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Electromagnetic Modelling & Experimental Analysis of Weld Tool Coil in Magnetic Pulse Welding

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Abstract

Magnetic Pulse Welding (MPW) is a high-velocity, solid-state welding technique utilized to join dissimilar metals through the application of a strong magnetic field. The MPW system comprises a 208 µF capacitor bank and a specialized weld tool coil. In this study, the capacitor bank was charged up to 11 kV, resulting in a discharge current of 100 kA at a frequency of 12.5 kHz through the tool coil. The weld tool coil is designed with six 6-turn copper discs and is integrated with a copper field shaper to enhance the welding process.

This paper presents the development of a two-dimensional (2-D) model using COMSOL Multiphysics to analyze the impact of the field shaper on the magnetic field intensity generated by the 6-turn coils. Simulation results revealed that the discharge current of approximately 100 kA at 12.5 kHz produced an average magnetic field intensity of around 29 Tesla (T). The field shaper effectively concentrated the magnetic flux within a smaller, targeted region of the workpieces. The inclusion of the field shaper in the coil's axis led to an approximate fourfold increase in the magnetic field intensity, thereby demonstrating its significant role in enhancing the efficiency of the MPW process.

Keywords: Electromagnetic, Magnetic Pulse, Coil

1. Introduction

Magnetic Pulse Welding (MPW) is an advanced solid-state welding technique that joins two metals through high-velocity impact induced by Lorentz forces. These forces are generated due to the interaction between the magnetic field density and a damped sinusoidal transient current. MPW is primarily an axis-symmetric welding process, typically employed to weld configurations such as tube-to-tube and tube-to-rod joints.

A critical component of MPW is the tool coil, which is responsible for generating the magnetic field density necessary for creating the high impact velocity required for effective welding. The magnetic field is produced by a multi-turn coil energized by a capacitor discharge current. However, when the volume inside the coil is large, the magnetic field density generated by these coils alone is often insufficient to achieve a strong weld. High magnetic field density in the vicinity of the workpieces is essential for a successful welding process.

To enhance the magnetic field density near the job pieces, a field shaper is employed. The field shaper, typically made of copper, is cylindrical with a strategically placed slit. This design focuses the current into a small area, thereby generating a high-density magnetic field. Initially, the discharge current flows through the coil, creating a magnetic field that induces a current in the field shaper. The field shaper, being mutually coupled with the coil, produces an additional magnetic field, which is significantly stronger than the field generated by the coil alone.

To accurately calculate and analyze the magnetic field generated in this process, we employed COMSOL Multiphysics to simulate the coil in a 2D axisymmetric model, both with and without the field shaper. This simulation provides a comprehensive understanding of the role of the field shaper in amplifying the magnetic field density, thereby improving the overall efficiency and effectiveness of the MPW process.

2. Theory of Magnetic Pulse Welding (MPW)

2.1 Process of Magnetic Pulse Welding

Magnetic Pulse Welding (MPW) operates on the fundamental principle of achieving metal bonding through high-velocity impact facilitated by a high-intensity pulsed magnetic field [1, 2]. The process flowchart for MPW is depicted in Fig 1. Initially, electrical energy is stored in a capacitor bank by charging it to the required voltage. Upon triggering the switch, this stored energy is rapidly discharged into a specialized tool coil.

During this discharge process, a portion of the energy is dissipated as heat in the coil, while the remainder induces a current in the workpiece [3]. This induced current generates Joule heating within the job piece, heating it to a suitable temperature for plastic deformation. Simultaneously, the workpiece is deformed and accelerated to a high velocity, enabling it to impact another workpiece with sufficient force to create a metallurgical bond [4, 5].

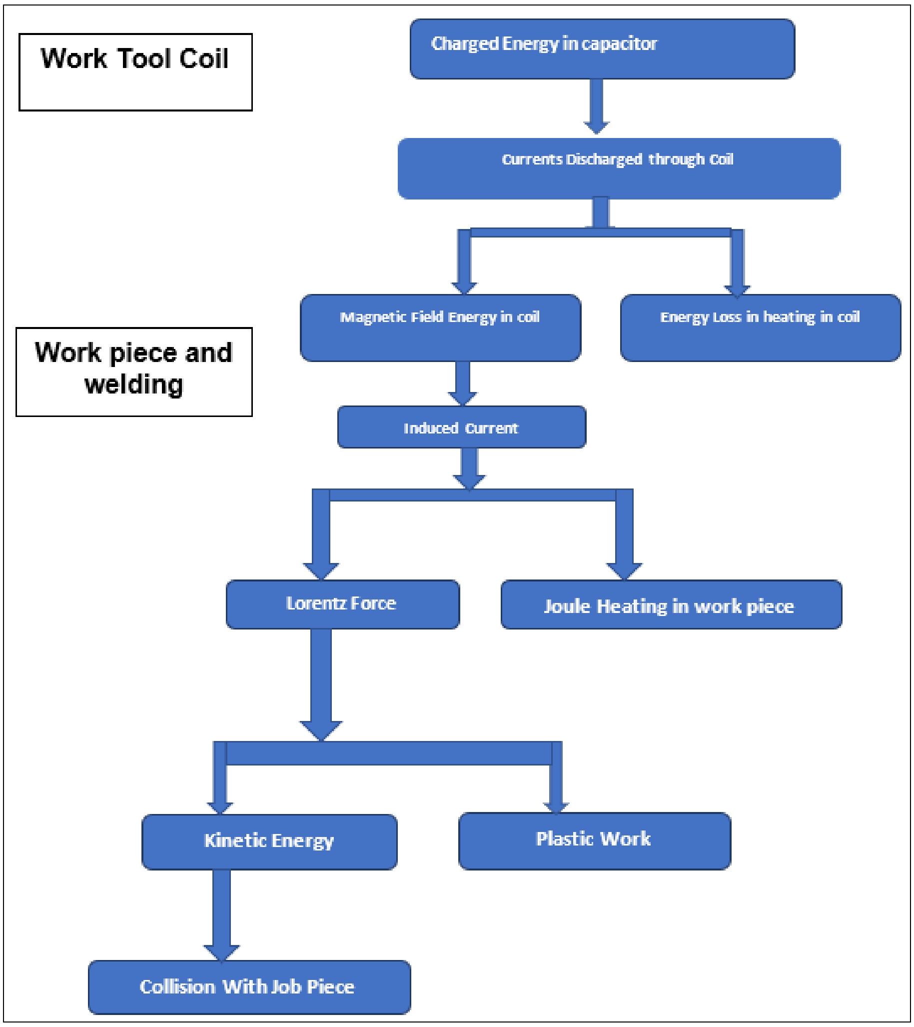

Fig 1: Flow chart of MPW

2.2 Designing of Electromagnetic Tool Coil

The design of the electromagnetic weld tool coil is critical for generating the necessary magnetic field for Magnetic Pulse Welding (MPW). The tool coil is constructed using six turns of aluminium plate, each made from 10 mm thick aluminium and insulated with Mylar sheets to ensure electrical isolation. The disc coil features an inner diameter of 60 mm and an outer diameter of 120 mm.

A 208 µF capacitor bank, charged to 11 kV, discharges a peak current of 110 kA at a frequency of 12.5 kHz through this coil [6-8]. This discharge creates a magnetic field density of approximately 6 Tesla within a 60 mm diameter region. To further enhance the magnetic field density, a field shaper is placed inside the tool coil. This field shaper, made from copper and designed to focus the magnetic flux, amplifies the magnetic field density by a factor of four to five times.

The design and performance of the weld tool coil, including the effects of the field shaper, were simulated using a 2D model in COMSOL Multiphysics, as shown in Fig 2. This simulation provides valuable insights into the electromagnetic behavior of the coil and the efficacy of the field shaper in increasing the magnetic field density, crucial for achieving high-quality welds in MPW.

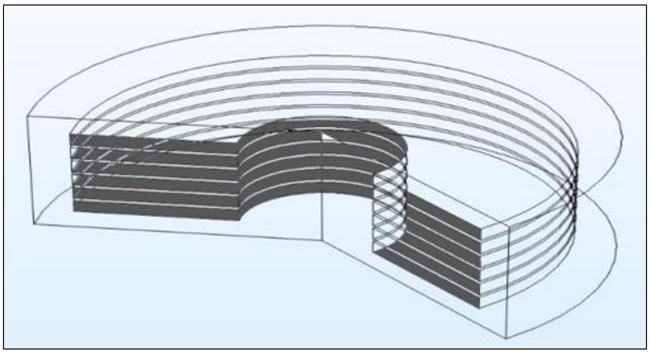

Fig 2: 6 turns coil in 3D

2.3 Field Shaper

The field shaper is a crucial and highly effective component in the weld tool coil system. Its primary function is to concentrate the magnetic field, thereby enhancing the impact force exerted on specific regions of the workpiece. The configuration of the field shaper used in our simulation is illustrated in Fig 3.

In an MPW system without a field shaper, the magnetic field distribution between the coil and the workpiece is relatively uniform and less intense [9-12]. The inclusion of a field shaper allows for the concentration of Lorentz forces on targeted areas of the workpiece, significantly increasing the efficiency and precision of the welding process. This focused application of force is essential for achieving high-quality welds, especially in cases involving dissimilar metals or complex geometries.

The field shaper is constructed from high-conductivity materials such as copper or aluminium. For our simulation, aluminium was chosen due to its excellent electrical and thermal properties. Fig 4 depicts the combination of the disc coil and the field shaper, demonstrating how the field shaper is positioned to optimize the magnetic field distribution and enhance the overall performance of the MPW system.

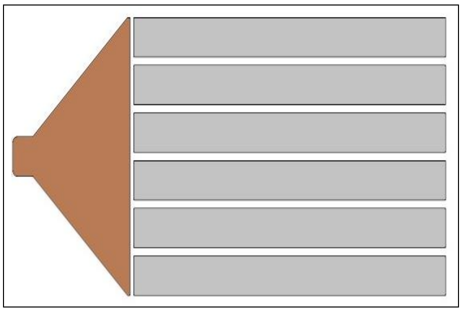

Fig 3: Structure of field shaper

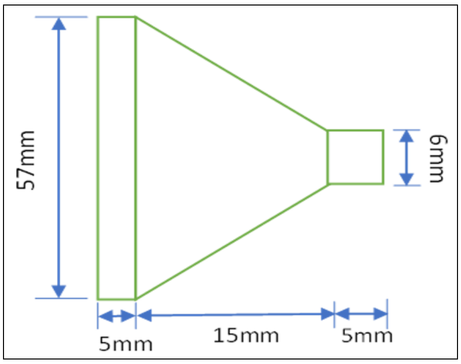

Fig 4: Field Shaper and coil

3. Experimental Setup

The experimental setup for the Magnetic Pulse Welding (MPW) process involves a capacitor bank consisting of four capacitors connected in parallel, each with a rating of 52 µF, resulting in a total capacitance of 208 µF. A high-voltage power supply is used to charge the capacitor bank up to 11 kV, which subsequently generates a pulse current of 100 kA in the tool coil. The energy stored in the capacitor bank, calculated to be 12.34 kJ, is discharged into the tool coil using a trigger ignitron switch.

Ignitron switches are specialized devices composed of several key components: An anode, a cathode, an ignitor, mercury, insulators, and a double metal wall with a cooling agent, as illustrated in Fig 5 [13-16]. These components are critical for effectively managing the high-current discharge required for the MPW process.

The weld tool coil itself is fabricated from aluminium plates, known for their excellent electrical conductivity and mechanical properties. The field shaper, which is used to enhance the magnetic field density and focus the Lorentz forces, is made from copper, chosen for its superior conductivity (Fig 6).

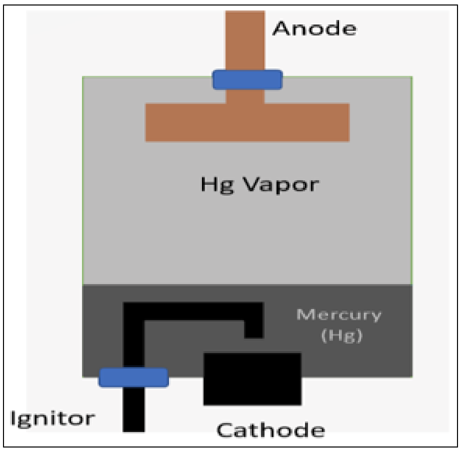

Fig 5: Ignitron Switch

Fig 6: 6 Turns Coil

To monitor and measure the current flowing through the system, a Rogowski coil is employed. The Rogowski coil is an effective sensor for measuring high-frequency, high-amplitude currents without saturation issues. The current waveform is then plotted on an oscilloscope, providing real-time visualization of the current profile and ensuring precise control over the welding process.

Initially, the capacitor bank is charged, storing an energy of 12.34 kJ. This stored energy is then discharged through an ignitron switch into the tool coil. The current passing through the coil is measured using an integrated Rogowski coil, which is specifically designed for accurately measuring high-frequency and high-magnitude currents. The current waveform is recorded on a cathode ray oscilloscope, providing a visual representation of the current profile. The recorded waveform indicates that the peak current generated reaches a magnitude of 100 kA (Fig 7).

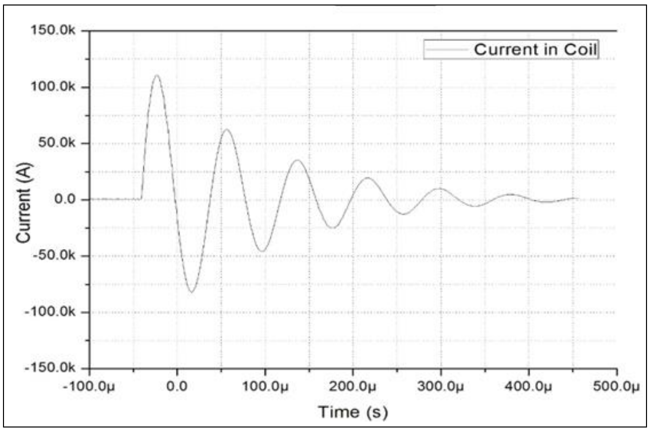

Fig 7: Capacitor bank discharge current in tool coil

4. Simulation and Analysis of Coil

4.1 Theoretical Calculation

Magnetic field intensity (B) inside a solenoid coil is given by:

$$B = \frac{\mu_r \mu_0 N I}{d}$$

Where, d is the length of coil, N is the number of turns and I is the current in the coil.

Electromagnetic tool coil is designed with the following parameters.

Length of coil(d) =78mm

Inner radius of coil=30mm

Outer radius of coil=90mm

Current in the coil(I)=100kA

No. of tuns in the coil(N)=6

Using these parameters, the theoretical calculation yields a magnetic flux density **B** of approximately 9.06 Tesla.

This theoretical calculation provides a baseline estimation of the magnetic field intensity generated by the coil under ideal conditions, which serves as a reference for validating the simulation results and understanding the expected performance of the electromagnetic system in Magnetic Pulse Welding (MPW).

4.2 By Simulation in 2D COMSOL

The six-turn coil was simulated in 2D axisymmetric COMSOL with an input current of 100 kA. The magnetic flux density was measured at the corner of the coil and found to be 6.84 T (Fig 8). The 3D field distribution is illustrated in Fig 9.

Average Magnetic Flux Density(B)=6.84T.

4.3 By simulation in 2D Axis Symmetry COMSOL

A copper field shaper, with dimensions of 58 mm in diameter and 57 mm in length, was introduced into the simulation. The inner dimensions of the field shaper are 8 mm in length and 6 mm in diameter. With the field shaper in place, the magnetic field density was measured to be 28.7 T in the central region (Fig 10). The 3D field distribution is depicted in Fig 11.

4.4 Energy stored in capacitor

The 208 µF capacitor bank is charged to 11 kV and discharges 100 kA into the weld tool coil. The energy stored in the capacitor bank can be calculated using the formula for energy stored in a capacitor:

$$E = \frac{1}{2} C V^2$$

Therefore, the energy stored in the capacitor bank is approximately 12.38 kJ.

This energy is discharged through the weld tool coil, generating the necessary magnetic field and current for the Magnetic Pulse Welding (MPW) process.

Table 1: Comparison of magnetic density with field shaper and without field shaper

S. No	Input current (kA)	No. of turns	Average B without Field shaper(T)	Maximum B with Field shaper(T)	Times
1	100	4	5.84	24.11	4.12
2	100	5	6.21	27.52	4.43
3	100	6	6.84	28.71	4.19

5. Results

The tool coil configurations, both with and without a field shaper, were modeled and analyzed using COMSOL simulation.

Without the field shaper, the magnetic field density was measured to be approximately 6.8 Tesla. In contrast, with the inclusion of the field shaper, the magnetic field density was significantly enhanced to approximately 29 Tesla in both 2D and 3D COMSOL simulations. This enhancement indicates that the field shaper increased the magnetic field density by approximately four times compared to the configuration without the field shaper [17-20].

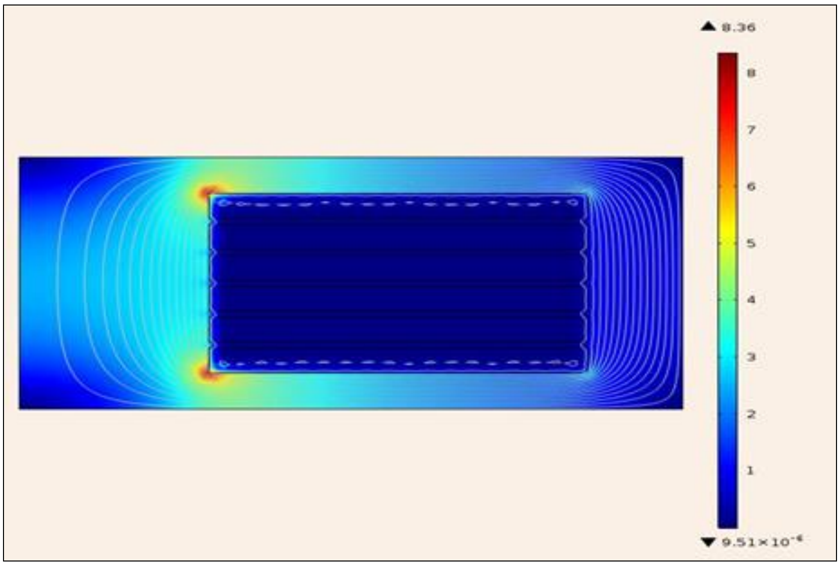

Fig 8: Magnetic field density in 2D COMSOL without Field Shaper

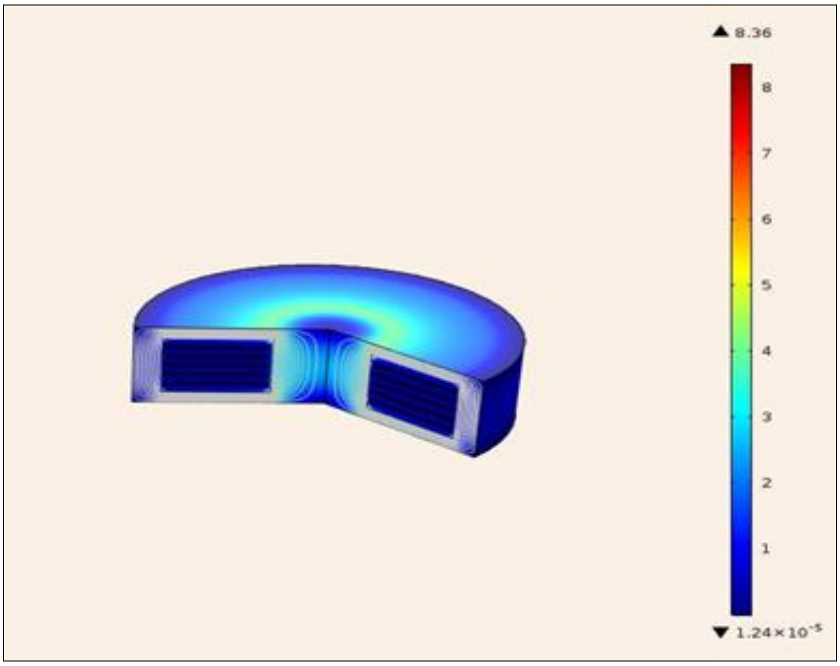

Fig 9: Magnetic field density in 3D COMSOL without Field Shaper

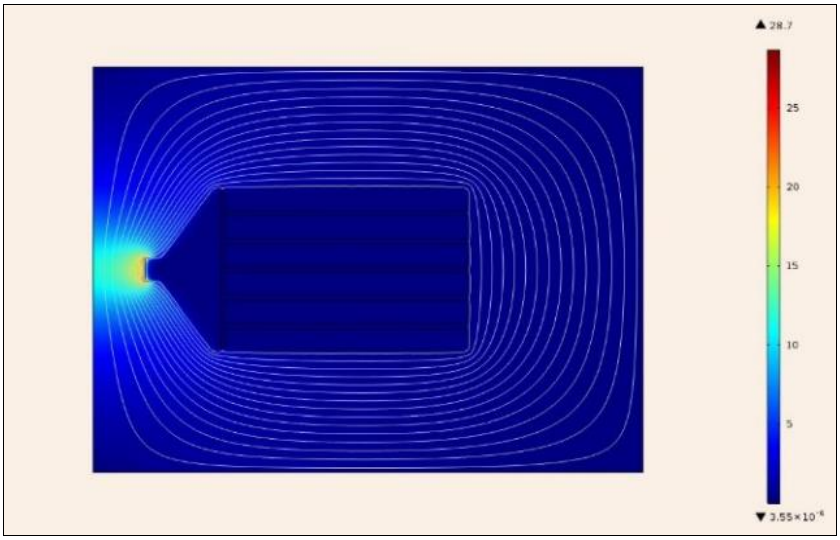

Fig 10: Magnetic field density in 2D COMSOL with Field Shaper

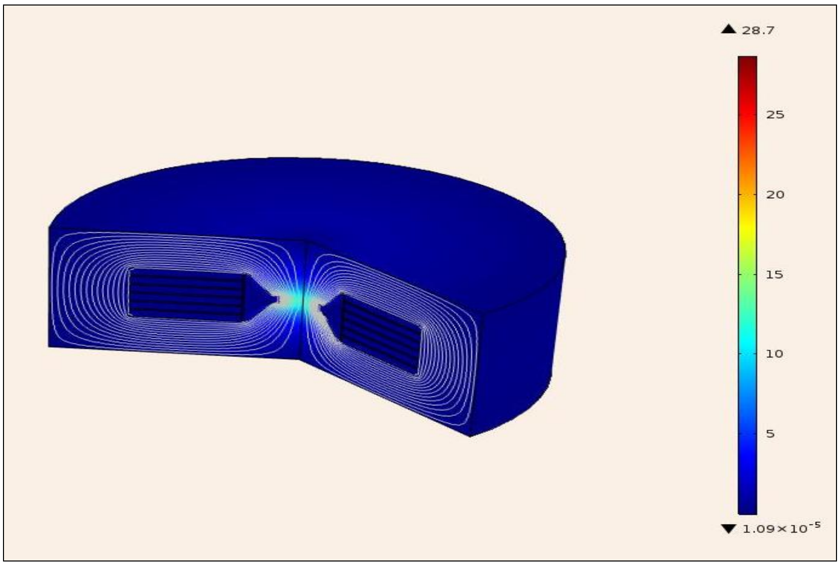

Fig 11: Magnetic field density in 3D COMSOL with Field Shaper

5.1 Magnetic Field Density inside the Surface of Field Shaper

The variation of magnetic field density inside the field shaper along the z-axis is illustrated in Fig 12. The graph plots the relationship between magnetic field density (B) and distance along the z-axis (d). Inside the field shaper, the magnetic field density remains relatively constant and significantly higher. This uniformity ensures effective concentration of magnetic flux within the desired region for enhanced welding performance.

Beyond the boundaries of the field shaper, the magnetic field density rapidly decreases, reaching negligible magnitudes. This sharp decline underscores the field shaper's role in confining and amplifying the magnetic field to targeted areas, crucial for optimizing the Magnetic Pulse Welding (MPW) process. Fig 12 shows the variation of Magnetic Field Density inside the Field Shaper along the Z-axis.

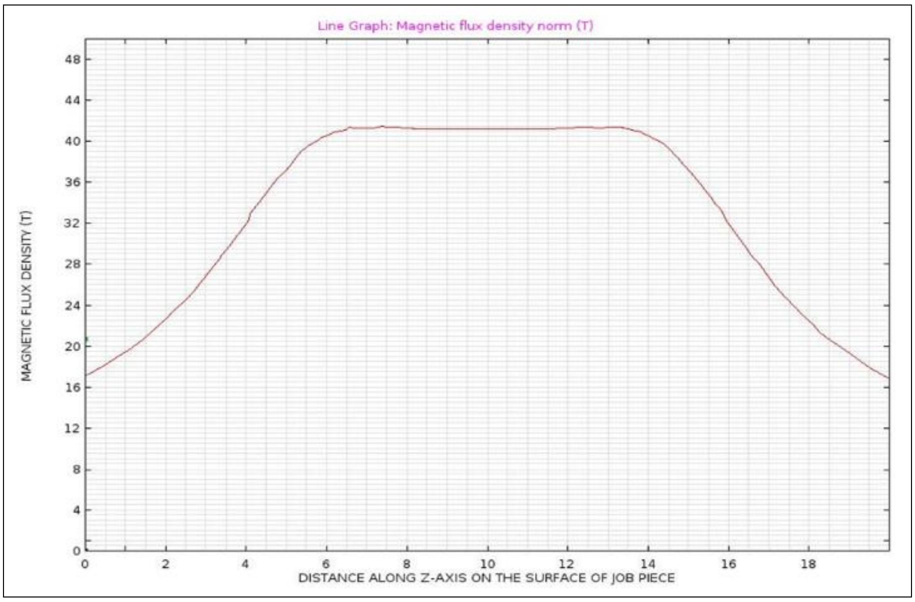

Fig 12: Magnetic field density along the axis with Field Shaper

The magnetic flux density along the z-axis inside the surface of the coil remains nearly constant across the distance d. This region exhibits maximum magnetic flux density, capable of generating the highest Lorentz force. This force plays a critical role in enhancing the weld quality, particularly in joining dissimilar materials.

6. Conclusion

Numerical simulations and experimental investigations were conducted to evaluate the impact of a field shaper. The inclusion of a field shaper resulted in a substantial increase in magnetic flux density, approximately four times higher compared to configurations without a field shaper. The use of a field shaper resulted in a more uniform distribution of magnetic flux density and Lorentz force. The magnetic flux density remained nearly constant throughout the interior surface of the field shaper, enhancing the welding process's uniformity and effectiveness. The choice of material and the precise shape of the field shaper play crucial roles in enhancing the magnetic field. Optimal design considerations for the field shaper are essential for maximizing the magnetic flux density and ensuring consistent performance in Magnetic Pulse Welding (MPW).

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