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REVIEW ARTICLE

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Review on electromagnetic welding of dissimilar materials

Abstract Electromagnetic welding (EMW) is a high-speed joining technique that is used to join similar or dissimilar metals, as well as metals to non-metals. This technique uses electromagnetic force to mainly join conductive materials. Unlike conventional joining processes, the weld interface does not melt, thus keeping the material properties intact. Extremely high velocity and strain rate involved in the process facilitate extending the EMW technique for joining several materials. In this paper, the research and progress in electromagnetic welding are reviewed from various perspectives to provide a basis for further research.

Keywords electromagnetic, welding, impact, dissimilar materials

1 Introduction

Manufacturing technologies aimed at sustainable development and efficient use of men, materials, and available energy are increasingly demanded. Several complex parts needs to be joined in various industries, such as automotive, aerospace, nuclear, medical, and electronics, which require special performances like corrosion or wear resistance, high temperature strength, and toughness, combined with high strength-to-weight ratio. These applications require design flexibility and the joining of materials with different chemical, mechanical, and thermal behaviors.

Joining dissimilar materials is often extremely challenging and difficult to achieve by conventional joining techniques because of thermal and metallurgical incompatibility. However, numerous dissimilar materials have been joined successfully with appropriate non-conventional joining processes. For dissimilar material combination, electromagnetic welding (EMW) is known to be a feasible joining process, allowing manufacturers to significantly improve their products, enabling the use of lighter and stronger material combinations. EMW is successfully applied for a variety of industrial materials, like aluminum, stainless steel, copper, magnesium, brass, titanium, metallic glass, and plastics [1–10].

EMW is a solid-state welding technique that uses high-speed electromagnetic force for welding [1]. Impulsive Lorenz force, which is generated by repelling magnetic fields because of pulse current, is used to accelerate one or both joining materials, resulting in high velocity collision and formation of joints. The bonding mechanism is reported to be similar to that of explosive welding. EMW has been proven to be beneficial because of minimal inter metallic phase formation at the interfaces, while establishing a strong metallurgical bonded structure. Presently, EMW has limited but rapidly growing industrial application in tube forming, sheet metal forming, crimping, welding, and cutting of metals with good success in highly conducting metals like aluminum, copper, steel, and so on [2].

2 Fundamentals of welding process

According to Faraday's law, an electrical conductor produces transient magnetic field and induces a current in the neighboring conducting object when loaded by a time-varying current. Lenz's rule states that induced current always opposes its origin and thus produces magnetic fields in the opposite direction. Therefore, a repelling Lorenz force (Fig. 1) will be established between two neighboring conducting objects when loaded by a current in the opposing direction [3]. EMW utilizes these principles and converts the discharging current in the coil into useful mechanical force either for joining or forming operation.

Lorenz force $\vec{F}$ acting on the workpiece is calculated on the basis of the current density $\vec{J}$ and magnetic flux density $\vec{B}$. Lorenz force is given by Eq. (1) [3]:

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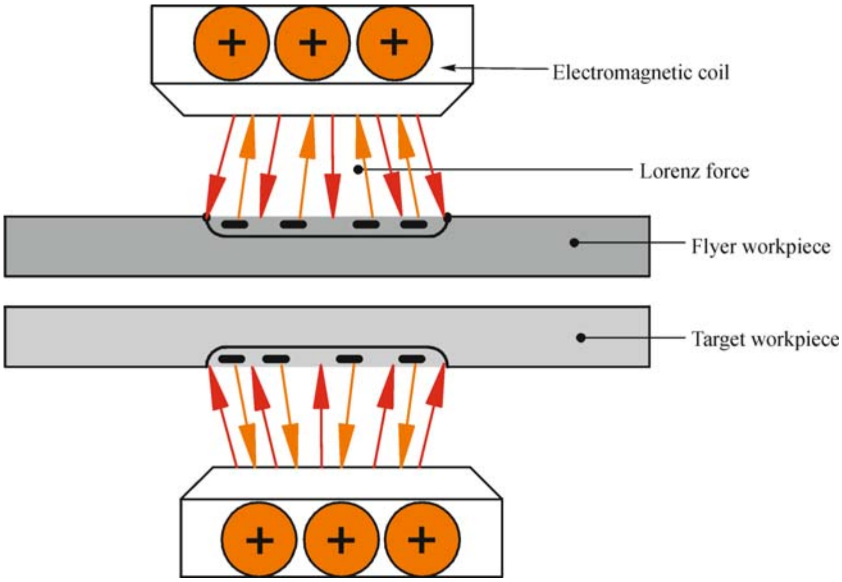

Fig. 1 Lorentz force interaction between coil and work

$$\vec{F} = \vec{J} \times \vec{B}. \tag{1}$$

3 Welding setup

EMW requires a high voltage power supply, a bank of energy storage capacitors, a triggering system, a coil with or without field shaper, and workpieces. The workpiece is surrounded by a coil that depending on the geometric shape of the piece [4].

The capacitor bank is charged to a certain predetermined voltage. Subsequently, the capacitor is discharged by a triggering system. Large and damped sinusoidal primary current flows through the electromagnetic coil. The primary current in the coil induces a secondary current in the neighboring flyer workpiece. In consequence, a repelling magnetic force is produced between the coil and the flyer, accelerating the flyer material and causing an impulsive colliding action at high velocity on the target plate. In certain cases, both joining materials can act as flyer plate [5].

Energy charged in the capacitor bank is given by Eq. (2) [2]:

$$E = \frac{1}{2}CU^2. \tag{2}$$

Charging and discharging circuits are designed as resonating circuits. Magnetic energy transferred to the coil is given by Eq. (3) [2].

$$E = \frac{1}{2}LI^2, \tag{3}$$

where C is the capacitance, U is the charging voltage, I is the discharge current, and L is the circuit inductance of the circuits.

During impact, the flyer plate travels over a distance that is equal to the stand-off distance. When the plate travels a stand-off distance, sufficient magnetic pressure is accumulated to cause both acceleration and yielding of workpieces. The workpiece attains sufficient velocity to collide on the target part. Finally, solid-state welding is created at the point of collision, if the velocity of the accelerated workpiece attains a certain critical velocity. EMW of tube-to-tube structures, typically require fairly high electrical energy to be stored in the capacitor bank in the range of 20–100 kJ. Aizawa and Kashani [5] reported that seam welding, which was developed for joining aluminum plates, required comparatively lesser energy. Improvements in rapid rise time in the capacitor discharge energy are responsible for this energy efficiency. The schematic of the electromagnetic setup is shown in Fig. 2.

4 Developments in EMW process

Most of the work on EMW is related to the effect of geometry and the metallurgical studies describing the interface wave formation in a qualitative manner and understanding the physics of the welding process. EMW has been applied to both similar and dissimilar metals [6]. EMW feasibility has been studied for a large combination of dissimilar metals, such as aluminum/copper, aluminum/steel, aluminum/magnesium, aluminum/zirconium-based bulk metallic glass, and copper/brass. Experimental work and simulation of the process are combined in several studies, providing a better understanding of the process and optimizing process parameters [11,12].

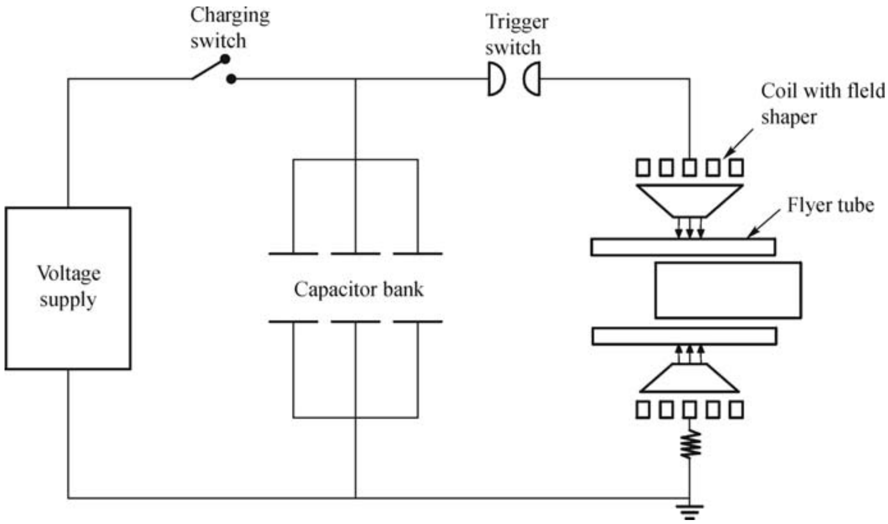

Fig. 2 Schematic diagram of EMW process

EMW is mainly limited by the electrical conductivity and cold formability of the outer workpiece [4]. Majority of the research in EMW have focused on aluminum alloys, copper alloys, steel, and magnesium. Materials with lesser conductivity are subjected to ohmic resistance, significantly diffusing the applied magnetic pressure and decreasing the collision force in turn. EMW of aluminum reportedly consumes the least amount of energy, which successively increases for copper and stainless steel [13]. At present, the electrical conductivity of structural steel represents the minimum value for successful direct EMW [2]. Low-conductivity metals or non-conducting materials are reported to be welded with the aid of drivers made of aluminum or copper [2,8]. Aluminum drivers were used by Kore et al. [14,15] to increase the feasibility of aluminum-magnesium and aluminum-steel welding. To avoid extreme deformation at the joint, studies have normally suggested that the target should possess higher yield strength in comparison with the flyer plate or tube.

The geometry of the EMW workpiece could be tubular or flat-sheet [7–10]. However, control of magnetic fields in EMW of flat sheets has been reported to be slightly difficult [11]. Tubular welding was observed to possess three different zones [4,16], with welding quality changing along the interface (Fig. 3). The actual weld zone is found in the middle region, with the run-in zone at the start and run-out zone at the end without welding or insufficient bonding. The outer tube is found to make a contact angle with respect to the inner tube at the run-out zone. Although the literature does not correlate process parameters with the run-in and run-out zones, the contact angle is found to increase with the increase in discharge energy.

For flat sheets, gradual change in the morphology has been observed at the interface, with the center region showing the absence of welding and a characteristic wavy morphology on both sides of the center (Fig. 4). The literature suggests that the collision angle is zero at the center, causing perpendicular collision at the center [11,17]. This phenomenon results in a rebounding of surfaces and creates no bonding or void at the center. With an increase in collision angle away from the center, an oblique collision creates a dynamic collision point. Jet is formed by flaying of the material, and a strong bonded interface is observed along the edges. Kore et al. [3] found that entrapment of oxide at the center at a low collision angle, which can also form a no-weld zone at the center. At higher discharge energy, the use of a driver can prevent a no-weld zone at the center for flat geometry.

Most of the literature on EMW is related to metallurgy of the interface and parametric study. Psyk et al. [18] reported two theories for interface formation. The first theory states that an interface is formed because of high strain rates and plastic deformation by the application of the pressure. In EMW of aluminum to steel, temperature increase is reportedly insufficient for melting either of the joint partners. Another theory states that rapid melting and solidification is responsible for interface formation.

Contradictory statements have been reported regarding the interfacial zone of dissimilar metal pairs. Raoelison et al. [6] compared the weld interface of Al/Cu with Al/Al under identical experimental conditions. The Al/Al interface reportedly presents metal continuity with no cracks or

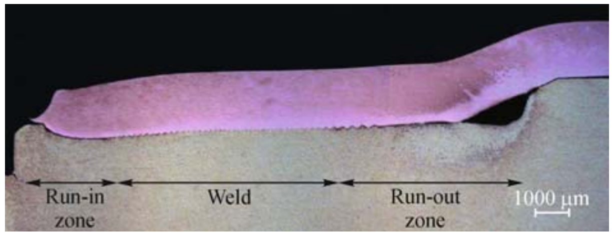

Fig. 3 Weld zone of tubular geometry [16]

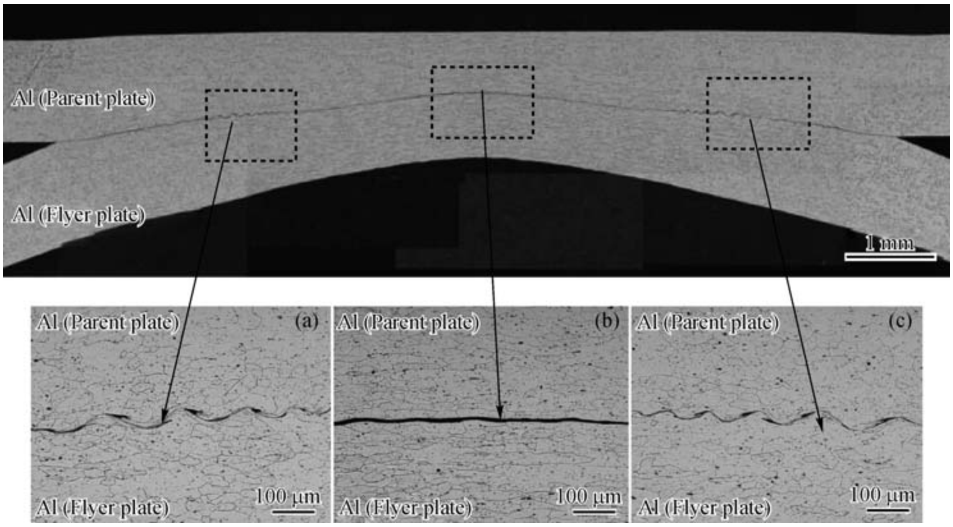

Fig. 4 Optical micrographs of the cross sectional view of the Al/Al lap joint. (a) Welding interface; (b) central position of the bulged region; (c) welding interface [17]

voids, whereas the Al/Cu interface possesses intermetallic phases with cracks. The formation of an Al-Cu amorphous compound confirms the theory of momentary rise in interface temperature because of Joule effect and rapid cooling. Short processing time does not create a significant heat-affected zone. In contrast, Kore et al. [14] observed the absence of a eutectic microstructure in the Al/SS (SS: Stainless steel) interface. The bonding is reportedly formed because of plastic deformation and mechanical mixing of the metal pair by grain compression and the seemingly free transition zone at the joint interface.

Yu et al. [19] investigated the interfacial microstructure of AA3003 aluminum alloy and steel 20 tubes. The interface zone is found to present high density dislocations, multidirectional micro cracks, and mutually diffused elements of Al and Fe, with Al content being higher than Fe. The hardness profile shows the highest micro-hardness of up to 5.1 GPa at the interface zone. Lee et al. [20] reported that, in an Al 6111/low-carbon steel joint, aluminum undergoes greater deformation than steel, with the hardness distribution showing work hardening of the material near the interface. Work-hardened layers around interface zone are assumed to facilitate bonding strength. Marya et al. [21] reported that intermetallic phases are formed at the interface because of non-equilibrium conditions in Al/steel joint and supported by the work hardening effect.

Göbel et al. [22] observed that localized melting is a prerequisite for successful bonding in an Al/Cu joint. Moreover, formation of intermetallic phases is inevitable, though the formation can be controlled by process parameters and majorly effective impact energy. Weld quality is reported to be sound for intermetallic film of thickness 5 μm, and the interface is devoid of cracks or voids. Faes et al. [16] tried welding copper to a brass mandrel and observed that proper selection of process parameters is necessary to avoid the formation of a thick interface and a brittle intermetallic phase. Joining of copper to iron disc by Kumar et al. [23] reportedly possessed excellent bonding at the Cu/Fe interface with a diffusion layer of around 2–3 μm. The interface only contained copper and iron without a eutectic microstructure.

Chen and Jiang [1] reported the formation of intermetallic compounds with extremely refined grains at the Al/Mg interface. Grain size is found to gradually increase away from the weld zone. Grain refinement is attributed to dynamic recrystallization. However, Kore et al. [15] contradicted the formation of intermetallic compounds in the electromagnetically welded Al/Mg interface. Inhomogeneous transition zones are found in the joints of Al/titanium alloy [18,21]. These zones are attributed to low charging energy.

Watanabe et al. [9] examined the lap joint of Al/metallic glass foils. The interface showed a thin layer of diffusion zone without fragmentation of metallic glasses. Transmission electron microscope (TEM) study demonstrated no change in glass structure, indicating minimal or no effect of temperature. Flexible printed circuit boards have been welded by Aizawa et al. [8]. The microscopic images confirmed the formation of a transition zone without any cracks or significant heat-affected zones at the interface. Virtually all of the available literature agreed that the thickness of the intermetallic film and chemical composition are strongly dependent on discharge energy level.

5 Bonding mechanism and interface morphology

The EMW bonding mechanisms are correlated to explosive welding and the jetting phenomenon [13]. During high-impact collision, the jet propagates along the mating interface, creating a chemically clean surface that is free of unwanted contaminants and oxide films and enabling the interaction of pure surface atoms at inter-atomic distances between joining surfaces. The literature suggests that high-impact collision causes severe plastic deformation with high strain rates. Moreover, the material behaves like a high-viscosity fluid for extremely short pulse duration and creates solid-state bonding [18]. The collision pressure at the point of collision is of the order of 100 GPa [10].

Numerous researchers have reported that the interface presents wave-like morphology with well-defined wavelength and amplitude [4,6,22,24–27]. The specific mechanism is not clearly defined for wavy morphology in an EMW. Several researches suggested mechanisms in impact welding, including plastic deformation, indentation, stress wave, vortex street, and Kelvin-Helmholtz instability mechanism [1]. Ben-Artzy et al. [24] reported that interface waves are formed through the Kelvin-Helmholtz instability mechanism. Several researchers have recently cited shear instability as the source of wavy interface formation [25,26]. Figure 5 shows the schematic of the collision mechanism and wavy interfaces.

The literature conveys that interface morphology is critically dependent on process parameters, such as collision energy, impact angle, impact velocity, properties of the materials, and geometry of welded plates. Contradictory statements are reported for joint strength and waviness correlation. Uhlmann et al. [27] stated that a wavy interface is a prerequisite for a high-strength weld. However, Göbel et al. [22] reported that wavy morphology at the interface was not a prerequisite for a successful weld. Lee et al. [20] stated that wavy interface in the weld seam corresponds to the shape of the intermediate layer between the two welding materials. The interface between the steel and the intermediate layer is found to be wavy, whereas the interface between aluminum and the intermediate layer is reportedly flat. Faes [4] also confirmed the dependence of the material on the waviness of the interface morphology. Reportedly, Al/Al, Cu/brass possesses well-defined wavy morphology, whereas Al/mild steel possesses a flat inter-

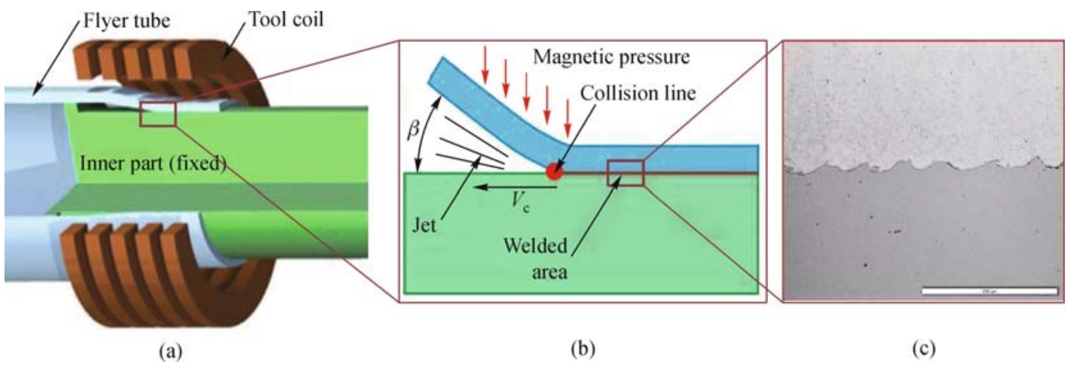

Fig. 5 Magnetic pulse welding: (a) Welding set up; (b) collision and jet formation; (c) wavy interface pattern [28]

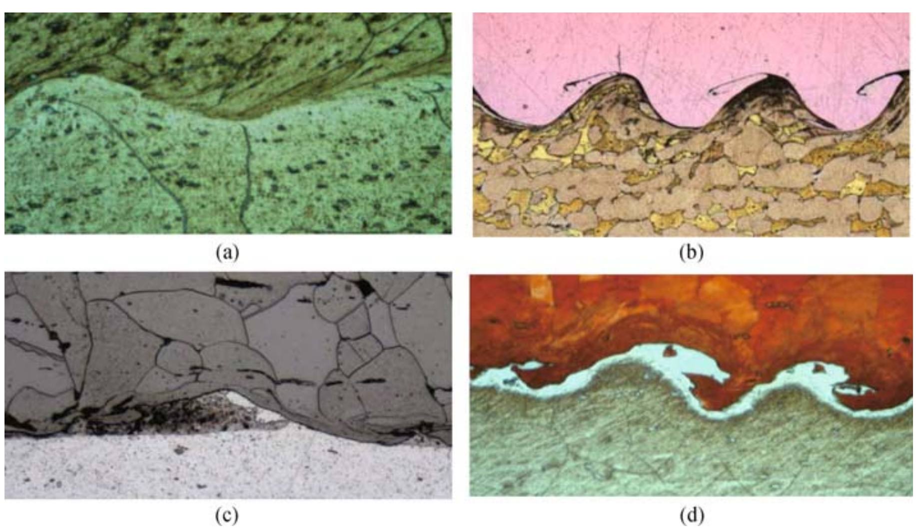

Fig. 6 Interface morphology. (a) Al/Al [6]; (b) Cu/brass [4]; (c) Al/steel [4]; (d) Al/Cu [6]

face (Fig. 6 [4,6]).

6 Weld quality evaluation

Specific tests for assessing weld quality are not defined. Common tests like helium/water leak and bust tests are conducted to demonstrate weld continuity [10]. Most of the literature reported tension-shear test, peel test, and torsion tests to evaluate joint strength. Failure is found to occur at the weak base metal in comparison with the welded zone in most of the EMW joints. Reports on the weld quality evaluation for EMW are few.

Torque shearing tests conducted by Raoelison et al. [6] demonstrated plastic deformation of the joint and ductile failure for Al/Al joint, whereas the Al/Cu joint presented brittle fracture with complete debonding of the interface. For flat geometry, shearing strength at the center of the weld is found to be higher than the strength of the weld at the edges [3]. Strength variation is attributed to the differential magnetic field with higher penetration at the center and weakening at the edges.

Xu et al. [12] carried out the artificial peeling test (Fig. 7) on an Al/steel tubular structure for joints produced under different impact velocities. The peeling test is correlated to the adherence strength of the metal pair. Joints formed in the impact velocity range of 278–355 m/s are found to be difficult to peel, exhibiting strong adherence of the outer flyer tube on the inner target. This finding indicates that the weld fulfils the required strength.

Yu et al. [19] performed uniaxial tension test and torsion test on Al/steel 20 tubes to assess the mechanical properties of the joint (Fig. 8). Pull-out by tensile force has reportedly left Al swarf on the inner target steel, indicating that the joint possessed higher strength than the base metal. The torsion test results are also reportedly higher than that of the base metal Al.

Numerous researchers have employed optical microscope, scanning electron microscope, TEM, nano-indentation for studying the microstructure, grain refinement, and hardness of the interface. In general, the interface and hardness is confirmed to be higher in comparison with base metal hardness in a dissimilar metal joint, thus indicating work hardening at the interface.

7 Process parameters

EMW quality is mainly dependent on impact velocity and impact angle during coalescence of the workpiece [4]. Impact velocity is related to magnetic pressure and the kinetic energy used to accelerate the flyer. Impact angle is the angle that is formed between the flyer and the target workpiece upon impact. Impact velocity is determined

(a) (b) (c)

Fig. 7 Peeling test under different impact velocities [12]: (a) 278 m/s, (b) 322 m/s, and (c) 355 m/s

(a) (b)

Fig. 8 Mechanical test on Al/steel joint. (a) Tensile test; (b) torsion test [19] from machine parameters, material parameters, standoff distance between flyer and target, while impact angle is decided based on the geometry of the workpiece. Machine parameters include discharge energy/voltage, frequency of discharge current, coil material, geometry, and shape. Material parameters include electrical conductivity and mechanical properties, such as yield strength, density, and geometry.

Numerous researchers have investigated the optimal range of process parameters for successful EMW. Recently, Chen and Jiang [1] reported that higher discharge voltage leads to stronger joint; however, intermetallics are formed beyond a certain optimum voltage level in Al/Mg joining. These findings are corroborated by those of Yu et al. [19] for Al/steel tubular joints. Kore et al. [3] reported the effect of process parameters, namely, discharge energy, standoff distance, and coil geometry, on weld strength. An increase in discharge energy has been observed to increases magnetic pressure. Thus, a higher impact force is applied on the flyer, increasing weld strength and weld width. A coil with reduced cross sectional area has been observed to increase magnetic pressure and produce a joint with higher weld strength.

When a magnetic force is applied on the flyer, a certain standoff distance between workpieces and time to attain optimum impact velocity is required for successful welding. The standoff distance presents an optimum value that yields the maximum weld strength for a given set of process parameters [3,7]. For a standoff distance less than the optimum value, the required impact velocity will not be generated, and the flyer is damaged. On the other hand, a large standoff distance leads to strong impact velocity and tears the joint/interface material, thus resulting in reduced weld strength. The effect of discharge energy on collision velocity and the effect of standoff distance on weld quality are shown in Figs. 9 [29] and 10 [14], respectively.

Skin depth is a parameter that is related to leaking of the magnetic field through the thickness of the flyer material

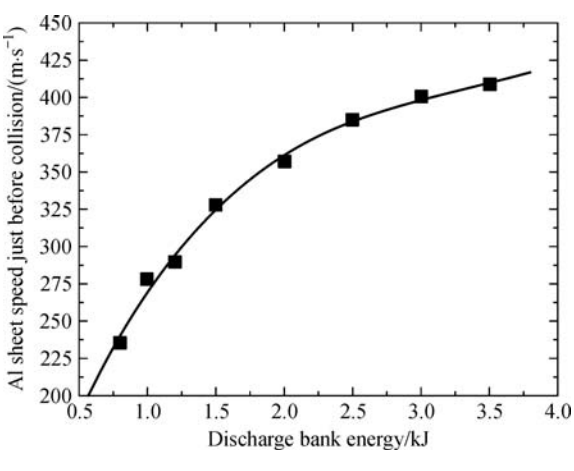

Fig. 9 Effect of discharge energy on collision velocity [29]

[30]. The induced magnetic field is the highest at the surface of the flyer workpiece and decays exponentially while moving through the thickness of the flyer and depending on skin depth. Current density decays by 1/e of the surface current density at skin depth, where e≈2.71. Skin effect produces a repulsive magnetic field, which exerts electromagnetic force on the flyer workpiece to attain the required impact velocity and impact on the base workpiece. Mathematically, skin depth is given by Eq. (4) [30]:

$$\delta = \frac{1}{\sqrt{\pi \sigma \mu f}}, \tag{4}$$

where σ is the electrical conductivity of the workpiece in S/m, μ is the absolute permeability of the workpiece in H/m, and f is the frequency of the current in Hz. The mathematical expression indicates that materials with low electrical conductivity and magnetic permeability will possess high skin depth and will not be able to shield the magnetic field. For a flyer with a thickness equal to skin depth, 86% of the magnetic field is shielded; for a material with thickness that is twice the skin depth, 98% shielding is achieved [30]. Skin depth is high for copper because of low magnetic permeability and low for steel because of high magnetic permeability.

Material formability is an important factor that limits EMW. Strain rate sensitivity increases beyond 10^{-4} s^{-1} for most metals. Material properties, such as yield stress, strain, and strain rate hardening, are related to material formability [4,30].

8 Analytical model for selection of process parameter

An analytical model is essential to understand and estimate the parameters governing EMW. A simplified analytical model was proposed by Pulsar [30] for a quick, approximate estimation of optimal parameters. According to this analytical model, voltage level can be calculated from the required collision velocity. The collision velocity is estimated to be in the range of 250–500 m/s. No specific criteria are established for the selection of collision velocity in EMW, whereas collision velocity is well-established for various materials in explosive welding. Considering the analogy between EMW and explosive welding, collision velocity for a material is selected from explosive welding.

Kore et al. [11] used an analytical relation to find the minimum collision velocity. For similar material combination, minimum collision velocity U is given by Eq. (5)

$$U = \sqrt{\frac{\sigma_{\mathrm{tu}}}{S}}, \tag{5}$$

where σ_{tu} is the ultimate tensile stress and S is the bulk

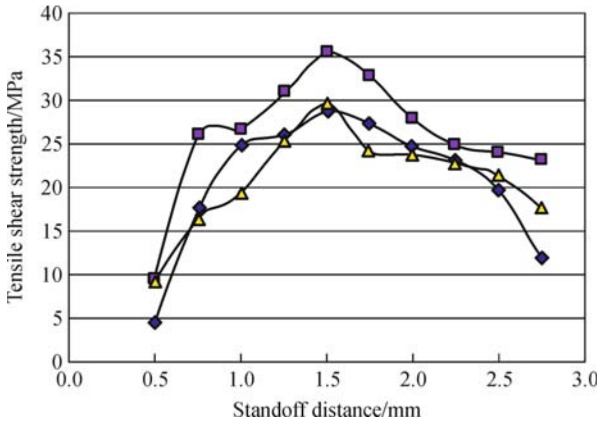

Fig. 10 Effect of standoff distance on weld quality [14]

velocity. For dissimilar metal combinations, the minimum impact velocity is calculated based on an analytical solution used in explosive welding. The relation among minimum impact angle ϕ, impact pressure P, and impact velocity is given in Eq. (6) [11]:

$$P = \frac{1}{2} Z_{\mathrm{eq}} U \cos\phi. \tag{6}$$

Eq. (7) represents Z_{eq}, which is the equivalent acoustic impedance of colliding materials [11]:

$$Z_{\mathrm{eq}} = \frac{2}{\frac{1}{Z_1} + \frac{1}{Z_2}}, \tag{7}$$

where $Z_1 = \rho_1 S_1$ (flyer impedance), $Z_2 = \rho_2 S_2$ (target impedance). S_1 and S_2 denote the speeds of sound, whereas ρ_1 and ρ_2 are the densities of the flyer and target materials, respectively.

Threshold pressure for successful EMW is given in Eq. (8) [11]:

$$P = 5 \times \text{Hugonoit elastic limit}. \tag{8}$$

Recently, a pure analytical model has been developed to predict collision velocity for a uniform pressure actuator [31]. In this model, electrical theory is used to determine the current and voltage output passing through the coil. Electromagnetic principles are used to determine the effective magnetic pressure. Classical mechanics theory is used to determine the critical velocity required for plastic deformation in successful EMW. The flow diagram for the analytical model is shown in Fig. 11.

From the classical mechanics theory, the pressure required to accelerate and deform the flyer workpiece is given by Eq. (9) [30]:

$$P = t\left(\frac{v_{\mathrm{c}}^2}{2s} + \frac{2Y_{\mathrm{s}}}{R}\right). \tag{9}$$

From the electromagnetic theory, magnetic pressure is

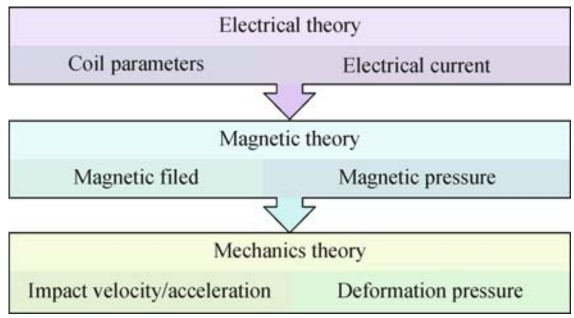

Fig. 11 Flow chart of the analytical model

given by Eq. (10) [30]:

$$P = \frac{B^2}{2\mu_0}\left(1 - \mathrm{e}^{\frac{-2t}{\delta}}\right), \tag{10}$$

where t is the thickness of the flyer, v_{c} is the collision velocity, s is the standoff distance between the flyer and the target, R is the outer radius of the flyer, Y_{s} is the yield strength of the flyer, B is magnetic flux density, δ is skin depth, and μ_0 is magnetic permeability.

Magnetic field intensity, H, is calculated using Eq. (11):

$$B = \mu_0 H. \tag{11}$$

Furthermore, magnetic field intensity is used to design the coil and set coil parameters and discharge voltage of the set-up.

9 Electromagnetic coils

Electromagnetic coils are used to transfer stored energy from the capacitor bank into the workpiece placed in its vicinity [4]. A coil is typically subjected to high operating voltage, the same magnetic pressure as that of the workpiece, and heating. Available literature on coil development is extremely limited, and the design involves issues of material selection with respect to electrical/mechanical properties, geometries, and configuration. Coils of different configurations are adopted depending on the shape of the workpiece geometry. For tubular structures, solenoid-type coils are placed surrounding the workpiece outside for compression and inside the workpiece for expansion. Plate-type coils are used for joining sheet structures. Commonly used coil materials are copper, beryllium copper, and aluminum. Different types of coils are shown in Fig. 12 [4,31].

10 Industrial applications

Despite being known for more than four decades, EMW has gained increased attention only in recent years and is

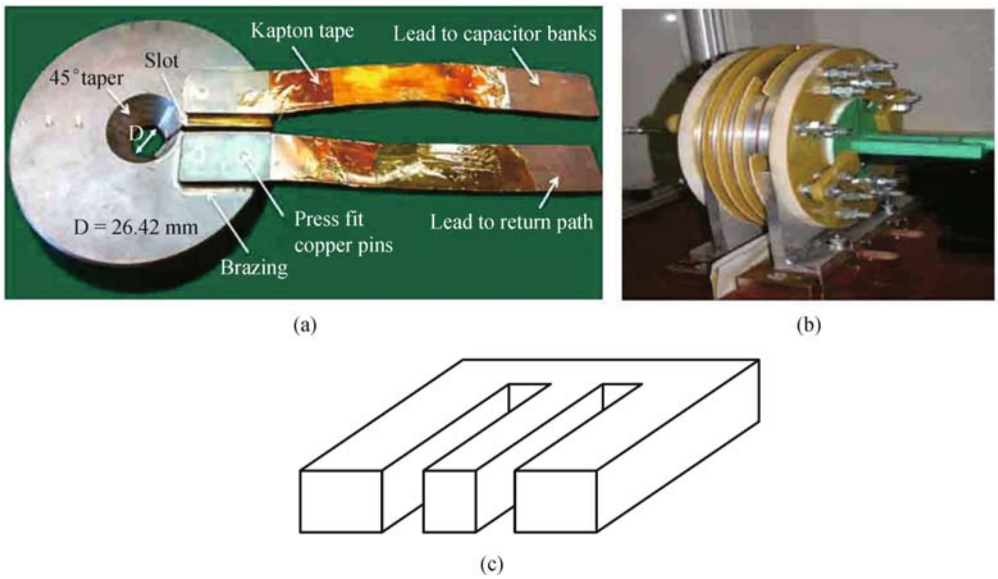

Fig. 12 Electromagnetic coils. (a) Single turn, axisymmetric coil [31]; (b) multi-turn coil with a field shaper [4]; (c) flat rectangular coil

slowly becoming a practical reality in numerous industries, such as automotive, HVAC (heating, ventilation and air conditioning), aerospace, nuclear, power/electrical, consumer products, and packaging [32–38].

Electromagnetic (EM) technology is proving to be reliable for high-volume production because of its advantage of excellent formability for fairly thin metals and capability to be combined with joining or assembly with dissimilar components, including metals, ceramics, plastics, and composites. In addition, EMW technique is often easier and cheaper to implement compared with other techniques, can be automated easily, and produces a component with close tolerance and free from surface defects. Companies like Elmag, Dana Corporation, PST Products, Pulsar, BMax, Magpulse Technologies, WELMATE, and several others are leading in the development of EMW machines and products.

EM technology is used at present in the manufacture of a variety of automotive and aeronautical components, such as drive shafts, sheet metal products, and lightweight tubular structures. Dana has been using EM technology to weld aluminum and steel drive shafts for more than 10 years. Although the literature suggests heavy energy consumption in EMW, Dana reports that the technique uses less than 1/100 energy than other equivalent welding techniques [33]. Copper rings are swaged around rubber seals in an automotive ball joint assembly with a process rate of 300 parts per hour [34]. A few of the automotive components produced by EM technology include space frame structures, flange mufflers in the exhaust system, components of oil filters, automotive earth connectors, air brake hoses, fuel pump, and shock absorber assembly.

The Institute of Forming Technology and Lightweight Construction of Germany has developed composite extrusion by embedding continuous reinforcements, such as steel wire and alumina fibers, in an aluminum profile [35].

ELMAG has developed an aircraft torque tube assembly and a rocket and missile component assembly by using EM technology [37]. These components are subjected to extremely high torque and have been used successfully in aircraft operations without any sign of damage at the weld zone. Electromagnetic dent pullers are used in the aerospace industry to remove dents from structures like tanks, honeycomb surfaces, and double-walled surfaces.

The electrical industry has been using EM technology in joining high voltage cables, switch gear assemblies, and high-voltage fuse electric motor assemblies. EM technology has been used to bond flexible printed circuit boards. Metal-ceramic joining is a common technique used in modern-day accelerators. The Bhabha Atomic Research Center has successfully joined copper sleeves on alumina rods [36]. Several industrial applications are shown in Fig. 13 [4,36,37].

11 Conclusions

Electromagnetic welding is a type of solid-state welding that uses electromagnetic force for joining dissimilar materials. Although the process exhibits potential for enhancing the economic viability of a wide range of joining applications, extremely limited attempt has been made to popularize the process. Most of the literature on the electromagnetic welding is based on a limited number of specimens with virtually identical parameters.

Although electromagnetic welding is successfully applied on several metal pairs, feasibility of the process

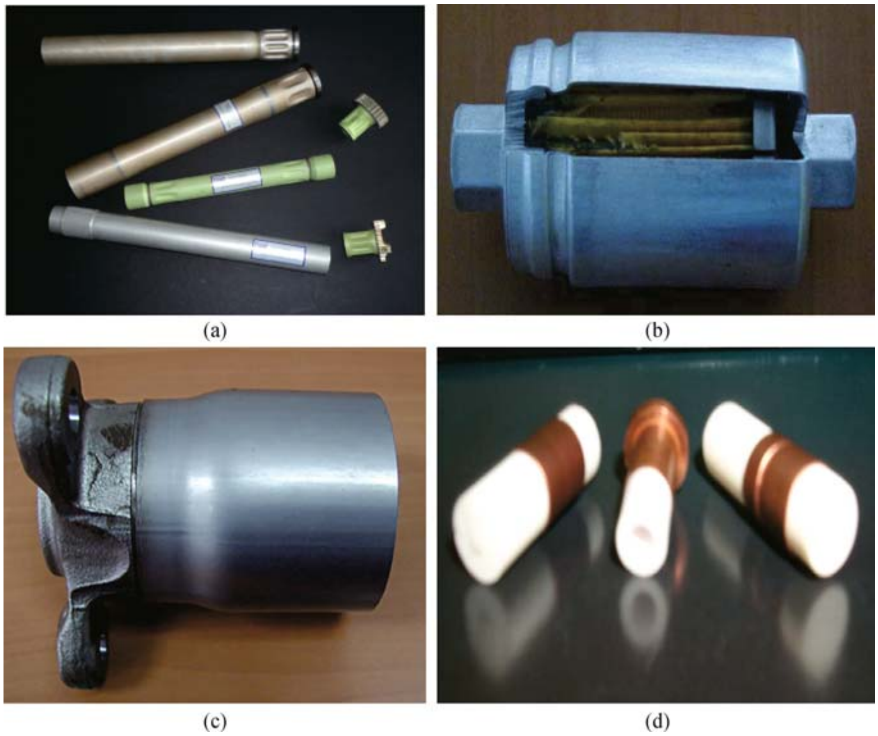

Fig. 13 Applications of electromagnetic welding. (a) Aircraft flight control tubes (Copyright Elmag Inc., San Diego CA 2015) [37]; (b) Al fuel filter [4]; (c) Al/steel driveshaft (Pulsar Ltd.) [4]; (d) alumina/Cu accelerator parts [36]

for different size and shapes of materials needs to be tested. Several aspects of the process require, such as coil design and durability, process design and precise control of process parameters, modeling, and material behavior, need further development.

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References

1. Chen S, Jiang X. Microstructure evolution during magnetic pulse welding of dissimilar aluminium and magnesium alloys. Journal of Manufacturing Processes, 2015, 19: 14–21
2. Schäfer R, Pasquale P. The electromagnetic pulse technology (EMPT): Forming, welding, crimping and cutting. Biuletyn Instytutu Spawalnictwa, 2014, 58(2): 50–57
3. Kore S D, Date P P, Kulkarni S V. Effect of process parameters on electromagnetic impact welding of aluminum sheets. International Journal of Impact Engineering, 2007, 34(8): 1327–1341
4. Faes K. Electronic pulsetube welding. 2011. https://www.researchgate.net/publication/230757399_
5. Aizawa T, Kashani M. Experimental and numerical study on magnetic pulse welding to improving the life time of one-turn flat coil. IOP Conference Series: Materials Science and Engineering, 2014, 61(1): 012028
6. Raoelison R N, Racine D, Zhang Z, et al. Magnetic pulse welding: Interface of Al/Cu joint and investigation of intermetallic formation effect on the weld features. Journal of Manufacturing Processes, 2014, 16(4): 427–434
7. Raoelison R N, Buiron N, Rachik M, et al. Efficient welding conditions in magnetic pulse welding process. Journal of Manufacturing Processes, 2012, 14(3): 372–377
8. Aizawa T, Okagawa K, Kashani M. Application of magnetic pulse welding technique for flexible printed circuit boards (FPCB) lap joints. Journal of Materials Processing Technology, 2013, 213(7): 1095–1102
9. Watanabe M, Kumai S, Hagimoto G, et al. Interfacial microstructure of aluminum/metallic glass lap joints fabricated by magnetic pulse welding. Materials Transactions, 2009, 50(6): 1279–1285
10. Shribman V. Magnetic pulse welding for dissimilar and similar material. In: Proceedings of 3rd International Conference on High Speed Forming. Dortmund, 2008, 13–22
11. Kore S D, Dhanesh P, Kulkarni S V, et al. Numerical modeling of electromagnetic welding. International Journal for Applied Electromagnetics and Mechanics, 2010, 32(1): 1–19
12. Xu Z, Cui J, Yu H, et al. Research on the impact velocity of magnetic impulse welding of pipe fitting. Materials & Design, 2013, 49: 736–745
13. Zhang Y, Babu S S, Prothe C, et al. Application of high velocity impact welding at varied different length scales. Journal of Materials Processing Technology, 2011, 211(5): 944–952
14. Kore S D, Date P P, Kulkarni S V. Electromagnetic impact welding of aluminum to stainless steel sheets. Journal of Materials

Processing Technology, 2008, 208(1–3): 486–493
15. Kore S D, Imbert J, Worswick M J, et al. Electromagnetic impact welding of Mg to Al sheets. Science and Technology of Welding and Joining, 2009, 14(6): 549–553
16. Faes K, Baaten T, De Waele W, et al. Joining of copper to brass using magnetic pulse welding. In: Proceedings of 4th International Conference on High Speed Forming. Columbus, 2010, 84–96
17. Watanabe M, Kumai S. Interfacial morphology of magnetic pulse welded aluminum/aluminum and copper/copper lap joints. Journal of Japan Institute of Light Metals, 2009, 59(2): 140–147 (in Japanese)
18. Psyk V, Risch D, Kinsey B L, et al. Electromagnetic forming—A review. Journal of Materials Processing Technology, 2011, 211(5): 787–829
19. Yu H, Xu Z, Fan Z, et al. Mechanical property and microstructure of aluminum alloy-steel tubes joint by magnetic pulse welding. Materials Science and Engineering A, 2013, 561: 259–265
20. Lee K J, Kumai S, Arai T, et al. Interfacial microstructure and strength of steel/aluminum alloy lap joint fabricated by magnetic pressure seam welding. Materials Science and Engineering A, 2007, 471(1–2): 95–101
21. Marya M, Marya S, Priem D. On the characteristics of electromagnetic welds between aluminum and other metals and alloys. Welding in the World, 2005, 49 (5): 74–84
22. Göbel G, Kaspar J, Herrmannsdörfer T, et al. Insights into intermetallic phases on pulse welded dissimilar metal joints. In: Proceedings of 4th International Conference on High Speed Forming. Columbus, 2010, 121–136
23. Kumar S, Kulkarni M R, Saroj P C, et al. Metallurgical and mechanical testing of electromagnetically welded copper and iron sample. In: Proceedings of 13th Asia-Pacific Conference on NDT. Bombay, 2013
24. Ben-Artzy A, Stern A, Frage N, et al. Wave formation mechanism in magnetic pulse welding. International Journal of Impact Engineering, 2010, 37(4): 397–404
25. Nassiri A, Chini G, Kinsey B. Spatial stability analysis of emergent wavy interfacial patterns in magnetic pulsed welding. CIRP Annals-Manufacturing Technology, 2014, 63: 245–248
26. Cui J, Sun G, Li G, et al. Specific wave interface and its formation during magnetic pulse welding. Applied Physics Letters, 2014, 105 (22): 221901–221901-4
27. Uhlmann E, Prasol L, Ziefle A. Potentials of pulse magnetic forming and joining. Advanced Materials Research, 2014, 907: 349–364
28. Lorenz A, Lueg-Althoff J, Göbel G, et al. Influence of axial workpiece positioning during magnetic pulse welding of aluminum-steel joints. In: Proceedings of 6th International Conference on High Speed Forming. 2014, 189–198
29. Aizawa T, Kashani M, Okagawa K. Application of magnetic pulse welding for aluminum alloys and SPCC steel sheet joints. Welding Journal, 2007, 86: 119s–124s
30. Broeckhove J, Len W. Experimental research on magnetic pulse welding of dissimilar metals. Dissertation for the Master's Degree. Ghent: Ghent University, 2009–2010
31. Nassiri A, Campbell C, Chini G, et al. Analytical model and experimental validation of single turn, axi-symmetric coil for electromagnetic forming and welding. Procedia Manufacturing, 2015, 1: 814–827
32. PROGRESS INDUSTRIAL SYSTEMS SA. Equipment and technology for magnetic pulsed processing of metals. http://www.progressindustrialsystems.ch/en/technology-and-equipment/magnetic-pulsed-processing-of-metals/
33. AUTOMOTIVE DESIGN and PRODUCTION. Welding mixed materials, multiple ways. http://www.autofieldguide.com/articles/welding-mixed-materials-multiple-ways
34. Gary F. Benedict, Nontraditional Manufacturing Processes. Boca Raton: CRC Press, 1987, 103–123
35. Marré M, Brosius A, Tekkaya A E. Joining by compression and expansion of (none-) reinforced profiles. Advanced Materials Research, 2008, 43: 57–68
36. Rajawat R K, Desai S V, Kulkarni M R, et al. Electromagnetic forming—A technique with potential applications in accelerators. In: Proceedings of APAC 2014. Gyeongju, 2004, 187–189
37. ELMAG. EMF technology in the aerospace industry. http://www.elmaginc.com/emf-technology-in-aerospace/
38. Kochan A. Magnetic pulse welding shows potential for automotive applications. Assembly Automation, 2000, 20(2): 129–132