Recent developments in the design, development, and analysis of the influence of external magnetic-field on gas-metal arc welding of non-ferrous alloys: review on optimization of arc-structure to enhance the morphology, and mechanical properties of welded joints for automotive applications

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ABSTRACT

“External magnetic-field (EMF)” has been proved as an additional process parameter like voltage and current affecting the weld arc form, molten metal-flow, microstructure, and characteristics of the weld joint. This article analyzed the research work that has been done to promote EMF application in welding and discussed the recent development trends and research in the design and fabrication of EMF setup to the controlled arc welding process. It is found that even after the successful application of EMF in welding, still, there is no mass level initiation to integrate EMF with welding machines that hinder researchers and manufacturers to accept it as a regular process parameter to control weld quality.

1. Introduction

A welding process involves the combination of heat and pressure to cause the primary bonds in materials of similar fundamental types or classes to form and coalesce. A welding operation is an operation whereby continuity is achieved between parts for assembly via various means, as defined by the ISO standard. By utilizing the heat generated from an electric arc welding equipment, two or more pieces of metal are welded together. The history of “arc welding” dates back to the “late 1800s”, when while welding with a bare metal rod on iron, a stack of newspapers in the vicinity was set ablaze by the sparks created by the welding process. They have noticed that the wels have improved considerably. There are several factors contributing to this phenomenon. Firstly, the smoke deprived the welding environment of oxygen and significantly reduced porosity. An arc is initially generated between an electrode and a metal surface. A melting point is reached by heating the metal to the melting point of the materials participating in the process. In order to break the arc between the electrode and metal, the electrode is removed. As a result of this process, the molten metal solidifies. The arc is a very intense flame created when electrical current passes through highly insulated materials. In addition to creating a magnetic field around the electrode and plate, welding also creates a magnetic field in the plane of the components being welded. First, the “field surrounds the electrode”; second, the “field surrounds the plate, and the plates attached to the electrode”; and thirdly, the “field surrounds the plates adjacent to the arc in the same direction as the first field”. To avoid the consequences...
of magnetic fields, external supervision is necessary as a means of negotiating with them during welding operations. In the “plane normal to the field lines”, the “electromagnetic force (Lorentz-force)” created by the “external magnetic field” deflects the “welding arc”. Arcs are deflected farther away from their “normal paths” due to this “magnetic field exerting force on electrons and ions within the arc”.

The nonferrous metal due to their special characteristics of density and specific strength are extensively used in structural engineering but suffer the limitation of the wide variability of process parameters for joining. In high energy physics the magnetic field has always have a role to act as a container of the heated plasma matter. In relate to that the pioneer researcher Song [1] in the field of Mg alloys welding, observed that that GMA welding of Mg alloys has a narrow range of welding parameters and heat input is a crucial factor needed to be appropriately controlled. Few investigators have also suggested to find a novel method to control MIG welding problems so that the requirement welded structure of magnesium alloy will have increased applications in industrial production. The experiments manifest that both pulsed MIG and AC MIG methods can be used to weld magnesium alloy. However, the range of welding parameters is too small, especially for pulsed MIG. A decisive element in GMA welding of magnesium alloy is still how to regulate the input energy to the filler wire. It is important to find a novel power supply method of GMA welding to solve the above problem. If a new MIG welding method of Mg alloy can be realized easily and successfully, then the use of the welding structure of magnesium alloy will increase in industrial production. Nowadays research on “auxiliary energy-assisted arc welding processes” is a matter of interest. Wang et al. [2] enhanced the “arc-welding efficiency”, and the “welding characteristic of secondary-energy sources”. These modifications and regulation of “arc welding processes” by secondary energy sources are effective and appropriate techniques for process-alteration and progress in the welding process. The article analyses some auxiliary energy sources such as EMF-assisted MIG, ultrasonic vibration supported TIG welding, and ultrasonic-assisted plasma arc welding. Out of these secondary energy resources EMF is of prime interest for many decades.

In the last decade, this source of energy has got prominent space in the research domain. At the latest, many researchers have spent their time exploring this secondary energy source and found some good and interesting results in terms of reduced heat input, arc length, arc stability, and bead geometry, etc. Xiao et al. [3] designed a “two-dimensional model” of EMF regulated GMA method for the interface of the weld arc, wire-anode, molten metal-pool, and the vapor. The magnetic field twisted the plasma-flow and pushed metals vapors evaporating from the wire-anode towards the arc’s outer zone. Zhao and Chung [4] designed an effective numerical-model for the study of the interface between the metal droplet and welding arc in changeable polarity GMA welding. It was found that the arc form at the cathode terminal was wide in the absence of EMF. These constriction of the arc from the cathode due to the presence of EMF is very much crucial for appropriate droplet transfer for arc welding. This will lead to precise formation of the bead geometries which will lead to the formation of sound joints.

Wei et al. [5] investigated the importance of the “rotational-arc”, and the “stir-action” of the “molten-pool” on “weld shape” for “non-axisymmetric” “tungsten narrow-gap”, “tungsten arc-welding”. The EMF also favored this arc rotation and the stir action of the molten pool. Cai et al. [6, 7] built a complex system using the tandem methodology for “narrowest gap-welding”. However, a “consistent weld” was acquired under given welding parameters. The direction of the weld path was changed mechanically; thus heating the sidewall right away, and the sidewall infiltration is enhanced substantially. This experiment validates that control of arc path is effectively possible and application of EMF can avoid the complexity of the system. This application of EMF can lead to the appreciable improvement of the weld quality with precise utilization of heat generated. Xu et al. [8] established a numerical “heat-source-based-model” for the “weld arc motion”, and “shape”. The investigation characterized in detail the mechanism of weld formation and supported mathematical modeling and analysis of arc motion that can be further used for the integration of EMF.

Guo et al. [9] utilized the concept of arc rotation to improve the weld penetration depth. This stirring of weld arc also removed the slag at the interlayer thus reducing the possibility of the weld defect. This experiment also supported the necessity of a simple mechanism and setup for arc motion and rotation by improving the weld penetration. Zhang et al. [10] studied the “arc characteristics”, and different “metal transfer mode” for “heavy metal plates” that are generally used in naval, energies, transport industries, etc. The optimized joining methodology is critically influenced the weld strength. The reduced “heat-input”, and the “smaller plastic-distortion” adjacent to the depth of the metal reduces the residual stress to a great extent.

Avilov et al. [11] studied the magnetic-effect on regulated arc-welding technology to enhance the weld characteristic, production efficiency, along control on the welding bead formation. Qiang Chen et al. [12] proposed a novel magnetic-field-producing apparatus to control the crosswise and retrograde stream of the molten metal for GMAW at higher-speed. The simulation of compound EMF verifies the viability of the fabricated magnetic field setup. Similarly, recently some researchers also developed an EMF set up to explore the characteristic advantages of this secondary energy source [13, 14, 15]. The research accomplishments ensuing the progress have magnificently been instigated in many fields, for instance, welding of hollow tubes of different thicknesses, arc cutting, thin gap weld, and essentially unlike materials weld, and additive manufacturing. But different research works for EMF-assisted welding was supported by different thoughts of design and development of EMF setup. The wide variety in design and development also put a question mark on the reliability of results obtained and their acceptance due to the lack of any standardized procedure for their development. The wide variety of the proposed models have been discussed later in this paper in detail. In addition to that even after more than sixty years of research in this area, there is a lack of mass production and application of EMF integrated welding machines, and without any industry-based effort to support EMF as a secondary energy source even after the next fifty years situation will be same. This is the main motivation for such review paper to bring forth much awaited development of standardized EMF set up for precise welding. Thus, this review paper is an effort to summarize the research based on EMF application, mechanism, and development with a conclusive discussion on the necessity of customized EMF integrated welding machines for research.

2. Trends and advancements in EMF-assisted welding-process

The “higher volume” of “heat input” of the “GMA-welding process” is the prime reason behind the unsuitability for the welding of low melting/boiling points alloys (magnesium alloys). Thus, their high value heat input characteristic would be needed to regulate to minimize the uncertainties of welding operations. The past researchers attempted to control the heat input by regulating the weld arc density by applying EMF, open space for GMA, and low melting/boiling points alloys to get good welds. The discussion over the dynamical influence of the magnetic field was initiated with Faraday’s (1821) experimental validation of the directional force on the flow of electrons under an “external magnetic-field”. In the past few decades, the idea shifted from the macro-level (electric motors and generators) to the micro-level in terms of controlling the electron flow (plasma) to control arc profile and intensity. This control of the flow of electrons specially by the applied EMF is the main course of discussion.

2.1. Influence of “EMF” on “welding process”

The propensity of arc towards the EMF has initiated the lead to a comprehensive investigation for the past many years. This effect on the characteristics of weld joints is cost-efficient and user-friendly. In 1962, first introduced around the weld zone, the study determined this effect on
the molten pool. Since 2000, in TIG welding, GMA welding, metal active gas welding (MAG), application of a magnetically controlled welding method have been actively applied [16]. Many researchers experimentally discovered that it prevents weld distortion and enhances the arc shape and stability; controls metal transfer in addition to weld solidification; improves weld appearance and microstructure. The EMF has been successfully utilized in grain size and metal solidification to control molten metal thus electromagnetic stirring effect that stabilizes the solidification of molten metal [17]. Zang et al. [18] used pulsed GMA welding through varied pulse current frequency to achieve different metal transfer modes like spray, globular, and projected in AZ31B weld that eventually influences the weld strength and microstructure. Chai et al. [19] utilized the controlled short-circuiting in the inert gas welding process to check elevated crown weld and spatters. The system incorporates a process controller coordinating the wire electrode’s feed and speed with the welding current of the power source. Therefore, the requirement for a modified weld system is inescapable for effective AZ31B welds. Zhang et al. [20] explored the role of an EMF on arc stability considering the assumption that EMF controls the charged particles motion which can influence the arc form.

Kang and Na [21] investigated the impact of ‘longitudinal’ and ‘transverse’ magnetic-fields on the deflection of arc. An optimal relationship has been experimental among welding-speed and EMF for the arc stability to get welds free from defects. Li et al. [22] observed the consequence of the EMF in many welding processes for weld arc stability and weld pool behaviors. Li et al. [23] revealed the influence of EMF in resistance-welding of dissimilar metals for weld quality enhancement in conjunction with welding time and welding current. The additional magnetic field modified the grain shape and mechanical characteristics of the weld joints. The EMF-assisted weld joint has better oblique strength compared to non-EMF. Kuo [24] discussed the nature of the EMF force which has a tendency to enhance energy density at the wire end resulting in the narrow arc with stirring of the molten pool results in increased weld depth as well as lower heat input. Reis et al. [25] investigate the magnetically controlled advanced weld process in the welding to optimize the weld appearance, arc structure, arc stability, droplet transfer, molten pool solidification, and improved joint microstructure and properties.

In the “GMAW method”, Chen et al. [26] had been using a compounded “external magnetic-field (EMF)”. The EMF setup was arranged with the nozzle of the welding gun to generate the magnetic field. The welding arc molten metal drop inclined forward along the weld path underneath the influence of the EMF. Though, the complicated relations between the welding-arc, filler-metal, and EMF are exposed under real-time experiments. Wang et al. [27] have been using the LEMF in ‘lower-frequency’ pulsed-narrower “gap welding” to distribute arc-pressure and heat across the base and sidewalls of a thin-grooves. Considering varied magnetic-field variables, the LMF-assisted narrow-gap TIG-arc focused on the arc form. Wang et al. [28] have used an extra magnetic-field to the arc weld and effectively changed, the current density, heat flux, and fluid flow. These elements have a vital impact on weld formation.

Villaflue and Kerr [29] established a magnetic field and observed significant grain fineness in the microstructure. Sundaresan and Janaki [30] showed the effective outcome of EMF stirred arc on the grain size of the titanium alloy weld. Mousavi et al. [31] observed that EM stirring encourages “grain separation” and sophistication in “aluminum alloy welds”. Wu et al. [32] stated that “EMF regulates the ‘speed’ of the ‘retrograde-flow’ of the ‘weld-pool’ and holds the ‘bead-crown’ at increased “weld speed”. Nomura et al. [33, 34] studied the influence of the “cusp type magnetic-field” on “arc shape” from “circular” to “elliptical”. The theoretical outcomes are justified through experiments in “thin bead width”, “deep weld depth”, “elevated aspect ratio”, and “change of flow inside the molten pool”. Shen et al. [35] examined the influence of additional fixed “magnetic-field” on weld size in spot weld of steel. It established the increased size of the nugget and better surface features, grain shape, and mechanical characteristics.

Sharma et al [15] successfully applied EMF on GMA welding of AZ31B to improving the bead quality at the macro as shown in Figure 1, Figure 2(a)–(c), and micro-level has been shown in Figure 2(a) and (b). Table 1 has illustrated the observations for Yield Strength of the “Weld Zone”. Further, the consequence of EMF on mechanical characteristics has also been studied and significant improvement was observed in comparison with the “base metal” with the conforming abatement in heat-input as revealed in Figure 3(a) and (b). Figure 4 has depicted the Stress-Strain Curve plot for a specimen for AZ31B alloy [15].

Table 1 shows the YS as per the experimentation to assess the role of Magnetic flux on weld. Sun et al. [36] introduced a unique dual magnetic pole system for thin gap welding. The setup significantly affects the nature of magnetic field lines and enhanced their uniformity. Belous [37] developed the working model of the “longitudinal-magnetic-field (LMF)” in “thin-gap-welding” to weld “titanium-alloy”. The applied LMF significantly affects the weld quality with no defect weld. Wang et al. [38] found that GMA joining with EMF can alter the magnitude and structure of the arc. The reduced temperature gradient varies the “surface tension”, and “flow of the molten-metal”, and the “heap of the molten-pool”. This improves the “weld penetration” and eliminates the challenge of poor weld in high-speed welding and rises the “strength of the joint”. Zhai-nakov et al. [39] showed in the simulation that the gas flows of the weld arc under TEMF cause arc deformation. Gatzen [40] showed that low-frequency EMF pushes the arc cathode spot to minimize droplet

Figure 1. An illustration of the experimental-setup at IIT (ISM), Dhanbad.
formation in laser welding of nonferrous metal in conjunction with filler wire. Li et al. [41] considered the impact of magnetic-flux density on the current distribution in resistance welding all around the weld spot of nonferrous alloy. Chen et al. [42] stated the successful reduction of weld cracks in the laser welding of ferrous and non-ferrous metals under an axial magnetic field that steadied the “welding-arc”.

Malinowski-Brodnicka et al. [43] observed that electro-magnetic stir in TIG welds developed even weld beads. The rise in magnetic-field intensity increases the weld bead width with a refined grain structure. Chuanwei et al. [44] applied EMF at right angles to “U-shaped electric-arc” in the twin wire arc-welding process. The motion of molten-metal from the electrodes changes from a large globular to spray mode. Luo et al. [45] investigated the magnetic-flux path across the arc’s-axis. The setup includes the coaxial electrode-coils installed around the electrode. It found that under the influence of the Lorentz force, the arc spins and enhances the “arc-plasma stability”, and the route-way of rotation variations with the path of the current. The contour of the rotated arc at high speed under a magnetic field shifted from the initial pointed shape to the bell shape. Along with the rise in the magnetic field, the arc tends to constrict.

Qingjie et al. [46] and Yibo et al. [47] studied the optimization of magnetic-arc oscillation systems and concluded that in the welding activity, EMF can be steady or pulse type. Further depending on the nature of the EMF, it was classified such as the longitudinal (LMF), transverse (TMF), cusp (CMF), rotating (RMF), and axial (AMF) types of

Table 1. Observations for “Yield Strength” of the “Weld Zone”, where, $M =$ “magnetic field”, $F =$ “wire feed rate”, $S =$ “Welding Speed”, and $G =$ “gas flow rate”.

| Run order | M, Gauss | F, m/min. | S, m/min. | G, L/min. | Y.S., MPa |
|-----------|----------|-----------|-----------|-----------|-----------|
| 1         | 105      | 6.5       | 650       | 12        | 122       |
| 2         | 120      | 6.0       | 600       | 11        | 132.4     |
| 3         | 105      | 5.5       | 550       | 10        | 105       |
| 4         | 120      | 6.0       | 600       | 9         | 128       |
| 5         | 120      | 6.0       | 600       | 11        | 130.2     |
| 6         | 120      | 6.0       | 600       | 11        | 123.2     |
| 7         | 120      | 6.0       | 600       | 11        | 125.4     |
| 8         | 150      | 6.0       | 600       | 11        | 95        |
| 9         | 120      | 6.0       | 700       | 11        | 138       |
| 10        | 135      | 6.5       | 650       | 12        | 115       |
| 11        | 105      | 5.5       | 550       | 12        | 92        |
| 12        | 120      | 6.0       | 600       | 11        | 126.2     |
| 13        | 105      | 6.5       | 650       | 10        | 128       |
| 14        | 135      | 6.5       | 650       | 10        | 122       |
| 15        | 120      | 6.0       | 600       | 11        | 124.4     |
| 16        | 105      | 6.5       | 550       | 10        | 137       |
| 17        | 105      | 5.5       | 650       | 10        | 129       |
| 18        | 120      | 6.0       | 600       | 11        | 125.2     |
| 19        | 90       | 6.0       | 600       | 11        | 114       |
magnetic-field. The LMF effect on the deflection of the weld arc and heating of the weld zone is advantageous for the thin gap weld to impede the inadequate sidewall fusion.

Guoji et al. [48] developed the simulated model for analyzing the MAG surfaced deposited under the impact of “electromagnetic-stirring” controlling. The achievements successfully vouch for the application of EMF. Chang et al. [49] observed LMF enhanced physical property along with superior ductility in CO2 arc welded joints of hollow circular pipes 300 bars of weld pressure. Curiel et al. [50] noticed that the “axially magnetic-field” in “GMA-welding” of “AISI304 stainless-steel” increases the resistant to cracking, scouring, pits, spalling, and ‘inter-granular corrosion’, and lowers the degree of sensitization. Jones et al. [51] experiential the necking in GMA weld when the metal drop is separated from the filler wire under “externally magnetic-forces”, and the form of the metal-drop is altered by this force. Chang et al. [52] examined that LEMF represses hot cracks through GMAW of aluminum alloys in short-circuit mode and controls the bead shape. The optimized magnetic forces alter the path of the melt flow and validate the theoretically described relation between arc plasma and “electromagnetic-field”. García et al. [53] noticed that “EMF”-assisted “GMA-welding” encourages modification in the weld microstructure transformation. Thus, it initiates the development of the “passive surface-film” that defies “local-corrosion”. Zhu et al. [54] noticed that LEMF can control the shape of metal drops in welding. The molten metal drops were rotating spray type with LEMF, but in the absence of EMF, the molten metal drops were typically globular.

Min and Wang [55] studied the “grain structure”, and “mechanical-characteristics” of “resistance spot-welded”, “ferritic-steel” under the impact of a “magnetic-field”. The “resistance spot-nuggets” were created both with and without the use of a “continuous magnetic-field”. The morphologies and anticipated characteristics of the nugget with or without a “continuous magnetic-field” have been studied. The “static magnetic-field” was employed to enhance the diameter and intensity of every nugget. Yoshihiro et al. [56] experimentally investigated the effect of arc deflection in plasma arc cutting of thick plates. In the cutting, the “magnetic-field” is focused on the “cutting-face” during “cutting”, and the “EMF” generated by “magnetic-field” breakdown bends the “plasma-jet”. The “bent plasma-jet” indicates the inadequate “cutting-quality”, and occasionally begins “damage to the welding setup”. The correlation between working environments and the twin arc using EMF on a plasma jet was observed for curbing the twin arc triggered by the leak EMF by applying a “magnetic-shield cap” comprised of “ferromagnetic-material” across the “nozzle”. Bai et al. [57] explored the advantages of external magnetic field additive manufacturing in which EMF confined weld was used advantageous in the advanced manufacturing process.

Overall, the EMF’s relevance as a process parameter was noted to control the “microstructure”, and “weld strength of welded joints” by regulating the “energy redistribution”, and “flow of molten metal” in many welding processes. The specific optimistic effects are fine grain size, decreased weld defects and spatter, enhanced weld depth, good mechanical-strength, and bead-shape of the weld-joint. Additionally, the EMF enhances arc stability and controls the path. Though, an unoptimized EMF may cause a weak weld bead, poor surface finish, and lowered joint efficiency beyond optimum value.

2.2. Mechanism behind the effect of EMF on the arc shape

EMF tends to deflect charged particles. This concept of the EMF-based on Fleming’s Left-Hand rule given by Sir John Ambrose Fleming in the early ninety’s states that current-carrying conductors under the influence of EMF experience a mechanical force in the direction. This verified statement about the direction of the flow of deflected electrons is the base of any electromagnetic set up to use in electric motors, generators, accelerators, etc. Michael Faraday was the first scientist who demonstrated and validated this by experiments in 1821, soon after Oersted discovered electromagnetism. At the same time, Ampere states that magnetic fields are related to the electric current produced in them (as per Ampere law). Later Maxwell combined their work known as Maxwell equations. In vector mechanics, if three quantities having directional characteristics and are represented by three vectors, then for their cross product, they will be mutually perpendicular to each other. This remarkable thought changes the science at both macro (electric motors) and micro (control of charged particles in weld arc) levels respectively.

In the GMA joining process, the applied EMF can be longitudinal type (LEMF) or transverse type (TEMF). In the TEMF the path of the “magnetic

![Figure 3. (a) “Microstructure” of the “weld metal region”, and (b) “base metal region” at 100× magnification [15].](image)

![Figure 4. Stress-Strain Curve for a specimen for AZ31B [15].](image)
field” is at right-angles to the “welding-arc”, and “welding-direction” as shown in Figure 5(b). While in the LEMF the path of the magnetic-field is at right-angles to the arc-plasma and parallel to the welding-direction as exposed in Figure 5(c). Simultaneously shape of the arc in the lack of an EMF is shown in Figure 5(a) [58]. The EMF around the arc inevitably changes the “arc-shape”. The “scale of the EMF”, and the “shape of the arc” are usually associated with each other. The “strength”, and “nature of the EMF” depend upon the nature of the excitation current (direct or alternating excitation current) [59, 60, 61].

The control over heat-input owing to EMF alters the bead profile and qualities of the weld. “Heat-input per unit-length” is “directionally proportional” to “welding current”, and “inversely-proportional” to “welding-speed” at a given voltage. It also depends on the melting point, boiling point, thermal conductivity, and thermal expansion of weld materials [62]. Also, in GMA welding wire feed rate is proportional to welding current. The protective gas plasma impedes the heat dissipation rate. Because under typical operating conditions, increasing gas current. The protective gas plasma impedes the heat dissipation rate.

Comparing the above two equations for force due to the motion of the charge the relation between the “radius of gyration”, and the “magnetic-field” is shown in equations

\[ r_g = \frac{M_p V q}{B} \]  

where, \( F = \text{Lorentz-force}\), \( q = \text{charge} \) on “particle”, \( V = \text{velocity} \) of the “particle”, \( B = \text{external magnetic-field} \), \( M_p = \text{mass} \) of “charge particle”, \( r_g = \text{radius of gyration} \), Figure 6 has indicated the route path of a charged-particle of arc plasma under the “external magnetic-field” shown as about the “Y-axis”. The Lorentz force is along “X-axis”, as the path of this charged-particle of “arc-plasma” is at right angles to “velocity” as well as a “magnetic-field” (as “V”, and “B” are the “cross-product”) depicted in the “Maxwell equation” resulting in the “whirl of the particle (move-in circle)”. Comparing this Lorentz force on a charged particle with centripetal force gyro-radius (rg) obtained, as shown in Eq. (3). So, for any “charged-element”, if the “magnetic-field (M)” rises, the “radius of gyration (rg)” reduces (Eqs. (4) and (5)). Further, this “radius of gyration” (rg) is unservingly affecting the “arc-length (l)” on the workpiece, as exposed in Eq. (6). The equation number 7 and 8 are used for finding value of ‘X’ by

\[ \bar{F} = (q) \bar{V} \times \bar{B} \]  

Figure 5. Arc shape (a) without EMF, (b) with TEMF, and (c) with LEMF [58].

Figure 6. Movement of the charged particle of the plasma arc [70].
r² = D² + x²  
\text{(6)}

x² = r² - D²  
\text{(7)}

X = \sqrt{r² - D²}  
\text{(8)}

where X = r₂ - l, thus l = r₂ - X

l = r₂ - \sqrt{r² - D²}  
\text{(9)}

l = \text{length of the arc on the workpiece}, D = \text{distance between torch and workpiece.}

So, from equation 5.10, it is noted that for a certain value of D when r₂ reduces from the infinity for arc without external magnetic to “r₂” equal to “D”, then “l” will be maximum as the “radius (r₂)” must not be reduced below “D” else “arc” will be erratic.

\[ \alpha \leq r₂ \geq D \]

Simultaneously, the boundary condition for an elongated arc on the workpiece (l) is:

\[ R₀ \leq l \geq D \]

where R₀ = arc length on the workpiece without magnetic field.

Thus, from relation \( l = r₂ - \sqrt{r² - D²} \), it can be stated that the “length (l) of arc” on the “workpiece” is “inversely proportional” to the “radius of gyration (r₂)” as shown in Eq. (10).

\[ l = \alpha \frac{1}{r₂} \]

\text{(10)}

Figure 7 shows that the “length of the arc (l)” on the “workpiece” from the “center of the arc” is R₀ in the absence of EMF but as EMF introduced in the weld zone arc length (R₀) on the workpiece elongated along the weld length to (R₀ + L₀). Consequently, under “boundary-conditions”, the “EMF” is increasing the “heat-dissipating area”, this results in decreasing the heat input per unit length. Further, this “length of the arc” on the “workpiece” is “inversely proportional” to the “heat input (Qₘₐₜ)” as shown in Eq. (11) [70]. Thus, the rise in L₀ enhances the heat distribution area. So, in limited boundary conditions for stable arc, “heat input” per unit “length” is “inversely proportional” to the “EMF”.

\[ Qₘₐₜ = \int \frac{T W}{2L R₀} dR \cdot dx \]

\text{(11)}

T = \text{time}, W = \text{Total heat flux}, Qₘₐₜ = \text{heat input}.

Thus, a relationship has been observed between heat input and EMF along with arc length on the workpiece (l) and radius of gyration (r₂).

\[ H \propto \frac{1}{L₀} \frac{1}{r₂} \frac{1}{B} \]

\text{(12)}

2.3. Application of EMF assisted GMA welding

As discussed above and shown in Eq. (12), the “external magnetic-field” significantly affects the “heat-input” inversely, thus the concept of reduced heat input due to EMF along with arc voltage, wire feed rate, and welding speed may open scope for welding of low melting point alloys like magnesium alloy. The GMA welding in its conventional state is least popular for this alloy because of problems related to porosity and evaporation of alloying elements. However, attempts have been undertaken and outcomes are acquired in aspects of mechanical properties and morphology [15, 18, 71]. The previous studies for arc-welding implicated influencing conventional processing parameters such as, “welding-speed (S)”, “wire feed-rate (F)”,”welding-current (I)”,”arc-voltage (V)” as well as metal transfer and their impacts on “porous-structure”, “permeability”, “pore-volume”, “weld-strength”, “grain micro – structural”, “aspect-ratio”, and assessment of process performance as well as replicability of imperfection-free weldments [18, 71]. But under influence of EMF, Eq. (13) may change to Eq. (14).

\[ H = \frac{60 IE}{V} \]

\text{(13)}

\[ H = K (\frac{IE}{V} \times \frac{1}{EMF}) \]

\text{(14)}

From Eqs. (13) and (14), arc voltage (AV) directly affects the “heat-input (HI), and governs the “weld cooling-rates”. Thus, it affects the micro-structure of the “weld-metal”, and the “heat-affected-zone” results in changing the mechanical properties of welds. Owing to the “lower melting-point (660 °C)”, & “higher boiling-point (1100 °C)” of magnesium-alloy (A-Z31B), care must’ve been considered to prevent burning as well as vaporization of molten-metal. In the literature survey, it is observed that 26 V was used as arc voltage in the GMAW process without a magnetic field to achieve spray transfer to weld AZ31B and porosity was observed [71]. Sharma et al [15] experimentally confirmed the arc stability obtained under EMF at 18 V. Also, below 18 V arc was found unstable without magnetic field. The bead width for the 18 V arc voltage will be smaller compared to 26 V or any other value of higher arc voltage. This will reduce the HAZ and aspect ratio subsequently improve the weld quality. Further “microstructural study” shows that no “porosity”, and “weld-cracks” were experiential in the “weld-zone” at low arc voltage (18) at 120 Gauss (external magnetic field). The magnesium alloys being a special material in terms of weight and strength along with plentiful accessibility on the Earth makes it a “Green-material” of the “21st-century”. The commercial availability of EMF assisted GMA welding can be a milestone towards the popularity of magnesium alloys in BIW of automotive industries in the future as shown in Figure 8(a)–(c) that can significantly reduce the BIW part of weight from the gross weight of the vehicle that amounts 70% of vehicle weight [72, 73].

2.4. Recent effort to develop various EMF setup

The continuous effort in terms of research has been going on for the application of EMF in “fusion-welding processes” for “joining” a wide variety of “advanced materials”. The aims are to increase weld quality and avoid any kind of failure in the weld joint. This can be achieved by reducing “heat-input, and increasing the “cooling-rate” of the “fusion-
zone”. In the last fifty years, plenty of work has been accomplished at the international level to validate the constructive impact of the “EMF” on “weld-quality”. A wide variety of methods have been attempted to apply this EMF. Kang and Na [21] demonstrated the effect of EMF on arc deflection as shown in Figure 9. The “magnetic-arc” “deflection-model” has been considered only “arc-centerline deflection”. The “experiments”, and “simulation” results showed that “magnetic-flux intensity”, and “arc-deflection” are associated linearly in lesser “magnetic-flux intensity”.

Lin et al. [74] built a numerical simulation model of a TIG arc weld pool for the external LMF as shown in Figure 10. The ANSYS based finite element function of multi coupled analysis have been used to study the dispersal of “current-density”, and “magnetic-field”, in addition to “fluid-flow”, and “heat-transfer” in a “moving weld-pool”, to comprehend and expose the influence of “external LMF” on “liquid-metal” in a “moving GTA-weld”. This approach offers the base for the applicability of an “external-emf” in the “welding-process”.

Figure 8. (a) BIW of an automobile, (b) example of Bonnet, and (c) Inner panel of the door [72, 73].

Figure 9. EMF Setup for arc deflection [21].
Nomura et al. [33] developed the cusp type permanent EMF set up as shown in Figure 11 for experimental investigation. But it suffers a limitation that EMF is permanent so that it cannot vary as per requirement.

Yang et al. [75] developed the permanent type of EMF setup for resistance spot welding as shown in Figure 12 with two permanent disc type magnets.

Zhang et al. [20] studied the impact of “EMF” in “hybrid-GMAW-laser welding” as shown in Figure 13 and it showed that the crucial impact of the external-LMF on hybrid “GMAW”-“laser-welding-arc”/“plasma” is to get the “arc-stable”, and enhance the “coupling-effect of the two heating-sources”. Under an external LMF, the arc rotated and has greater intensity. Li et al. [76] applied EMF as shown in Figure 14 for controlling the weld condition and improving the weld quality in GMA welding and affecting humping bead at high welding speed.

Nomura et al. [33] also observed that the “external-cusp”-based “magnetic-field” can alter the bead width as well as improve the “aspect-ratio” of the “weld-bead” on the plate as shown in Figure 15. The excellent bead form is an additional advantage at high-speed welding.

Wu et al. [58], after an elaborated study on different types of EMFs, listed the advantages of EMF in different welding processes which describes several crucial aspects of the EMF types and gave a recommendation. The types of “EMFs” have an expected impact on the “arc-shape”, the “droplet-transfer”, and the “weld-quality”.

Ming et al. [77] developed an EMF setup for resistance spot welding as shown in Figure 16 (a,b,c) [77] for welding aluminum alloys. The EMF influences additional circumferential flow, causing reduced “cooling-rate”, and variation of “solidification-mode”. Thus, it finally affects the “nugget-shapes”, “microstructure-evolution”, and “mechanical-properties”.

Jian and Wu [13] observed that the arc assisted by an alternating LEMF in narrow gap TIG welding is effective in preventing weld defects in joining thick wall plates due to inadequate fusion at the sidewalls. The “welding-arc”, and “molten-pool in the LMF” were “simulated” to show the “effect of the LMF” on the development of consistent “penetration-depth” as shown in Figure 17(a)–(c) [13].

Miguel and Alexandre [14] also discussed the merits of “EMF on arc-shape”, “arc-stability”, “metal-transfer”, implications on “solidification” of the “weld-pool”, “weld-appearance”, “micro-structure”, and “mechanical-properties”, and proposed an equipment for “electro-magnetic constriction” of “electric-arc” in the “GTA welding method” as shown in Figure 18(a) and (b) [14].

A “longitudinal magnetic-field” was applied to the “welding-arc” while, “GMAW” was applied to aluminum and magnesium alloys by
Figure 12. EMF setup for RSW [75].

Figure 13. EMF setup [20].

Figure 14. EMF setup for GMAW [76].
Deminskii et al. [78]. A magnetic field of 40 gauss was applied in alternate directions. An oscillating arc was reported across the welding axis. If the electrode travels in a forward direction with respect to the transverse magnetic field, then transverse magnetic fields have some characteristic benefits. With an optimum magnetic field applied to both magnetic and nonmagnetic materials, welding speed can be increased several times, resulting in “undercut-free”, and “porosity-free welds”. There is evidence that the “degree of arc-deflection” is determined by the “flux-density” of the “applied magnetic-field” as well as the “arc-current”.

When there is a difference in direction between the “electron-stream”, and “magnetic-lines of force”, the “magnetic-force” acts on the “arc”. Arcs have a characteristic conical-shape, and electrons also travel mostly along the “surface of the arc”. Therefore, their motion can be divided into “two components”, “one perpendicular to the arc’s axis”, and the “other parallel to it”. As far as magnetic movement is concerned, the component along the arc does not contribute significantly. However, the “perpendicular component” exerts a “significant force on the arc”, influencing it to rotate “clockwise”, or “counter-clockwise”, primarily based on the “direction of polarity”, and the “magnetic-field”. Furthermore, Hicken and Jackson [79] report that the “constant transverse magnetic-field” has valuable implications when the “arc” is substantially “deflected-forward”. This is compared to the “electrode’s travel-speed” when “deflected forward”. In spite of the fact that the welding speed was improved nearly four times, undercuts were still avoided in the welds. As the magnetic field...
field increased, the weld width decreased. It has been demonstrated that a transverse magnetic field enhances the productivity of special welding processes like "submerged arc-welding" for "butt-joints" between "prepared-edges" [79, 80].

3. Results and discussions

Starting from 1960 to 2020 a lot of researches have been done, at the international level and to some extent at the national level, to ascertain the influence of EMF on weld feature and to advocate the same to be used process parameter [81, 82, 83]. Following the 2000s, the majority of the research has aimed at exploring the effect of variable magnetic fields on the "droplet-transfer", and the "spatter-control". Throughout the previous decade, new arc phenomena have been revealed and "magnetically-controlled welding" knowledge has broadly been applied in many welding methods including TIG, MIG, MAG, RSW, flash welding, stud welding, SAW, and brazing, LBW, and hybrid welding [84, 85, 86]. The achievements of these researchers did not attract manufacturers on a large scale. The foremost reason is that the setups developed for the applicability's of "EMF" in the "welding process" are good enough for pilot study but issue related to their standardization is not reliable [87, 88, 89]. Every time a different approach has been used by researchers to avoid conflict of plagiarism thus further refinement in setup reached a halt. Moreover, these setups have rarely been used in mass production units as industrial support is lacking [90, 91, 92]. These setups have an issue with ergonomics for long hours of production schedules.

3.1. Necessity of integration of EMF with welding machine

For every new research, the design and development of EMF setup is a time-consuming task that hinders new researchers to explore the EMF as a process parameter with as ease as arc voltage or current. Moreover, even after such extended research in welding about EMF as a process parameter, no welding machine manufacturers offer such types of facilities in their machines that may help researchers and industry for welding [92, 93]. The "EMF" has a significant influence on the "geometry of an arc", "droplet-transfer", "weld-form", "morphology", and "mechanical-properties" of the "joint-weld". But still, the burning issue that hinders the application of EMF in industries and research is the lack of such a user-friendly adaptable EMF facility integrated welding machines and its availability at a mass level easily. Even after a detailed study no effort for the commercial integration of EMF with welding machines has been done to improve the weld quality in mass production. Hence, it is necessary to design and develop a customized lightweight user-friendly EMF setup and integrated technology for welding machines. Such that just like the voltage, wire feed rate, or welding current, EMF can also be varied from the control panel of the welding machine in a calibrated and reliable manner. This will help researchers to go deep in this area and manufacture would not be needed to go for a special arrangement if it is part of a welding machine.

4. Conclusions

The article aims to review and collectively reveal the approaches which have been adopted for EMF application and the reason behind the lack of popularity in industries for mass adoption. Thus, the following conclusions have been made from this review are:

i. The dedicated user-friendly programmable EMF integrated with the control panel of the welding machine needed to be designed, developed, and fabricated.

ii. The EMF setup should be a lightweight lean physical model integrated with a welding torch keeping in mind all kinds of ergonomics.

iii. The programmed software base unit for controlling the current in the EMF coil and the integration of this programmed current control unit with the existing control panel of the welding machine may be carried out with the aid of sensors and microcontrollers.

iv. The suitable conversion of the magnitude of current (in Amperes) supplied to the "magnetic coil" with the "magnetic field (Gauss)" is needed.

v. The calibrated display unit with the suitable means for the variation in magnitude and frequency of EMF is imperative

vi. The designed and developed digital EMF unit will help in applying EMF as a new process parameter along with arc voltage and current in a user-friendly manner to improve the weld quality of products and will enable manufacturers to adopt it.

5. Scope of future work

FEM-based modeling of the magnetic field for constriction of weld arc will be important for understanding the generation of the precise bead geometry. If it is appropriately modelled and verified with experimental results, the optimum setting of the magnetic flux will enable the user to achieve the best possible bead geometry related parameters like bead width, bead reinforcement and bead penetration for a sound weld joint.

Declarations

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