Influence of the magnetic field on the melting and solidification behavior of narrow-gap laser welding with filler wire

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Abstract
This study analyzed the influence of magnetic induction intensity on the plasma electron temperature distribution and the molten pool flow behavior by high-speed imaging and spectral analysis. With the increase in magnetic induction intensity, the plasma high-temperature center region gradually increased, and the plasma electron temperature increased from the bottom of the groove to the edge of the groove. The magnetic field showed a stirring effect on the molten pool. Certain magnetic field intensities can make the molten pool more uniform and flow more stable. Compared with the penetration depth and penetration area size of the weld with or without a magnetic field, the penetration depth and penetration area of the weld under the magnetic field increased. A certain range of magnetic induction intensity can be coupled with other process parameters to achieve an ideal effect and form a weld.

Keywords Laser welding · Magnetic field · Melting behavior · Droplet transition · Weld formation

1 Introduction
The technology of narrow-gap laser welding with filler wire has been increasingly used in laser welding [1]. Low heat input, small groove size, less filling metal consumables, and high welding efficiency are the major advantages when using narrow-gap laser welding with filler wire [2–4]. Narrow-gap laser welding with filler wire has been widely used in nuclear power engineering, equipment manufacturing, and aerospace [5–7]. In narrow-gap laser welding with filler wire, the addition of welding wire can control the composition and structure of the welding seam by changing alloying elements, thus improving the comprehensive performance of the joint, improving the fault tolerance and adaptability of laser fusion welding to welding gap, and reducing the joint heat affected zone and welding stress deformation [8–11]. However, due to the high depth-width ratio of single weld in narrow-gap laser welding with filler wire, it is difficult for the gas in the weld pool to escape during the solidification of the weld pool. In addition, the laser’s energy mainly acts on the bottom of the weld, so porosity and non-fusion defects are often found in the weld [12, 13].

The recent development of magnetic field-assisted laser welding successfully overcame these shortcomings of laser welding with filler wire [14–16]. The role of the magnetic field in laser welding could be divided into two aspects: (1) the magnetic field can improve the utilization rate of the laser and increase the welding depth by controlling the plasma with high energy density, and (2) the magnetic field can improve the weld formation and welding quality by changing the heat and mass transfer mechanism of molten pool metal [17–22].

In this work, the S32101 duplex stainless-steel plate was welded via narrow-gap laser welding with filler wire under the magnetic field generated by the Nd–Fe–B permanent magnet. The welding process was observed through high-speed imaging and spectrum analysis. The welding joint was analyzed by the macroscopic morphology analysis. Finally, the magnetic field-assisted welding mechanism was discussed.
2 Materials and experimental procedure

2.1 Materials

The S32101 duplex stainless steel with a thickness of 12 mm was selected as the base material. The sheets were milled and assembled to form a 12° trapezoidal profile with a $3 \times 5 \text{ mm}^2$ gap root, as illustrated in Fig. 1. ER-2209 was used as filler metal in the welding process, and the diameter of the welding wire was 1.2 mm. Considering the production cost and protection efficiency, 99.99% pure argon was used as the shielding gas. The chemical compositions of the S32101 duplex stainless steel and ER-2209 are shown in Table 1.

The external magnetic field was provided by a rectangular Nd–Fe–B permanent magnet with a size of $150 \times 50 \times 20 \text{ mm}^3$. The direction of magnetization was done along the thickness direction, and the maximum magnetic induction intensity on the magnet surface was 280 mT. The diagram of magnetic field-assisted narrow-gap laser welding with filler wire is shown in Fig. 2.

2.2 Experimental methods

A 6-kW, 1.064-μm IPG fiber laser was used as the primary heat source. A six-axis robot of ABB was used to perform the welding motion function. A welder of Fronius was used to supply the filler wire and provided continuous and stable wire feed along with a wire straightening device with four rollers. In addition, the macroscopic morphology and physical properties of plasma were studied by high-speed imaging and spectral analysis. The plasma macroscopic morphology and spectral diagnostic data of physical characteristics for narrow-gap laser welding with filler wire are shown in Fig. 3. The experiment was performed in the narrow-gap groove by laser welding with the filler wire. The welding parameters used in this paper are shown in Table 2.

3 Analysis of welding wire melting behavior in narrow-gap groove under magnetic field

3.1 Influence of magnetic field intensity on plasma electron temperature distribution

The laser welding was carried out in the atmospheric environment, and the plasma generated in the welding process was in the local thermodynamic equilibrium state. The plasma temperature was approximately equal to the temperature of the electron in the excited state, so the plasma temperature could be obtained by calculating the temperature of the excited state electron.

In this paper, the excitation temperature was measured by the Boltzmann diagram method. Since the laser plasma core region system belongs to the local thermodynamic equilibrium (LTE) when the spectral line changes from energy level $k$ to $i$, the number of excited plasma particles could be described by the Boltzmann function:

![Schematic diagram of the narrow-gap groove](image)

![Diagram of narrow-gap laser welding with filler wire assisted by a magnetic field](image)

| Materials | C  | Cr | Ni  | Mn  | Si  | Mo  | N   | P   | S    |
|-----------|----|----|-----|-----|-----|-----|-----|-----|------|
| S32101    | 0.029 | 21.34 | 10.60 | 5.65 | 0.57 | 0.24 | 0.19 | 0.018 | 0.002 |
| ER-2209   | 0.02 | 23.00 | 9.00  | 3.3  | 0.55 | 1.20 | 0.160 | 0.013 | 0.008 |
where $Z$ represents the ground state partition function, $n_k$ denotes the number of particles in the excited state, $n_0$ represents the number of particles in the ground state, $g_k$ indicates the statistical weight of the upper energy level, $E_k$ signifies the ionization energy of the $k$-level, $K$ represents the Boltzmann constant, and $T$ represents the electron temperature.

According to the principle of spectroscopy, when a particle transforms from a higher energy level $k$ to a lower energy level $i$, the intensity of the characteristic spectral line $I_{ki}$ produced can be expressed as

$$I_{ki} = A_{ki}hV_{ki}n_k$$

where $V_{ki}$ is the transition frequency of the characteristic spectral line, $A_{ki}$ is the transition probability of the characteristic spectral line $k$-level to $i$-level, and $h$ is the Planck constant.

Combining Eqs. (1) and (2), and substituting the elimination parameter for $n_k$, the logarithm of $\ln$ on both sides can be calculated as follows:

$$\ln \left( \frac{I_{ki} \lambda_{ki}}{A_{ki} g_k} \right) = \ln \left( \frac{n_0 \hbar c}{Z} \right) - \frac{E_k}{KT}$$

where $c$ is the speed of light, $\lambda_{ki}$ is the wavelength of the characteristic spectral line, $\ln (n_0 \hbar c / Z)$ is the constant. Using the least square method and computer software to linearly fit the $\ln \left( \frac{I_{ki} \lambda_{ki}}{A_{ki} g_k} \right)$ and $E_k$ data of multiple spectral lines, the slope of the fitted straight line obtained is $-1/KT$, and the slope is the temperature $T$ of the plasma could be obtained.

The physical characteristics of the laser wire-filled welding plasma in the narrow gap groove under the action of the magnetic field were extracted by high-speed imaging and spectral analysis. Four characteristic lines of FeI, i.e., FeI 438.84 nm, FeI 461.88 nm, FeI 465.46 nm, and FeI 520.23 nm, were used to calculate the electron temperature. The calibration of the corresponding characteristic peak spectral line is shown in Fig. 4.

![Fig. 4 Selection of characteristic peaks for temperature calculation of plasma](image)

During the single-line collection of plasma spectroscopy diagnosis, 8 collection points were included in this study, which are evenly distributed from bottom to top along the centerline of the
The #1 collection point was 0.4 mm away from the bottom of the groove, and the distance between every two adjacent test points was 1.2 mm, as shown in Fig. 5. In the test, the depth of the groove was 8 mm, so there were seven collection points located inside the groove, and the remaining one (#8 collection point) was located at outside of the groove, which was 0.9 mm away from the top surface of the groove. The #8 collection point was within the range of the plasma’s core and is used to study the boundary electron temperature of the core region of the plasma. According to the Boltzmann multi-line slope method, the plasma electron temperature distribution law at the centerline of the narrow gap groove is calculated as shown in Fig. 6.

As seen in Fig. 6, the electronic temperature distribution in the vertical direction inside the groove has a very similar trend with the distance increase from the bottom of the groove despite the different magnetic fields. In the same group, as shown in Fig. 6a, except for an “inflection point” at position #2, the overall trend of electron temperature of #1 to approximately #8 plasma decreased with increasing distance from the bottom of the groove (a). The laser-induced plasma was ejected out of the hole and entered the air. With the decay of the electron energy, the kinetic energy of the electron gradually decreases, so the overall trend of the curve conforms to the law of energy conservation. The sudden decrease of electron temperature in point #2 (inflection point) was due to that point being the intersection of light and wire. The energy changed at the “inflection point,” with the wire end melting and dripping.

Meanwhile, the wire absorbed metal vapor and plasma thermal radiation energy, which decreased the total kinetic energy of the electrons in the plasma. As a result, the temperature dropped quickly from #1 to #2. However, due to the space limitation of the narrow gap structure, the lower plasma continued to be ejected upward, bypassing the droplet at the end of the welding wire and entering into the upper space position of the droplet and reassembling, so the electronic temperature rose. In addition, the electron temperature gradient of these collection points was slight, which fully reflected the extrusion and confinement effect of the narrow gap groove on the plasma and improved the utilization rate of the laser energy.

As the magnetic induction intensity gradually increased from 0 to 120 mT, as shown in Fig. 6b, the electron temperature at positions #1 to approximately #6 showed an increasing trend, and position #1 was the closest point to the bottom of the groove. The electron temperature increased from 4909 to 5069 K with an increment of 160 K. This is because the plasma was ejected from the small hole, but the direction of electron movement was not completely parallel to the magnetic induction line of the longitudinal magnetic field. Some high-speed moving electrons cut the magnetic induction line and are subjected to the Lorentz force in the magnetic field. As a result, the electrons obtain additional kinetic energies, which cause the rise in electron temperature. The electron temperature at positions #7 and #8 first decreased and then increased. When the magnetic induction intensities were 60 and 90 mT, the electron temperatures were similar, and the minimum temperature value was at 60 mT, which are 4741 K and 4677 K, respectively. On the one hand, under the action of an external magnetic field, the plasma was compressed as a whole, which caused the decay of the kinetic energy of the plasma electrons outside the groove. On the other hand, the magnetic field had a more significant effect on the plasma when the magnetic induction intensity lay in the range between 60 and 90 mT. Under this condition, the energy concentrates inside the groove and melts the welding wire and base metal.

As shown in Fig. 5b, the multi-line acquisition method was used to diagnose the plasma in the narrow gap groove. Twenty-four locations were collected, and all the spectral
calculation results were drawn in the form of cloud diagrams. The plasma electron temperature distributions at different magnetic induction intensities are shown in Fig. 7. The plasma high-temperature center appeared at the bottom of the groove and near the intersection of the light and wire, which were the positions directly irradiated by the laser beam. Half of the laser spot was projected on the end of the welding wire, and the other half was projected on the surface of the base metal. The laser beam acts on the metal vapor above the irradiated point to excite a large number of electrons. Therefore, the electron temperature at these two places was relatively high, and the plasma electron temperature decreased from the center to the surroundings. In addition, the plasma electron temperature in the range of 60 to approximately 90 mT was more concentrated in the groove. The electron temperature in the groove ranged from 4781 to 5033 K, and the electron temperature outside the groove was lower than 4682 K.

3.2 The influence of magnetic induction intensity on the flow behavior of the molten pool

In the process of narrow-gap laser welding with filler wire, when other technological parameters are constant, the molten pool height increases with the increase of magnetic induction intensity, which indicates that the stability of molten pool flow is strengthened. Under the action of Lorentz force, the magnetic field interacts with the plasma with high energy density in the laser keyhole, and the magnetic field can stir the molten pool and stabilize the flow state of the molten pool liquid surface by controlling the swing of the keyhole. The evolution of the stability of the molten pool level under the action of a magnetic field is shown in Fig. 8. 

Figure 8a represents the state of the molten pool with no magnetic field, while Fig. 8b–d represent the state of the molten pool under different applied magnetic fields ($B_1 < B_2 < B_3$). An appropriate magnetic field can relieve the violent shock of the molten pool during the droplet transition and keep the liquid level relatively calm. The liquid level increases from $h_0$ to $h_1$ with the magnetic field from $B_0$ to $B_2$. However, with the further increase of the magnetic field to $B_3$, the liquid level decreases to $h_3$. The stirring effect of the magnetic field on the molten pool accelerates the movement of the fluid in the molten pool, causing the liquid level to become unstable, resulting in $h_2 > h_3$.

Duplex stainless steel contains a ferritic structure and therefore has weak ferromagnetism. Under the action of the magnetic field, molten pool metal in a high-temperature melting state is magnetized to form a magnetic fluid. Magnetic fluid and laser holes in molten pools interact with the magnetic field together, and the dynamic behavior of the hole has a great influence on molten pool metal flow. In this case, the magnetic fluid's interaction with the laser keyhole, and the magnetic field can stir the molten pool and stabilize the flow state of the molten pool liquid surface by controlling the swing of the keyhole.
study, high-speed cameras were used to take fixed shots of the molten pool of magnetic field-assisted laser self-fusion welding on the surface of the test plate to characterize the flow behavior of the molten pool in the laser welding process under the action of a magnetic field, as shown in Table 4.

After a short time of laser focusing on the surface of the plate, a photoinduced hole appeared in the center of the molten pool, and the hole remained relatively stable in the welding process until the end of the welding. Taking the laser hole as the reference position, the liquid metal in the molten pool showed different flow behavior under different magnetic induction intensities. As shown in sequence images (a), without a magnetic field, liquid metal melts forward together in the direction of welding holes on the front, after which front metal volume increases gradually, and then, under the action of gravity level, the flow is reduced backward. At this point, a large number of cutting-edge metals instantly came back into contact with laser holes, causing wild shocks to occur in the molten pool. (b) shows that when the magnetic induction intensity is 60 mT, there is no accumulation and backflow of the metal at the front of the small hole in the welding process, the liquid level of the molten pool remains calm, and the welding process is very stable. In (c), the magnetic induction intensity is 90 mT, and obvious ripples can be seen on the molten pool metal liquid surface of the molten pool first. The convergence and backflow behavior of the metal at the front of the hole appears again, but the shock degree of the molten pool caused by the backflow of the metal at the front becomes significantly smaller. In (d), when the magnetic induction intensity is 120 mT, the molten pool liquid flows too fast toward the front of the laser hole, resulting in a large amount of metal spatter, and the welding process is extremely unstable. When a magnetic field is applied, the plasma electron temperature rises under the action of Lorentz force (Fig. 7). The high-temperature center is concentrated near the bottom of the groove, and the intersection of the light and wire intersection, which makes the metal droplet transition instantly cause violent vibrations on the surface and inside of the molten pool, and the molten pool liquid level becomes more up and down. The distance between the lowest position of the molten pool and the upper surface of the bottom of the groove gradually increases with the magnetic field increases, and the range of the high-temperature central area in the groove gradually increases. The vibration of the molten pool becomes more intense, and the height of the molten pool increases accordingly. When the magnetic field intensity increases above the critical value, the high-temperature central area becomes too large to keep the surface of the molten pool stable, which causes the thickness of the molten pool to decrease.

4 Analysis of magnetic field on weld formation

The magnetic field has no direct effect on the laser beam itself, but the magnetic field can affect the absorption of laser energy by the welding wire and the base metal by controlling the dynamic behavior of the plasma and the electron temperature, thereby affecting the weld formation. Figure 9 shows the macroscopic morphology of the cross-section of

| Parameter | Image of molten pool flow |
|-----------|---------------------------|
| (a) B=0mT | ![Image](image1.png)       |
| (b) B=60mT| ![Image](image2.png)       |
| (c) B=90mT| ![Image](image3.png)       |
| (d) B=120mT| ![Image](image4.png)       |
the weld with no magnetic field and the applied magnetic induction intensity $B$ from 60 to 120 mT. Figure 9a is the weld obtained without a magnetic field. Since the wire feeding speed was 5.5 m/min and the welding speed was 0.48 m/min, the filler metal of the welding wire was too large, and the base material could not absorb and utilize the laser beam energy. Poor fusion of the solid–liquid boundary occurred between the filler metal and the base metal, resulting in the sidewall non-fusion. Figure 9b–d shows the welds obtained with the magnetic field $B$ of 60 mT, 90 mT, and 120 mT, respectively, which were uniform and harmonious, and no obvious welding defect was found. It can be seen that the curvature of the upper surface of the weld decreases with the magnetic field increasing from 60 to 120 mT. The upper surface was flat of the weld with a 120 mT magnetic field. When the magnetic induction intensity is 60 mT, the upper surface of the weld is obviously concave, which is more advantageous for multi-pass filler wire welding.

As shown in Fig. 9a, without the assistance of a magnetic field, serious sidewall non-fusion appears on both sides of the root of the weld despite the uniform and symmetrical weld morphology. After the magnetic field was added, the welding defect disappeared, as shown in Fig. 9b–d. The magnetic field changes the macroscopic morphology and physical properties of the plasma, and the laser hole that ejects the plasma is jittered, thereby continuously stirring the molten pool. This improves the absorption and effective utilization of the laser beam energy by the molten metal in the groove, causing the molten pool to expand and flow to the roots on both sides of the groove under the guidance of the laser hole, which accelerates the heat conduction between the fluid and the solid. This makes the unfused part melt, and the weld expands on both sides. The evolution process is shown in Fig. 10.

To compare the penetration depth and width under different magnetic fields, the distance between the lowest position of the groove and the lowest position of the molten pool was defined as the penetration depth. The penetration width of the molten pool on the lowest plane of the groove was defined as the penetration width, as shown in Figs. 11 and 12.

![Fig. 10 Keyhole stirring evolution process assisted by a magnetic field](image)

**Fig. 10** Keyhole stirring evolution process assisted by a magnetic field

![Fig. 12 Effect on penetration and width on filling weld of magnetic induction intensity](image)

**Fig. 12** Effect on penetration and width on filling weld of magnetic induction intensity
shown in Fig. 11. Moreover, Fig. 12 shows the geometric dimension evolution under the melting groove with different magnetic fields. It can be seen that the effect of the magnetic field on the filled weld does not proportionally change. When the magnetic induction intensity increases from 0 to 60 mT, both the penetration width and depth of the weld show an increasing trend. From 60 to 90 mT, the penetration width decreases slightly with the magnetic induction intensity, while the penetration depth increases obviously to the maximum. The weld penetration width and depth gradually decrease with the further increase of the magnetic induction intensity from 90 to 120 mT. Therefore, the macro morphology of the filled weld and the size of penetration depth, width, and area were comprehensively analyzed. The weld forming was better when the applied magnetic induction intensity was between 60 and 90 mT, and the weld forming was best when the magnetic induction intensity was 90 mT.

5 Conclusions

The main findings of this study are: (1) With the increase of the magnetic induction intensity, the plasma high-temperature center region gradually increases, and the plasma electron temperature decreases from the bottom of the groove to the edge of the groove. (2) The magnetic field has a stirring effect on the molten pool. A certain magnetic field intensity can make the molten pool more uniform and the molten pool flow more stable. (3) Compared with the penetration depth and penetration area size of the weld with or without a magnetic field, the penetration depth and penetration area of the weld under the magnetic field increases. (4) A certain range of magnetic induction intensity can be coupled with other process parameters to achieve an ideal effect, and the weld is well formed.

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Author contribution All authors contributed to the study’s conception and design. Material preparation, data collection, and analysis were performed by Yong Zhao, Jiasheng Zou, Xin Liu, and Yanfei Pan. The first draft of the manuscript was written by Juan Fu, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The data used to support the findings of this study are available from the corresponding author upon request.

Declarations

Competing interests The authors declare no competing interests.

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