# SIMULATION STUDY OF CRITICAL ASPECTS OF MIAB WELDING FOR ANALYSIS OF POTENTIAL FACTORS GOVERNING THE PERFORMANCE OF WELD FORMATION

C. Mukti*, Arungalai S. Vendan

Department of Electronics and Communication, Dayananda Sagar University, Bangalore, India
*Corresponding author's e-mail address: cmukti-ece@dsu.edu.in

## ABSTRACT

*Magnetically Impelled Arc Butt (MIAB) welding, is a solid-state welding technique. The magnetic system of this technique is pivotal for the generation of the Lorentz force, which impels an arc to rotate along the periphery of the weld tubes and thus facilitates the heating of faying surfaces. The magnetic arrangement and the arc dynamics significantly impact the effectiveness of the welding process, eventually dictating the efficiency. This study case investigates the impact of the magnetic arrangement on the arc rotation and possible factors that cause irregularities in the (MIAB) welding through COMSOL simulation. The COMSOL simulation has served as a powerful tool to comprehensively analyse various arc dynamics and magnetic systems and extrapolate the observations to analyse the arc dynamics and magnetic systems involved in MIAB welding. By employing simulation studies, the research aims to unravel critical insights for an efficient design of the MIAB welding system. This work includes a study of the effect of magnetic forces on arc dynamics using various models and attempts to develop an analogy to the MIAB welding process. This is further utilized to explain the process variations in the form of arc displacement, electric potential distribution, and the possibility of self-demagnetization of AlNiCo magnets. Thus, it provides a foundation for advancing the technological aspects of MIAB welding to overcome the limitations and irregularities. This research is instrumental in enhancing the understanding of magnetic interactions involved in the MIAB process, which can further pave the way for improved welding machine designs and consequently, enable research on these lines that can help in establishing an optimized parametric window.*

**KEYWORDS:** MIAB, AlNiCo, electric arc, magnetization, COMSOL

## 1. INTRODUCTION

Magnetically impelled arc butt welding (MIAB) is a solid-state welding process that employs the arc for surface heating of the parts followed by forging in the weld sequence. During the MIAB welding process, an arc is created in the space between the tubes and is impelled along the tube's periphery by the interaction of the arc current with an externally applied magnetic field. The arc is considered to be a moving heat source. It causes heating of the faying surfaces which then fuse on forging. This is due to localized melting and nearby softening in the heat-affected zone (HAZ). This type of welding has been tested in the automotive sector in some European nations to fabricate butt welds on tubular sections of thickness ranging between 0.7 and 6 mm [1]. Compared to other solid-state welding procedures, this weld takes lesser time to create the weld. MIAB Welding is appropriate for critical applications as it produces accurate and consistent welds while using less energy. High-speed MIAB welding does not involve the movement of idle components, thus it avoids wear and tear due to friction. Both steel and aluminum alloys have been successfully welded with this technique [2].

The MIAB welding technique has the limitations of not being applicable for tubes of thickness higher than 8 mm [3]. This technique also has certain irregularities and the weld performance is not reproducible in every iteration. These are the drawbacks that necessitate improvisations for wider acceptance of MIAB welding in versatile industrial applications. The schematic of this process, (Fig. 1) indicates the mechanism of arc formation, impelling, and extinction in the last stage of the process. The process can be divided into three stages viz. arc formation and sustenance, heating, and forging. These stages have distinct requirements of time duration and amperage guided by the energy required to bring the material to its solidus temperature.



Date of submission/acceptance: 17.11.2023/22.12.2023
https://doi.org/10.35219/awet.2023.05

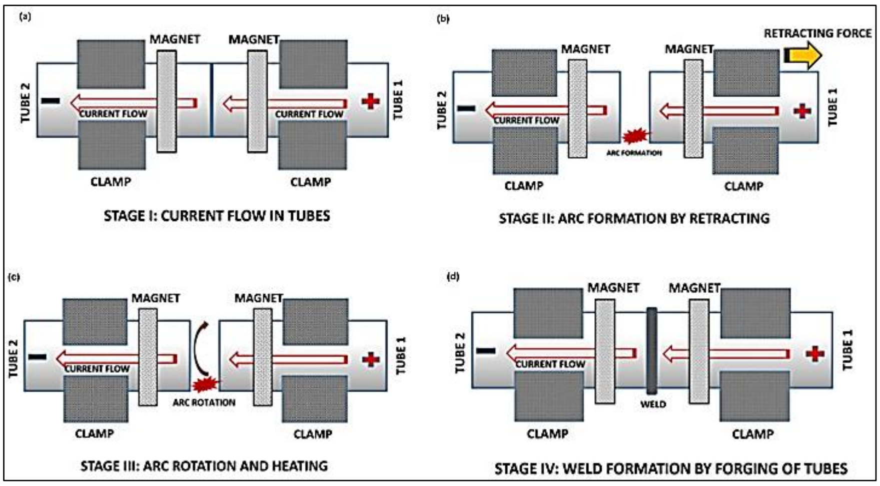


**Fig. 1.** Principle of the MIAB welding process

Defects, such as undercut, incomplete fusion, and distortion are reduced by the controlled arc behaviour. The energy generated by the Joule heating caused by the arc also varies during the welding process due to variations in the arc speed in different stages of the welding sequence, as figure 2 shows [4].

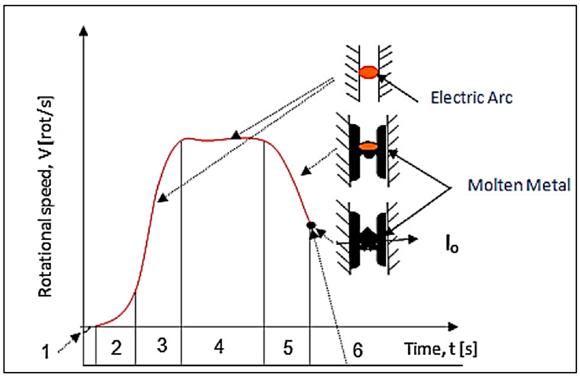


**Fig. 2.** Arc speed variation in MIAB welding phases

Arc rotation is caused by the electromagnetic interaction of the external magnetic field and the weld current. The speed of the arc rotation depends on several factors, like the amperage, magnetic field strength, air resistance, tube thickness, the orientation of the magnetic and electric fields in the weld region, and joule heating effects on the weld surfaces.

## 2. SIGNIFICANCE OF MAGNETIC FIELD IN MIAB WELDING

The rotation of an arc at a stable speed is influenced by the magnitude and the uniform distribution of the magnetic field. The studies on steel pipe welding indicate that the speed of arc rotation expands with increasing flux density of the radial magnetic field [5].

Initially, in the design of the MIAB welding machine, the external magnetic systems were designed using electromagnetic coils [6]. The design and position of the magnetic coils, along with the supply needed to be optimized to obtain consistent arc rotation. The system's complexity is high when a solenoid is used for establishing a magnetic field in the tube gap region because the number of input parameters and power supply numbers also increases the bulkiness of the system. Hence, the MIAB module in its latest design [7] is modified by replacing the magnetic coil arrangement by permanent magnets.

Alnico magnets are non-brittle and can have a thinner form than the ferrite magnets. Alnico alloys contain iron, cobalt, nickel, aluminium, and minor amounts of copper. These constituents form a two-phase alloy with a strongly magnetic α1 phase (Fe-Co) and a weak magnetic α2 phase (Ni-Al), providing pinning sites to control magnetic domain wall motion. Quenching and tempering at 700°C increases the alloy's magnetic characteristics. The coercivity and maximum energy product of these magnets increase due to annealing in a magnetic field. Thus, alnico magnets reduce demagnetization. Though less brittle than ferrite magnets, alnico magnets have hardness and brittle character because the particles are encased in a nickel-aluminium matrix that inhibits domain wall motion [8,9]. This latest design of the MIAB welding machine is fabricated and is used for experimental trials at Dayananda Sagar University, Bangalore.

Magnetic flux density is identified as one of the main factors that affect the arc rotation behaviour in MIAB welding. The arc dynamics during the welding sequence control the uniformity and intensity of the heating at the weld surface [10]. The heated and plasticized weld surfaces are forged together at a preset time to form the weld. Thus, the effective design of the electromagnetic system is an essential task for the construction of the MIAB welding setup.

## 3. ANALYSIS OF MAGNETIC FIELD

Magnetic field analysis in MIAB welding systems is essential for optimizing the welding process, ensuring stability, controlling the heating, and designing efficient and reliable welding machines. It provides a deeper understanding of the forces at play, allowing engineers and researchers to make informed decisions for improving the performance and quality of MIAB welding.

This study focuses on the simulation and analysis of the magnetic system involved in the MIAB welding setup. The simulation accounts for factors, such as the magnetic field strength and its variation, the arrangement of magnets for the generation of appropriate polarity, the strength magnetic field, and the Lorentz force created with the interaction of electrical and magnetic field in the weld region.

## 4. METHODOLOGY

An Analysis is performed using the COMSOL simulation application, considering permanent magnets as used in the prototype machine installed at Dayananda Sagar University, Bangalore.

The AC/DC Module in COMSOL Multiphysics is a powerful tool for electromagnetic simulations, particularly in the context of time-varying electric and magnetic fields. It offers a range of features to accurately model and analyse problems related to electromagnetics like the simulation of electromagnetic waves, modelling of ferromagnetic materials, simultaneous modelling of electric and magnetic fields, modelling of hysteresis effect in ferromagnetic materials. It provides tools for analysing the problems in electrostatics and magnetostatics. These tools provide a platform for performing simulations on rotating machinery. Simulation study allows us to tailor the analysis to a specific research application and gain insights into the electromagnetic interactions within this welding process.

There are several interdependencies involved in this multidisciplinary domain application of welding. This simulation study covers some of the aspects of the components involved in the MIAB welding technique:

- Arrangement and influence of the permanent magnets on the arc.
- Divergence and damping experienced by the arc in the static magnetic field.
- De-magnetization of the Alnico magnets.

The first part analyses an extension of the Halbach arrangement of magnets which generates a high flux density as compared to conventional and concentrate arrangement [11]. The design of the MIAB system requires the use of permanent magnets that generate the maximum flux density in the weld region for appropriate impelling of the arc with the Lorentz force.

For this study, the arrangements of magnets are considered to be in close similarity to the quadrupole, consisting of assembly of four permanent magnets. This is also the arrangement of magnets in the MIAB welding machine used for experimental trials.

The second part of this study considers the damping and divergence of the arc due to static magnetic field and electric field due to space charge respectively.

The third part of the study considers the self-demagnetization of soft AlNiCo magnets when taken out of their protective magnetic circuit and their partial magnetization on placing back into the magnetic circuit.

The insights gained from the simulations contribute to a deeper understanding of the design of the magnetic system in the MIAB welding process and the magnetic field's influence on the resulting weld. It provides a foundation for establishing dependencies and deciding on an optimum design of the critical magnetic system in the weld setup. The research also highlights the intricate interplay between the magnetic field, arc behaviour, and material flow during MIAB welding of ferrous tubes. The distribution of magnetic flux lines and their impact on arc column stability, heat input, and material mixing are analysed. Furthermore, the study summarizes the correlation between magnetic field and arc dynamics to suggest design refinements for this advanced welding technique.

## 5. SIMULATION MODEL & WAVEFORMS

### 5.1. Permanent Magnet Arrangement and Influence

Magnetic quadrupole lenses are commonly used in focusing ion and charged particle beams in various machines. In the MIAB welding machine, 3 magnets are used on each welding head (Fig. 3). COMSOL Multiphysics is used to model ions passing through three consecutive permanent magnets. This model uses all components of particle velocities and fringing fields into account for the calculation of forces on the ions. The polarity of the magnets is reversed in the considered model (Fig. 4) [12]. The welded tubes carry 150A current to achieve a weld geometry of tubes of 27mm OD and 3 mm thickness. Electron distribution in the plasma formed between the electrodes along the circumference of the tubes.

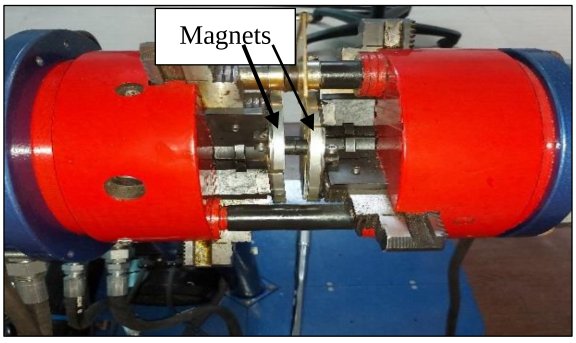


**Fig. 3.** Magnets positioned on each welding head

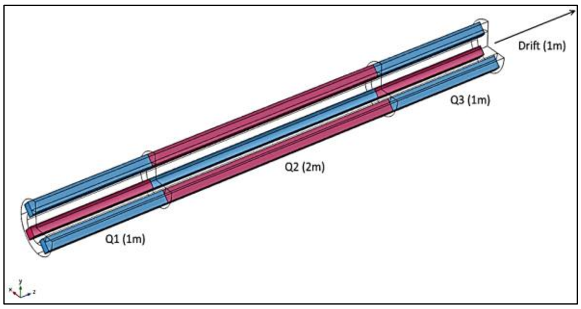


**Fig. 4.** Cutout of the quadrupole lens. The second quadrupole (Q2) has its polarities reversed compared to Q1 and Q3

In the simulation model, ions are sent through the quadrupole assemblies. Particles are assumed to have zero initial transverse velocity which increases with time. Each quadrupole then focuses on the ion beam from all directions. Domain equations are used in COMSOL to compute the magnetic field (Fig. 5) and the Maxwell's force acting on each ion which imparts them energy to pass through the quadrupole lens (Fig. 6) [12].

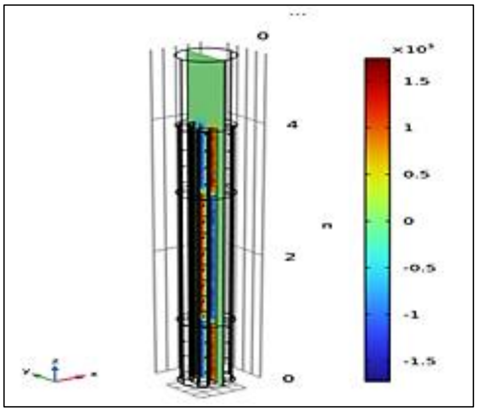

**Fig. 5.** Arrows of the magnetic field and slices of its x-component in the quadrupole lens

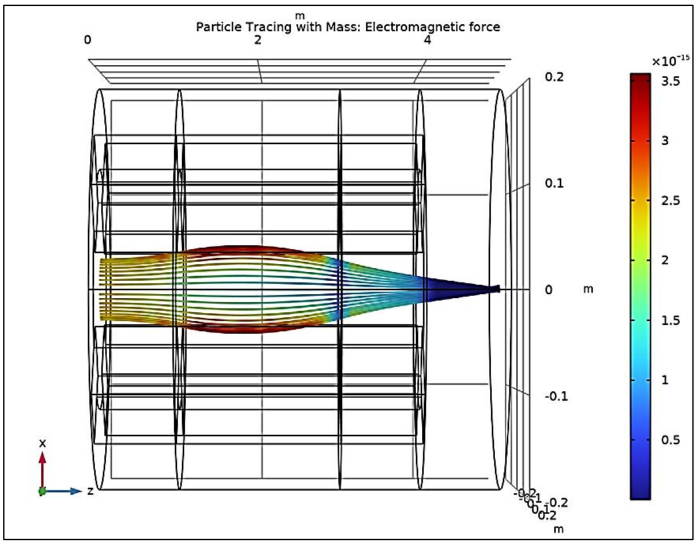


**Fig. 6.** Particle tracing plot of the ions [12]

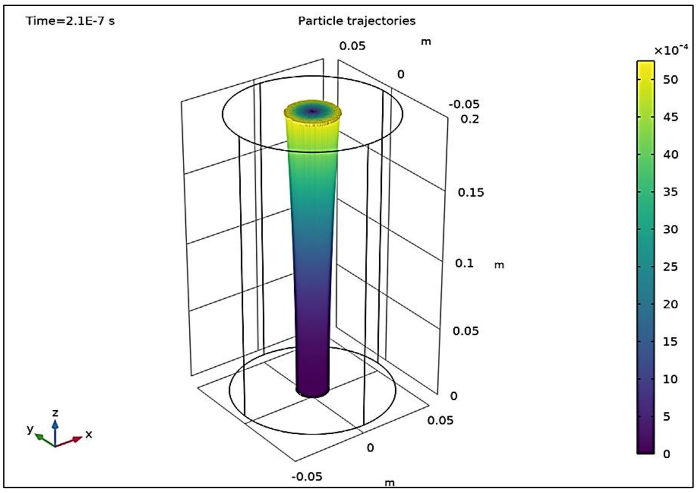


**Fig. 7.** Beam of electrons showing radial displacement from the initial position.

### 5.2. Divergence and Damping experienced by the Arc in the Static Magnetic Field

The arc is modelled as a charged particle beam propagating at a high current that causes significant Coulomb interaction. In such a beam, due to the space charge of the beam, the electric field significantly affects the trajectories of the charged particles. Disturbances to these trajectories affect the space charge distribution. Accurate prediction of the beam behaviour requires consistent computation of particle trajectories and fields. COMSOL does this by the use of coupled equations for the beam potential and electron trajectories described by the equation (1).

$$\nabla \cdot \varepsilon_0 \nabla V(\mathbf{r}) = \sum_{i=1}^{N} e\delta(\mathbf{r} - \mathbf{q}_i)$$

$$\frac{d}{dt}\left(m_e \frac{d\mathbf{q}_i}{dt}\right) = e\nabla V \qquad (1)$$

where:

- $m_e$ = 9.10938356 × 10-31 kg is the electron mass
- e = 1.602176634 × 10-19 C is the elementary charge
- $\varepsilon_0$ = 8.854187817 × 10-12 F/m is the permittivity of vacuum
- V (SI unit: V) is the electric potential
- N (dimensionless) is the total number of particles
- r (SI unit: m) is the position vector
- $q_i$ (SI unit: m) is the position of the $i^{th}$ particle
- δ (SI unit: 1/m3) is the Dirac delta function.

The simulated model does a time-dependent analysis of the particle trajectories and a stationary analysis of the electric potential. Electron trajectory and the beam potential are obtained after several iterations of computations and are plotted in figure7 [13]. The electric potential distribution in the beam is shown in figure 8 [12].

### 5.3. Demagnetization of Alnico Magnets

Soft permanent magnets like Alnico get self-demagnetized when taken out of their protective magnetic circuit. When they are placed back in the magnetic circuit, linear recoil is observed, which helps in gaining back the partial magnetism. The magnetic circuit, represented by a soft iron yoke is modelled as the initial stage in figure 9 [14].

When the magnet is removed from the magnetic circuit (Fig. 10), [14], the magnetic field strength approaches the coercive magnetic field. Linear Recoil model is used to study the regaining of the magnetization when placed back in the magnetic field, as it shows the figure 11[14].

## 6. RESULTS AND DISCUSSIONS

Each ion passing through the assembly experiences Maxwell forces according to equation (2):

$$F = qv \times B \qquad (2)$$

where v (SI unit: m/s) is the velocity of the ion.

The transverse position as a function of time can be determined by Newton's second law for each ion (3):

$$qv \times B = ma \qquad (3)$$

The line colours in the particle tracing plot show the local force acting on each ion (Fig. 6). The force grows larger (red) far away from the centre of the beamline and smaller (blue) where two oppositely polarized quadrupoles join. This variation in the force experienced by the beam of charged particles is relatable to the reasons that may cause the non-uniform rotation speed of the arc and the magnetic arc blow effect in MIAB welding [15].

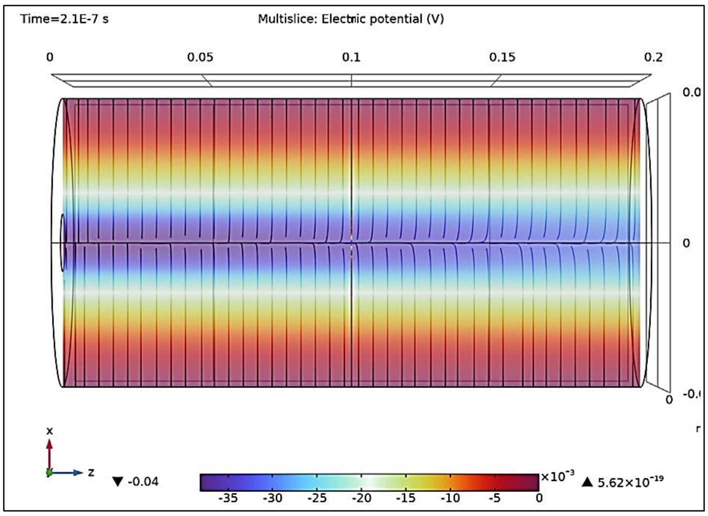


**Fig. 8.** Electric potential distribution in the electron beam

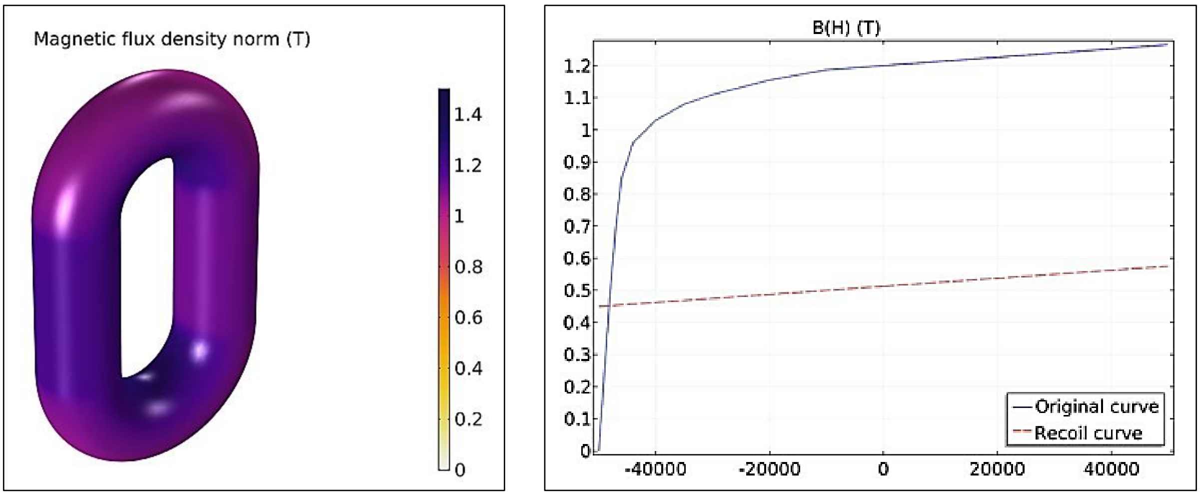


**Fig. 9.** AlNiCo magnetized in Magnetic circuit and its B-H Curve [14]

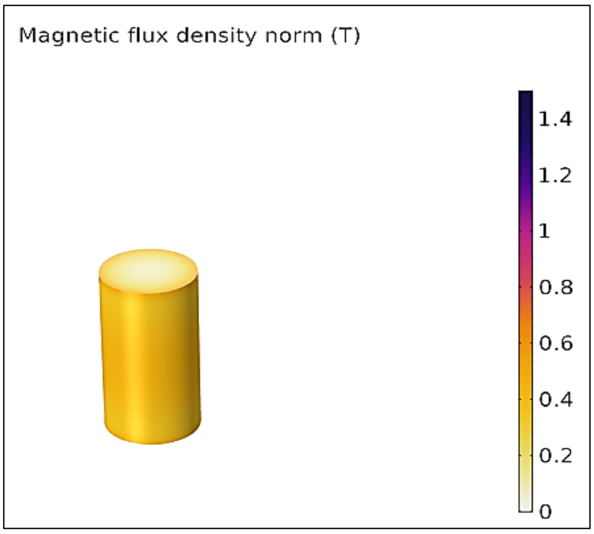


**Fig. 10.** AlNiCo magnet removed from magnetic circuit [14]

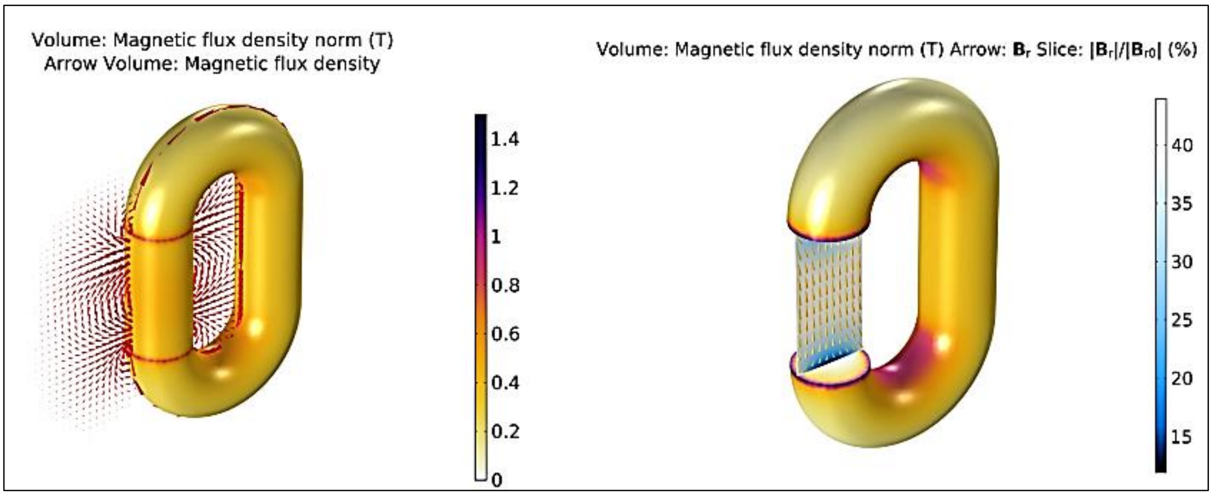


**Fig. 11.** Re-magnetisation on placing it back in the circuit [14]

A beam of electrons with a waist located at z = 0 (Fig. 7) diverges due to transverse beam forces. The colour represents the radial displacement of each electron from its initial position. The beam propagates from left to right, and the beam electrons initially move in the positive z direction. The left end of the plot has the smallest beam radius and corresponds to the beam waist. The electric potential (Fig. 8) is greatest in magnitude close to the beam waist.

This observation explains another factor for the drift of electrons in the region between the weld tubes in MIAB welding. The diverged arc thus experiences drift between the inner and outer diameter of the ferrous tubes. Rotation of the arc causes changes in the magnetic field distribution as well. This variation causes variation in the Lorentz force acting on the arc. The added force acting on the arc counteracts the motion and thus the rotating arc experiences a drop in the rotation speed due to structural damping.

When the AlNiCo magnet is placed in its magnetic circuit, the magnetic flux density in the AlNiCo and the magnetic circuit is almost constant and close to the **H**= 0 point of the AlNiCo demagnetization curve with **BB** = 1.2 T. Such soft permanent magnets are easily demagnetized if handled incorrectly. When it is removed on purpose or accidentally from its magnetic circuit, the magnetic field strength in the AlNiCo approaches the coercive magnetic field: 50 kA/m. The linear recoil model employed in COMSOL shows that on placing it back in the magnetic circuit, the magnetic flux density in the circuit and remanence of the magnet is reduced to about 40% of the original value.

## 6. CONCLUSIONS

This simulation-based study about the dynamics of the arc in the presence of magnetic fields highlights the intricate factors that can be utilized in understanding the mechanisms involved in MIAB welding of ferrous tubes.

The following observations from the simulation models have been found appropriate and can be extended to the mechanism of MIAB welding which provides insights into the analogies of interdisciplinary science:

- Moving charged particles in the effect of a magnetic field of a quadrupole arrangement will experience a force of magnitude varying from the joint location of oppositely charged magnets to the centre of the beamline. The magnetic arrangement in the MIAB welding technique will exert such a varying force on the arc formed in the gap length.
- Electrons in the charged beam experience radial displacement from its initial position, causing the beam propagation from left to right. The electric potential is observed to have a varying distribution in the beam. The arc in the MIAB welding has been noticed to have a displacement from the inner diameter of the tubes to the outer diameter, which can be an effect of such a displacement and variation in potential experienced by the arc.
- Soft AlNiCo magnet experiences self-demagnetization in case of improper handling like accidental or intentional removal from its magnetic circuit. For maintenance and cleaning purposes, improper handling of these magnets in the MIAB welding technique may result in partial de-magnetization and explain the inconsistencies involved.

Since the considered models are not the same as the setup involved in MIAB welding, but the underlying concept is about the impact on charged particles moving in a magnetic field, thus the observations made in these studies have been considered to partially explain the irregularities and the non-reproducible results observed in the MIAB welds.

Despite the differences in the models, there is a shared or similar concept that underlies both of them. This means that at a fundamental level, they are addressing or representing a common idea or principle. The following inferences can aid the refinement of the welding process design in the suggested ways:

- The heat energy calculations as part of the design of the welding technique should consider that the arc, which is a moving heat source, experiences varying force which will result in arc velocity variations that can affect the heat generated to soften the weld tube surfaces.
- Displacement of the arc and varying electric potential distribution can be significant factors for the non-uniform heating of the faying surfaces and for the inconsistencies observed in weld iterations.
- Design of the magnetic arrangement and the complete MIAB welding setup should be made in a way to avoid any improper handling of the soft AlNiCo magnets to minimize the chances of self-demagnetization

This research serves as a valuable resource for welding engineers, researchers, and practitioners seeking to harness the advantages of MIAB welding for the precision joining of ferrous tubes through informed process control and optimization.

The findings of this study contribute to establishing the design requirements for an industry-acceptable configuration of MIAB welding setup. This attempt will empower the engineers and researchers with the knowledge to effectively utilize magnetic fields for precision welding applications.


## ACKNOWLEDGEMENTS

The authors would like to thank the Department of Science and Technology (DST), Government of India for sponsoring this research study under the Advanced Manufacturing Technology, Scheme. (Ref: DST/TDT/AMT/2017/228). The authors thank Dr. Vladimir Kachynskyi for mentoring us in understanding the MIAB welding process and for the support in carrying out experimental work.

The authors acknowledge that the COMSOL simulation work reported here was supported in part by I-STEM (Indian – Science, Technology and Engineering Facilities Map) funded by the Office of the Principal Scientific Advisor to the Govt. of India.

## REFERENCES

[1] **Arungalai Vendan S., Thangadurai V., Vasudevan A., Senthil Kumar A.**, *Investigations on temperature distribution during revolutionary and zigzag movement of arc in magnetically impelled arc butt welding of tubes*, International Journal of Applied Electromagnetics and Mechanics,Vol. 46(1), 2014, pp.155-163.

[2] **Vendan S. A., Manoharan S., Buvanashekaran G, Nagamani C**., *Magnetic flux distribution modelling of magnetically-impelled arc butt-welding of steel tubes using finite-element analysis*, Proc. of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. Vol. 222(9), 2008, pp. 1783-1790.

[3] **Kachinskiy V. S., Krivenko V. G., Ignatenko V. Y.,** Magnetically impelled arc butt welding of hollow and solid parts. Welding in the World, Vol. 46, 2002, pp. 49-56.

[4] **Dhivyasri G., Rahul S. G., Kavitha P., Vendan S. A., Kumar K. R., Gao L., Garg A.,** *Dynamic control of welding current and welding time to investigate ultimate tensile strength of MIAB welded T11 tubes*. Journal of Manufacturing Processes, Vol. 32, 2018, pp. 564-581.

[5] **Vendan S. A., Manoharan S., Buvanashekaran G., Nagamani C.,** *Some studies on the electromagnetic aspects governing the magnetically impelled arcs through experimentation, finite element simulation and statistical analysis*, International Journal of Applied Electromagnetics and Mechanics, Vol. 31(2), 2009, pp. 113-126.

[6] **Vendan S. Arungalai, Manoharan S., Buvanashekaran G., Nagamani C.,** Development of a MIAB welding module and experimental analysis of rotational *behavior of arc—simulation of electromagnetic force distribution during MIAB welding of steel pipes using finite element analysis*, The International Journal of Advanced Manufacturing Technology, Vol. 43(11-12), 2009, pp. 1144-1156.

[7] **Arungalai Vendan S., Manoharan S., Nagamani C., Buvanashekaran G.**, *Experimental and statistical analysis of impact of various parameters on arc rotation in MIAB welding process by developing a laboratory module*, Experimental Techniques, Vol. 34, 2010, pp. 40-48.

[8] **Vendan S. A., Manoharan S., Buvanashekaran G., Nagamani C.,** *Some studies on the electromagnetic aspects governing the magnetically impelled arcs through experimentation, finite element simulation and statistical analysis*, International Journal of Applied Electromagnetics and Mechanics, 2009, Vol. 31(2), pp. 113-126.

[9] **Vendan S. A., Manoharan S., Buvanashekaran G., Nagamani C.,** *Magnetically impelled arc butt welding of alloy steel tubes in boilers–establishment of parameter window*, Mechatronics, Vol. 21(1), 2011, pp. 30-37.

[10] **Sivasankari R., Balusamy V., Venkateswaran P. R., Buvanashekaran G., Kumar K. G.,** *Characterization of magnetically impelled arc butt welded T11 tubes for high pressure applications*, Defence Technology, Vol. 11(3), 2015, pp. 244-254.

[11] **Zhu Y., Wang H., Li H., Yang C., Gui, J.,** *Transmission Performance of Halbach Array Cylindrical Permanent Magnet Governor*, Electronics, Vol. 12(5), 2023, p. 1161.

[12] https://doc.comsol.com/5.6/doc/com.comsol.help.models.acdc.quadrupole_lens/models.acdc.quadrupole_lens.pdf

[13] https://doc.comsol.com/6.0/doc/com.comsol.help.models.particle.electron_beam_divergence/models.particle.electron_beam_divergence.pdf

[14] https://www.comsol.com/model/download/1152341/AlNiCo_self_demagnetization_61.pdf

[15] **Arungalai Vendan S., Thangadurai V., Vasudevan A., Senthil Kumar A.,** *Investigations on temperature distribution during revolutionary and zigzag movement of arc in magnetically impelled arc butt welding of tubes,* International Journal of Applied Electromagnetics and Mechanics, Vol. 46(1), 2014, pp. 155-163.