Experimental and numerical investigations of 2A16 aluminium and pure copper magnetically assisted dissimilar laser wire feed welding brazing

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Abstract
Magnetic field–assisted welding has been found to have a valuable function in significantly improving properties of weld bead. This paper presents a full-factor experiment for coaxial magnetic field–assisted welding to investigate the mechanism of the influence of magnetic field on the dissimilar laser wire feed weld brazing profile of aluminium and copper. Additionally, a three-dimensional numerical simulation model was built to analyze the influence of magnetic field on the weld bead. It was found that as the magnetic flux density increased from 10 to 50 mT, the properties of the weld bead were improved significantly, the wetting angle decreased from 53 to 26°, and the main fluid flow direction of the weld bead changed into a horizontal direction. Meanwhile, EDS and XRD results showed that the main intermetallic compounds (IMC) of Al₂Cu and CuZn composition changed to Al₄.2Cu₃.2Zn₀.7 in welding beads. Computed and measured distortions illustrated good agreement in the fusion zone.

Keywords 2A16 aluminium · T2 copper · Numerical simulation · Magnetic field–assisted welding · Dissimilar laser welding

1 Introduction

Following the rising demands for high-performance and weight-saving structures, technological advances have encouraged manufacturing innovations involving the application of multi-material products [1–3]. Aluminium, with excellent corrosion resistance, low cost, and density, and copper, with high thermal and electrical conductivity, both are widely used in industry. The welding between aluminium and copper explores the possibility of reducing the mass and cost in engineering, improving the performance of multi-material properties [4, 5]. However, welding aluminium to copper is also challenging because of significant differences in their material properties, such as melting point, coefficient of thermal expansion, and thermal conductivity [6, 7].

Until now, many researchers have dedicated themselves to investigating favourable welding methods, optimizing process parameters, and so forth to improve the performance of Al/Cu joint components, including ultrasonic spot welding [8–10], explosive welding [11, 12], friction stir welding [13–16], and laser welding [17–21], which are already utilized in numerous industrial productions. Nevertheless, when joining Al/Cu dissimilar metals, these methods would inevitably result in a severe deterioration of the mechanical properties of the Al/Cu joints because of the irresistible formation of brittle phases of IMCs [22]. Recently, brazing fusion welding technology has been widely adopted in dissimilar metal welding because of its noted controllability of heat and formation of IMC [23]. Researches indicate the advantage of brazing fusion welding in dissimilar metals whose melting points differ significantly [24–26].

The utilization of the magnetic field in laser and arc welding effectively improves the properties of weld beads because of the Hartmann and thermoelectric effects [27, 28]. Wu et al. [29] found that the external magnetic field could significantly adjust the weld pool fluid flow field, decreasing the momentum of the backward flowing molten jet, which improves the quality of the weld bead considerably. Avilov
et al. [30] verified that surface tension fails to prevent gravity dropping without the support of the external magnetic field. Cao et al. [31] built a hybrid methodology by combining radial basis function neural network (RBFNN) and genetic algorithm (GA) to solve the problem of the selection about appropriate processing parameters. They also conducted verification experiments to illustrate the validity of the calculated optimal processing parameters. Their results indicate that the processing parameters chosen by the model have significantly improved the quality of the welding beats. Fan et al. [32] investigated that the static magnetic field has an inhibitory effect on the interdiffusion behaviour of Fe-Fe50wt.%Si diffusion couples. However, there is no observable difference in diffusivity between parallel and perpendicular to the magnetic field direction.

As mentioned above, several influences of magnetic fields have been experimentally concluded; however, there is a complex mechanism concerning the effect of magnetic fields on the molten pool. Therefore, a more efficient numerical model is desired when analyzing the molten pool dynamics with magnetic field-assisting. Cao et al. [27] created a three-dimensional numerical model for studying the mechanism of magnetic field by analyzing characteristics of the molten pool. Their simulation results demonstrated that the external magnetic field plays a significant role in influencing the width of the melt pool. Bachmann et al. [33] erected a three-dimensional turbulent steady state numerical model for analyzing influences of an alternating magnetic field during penetration laser welding. Their simulations indicated that the application of the alternating magnetic field could prevent the molten pool’s gravity drop-out which caused by the hydrostatic pressure. Wu et al. [34] built a three-dimensional (3D) numerical simulation to investigate the behaviour of heat transfer and the fluid flow of the molten pool under a longitudinal magnetic field. According to their simulations, with the magnetic field strength increased, the fluid flow velocity increases continuously, and the temperature declines gradually. Besides, the magnetic field strength is correlated positively with the molten pool’s surface profile in 0 ~ 30 mT.

The purpose of this paper is to design a CFD model to predict distortions to investigate the influence of the magnetic field by analyzing the fusion zone of laser welding brazing of 2A16 aluminium (Al) and T2 pure copper (Cu). The experimental work includes the following:

1. Investigating the weldability of the Al-Zn filter wire under the influence of different magnetic field parameters by OM and SEM.
2. Characterization of the IMC’s of the weld bead produced under different magnetic field parameters by EDS and XRD.

The modelling results include the following:

1. A three-dimensional numerical model of laser welding brazing of 2A16 aluminium (Al) and T2 pure copper (Cu) for prediction of temperature distribution and velocity distribution under different magnetic field parameters.
2. Comparing simulation results with experimental results.

## 2 Material used and experimental method

### 2.1 Material

The type 2A16 aluminium plate and the type T2 pure copper are utilized for carrying out weld experiments. The dimension of the weldment is 120 mm × 60 mm × 2 mm. The welding flux-core wire is Zn-10%Al, Al-Zn alloy, which is selected as filter wire to join the Al and Cu sheet. The chemical compositions of the above materials are listed in Table 1.

### 2.2 Experimental method

Figure 1 illustrates the experimental platform. The laser beam was generated by an IPG YLS-6000CUT ytterbium
laser, transmitted by an optical fibre, and reached the welding head mounted on a KRC-30 6-axis robot. The laser spot had a radius of approximately 0.1 mm and was skewed towards the side of the aluminium alloy plate with an offset value of 0.5 mm. Pure argon (35 L/min) was applied as shielding gas for performing laser butt welding. Before welding, all samples were degreased by alcohol and drying treatment. In particular, prior to welding, the surface of the aluminium plates was brushed with a steel brush for the removal of surface oxides in order to avoid aluminium oxides layer \( (\text{Al}_2\text{O}_3) \) inducing inclusion, adsorbing moisture as well as leading to the formation of hydrogen porosity.

Figure 2a shows the schematic of a magnetic head which was installed on the welding torch and generated the coaxial magnetic field. The excitation coil was fixed on the laser head to make sure the magnetic field was coaxial with the laser head, and during the welding process, the distance between the bottom of the excitation coil and the welding head was kept at 5 mm. The structure of the magnetic head is displayed on Fig. 2b.

After butt welding, the metallographic samples, which were cut from the weldments with a wire-cut EDM, were gradually ground with 240#, 400#, 800#, 1000#, 1200#, 1500#, and 2000# grit SiC paper, before being polished with HYP-1 metallographic sample polishing machine, as well as cleaned with ultrasonic in alcohol and dried. Then, these samples were immersed in the Keller’s reagent \( (5 \text{ mL HNO}_3 + 3 \text{ mL HCl} + 2 \text{ mL HF} + 19 \text{ mL H}_2\text{O}) \) for 15 s, and observed by the OM (Axio Scope.A1) as well as the SEM (FEI Nova Nano SEM450) equipped with energy dispersive spectrometer system (EDS) for microstructure and element analysis respectively.

### 3 Mathematical formulations

A three-dimensional transient numerical model has been developed to analyze the magnetic field’s influence in welding. The heat transfer, phase change, fluid flow, and the magnetic field are coupled in this model. The formulations are given in this section.

#### 3.1 Governing equation

Because of the extreme complexity of the physics of magnetic field–assisted laser welding, several simplifications during physical processes are inevitably made while maintaining the essential processes. Simplification assumptions have been made as follows:

1. The welding is performed in conduction mode (no keyhole formation), and the melt pool varies in accordance with the melt pool convection.
2. No chemical reaction in the welding pool.
3. The effects of shielding gas jet, nozzle’s parameter on the weld bead are assumed negligible.
4. The mechanical behaviour in the welding process is of minor influence on the weld pool.

In this study, commercially available CFD solver COMSOL Multiphysics 5.6 is applied to simulate transient thermal and velocity fields. Figure 3a–c shows the geometry model and mesh model employed in CFD analysis. In this model, 322,289 hexahedral cells are chosen for mesh independence analysis. The minimum mesh size is 0.005 m in the fine zone utilized along the welding direction, and beyond this zone, the coarse mesh is used. The governing
equations for mass conservation, momentum, and energy conservation hold for modelling. They are as follows [27]:

Mass conservation:
\[ \nabla \cdot (u) = 0 \]  

Momentum conservation:
\[ \frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho uu) = -\nabla p + \nabla \cdot (\nabla u + (\nabla u)^T) - \frac{2}{3} \mu (\nabla \cdot u) I + F \]  

with source term \( F \):
\[ F = \rho g [1 - \beta(T - T_{mel})] - Z_{mush} \frac{(1 - f_{\text{liquid}})^2}{f_{\text{liquid}} + c_1} + F_{\text{mag}} \]  

In Eqs. (2) and (3), \( \rho, \rho, g, \beta, T, \) and \( T_{mel} \) are the mass density, pressure, gravity acceleration, thermal expansion coefficient, local temperature, and melting temperature. \( c_1 \) is a minimal number (0.00001) to avoid division by zero; \( (Z_{mush}) \) is a default value of \( 10^5 \) which is used as mushy zone constant. \( F_{\text{mag}} \) is the Lorentz force generated by the external magnetic field. The liquid fraction \( f_{\text{liquid}} \) is calculated as:
\[
\begin{cases}
0 & T < T_s \\
\frac{T-T_s}{T_l-T_s} & T_s \leq T \leq T_l \\
1 & T > T_l
\end{cases}
\]  

where \( T_s \) and \( T_l \) denote the liquidus and the solidus temperature of the material, respectively.

Energy conservation:
\[ \frac{\partial (\rho H)}{\partial t} + \nabla \cdot (\rho u H) = \nabla \cdot (\lambda \nabla T) \]  

where \( H \) and \( \lambda \) are enthalpy and thermal conductivity.
\[ H = h_{\text{ref}} + \int_{T_{ref}}^{T} c_p dT + \Delta H \]  

where \( \Delta H, c_p, \) and \( h_{\text{ref}} \) are latent heat, specific heat, and reference enthalpy.

### 3.2 Heat source model and magnetic field condition

Latest researches have been devoted various type of heat source model in laser penetration welding [31, 35–38]. In this research, the heat source is based on Behúlová’s model [38],
\[
Q(x, y, z) = \frac{9\eta Q_0 e^3}{\pi (e^3 - 1)} \frac{1}{(z_e - z_i) (r_e + r_e r_i + r_i^2)} \exp \frac{3(x^2 + y^2)}{r_i^2(z)}
\]  

where \( Q_0 \) is the laser power input, \( \eta \) is the efficiency; \( r_e \) and \( r_i \) are the surface radii in planes; \( z_e \) and \( z_i \) are the coordinate of the plate’s top surface and bottom surface respectively; and \( x, y, \) and \( z \) are the coordinates of the instant position of the heat source.

According to general Ohm’s law, the movement of conducting particles in the magnetic field induces a current; its expression is:
\[ J = k(E + u \times B) \]
where $J$, $k$, $E$, and $B$ are current density, electric conductivity, electric field, and magnetic flux density. For a steady magnetic field without external electric current source in this zone, the current electrical density calculated as:

$$J = k(u \times B)$$

(9)

Then, the Lorentz force can be calculated as

$$F_{\text{mag}} = J \times B$$

(10)

4 Experimental result and analysis

Figure 4a–e present the influence of the magnetic field strength on the morphology of the joint section under the same laser welding parameters. As seen from Fig. 4a–e, when the magnetic field increases with reference flux density from 10 to 50 mT, the wetting angle gradually decreases from 53° to 47°, 37°, 32°, and finally 26°, indicating that the wetting ability of Zn-Al wire gradually increases with the

![Microstructure images of the Al/Cu welding brazing joint in different flux density](image)
increase of magnetic field intensity. Because of the coaxial longitudinal magnetic field being applied, the spread of the liquid metal on the molten pool surface to the copper base metal will be accelerated by the electromagnetic stirring effect through the welding process, which is conducive to the diffusion of the liquid metal on the molten pool surface to the copper base metal.

Figure 5a, c, and e, respectively, manifest the copper side brazing zone of the joint under different flux densities in 10 mT, 30 mT, and 50 mT. The thickness of IMC layer is measured as follows: 3.85 μm, 5.0 μm, and 8.97 μm, which means the average thickness of IMC layer increases with the increase of magnetic field intensity. Figure 5b, d, and f display the magnified images of their corresponding brazing zones on the copper side respectively. EDS analysis is shown in Table 2, and the XRD results are shown in Fig. 6. According to the EDS results, when $B = 10$ and $B = 30$ mT, the ratio of Cu and Zn atoms at point 1 is 1:1, and the ratio of Al and Cu atoms at point 3 is 2:1. The IMC layer is composed of CuZn and Al$_2$Cu compounds, but the growth trend of Al$_2$Cu morphology along the weld zone is becoming conspicuous.

When the magnetic field intensity increases to $B = 50$ mT, IMC layer II comprises two parts: one part is layered next to the I layer; the other part is dendritic growing towards the weld zone. These dendritic structures are long, thin, and abundant. According to the atomic ratio of Al, Cu, and Zn at point 2 and point 3 combined with EDS and XRD patterns, these two parts are all Al$_{4.2}$Cu$_{3.2}$Zn$_{0.7}$ ternary compounds. As the magnetic field strength increases continuously, the electromagnetic stirring effect in the molten pool is enhanced, and the heat on the molten pool surface is distributed more evenly. Meanwhile, the period of the molten pool at high temperature is reduced so that the formed CuZn is promoted to transform into Al$_{4.2}$Cu$_{3.2}$Zn$_{0.7}$ compound. Besides, due to the charged fluid in the molten pool driving the liquid metal to rotate in the same direction, the flow rate of the molten pool increases to scour the copper interface, making more Cu diffused to the molten pool. After the molten pool solidification, Al$_{4.2}$Cu$_{3.2}$Zn$_{0.7}$ compound is precipitated. The presence of elongated dendritic Al$_{4.2}$Cu$_{3.2}$Zn$_{0.7}$ ternary compounds in the weld and its specific distribution of morphology gradually inhibit the growth of Al$_2$Cu. As the magnetic density increases to 50 mT, the IMC is composed of CuZn in layer I and Al$_{4.2}$Cu$_{3.2}$Zn$_{0.7}$ in layer II. However, a part of layer II forms a strip adjacent to layer I, while another part, with a significant reduction in Al$_2$Cu compounds, develops as an elongated branch along with the weld bead.

### Table 2: EDS analysis result of weld joint (atom%)

| Magnetic density: | Point | 1 | 2 | 3 | 4 | 5 | 6 |
|------------------|-------|---|---|---|---|---|---|
| $B = 10$ mT      | Al    | 0 | 3.63 | 67.78 | 78.41 | 20.12 | 47.67 |
|                  | Cu    | 100 | 51.62 | 26.77 | 0.65 | 3.32 | 5.39 |
|                  | Zn    | 0 | 44.75 | 5.35 | 20.93 | 76.56 | 46.94 |
| Possible phase   | Cu    | CuZn | Al$_2$Cu | α-Al | β-Zn | α-Al + β-Zn |
| $B = 30$ mT      | Al    | 0 | 8.73 | 66.56 | 79.25 | 15.73 | 48.20 |
|                  | Cu    | 100 | 49.98 | 26.75 | 8.07 | 3.56 | 5.42 |
|                  | Zn    | 0 | 41.29 | 6.69 | 12.68 | 80.71 | 46.38 |
| Possible phase   | Cu    | CuZn | Al$_2$Cu | α-Al | β-Zn | α-Al + β-Zn |
| $B = 50$ mT      | Al    | 7.78 | 56.68 | 53.21 | 69.09 | 18.25 | 56.15 |
|                  | Cu    | 92.22 | 32.64 | 32.10 | 28.94 | 12.93 | 2.98 |
|                  | Zn    | 0 | 10.68 | 12.73 | 1.96 | 68.82 | 40.87 |
| Possible phase   | Cu    | Al$_{4.2}$Cu$_{3.2}$Zn$_{0.7}$ | Al$_{4.2}$Cu$_{3.2}$Zn$_{0.7}$ | Al$_2$Cu | β-Zn | α-Al + β-Zn |

**Figure 6** XRD analyze results in different magnetic flux density: a $B = 10$ mT; b $B = 50$ mT
5 Simulation result and discussion

The simulation of the influence of the magnetic field on the molten's flow and weld pool is based on the fluid flow simulation carried out by varying the magnetic flux density in 0 mT, 30 mT, and 50 mT for a welding parameter in 2200 w, 0.12 m/s, defocus distance in +10 mm. The material properties of 2A16, T2 copper, and the filter wire used in analysis are given in Table 3.

Table 3 Physical properties of substrate

| Physical properties | Symbol/unit | 2A16 aluminium | T2 copper | Filter wire |
|---------------------|-------------|----------------|-----------|-------------|
| Melting point       | $T_m$ (K)   | 933            | 1356.15   | 798.15      |
| Mass density        | $\rho$ (kg/m$^3$) | 2700           | 8970      | 5560        |
| Thermal conductivity| $\lambda$ (W/m K) | 175.2          | 416.3     | 67.98       |
| Dynamics viscosity  | $\mu$ (Pa s) | $1.54 \times 10^{-3}$ | $3.78 \times 10^{-3}$ | $1.38 \times 10^{-3}$ |
| Specific heat       | $C_p$ (J/(kg K)) | 1176.52        | 572.2     | 525.6       |
| Melting latent      | $L$ (kJ/kg)  | 385.3          | 188.5     | 147.9       |
| Marangoni coefficient| $\mu_s/\rho_s$ (N/(m K)) | $-0.6 \times 10^{-4}$ | $-1.56 \times 10^{-4}$ | $-0.43 \times 10^{-4}$ |
| Electrical conductivity $\sigma$ (S/m) | $3.93 \times 10^{6}$ | $1.43 \times 10^{7}$ | $2.57 \times 10^{6}$ |

Fig. 7 Temperature contour and velocity magnitude without magnetic field along the x-z direction: a velocity field; b temperature field; c velocity field at weld bead (magnified); d velocity field at barrier between fusion zone of the aluminium and copper (magnified)
presented in Table 3. 2A16 and filter wire’s physical properties are calculated by a commercial thermal-analysis software Jmatpro, and the material properties of T2 copper are adopted according to previous researches [39–41]. The predicted temperature and velocity profiles of the weld pool for magnetic field–assisted welding brazing are presented and analyzed.

Fig. 8 Temperature contour and velocity magnitude with 30 mT magnetic field along the x–z direction: a velocity field; b temperature field; c velocity field at weld bead (magnified); d velocity field at barrier between fusion zone of the aluminium and copper (magnified)
5.1 Temperature field and velocity field simulation

A reference case without the magnetic field was simulated for comparison and validation. Figure 7a–d demonstrate the molten pool’s velocity and temperature fields without the magnetic field. The typical flow pattern, in this case, is that the liquid metal flows from the centre towards the edge of the molten pool. The maximum weld surface temperature observed is 1393 K, as shown in Fig. 7a; the maximum fluid flow velocity in the $x$-axis direction achieved is about 0.07 m/s at the top surface of the weld bead.

Figure 8a–d demonstrate the molten pool’s temperature and velocity field under magnetic field in 30 mT. Figure 8b shows that the isothermal narrowed obviously compared to the sample without magnetic field assistance. The liquid flows upwards close to the barrier of Al’s molten pool and downwards in line with the edge of the molten pool. Assisted by the magnetic field, the Lorentz force changes the fluid flow direction, and the velocity field at the weld bead undergoes a significant change, with the maximum fluid flow velocity increasing to 0.084 m/s at the top surface of the
weld. As the magnetic flux density increases to 50 mT, the maximum fluid flow velocity and the flow pattern have not changed obviously compared to the sample with the magnetic field in 30 mT. Two characteristic points are selected from the simulation results to quantitatively analyze the influence of the magnetic field on the flow velocity. The flow velocity data of the two points were recorded in horizontal direction simultaneously for comparison. The locations of the characteristic points are displayed in Fig. 9a, while the comparison of the two flow velocities is exhibited in Fig. 9b. From Fig. 9b, it is apparent that the flow velocity in the horizontal direction increases as the flux density increases. Combined with the experimental results, it is found that the wetting angle decreases as the magnetic flux density increases. Because the minor amounts of copper being scoured from the copper side, which is verified by EDS and XRD results, the surface tension gradient of the mixed molten pool formed by the welding wire and aluminium is getting lower than that of the pure metal. Furthermore, with magnetic field assisted, a volume force produced by Lorentz force changes the main direction of the fluid flow to the horizontal direction and enlarges the velocity, which may be the main factor to cause the decrease of the wetting angle.

Moreover, by comparing Figs. 8d and 9d, it is noticeable that the Lorentz force has a stirring effect on the molten pool, accelerating the erosion of the copper interface, with a decrease in the temperature gradient and the time of high temperature. With the magnetic flux density increased to 50 mT, which enhances flow stirring and allows more Cu to spread to the molten pool, and combing the experimental results of EDS and XRD, the main IMCs’ composition of Al₂Cu and CuZn changes into the Al₄.2Cu₃.2Zn₅ ternary compounds.

5.2 Comparison between simulation and experimental results

To validate the numerical model, the comparison between simulation and experimental displayed in Fig. 10. It can be seen from Fig. 10 that the simulation results have a good agreement with the experimental results concerning width, but differences exist between the simulation and experimental results, including the geometry and wetting angle of the weld bead. One reason for this is that under high-temperature conditions, the real material properties are difficult to acquire, and the modelling are simplified by several assumptions that the molten pool is incompressible, laminar, solid–liquid, two-phase Newtonian fluid, and that the influence of the wettability of the filter wire at different magnetic field strengths is not considered.

6 Conclusion

With experimental and numerical simulation investigations, this paper studies the influence of the magnetic field on the weld profile of aluminium and copper dissimilar laser wire feed welding brazing in terms of molten pool flow and heat transfer. The primary conclusions are as follows:

1. A full factorial experiment was conducted. The results prove that the wetting angle gradually decreases as the magnetic flux density increases.
2. The average thickness of IMC layer increases with the increase of magnetic the coaxial field intensity. When the magnetic flux density increases to 50 mT, the main composition of Al₂Cu and CuZn changes into the Al₄.2Cu₃.2Zn₅ ternary compounds.
3. The simulation results have a good consistency with the experimental results concerning the width. With the coaxial magnetic field assisted, the main melt fluid flow direction of the weld bead changes into the horizontal direction. The flow velocity in the horizontal direction increases as the magnetic flux density grows.
4. The coaxial magnetic field impacts the melting fluid convection, increases the width of weld bead, improves wettability, and changes the thickness of IMC layer and IMC compounds, which demonstrates the magnetic field, surface tension, gravity, thermal convection, and Lorenz force; constitutes a hierarchy structure to control the melting pool and solidification of the welding; and finally controls the characteristics of welding beads.

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Declarations

Ethics approval Not applicable.
Consent to participate Not applicable.
Consent for publication Not applicable.
Conflict of interest Not applicable.

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