Development of electromagnetic welding facility of flat plates for nuclear industry

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Abstract. Electromagnetic pulse welding (EMPW) process, one of high speed welding process uses electromagnetic force from discharged current through working coil, which develops a repulsive force between the induced current flowing parallel and in opposite direction. For achieving the successful weldment using this process the design of working coil is the most important factor due to high magnetic field on surface of work piece. In case of high quality flat plate welding factors such as impact velocity, angle of impact standoff distance, thickness of flyer and overlap length have to be chosen carefully. EMPW has wide applications in nuclear industry, automotive industry, aerospace, electrical industries. However formability and weldability still remain major issues. Due to ease in controlling the magnetic field enveloped inside tubes, the EMPW has been widely used for tube welding. In case of flat components control of magnetic field is difficult. Hence the application of EMPW gets restricted. The present work attempts to make a novel contribution by investigating the effect of process parameters on welding quality of flat plates. The work emphasizes the approaches and engineering calculations required to effectively use of actuator in EMPW of flat components.

1. Introduction
Electromagnetic pulse welding (EMPW) is a technique for welding of metals by means of plastic deformation generated by a repulsive force on account of the interaction between the magnetic field of the coil and the current induced in the workpiece. Being a high-strain rate forming method, the EMF process has all the advantages of high-velocity forming process, viz. increased formability, reduced springback and reduced wrinkling of formed parts [1-2]. In case of flat components controlling the magnetic field is difficult. Hence, the application of EM technique is restricted. The research on electromagnetic impact welding of flat sheets has not been extensively documented, and the literature prominently shows the activity of only few researchers in this field [3-4]. This article discusses the theoretical aspects involved in the design of EMPW process. The behaviour of electromagnetic parameters such as magnetic field, voltage, current induced and Lorentz force is explained on the basis of Maxwell’s equations. For effectiveness of EMPW process, it is desirable that more magnetic field is screened by the job piece and less diffuses out. Thus the discussion about diffusion process is important. The Lorentz force is to be coupled with electrodynamic and structural equations to get the information about deformation and the kinetic energy generated in the job piece. The article concludes with the detailed discussion on the theoretical aspects work with these the design procedure for welding coil. Recent studies and advances in the welding fraternity have been made in order to develop a newer process which enables us to achieve better quality, increase productivity and is
environment friendly. EMPW is a step forward into the future of welding. In the past few decades the development of a joining technology to weld multimaterial combinations and efficiently join lightweight structures has been an area of significant and growing interest. In the specific case of multi-metallic assembly, the MPW process is known as a potential joining solution [5]. EMPW has wide applications in nuclear industry, automotive industry, aerospace, electrical industries [6].

Nuclear industry responsible for the discovery and the initial development of EMPW on the production of end closures and nuclear fuel rods. The need for a reliable method for joining T91 and ODS steels is central to the fabrication of fuel pins using these materials. Nuclear clad to tube welding, stainless steel joints, stainless steel telemanipulator cables crimping, Aluminium container covers crimping, Welding of closing caps, Stainless steel Tele manipulator cables crimping, Aluminium container covers crimping, Metal canisters welding etc. are some examples related to nuclear industry where EMPW technique can be applied for better performance. Owing to the increasing demand in nuclear industry, there is a need to develop joining process [7-9].

The fusion and fission reactors are faced with important challenges, notably in the field of materials. A class of materials, susceptible to resist the anticipated severe environments, is the ODS (oxide dispersion strengthened) family, which are metallic alloys strengthened by a very fine oxide dispersion. Oxide particles, which have excellent high temperature stability and fine disperseoid distributions, provide the ODS steels with excellent resistance to neutron irradiation-induced swelling, hydrogen embrittlement over austenitic steels and high-temperature creep.

A barrier of these materials for application is their weldability. It has been found that conventional fusion welding methods can disturb the dispersion of the fine oxide particles in the alloy. Hence, fusion welding methods are not applicable and should be substituted by better welding methods. Oxide dispersion strengthened (ODS) steels have the microstructure and mechanical properties required for advanced nuclear reactor applications. These alloys have a very high strength at room temperature, but the strength diminishes slowly at higher temperatures. Fe-based oxide dispersion strengthened (ODS) alloys contain fine and uniformly dispersed yttrium oxide particles in a ferritic matrix. The high temperature stability of the nano-oxide dispersoids act as pinning points to inhibit dislocation movement and provide excellent creep strength and irradiation resistance. Therefore, these materials are of potential use in advanced energy generation such as hydrogen fuel cells and fission/fusion nuclear reactors. For ODS alloys, agglomeration of fine oxide particles would result in loss of strength in the ODS joints [10-11].

Friction stir welding (FSW), electron beam (EB) welding, Laser beam welding, Pressure Resistance Welding (PRW) are some solid state joining process tried on ODS steel by different researches for successful welding but each process have some limitations to qualify for successful welding of ODS due to affecting particle dispersion consistency near welding zone.

2. Basic Principle

Figure 1(a) shows a schematic diagram of a discharge circuit. The circuit for the present method consists of a capacitor for a supply of electrical energy, a discharge gap switch and an E-shaped one-turn flat coil. The two plates are placed above the coil, with a little space between them. The plate nearest the coil is termed the “flyer plate” and the plate above it, which is fixed firmly in place, is referred to as the “parent plate”. When the capacitor is charged and the discharge gap switch is closed, a discharge pulse is released to the coil. The electrical energy stored in the capacitor is called “discharge energy”, the welding conditions are mainly controlled by this parameter. Figure 2(b) shows a close-up around middle section of the coil. When a discharge pulse passes through the coil from the capacitor, it induces a high-density magnetic flux around the coil.
Figure 1. Schematic illustrations of welding process of magnetic pulse welding. (a) Set-up of the lapped plates over the E-shaped one-turn coil. (b) Principle of the magnetic pulse welding.

The generated magnetic flux lines intersect with the flyer plate, and in accordance with Lentz’s law, eddy currents are excited in the surface of the flyer plate adjacent to the coil. In accordance to Fleming’s left-hand rule, the eddy current and the magnetic flux generated around the coil induce an electromagnetic force upward. The electromagnetic force drives the flyer plate toward the parent plate at a high velocity and the flyer plate is welded to the parent plate [12].

3. Experimental Apparatus

Figure 2 shows the general outlines of the magnetic pulse welding apparatus, which consists of a capacitor bank (C) and a spark gap switch (G) with a one-layer, E shaped flat coil. It was attempted to make a low-inductance discharge circuit that can generate a high-density magnetic flux around the coil area. The capacitor bank that drives the discharge system of the MPW device consists of 16 capacitors of 4 μF/75 kV in parallel. It is connected to the gap switch and one-turn coil by a low-inductance transmission line. The circuit is designed to keep the inductance as low as possible to carry out fast welding. The flat, E-shaped, one-turn coil was made of Cu. The coil thickness is 20 mm and the inductance of the coil is 0.02 nH. When the gap switch is closed, an impulse discharge current from the capacitor bank (C) passes through the coil and the MPW process begins. The aluminum work sheet were 25 mm long, 25 mm wide and 1 mm thick whereas stainless steelwork sheet was 35 mm long, 35 mm wide and 2 mm thick. Distance between flyer plate & parent plate before start of welding is 1 mm. The contact surface between two samples was polished and cleaned. The 0.1~0.3-
mm-thick insulating sheets were loaded between the coil surface and the overlapped ends of the workpiece sheet.

Figure 3. Photograph of three-dimensional flat coil for electromagnetic impact welding. (a) Bus bars connected to high voltage and ground terminal (b) High voltage and ground cables connected to coil by bus bar (c) Sample placed and tightened properly on coil web to withstand high pressure (d) 2D model of coil (e) 3D model of the coil (f) Coil processed by water jet cutter for EMPW application

A three-dimensional, ‘E’-shaped, flat one turn copper coil with its set-up as shown in Figure 3 was designed and fabricated for the electromagnetic impact welding of 1mm thick aluminum sheet to stainless steel sheet. The web of 10mm wide and 50mm long at the center leads to concentration of the current, thereby increasing the current density $J$ [3]. An increase in current density gives a corresponding increase in the resultant Lorentz force that generates stronger impact between the sheets to be welded. The Lorentz force is given by [13].

$$F = J \times B$$

Where, $F$ is the Lorentz force in N, $B$ the magnetic flux generated by the coil in Tesla and $J$ is in Am$^{-2}$.

4. Result
A typical current waveform is shown in figure 4. This current signal was obtained at 9 kJ discharge by using a magnetic probe. The current signal shows that a damping and oscillating current flows through a one-turn coil for the duration of about 50 $\mu$s. The maximum current was measured at about 280 kA. If the discharge current flows uniformly on the surfaces of the middle portions of the coil, The aluminum work sheet were 25 mm long, 25 mm wide and 1 mm thick whereas stainless steel work sheet was 35 mm long, 35 mm wide and 2 mm thick. Figure 5 (a) shows the photograph of 5 representative samples of Al sheets welded to SS sheets and copper sheets at same energy values.
The bank capacity used for all the experiments was 9 kJ at 15 kV. Copper coil having inductance of 0.2 nH was used. Electromagnetic force generated to drives the flyer plate toward the parent plate is 14.36 kN. Velocity of the flyer plate achieved is 92 m/s. The web of the coil was supported with a specially designed and fabricated nested type nylon fixture to avoid its bending in the process of welding of the sheets. Figure 5 (b) show the cross-section view of Al-Cu sample with welded zone at center and non-welded zone.

![Current waveform at 9 kJ discharge energy](image1)

**Figure 4.** Current waveform at 9 kJ discharge energy

![Sample images](image2)

**Figure 5(a)** Al-to-SS and Al to Cu electromagnetic impact welded samples. **(b)** Al to Cu electromagnetically welded sample showing weld and no-weld zones.

5. **Conclusion**

In this work, a process of electromagnetic impact welding of inferior electrical conductive stainless steel sheet to aluminum and copper sheets have been successfully established. The feasibility of electromagnetic impact welding of aluminum sheets has been established. Electromagnetic welding technique overcomes problems in welding Cu-to-Al, Al-to-SS sheets that could be encountered in the conventional techniques. It proves to be a potential welding technique for various industrial components requiring dissimilar sheet metal joints. In the future, the feasibility of electromagnetic welding process can be checked for the difficult-to-weld materials like magnesium, galvanized steel, etc. The effect of process parameters on the strength and metallographic structures of the EM welds can be studied in detail for various dissimilar metal combinations. Numerical simulations of the process can lead to better understanding and prediction of the EM weld characteristics. EMF method
of joining dissimilar metals specially, which is difficult to weld by conventional method, has shown promising results. Although, the trial was basically a mechanical joint, this technique has potential for diffusion bonding between dissimilar metals. This has possibility of an alternative to the explosive welding in laboratory scale. Magnetic Pulse Welding has been growing since the 70’s and there is an increasing interest in the welding process in several industrial sectors. It is a cold welding process in which two metal surfaces in placed in close contact by the effect of a high speed electromagnetic force produced in a short pulse capacitor in the range of few tens of millisecond. Due to this no heat developed in the interfaces.

EMPW is a technology with proven repeatability, with widespread applications in mass-production processes. The solid state joint produced does not adversely affect the particle dispersion consistency of ODS steel. Problems associated with a heat-affected zone, like grain growth, are eliminated. EMPW can potentially make joining of these materials simple, reliable and repeatable. It involves no physical contact with the cladding at the joint, which could even enable the joining of cladding materials with dedicated coatings.

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