Chapter 23

Electro-magnetic Manufacturing Techniques

–– Dr. Surender Kumar Sharma

Electro-magnetic Manufacturing (EMM) technique is an advance manufacturing processes which is gaining popularity and acceptance in industry. This technique uses a high pulsed magnetic field inside a tool coil generated by a discharge of capacitor bank, which applies a transient force on the work piece without any direct contact and deforms it (Figure 23.1). The tool coil design influences forces on the work piece, mechanical stress in coil and heating effects. Numerical modeling of high velocity impact and high strain rate process are extremely challenging due to the multiple coupled physics phenomenon. EMM process is a multi-physics process, involving electrical circuits, electromagnetic fields, and mechanical deformations

Coupled multi-physics simulations are carried out to model the physical phenomenon and simulate the transient effect of magnetic fields on work piece, deformation and coil.

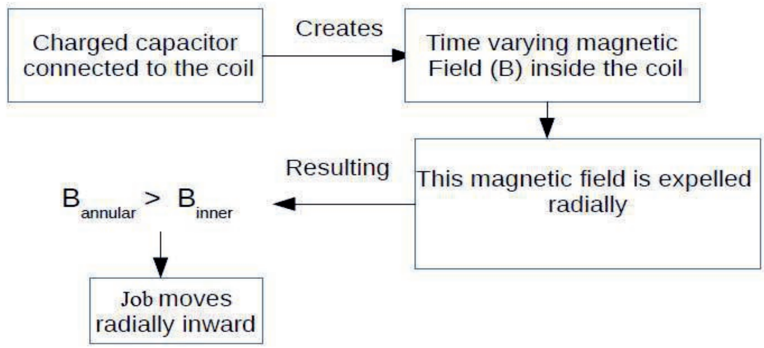

Figure 23.1. Electromagnetic Process.

Electromagnets in the forms of single turn coil or disc coil are used for the generation of high magnetic flux density (B), which induces the eddy current (J) in work piece. Electromagnetic tool coils are used to concentrate magnetic fields onto conductive work pieces. This electromagnetic force accelerates the work piece. The maximum magnetic flux density is limited by high stress in coil due to Lorentz force. The equations governing the EMM process are,

$$\nabla \times J = -\sigma \left(\frac{\partial B}{\partial t}\right) \tag{23.1}$$

$$P = (B_0^2 - B_i^2) / 2\mu \tag{23.2}$$

$$B_i^2 = B_0^2 e^{\frac{-2t}{\delta}} \tag{23.3}$$

$$\delta = \frac{1}{\sqrt{\pi\sigma\mu f}} \tag{23.4}$$

EMM system has high energy capacitor, discharge switch, trigger generator and the electromagnetic tool coil. The schematic of EMM system is shown in Figure 23.2.

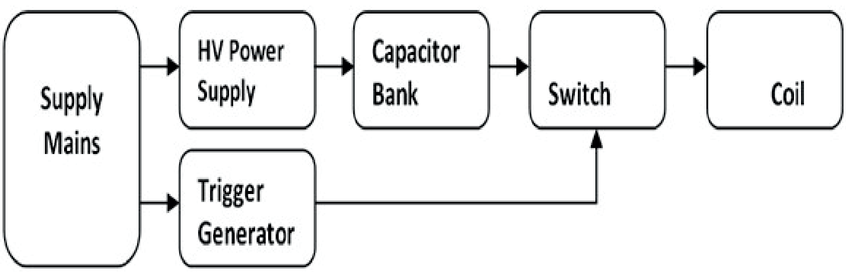

Figure 23.2. Schematic of EMM System.

This EMM system can be used for Magnetic Pulse Welding (MPW), Magnetic Pulse Forming (MPF), Magnetic Pulse Crimping (MPC), Magnetic Pulse Shearing (MPS), Electro pulsing, Magnetostriction [1]. Automation of EMM system will help in ease of operation, increasing the productivity rate and give wider acceptability to industry.

23.1. Magnetic Pulse Welding

The Magnetic Pulse Welding (MPW) is a high velocity impact welding technique analogous to explosive welding technique, wherein joining bond is achieved by penetration of materials into each other by high velocity impact [2]. It is characteristically different than fusion welding processes. Welding of dissimilar and similar materials and there alloys like nickel, aluminum, titanium, zirconium and stainless steel using conventional fusion welding methods is challenging. Some of these alloys are heat sensitive as the alloying element has lower melting point than base material. It is difficult to join these metals by conventional fusion welding process, as the alloying element will start vaporizing even before base material start melting. The main disadvantage related to fusion welding of these dissimilar materials is formation of inter-metallic compounds which are susceptible for failure. The MPW is the only solution to join these materials. The refractory metals like Titanium, Molybdenum and Zirconium has higher melting points and becomes difficult to weld by conventional welding techniques. Since melting point is not of much consequence in MPW, these materials can easily be welding by MPW technique. MPW is high speed joining technology which deforms job pieces at very high strain rate (10^6–10^7 s^{-1}). The welding is achieved by high velocity impact (300–1000 m/s) at proper impact angle (5–20 degree). The main advantage of MPW process is that, it does not require any pre-or post-treatment. Other advantages are ability to join high melting points similar and dissimilar materials in few micro seconds and also provides safe and hazard-free work environment [3, 4]. MPW technique can be used for joining sheets metals and tubes. Tool coils are designed specifically as per the job requirements. Tube joints can be achieved by compression and impact of work piece (Compression Welding) or by expansion and impact of work piece (Expansion Welding).

23.1.1. Magnetic Pulse Compression Joint

In Magnetic Pulse Compression joint, the electromagnetic tool coil is placed outside the work piece and the magnetic field applies the radial inward pressure on the work piece to accelerate and impact with other material (Figure 23.3).

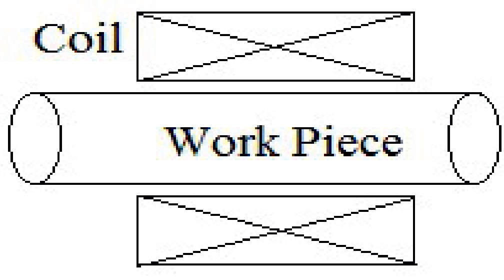

Figure 23.3. Magnetic Pulse Compression Welding

The main challenge in magnetic pulse welding technology is the development of stable and rugged coils, which could produce high magnetic fields reliably at higher frequency in the weld region. Higher frequency is required because the work pieces are generally thin walled and are made of low conductivity material. The high system frequency dictates the design of coil. A single turn coil is preferred over multi-turn coil because of its mechanical, thermal and electrical isolation. Multi turn coil and field shapers can also be used for producing very high magnetic field in the welded region. These coils consists of one or more turns made up of conductive material and the filed shaper is sectioned with a radial slit and electrically insulated with the job piece and the coil. Single turn coil has advantage over multi turn coil as it has less inductance (< 25 nH) and can produce higher magnetic field and very high frequency. The main characteristics of tool coil materials are high yield strength, high ultimate strength, at higher field strength.

Magnetic field strength (H) in the single turn coil is

$$H = NI/L \tag{23.5}$$

Where, N is the number of turn

Considering k as the coupling between the tool coil and work piece, Magnetic field (B) is

$$B = k\,\mu H \tag{23.6}$$

At higher magnetic pressure which exceeds the tool coil material yield strength, plastic deformation takes place in tool coil. This results in enlargement of inner dimensions of tool coil so it is preferred to use replaceable insert in the coil [5].

23.1.2. Magnetic Pulse Expansion Joint

In Magnetic Pulse Expansion joint, the electromagnetic tool coil is kept inside the work piece and the magnetic field applies the radial outward pressure on the work piece to accelerate and impact with other material (Figure. 23.4).

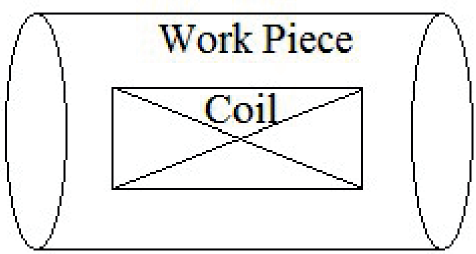

Figure 23.4. Magnetic Pulse Expansion Welding.

Magnetic Pulse expansion joint of Al tube to Al block is carried out with solenoid coil. The expansion welding process is influenced by thickness of tube, stand-off distance, work piece dimensions and the electrical circuit parameters. Experimental studies were carried out on Al 5052 tube- tube sheet to obtain a good weld between them [6]. The capacitor bank discharge current in the tool coil determines the magnetic pressure generated in the vicinity of the job and the impact velocity. When energy from the capacitors is discharged into this coil, it causes the inner Al tube to accelerate and impact on the outer Al flange at high velocity due to which a metallurgical bond occurs at the tube to flange interface.

Figure 23.5. Weld Wavy Interface.

The weld interface of the welded Al tube-Al flange was found to be wavy in shape (Figure.23.5).

23.2. Magnetic Pulse Forming

Magnetic Pulse Forming (MPF) is a very high strain rate, high velocity, cold forming process for electrically conductive materials. It has advantages of light weight, one side die, good formability, reduced wrinkling, and lower spring back on formed parts. It has high potential for forming large sheet metal parts in industries. The forming process involves high acceleration and deceleration, so the mass of the work piece plays a critical role. The MPF can also form sheet metal by impacting the work piece onto a die at a high velocity. High quality joints can be formed by magnetic pulse forming. Aluminum alloys finds its wide application in industries and can be easily formed using this technique. Free expansion forming of Al 6061 tube is carried out with EMM system (Figure 23.6). This process will also relieve the residual stress in the Al tube. The input energy to electromagnetic coil has to be limited to get the desired forming.

Figure.23.6. Forming of Al tube.

23.3. Magnetic Pulse Crimping

Traditionally crimping of cables is done by inserting the stripped end of an electrical cable into the lug and then mechanically compressed around the wire. This technique will deform the lug past its yield strength and also causes stress in the connector. These connections are highly resistant to vibration and thermal stress. This mechanical compression is usually done by hydraulic and mechanical tools. Magnetic pulse crimping of lug will provide uniform pressure across the lug which will provide better contact resistance and also reduces the gap between the metal strands in cable. EMM system provides the magnetic to crimp the lug by accelerating lug towards the cable strands at high velocity. A good quality electrical contact is formed between the electrical cable wire strands and the lug by applying uniform pressure along the circumference of lug. Electrical cable is mechanically crimped and compared with magnetic pulse crimped lug [7]. The MPC lug joint had better contact resistance compared to conventional crimping technique.

23.4. Magnetic Pulse Shearing

Magnetic Pulse Shearing (MPS) is very high strain rate shearing process using high magnetic field. Intense magnetic field is generated in the vicinity of job piece due to high current discharge from EMM system. This high magnetic field acts as punch for shearing in the job piece. The die with required shape is placed near the work piece. High intensity of electromagnetic force generated due to discharge of current from EMM system will pushes the work piece with very high velocity in the die. Since this is a very high strain rate phenomenon, the defects are comparatively less in magnetic pulse shearing technique. This technique is also capable to shear sheets of high strength material.

23.5. Electro-pulsing

Electro-pulsing of materials is a newer technology in which very high current density (less than explosion limit) is passed through the material, which causes changes in microstructure and mechanical behavior of materials such as precipitates distribution, yield strength, stain and hardness. When high current is passed through the metallic conducting material, the free electrons in material drift from low to high electrical potentials and are also scattered by the atomic cores. This scattering cause's unsymmetrical distribution of electrons around a dislocation in the material develops the net electromagnetic force which promotes dislocation mitigation. This effect in the material is also known as electro-mitigation which also promotes a structural evolution in materials towards the state with lower electrical resistance. The technology of electro-pulsing is applied to increase the performance of metallic conducting materials and had shown significant advantages in mechanical properties over conventional heat treatment methods. Electro-pulsing technique holds greater advantages by improving the deformation limit in materials and repairing defects in the metals.

23.6. Magnetostriction

Magnetostriction is a property of ferromagnetic materials which causes the material to contract or expand in response to an external applied magnetic field. The magnetic field is generated inside the electromagnetic coil by the capacitor bank discharge current, which interacts with the nearby placed material. This Magnetostriction effect allows materials to convert electromagnetic energy into mechanical energy. When the magnetic field is applied to the magnetostrictive material, its molecular dipoles and magnetic field boundaries rotate to align with the magnetic field. This causes the magnetostrictive materials to elongate and change the shape. Magnetostrictive material can convert magnetic energy into kinetic energy or vice-versa. These materials can be used to develop sensors and actuators. This property can be quantified by the magnetostrictive coefficient, λ, is defined as the fractional change in length as the magnetization of the material increases from zero to the saturation value. EMM system has been used to generate > 100 T magnetic field using single turn destructive coil and > 50 T using dick coil with field shapers [5].

23.7. Automation in EMM

EMM is the state of art technology for shaping and joining of materials based on electromagnetic technique, it is one of the emerging processes which aid in industrial automation. Automation in manufacturing is one of the most important need in industrial process. EMM system with automation and remote handling of long thin tube is designed and developed [8].

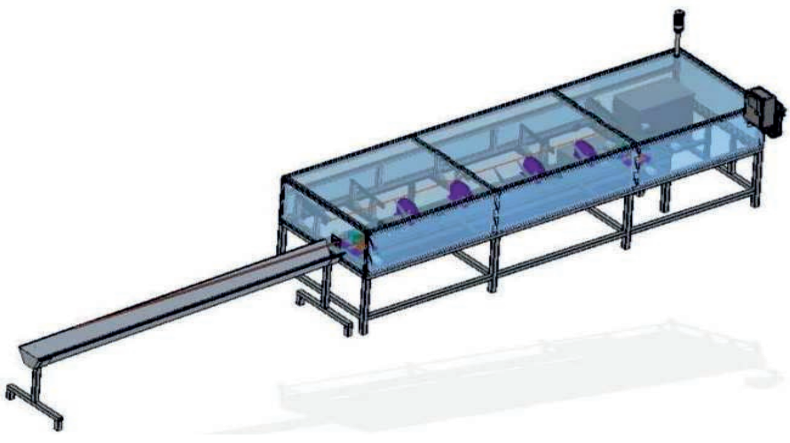

Figure 23.7. Automation and Remote operation of EMM system

This system consists of capacitors bank, power supplies and the electromagnetic tool coil (Figure 23.7). This automation system is installed and commissioned to automate the process of MPW thin walled tube to rod welding. The automation system includes movement of tube and press fitted rod on inclined tray, segregation of one pin from array of tubes, opening and closing support. Suitable arrangements are also made using gripper and rollers to hold the tube rigidly while applying the high magnetic pressure on tube. After MPW the tube will be removed and transferred to separate tray.

References

[1] Umer, Sabith. "Magnetic pulse welding, forming & crimping. Mechanical Engineering." Int. J. Sci. Technol. Res. 2 (2013): 79-82.

[2] S K Sharma & Archana Sharma, “Electromagnetic Welding of tubular joints for Nuclear Application” In: Dixit U, Narayanan R (eds), Strengthening and Joining by plastic Deformation, Lecture notes on multidisciplinary industrial engineering, pp 217 – 246, Springer, Singapore (2019).

[3] Zhang, Yuan. Investigation of magnetic pulse welding on lap joint of similar and dissimilar materials. Diss. The Ohio State University, 2010.

[4] Loncke, Kevin. "An exploratory study into the feasibility of magnetic pulse welding." Department of Mechanical Construction and Production, Ghent University, Ghent (2009): 1-150.

[5] Sharma, Surender Kumar, et al. "Generation of 0.5 to 0.6 Mega Gauss Pulse Magnetic Field for Magnetic Pulse Welding of High Strength Alloys." 2018 16th International Conference on Megagauss Magnetic Field Generation and Related Topics (MEGAGAUSS). IEEE, 2018.

[6] Mishra, Shobhna, et al. "40 kJ magnetic pulse welding system for expansion welding of aluminium 6061 tube." Journal of Materials Processing Technology 240 (2017): 168-175.

[7] Saxena, Rajat, and Surender Kumar Sharma. "Investigation of pulse power technology for crimping of electrical cables." 2021 IEEE 2nd International Conference on Applied Electromagnetics, Signal Processing, & Communication (AESPC). IEEE, 2021.

[8] Renu Rani, Surender Kumar Sharma, Nitin Waghmare, Shobhna Mishra, JMMVS Aravind, Rishi Verma, Archana Sharma, P.V. Suresh Verma, Nagendra kumar, D. B Sathe, and R. B. Bhatt, “Special Purpose Machine for Automation of Magmatic Pulse Welding of PFBR Fuel Pin End-Plug Adaptable Inside Glove-Box Chamber” BARC Newsletter Mar-Apr 2022.