to tube or tube to bar configuration and where conventional technique cannot attain the quality of the product.

2.0 EXPERIMENTAL SET UP

FIG 1. ELECTROMAGNETIC MANUFACTURING MACHINE DEVELOPED AT ACCELERATOR AND PULSE POWER DIVISION (APPD), BHABHA ATOMICRESEARCHCENTRE (BARC)

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The 40 kJ electromagnetic manufacturing machine [2] developed at Accelerator and Pulse Power Division (APPD) has been up graded to 70 kJ, 25 kV that has shot circuit parameter better than 600 kA, 20 kHz is shown in Figure 1 This system has been used for different forming and welding application for in house and industries. The Bitter coil [3] and field shaper [4] have been developed for welding D9 austenitic steel tube [5] (close variant of SS316L) to austenitic SS316 end cap.

3.0 TOOL COIL

The coil is the actual tool of the electromagnetic process and analogous to conventional forming processes. It needs to be adapted to each specific forming task. The major task of the tool coil is to conduct the current and consequently establishing a suitable temporal and local distribution of the magnetic field and pressure. Most of the inductance should lie in the tool for efficient process. The coil system should be self supportive i.e. its strength should not be dictated by weak insulating material. For mass production, coil pressure generated is limited to 50 MPa.

3.1 Bitter Coil with Field Shaper

Detailed Bitter coil [3, 10] and field shaper [4, 6] design and analyses have been done. As the diameter of the working field comes down below 25mm and field goes above 25 Tesla corresponding to Maxwell's stress of 250 MPa, it is not economical to adopt only Bitter coil for forming and welding application. The high stress zone i.e. electromagnetically, mechanically and thermally in a smaller volume is practically not possible to contain by applying the stronger axial pressure by studs. The highest electromagnetic pressures can be generated when the working surface of the coil is made from a monolithic block of a high strength and high conductivity metal. Hence, large pressures can often be created with single turn coils, but are inefficient due to low inductance. Field shaper with bitter coils can be used to develop high electromagnetic pressure while being able to increase and tailor the inductance of the coil. In efficient designed tool system, the entire current flux that is created in the Bitter coil can be transferred to the inner bore of the shaper. The field shaper homogenizes the field created by Bitter coil and concentrate large magnetic pressures in a desired area keeping high pressure zone away from the main coil.

3.2 Design Procedure

The tool has been designed to weld 6.6 mm OD X 0.45 mm thick D9austenitic steel tube having yield strength 550 MPa, ultimate strength 770 MPa and conductivity 1.35 MS/m with specially designed steel end cap. This welding depends on many factors like magnetic impulse, collision velocity, collision angle, acceleration step andoptimized conditions yield best weld. As short circuit frequency was close to 20 kHz, conductive drive like copper was essential as it cannot meet skin depth[1] without the driver[1]. As short circuit current of the system is close to 600 kA, it was not possible to use single turn coil efficiently. Hence Bitter coil with field shaper was the ideal solution.

The upper bound of magnetic pressure P_m is the magnetic energy density in the gap between field shaper and workpiece

$$Pm = \frac{BH}{2} \qquad \text{...(1)}$$

B and H are the magnetic field in Tesla and magnetizing force in AT/m for non-magnetic work piece $B = \mu_0 H$

$$Pm = \frac{B^2}{2\mu} \qquad \text{...(2)}$$

where μ is a permeability of high field zone.

The required magnetic pressure to start thecircumferential deformation P of the work piece is given by the relation.

$$P = N(\sum ys\ 2\Delta)/Dow \qquad \text{...(3)}$$

Where $\sum ys$ is the yield strength, Δ is the thickness and Dowouter diameter of the jobpiece. The factor

N□ (1, 10], taking into account of inertia, workpiece length, strain and strain rate hardening, through thickness stress because the workpiece is not thin walled (*i.e* $2\Delta/Dow > 0.1$) tube.

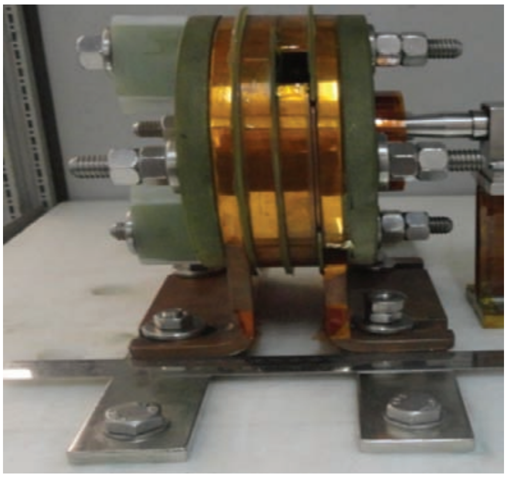

FIG. 2. BITTER COIL WITH FIELD SHAPER

For design of field shaper and coil, workpiece geometry,its conductivity, field required to be generated with rise time and parameters of the pulse generator are prerequisites.

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

$$\delta = \frac{1}{\sqrt{\sigma\pi\mu f}} \qquad ...(4)$$

Where and f are the conductivity of work piece in S/m and operating frequency in Hz respectively. When the thickness of the material equals the skin depth, 86% of the magnetic field is shielded. If the thickness of the material equals two times the skin depth, 98% of the magnetic field is shielded. The net magnetic pressure P_{mag} acting on the surface of the work piece is given by the relation

$$P_{mag} = (B^2_{out} - B^2_{in})/2\mu_0 Pa \qquad ...(5)$$

Where B_{out} is the field acting on outer surface and $B_{in}$is the diffused field inside the work piece in Tesla

To meet the condition stated in equation (4), 0.6 mm thick annealed copper driver having conductivity 58 MS/m and yield strength 70 MPa was chosen

For electromagnetic pulse welding 40 Teslafield having risen time below 25 microsecond meats the most of the welding jobs [3] and satisfies the conditions stated in equations (3) and (4). The field concentration factor by field shaper is highly sensitive to active length ratio of Bitter coil to field shaper. Reasonably four to five concentration factor can be practically attainable by proper selection of material and design. The field shaper inner dimensions are dictated by the geometry of the workpiece and the outer dimension depends upon the mechanical stiffness and the field that can be generated by Bitter coil without deteriorating for large number of shots. Meantime inductance offered by the tool should be such that ringing frequency better than 10 kHz is attainable. The Bitter coil designed has four discs having inner diameter 92 mm spread along the length of 60 mm. This coil offers 600 nH inductance at 20 kHz. When operated with the system, generates 8 Tesla field at mid plane of the coil, close to coil surface at 250 kA, 10.5 kHz discharge.

In welding set up field shaper was held firmly by two end fiber reinforced plastic (FRP) stopper. The field concentration zone was at other end of the collar in second with replaceable ETP grade copper insert. Each shot new insert was used. Different insert materials like SS,Nb,Ta,W-Cu, Be-Cu, Cu-Ti, Cu and AA2024 have been tried.

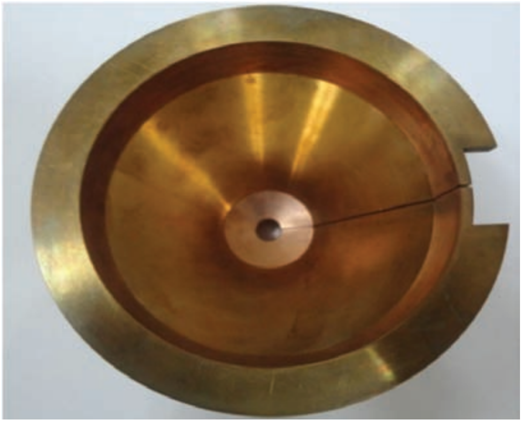

FIG. 3. BERYLLIUM COPPER (BE-CU) FIELD SHAPER WITH COPPER INSERT

Among them copper has been found most efficient and cost effective at 10-20 kHz frequency regime. Replaceable insert concept was adopted, because at 40T field saw effect [7] was observed in Be-Cu field shaper. Saw effect caused arcing at active portion that made field shaper not useful in successive shots effectively even though it was not yielded mechanically. The active field volume was Ø 8.8mm x 13 mm, dictated by workpiece and driver dimensions. The slit of field shaper and copper insert are perfectly matched to avoid arcing and was kept 0.6 mm wide.

3.3 Material Selection

For better performance, conductor of coil and field shaper should have high dynamic ultimate and yield strength, high impact viscosity, high density, high conductivity and high melting point. If magnetic pressure exceeds the material yield strength, residual plastic deformation takes place and accumulates in each successive pulse. These causes enlarge in inner dimensions and lowering field. High material conductivity will improve system efficiency and high material yield strength provides a strong, robust, long life coil.High strength aluminium alloys, beryllium copper, copper titanium, brasses and oxide dispersion strengthened materials such as Glidcop are all good candidate coil materials. Polyamide films (Kapton) provide slit isolation, insulation between field shaper and coil, between field shaper and workpiece. Mylar laminated FRP discs were used as inter disc insulator. Be-Cu having yield strength and conductivity 1000 MPa and 23% IACS respectively was used for field shaper. Half hardened copper having yield strength 310 MPa and conductivity 56 MS/m had been used for coil and inter connecting sectors. SS 304 steel studs isolated with Kapton hold the coil discs firmly. A fixture was designed to hold the workpiece firmly at high field zone till it dies without affecting distribution

4.0 EXPERIMENTS AND RESULTS

Figure 4 shows the current waveforms at 36 kJ, 18 kV with only coil and coil with field shaper and work piece. Field was measured with B dot probe. Figure 5 shows the austenitic steel D9 tube to SS316 end plug welded sample, its optical micrograph and SEM image. In these trials all plugs were fine machined to 1.5 micro meter roughness [8] and cleaned with acetone prior to shot. These joints passed the helium leak rate better than $5x10^{-9}$ mBar.l.s^{-1}. The plug had optimised taper angle of 8 degree [8].

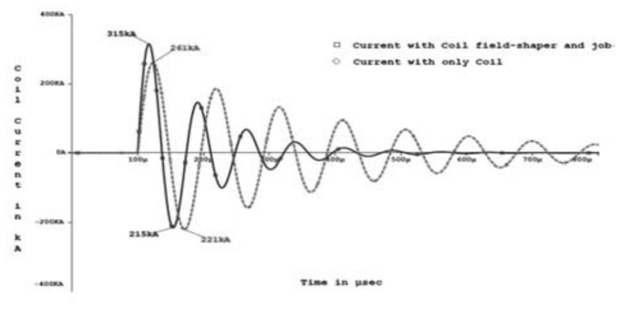

FIG. 4. CURRENT WAVE FORMS WITH AND WITHOUT FIELD SHAPER

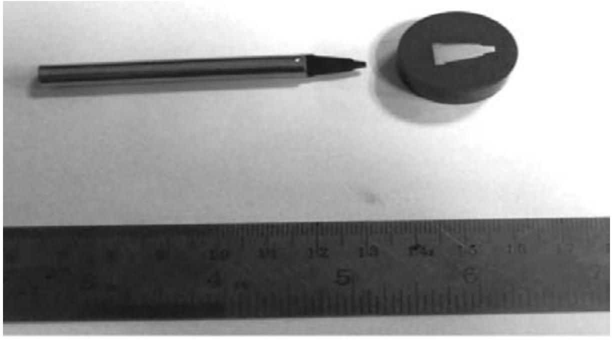

FIG. 5. (A) CUT SECTION OF TUBE TO END PLUG JOINT

Under pull out test, failure occurred at parent tube but joint was intact. Complete circumferential weld was observed close to 3 mm away from the tip of the tube. Axially also weld zone of 4 to 6 times the thickness of the tube was observed. The Scanning Electron Microscopy (SEM) revealedthe migration of titanium from D9 steel at welded zone. Hydraulic pressure test was also been conducted on two samples at room temperature up to 35 MPa for two minutes. The joint withstood the pressure without leak. Subsequent helium leak test confirmed the quality of joint.

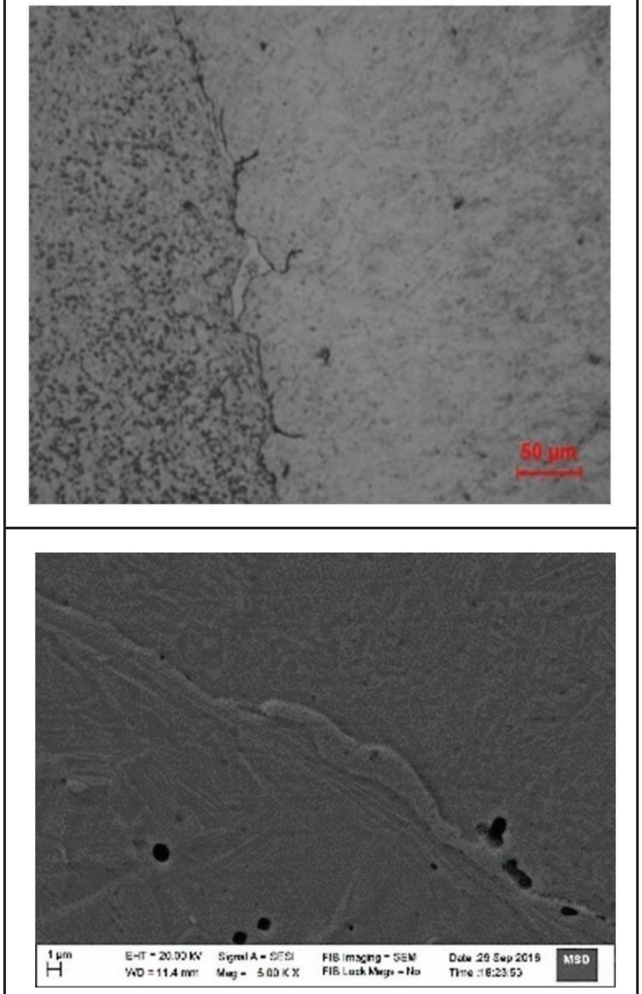

FIG. 5. (B)OPTICAL MICROGRAPH. FIG. 5C. SEM IMAGE

5.0 CONCLUSION

The Bitter coil with field shaper have been developed that can generate more than 40 T magnetic field in a volume of Ø 8.8 mm x 13 mm with replaceable inserts. Its applicability to joining of austenitic tube to plug has been demonstrated.

APPENDIX

Detailed analysis of B dot probe has been reported [9]. The step response of the B dot probe that was used in the trials for field measurement is shown in Figure.6.

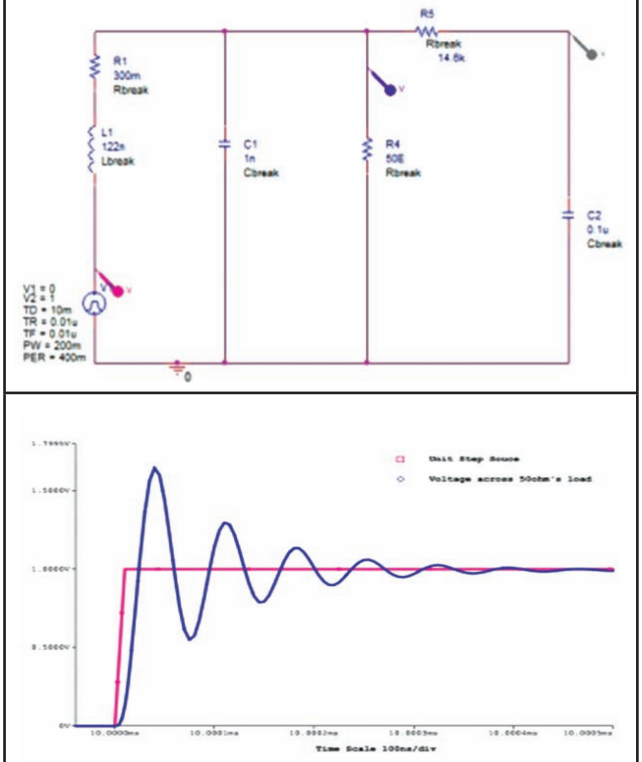

FIG. 6. DOT PROBE WITH RC INTEGRATOR AND STEP RESPONSE

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