UHV Compatible Al to SS Joining Through Electro Magnetic Forming Technique

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Abstract: Fusion welding, which is the most versatile and widely used method of metallurgical bonding, can be troublesome in certain applications like dissimilar metal joining for Ultra High Vacuum requirements. Welding of Stainless Steel to Aluminum by conventional technique is very difficult due to thermal & metallurgical incompatibility. Consequently a number of non-conventional specialized joining techniques were developed. Joining of SS to Al by Electro Magnetic Forming (EMF) method is an effort in this direction. The paper discusses in detail the joining process, joint design and the results achieved.

1. Introduction
Electro Magnetic Forming (EMF) joining is classified as a high-energy rate joining process. It uses electromagnetic energy induced by a large electric current fed by a capacitor bank through a coil. When a coil is placed concentrically in a tube and a tube sheet, the tube traverses radially the space between them at a high speed comparable to sonic speed and collides against the tube sheet.¹

2. Basic principle
The principle of electromagnetic forming is manifested in the very definition of the unit Ampere. Simply told, any two current carrying conductors exert force on each other, this very observation is stated by Lorentz force law as $\mathbf{J} \times \mathbf{B}$, where $\mathbf{J}$ and $\mathbf{B}$ are current density and flux density respectively. The ingenuity lies in the generation of two currents for shaping or joining of metals or metals to plastics or even metal to ceramics. The ‘figure 2’ bellow illustrates the technique. Depending on the proximity of the two currents and their magnitudes, the force magnitude can be estimated. As depicted in ‘figure 1’, the primary current in the coil, which is generated by discharging energy storage capacitors, induces large secondary currents on axis-symmetric tubular job piece. The induced currents in the job piece oppose the very cause (primary current), in accordance with the Lenz’s law. In EMF technique this is manifested as the repulsion between the two currents, thus the two current carrying members physically distance from each other. As one does not want to deform the work coil, it should be strong enough to sustain repulsive forces. In this technique mechanical stress close to 350 MPa are routinely generated. Generally above this value, shot life of the coil is the limiting factor for an

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industrially viable system. A simple design guideline to estimate the energy of capacitor bank and minimum magnetic flux density requirement for the job coil, can be had by equating the hoop stress required to plastically deform the tubular job piece to the magnetic energy stored in the volume to be deformed, i.e., \( \frac{1}{2}(B^2/\mu_0) = \Sigma y \ t/r \), where \( B \) is the flux density generated by the forming coil, \( t \) is the thickness of the job piece, \( r \) is the mean radius of the job and \( \Sigma y \) is the yield strength of material of the job. The criterion to choose the ringing frequency of the damped discharge waveform can be had by equating skin depth for the tube material with the tube thickness.

A simple solenoid coil with a cylindrical work piece, spiral flat coils and coils of various other configurations may be used to produce magnetic pulses of various configurations, expansion and forming flat sheets.

\[ \text{Figure 1 Schematic of EMF joining process in Axisymmetric Case} \]

Coils will be designed in such a way that stray inductance is to be minimized and current concentrations are avoided. Since high permeability materials generally cannot be used in this application because of high flux densities required, fields might be ordinarily shaped only through the use of current carrying conductors. These current carrying conductors need not be directly connected to the basic coil but may be inductively coupled configurations. Carefully designed coils when operated within their design limits would last long enough to meet production requirements of typically 50,000 shots. There is no theoretical limit to the maximum energy, which can be built into electro magnetic forming equipment. Inertial effects play a very important role in all Electro Magnetic Forming operation and are basis for many unusual capabilities.

2.1. Effects of Resistivity and Geometry

The efficiency of Electro Magnetic Forming depends upon the resistivity of the metal being formed. Most suitable for this operation are those having high electrical conductivity, such as copper, silver, gold, aluminum etc. For good practical results, resistivity should be less than 15 micro-ohm-centimeters. For working with high resistivity material, forces can be imparted indirectly by using a good conducting material between the coil and the non-conduction workpiece. The intervening good conducting material is called ‘driver’ in EMF parlance.
3. Equipment
The equipment consists of energy storage capacitor bank, a DC power supply, trigger generator, current & voltage monitor, work coil and control and protection circuit. The basic discharge circuit consists of an energy storage capacitor, triggered spark gap and the work coil as depicted in ‘figure 2’. Various Components of EMF Joining Set-up is shown in the ‘figure 6’.

4. Experiment
Our trial was for Al tube to Stainless Steel tube-sheet joining of UHV quality. The schematic of the joint and its relative position is shown in the ‘figure 3’. For efficient operation, the fit of the workpiece to the coil should be considered. Efficiency is best achieved when the gap between the coil or the field shaper and the workpiece is minimum. Fit between Al tube and Stainless Steel tube-sheet should be such that the recoil of the tube from Stainless Steel tube-sheet should be minimum. This was achieved by

a) Joint design
b) Keeping a particular gap between the Al tube to Stainless Steel tube-sheet
c) Grove design in the tube sheet

4.1. Metal-to-Metal joining Procedure
Metal-to-metal joints are useful for fabricating vacuum as well as pressure tubing and pipe assemblies. To obtain good metal-to-metal seal, the following factors are to be considered:

1. Metal of the tube/shell can be forced into the groove/grooves in the outer member
2. The metal of the tube/shell can be bent/folded around the corner
3. Sharp edges on one member of the joint can be made to exert high local pressures on the other member of the joint
4. A joint can be made to take the advantage of the elasticity of the materials being joined
For best results, the groove in the insert or the plug should be wide in relation to the thickness of the tube/shell. The seal gets formed on the shoulder of the groove. The material forced into the groove does not contact the bottom of the groove because such contact tends to cause a reaction, which loosens the seal. When relatively hard materials are used for tube/shell, the groove is wider than when softer materials are used. Although number of grooves varies from specimen to specimen, two or more grooves provide

1. More rigid connection than a single groove
2. Increase in the axial pullout strength
3. Tolerance in gap between the tube/shell to tube-sheet is relaxed

Al to Stainless Steel being difficult to weld by conventional method, our experiment was to achieve a mechanical joint using EMF technique. Salient Features are as follows:

1. No heating of jobs hence no heat related problems
2. Joint preparation is easy and flexible
3. Any metal to metal similar or dissimilar joint is possible
4. Actual joining time is fraction of a second
5. Second trial on the job improves results

In fact parameters affecting the results are number of groove in the tube sheet, groove shape & size, gap between tube sheet & tube, charging Voltage, Discharge current, cycle period of the discharge current. Few trial results are shown in the ‘table 1’.

We took around 50 trials for finalizing different parameters of EMF joint to establish relationship between various joint parameters. ‘Table–1’ gives relationships between various parameters and the results.

4.2. Results
We achieved the following results

a) Leak rate < 1 X 10^{-10} std-cc/sec (MSLD Test)
b) Hydro test results show no leakage of water even at 28 kg/cm^2
c) Pull out test shows that the joint is stronger than the weakest member of the joint
5. Conclusion
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.

References:
[1] Personal Communication, “Special Forming Methods” Chapter 19, MAxwell Laboratories Inc. 8888 Balba Avenue, San Diego, California92123, USA

Acknowledgements:
We gratefully acknowledge the encouragement and support from
1. Dr. V C Sahani, Dir Physics Group, BARC, Mumbai
2. Dr. L M Gantayake, Associate Director BTDG, BARC, Mumbai
3. D P Chakarborty, Head, APPD, BARC, Mumbai
Figure 6 Various Components of EMF Joining Set-up

(iii) Table-1

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Description of Tube sheet</th>
<th>Description of tube</th>
<th>Charging Voltage</th>
<th>Discharge Current</th>
<th>Cycle Period</th>
<th>Vacuum (torr.)</th>
<th>Leak rate (Std.-cc/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>SS (commercial) tube sheet with three grooves with bore=63 Ø</td>
<td>ID=57 mm OD=60 mm Material: 1S Aluminum</td>
<td>10 KV</td>
<td>78.8KA</td>
<td>162 µs</td>
<td>No Vacuum</td>
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</tr>
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<td>2.</td>
<td>do</td>
<td>do</td>
<td>9.6 KV</td>
<td>75.6 KA</td>
<td>162 µs</td>
<td>Rotary Vacuum</td>
<td>-----</td>
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<tr>
<td>3</td>
<td>do</td>
<td>do</td>
<td>9.2 KV</td>
<td>73.2 KA</td>
<td>162 µs</td>
<td>UHV</td>
<td>&lt; 1 X 10^{-10}</td>
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