Temperature and stress field analysis of 7075 aluminum alloy laser-MIG composite welding

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Abstract

In this paper, Simufact.Welding simulation software is used to simulate the temperature field and stress field of 6 mm thick 7075 aluminum alloy laser-MIG composite welding, and the influence of different welding process parameters on the temperature field and stress field is explored for simulation and analysis. By using welding simulation software, a numerical simulation model is established, and reasonable welding process parameters are selected to analyze the simulation results. The influence law of welding parameters on temperature field and stress field of laser-MIG composite welding of 7075 aluminum alloy was explored, plotting the temperature field distribution of the weldment during heating and cooling, and analyzing the temperature change of the molten pool and the nearby area in each time period. The thermal cycle curves of each point on the workpiece were recorded and compared with the simulation results to verify the accuracy of the temperature field simulation. A cloud diagram of the dynamic change characteristics of stress in the workpiece during welding heating and cooling is drawn to analyze the influence of welding process parameters on the residual stress in different directions.

Introduction

7075 high-strength aluminum alloy is a promising lightweight material, due to its high strength, good plasticity and other characteristics, it is widely used in aerospace, railway and other fields. [1, 2]. Welding is one of the most important connection methods of 7075 aluminum alloy, due to the unique physical and chemical characteristics of 7075 itself, the possibility of various welding problems in the welding process, such as: its strong oxidation, easy to form alumina (Al₂O₃) film on the surface of the material, and easier to form slag inclusion in the weld; Large thermal conductivity and specific heat capacity, fast heat dissipation in welding heating process, requiring greater welding heat input; It is easy to produce hydrogen pores and cracks.

In recent years, the proposal and application of laser-MIG composite welding has not only successfully solved many problems in aluminum alloy welding, but also its high welding efficiency, good joint performance, low requirements for workpiece assembly accuracy, and has the advantages of arc welding and laser welding, and has been more and more widely used in industry [3]. Due to the high cost of laser welding, if the exploration of the process in the early stage adopts the actual welding operation, it will cause a large waste [4, 5]; In the laser-MIG welding process, defects such as porosity and porosity are easily produced. The use of numerical simulation to explore the welding process of the laser-MIG welding process and to study the temperature field and stress field during laser-MIG welding of aluminium alloys can save costs and be more efficient [6, 7]. Compared with experiments, numerical simulation has the characteristics of low cost and high efficiency, which is very important to guide the exploration of the process in the early stage. At present, researchers at home and abroad have carried out a large number of process exploration simulations of laser-MIG welding by means of numerical simulation [8–10], which has played a very obvious role in reference to the actual welding. Many researchers have carried out detailed numerical simulation on the laser-MIG composite welding of aluminum alloy [11–15], but in the process of 6 mm thick 7075 aluminum alloy laser-MIG composite welding, the influence of welding
The influence of welding process parameters on temperature field and stress field is basically not studied [16–19]. The influence of welding process parameters on temperature field and stress field is studied by numerical simulation [20–24].

1 Experimental materials and methods

1.1 Materials

This simulation material uses domestic 6 mm thick 7075 aluminum alloy, after solid solution and complete artificial aging treatment (T6 state). The low melting point of magnesium (Mg) in the parent metal is easy to burn during the welding process, therefore, the welding consumables are chosen to be close to the parent metal composition and contain Mg elements of ER5356, the main components are shown in Table 1.

| Chemical composition of parent metal and welding consumables (wt.%) |
|-----------------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Cu   | Mg   | Mn  | Si  | Fe  | Zn  | Ti  | Cr  | Al  |    |
| 7075 | 1.49 | 2.64| 0.05| 0.06| 0.17| 5.69| 0.03| 0.21| Bal.|
| ER536 | 0.10 | 4.80| 0.15| 0.25| 0.40| 0.10| 0.12| 0.10| Bal.|

1.2 Methods

The welding equipment system for a series of welding experiments of laser-MIG composite welding is mainly based on the disc LASER of TRUMPF LASER TRUDISK 10002 and the MIG welding machine of Fronius TransPlus Synergic-4000. At the same time, there are positioner, ABB robot, operating handle and other auxiliary equipment. In this MIG welding, the current and voltage of MIG welding were adjusted by controlling the wire feeding speed. With reference to the literature consulted, the laser power was selected as 3 KW and the wire feeding speed as 12 m/min. With these parameters as a comparison, the verification experiment was designed as shown in Table 2.
Table 2
Laser-MIG welding process parameters

<table>
<thead>
<tr>
<th>Case</th>
<th>Speed (mm/s)</th>
<th>Power (KW)</th>
<th>Current (A)</th>
<th>Voltage (V)</th>
<th>b (mm)</th>
<th>r_e (mm)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>3</td>
<td>200</td>
<td>24</td>
<td>4.97</td>
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<td>0.43</td>
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<td>3</td>
<td>200</td>
<td>24</td>
<td>4.90</td>
<td>0.44</td>
</tr>
<tr>
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<td>18</td>
<td>3</td>
<td>200</td>
<td>24</td>
<td>4.86</td>
<td>0.41</td>
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<td>3</td>
<td>200</td>
<td>24</td>
<td>4.80</td>
<td>0.42</td>
</tr>
<tr>
<td>6</td>
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<td>2</td>
<td>200</td>
<td>24</td>
<td>4.99</td>
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<td>7</td>
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<td>4</td>
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<td>24</td>
<td>5.13</td>
<td>0.43</td>
</tr>
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<td>3</td>
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<td>3</td>
<td>240</td>
<td>24</td>
<td>5.13</td>
<td>0.41</td>
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</tbody>
</table>

Aluminum alloy in the laser-MIG composite welding, the protective gas should be selected pure Ar, the beam and the welding torch axis Angle [25] is an important parameter of the design of the composite welding torch, generally 30° ~ 45°, the length of the welding wire is generally selected 15 mm ~ 22 mm. The change of welding current in the welding process is regulated by changing the wire feeding speed, this makes it easier and faster to receive information about the welding process, can be better and safer to adjust the welding parameters. In this paper, the welding method used for the plate butt welding, welding laser in the front, the arc in the back; light wire spacing 3 mm, the amount of off-focus − 1 mm, the shielding gas is 99.99% of argon (Ar), gas shielding flow rate of 20 L/min, the welding gap of 0.8 mm; beam and torch axis angle of 30 °; wire dry elongation of 15 mm.

In order to verify the accuracy of the simulation, the method of embedding a thermocouple before welding is used to verify the temperature variation trend of some specific points corresponding to the simulation under the same conditions. One end of the thermocouple is fixed on the workpiece by resistance spot welding, and the other end is connected to the EX4000 multi-channel temperature recorder. The temperature recorder is used to collect the change of the thermal cycle curve during the welding process, and the temperature is recorded once a second. The recording results are fitted by Origin software. In order to improve the accuracy of measurement, try to ensure that the front section of the thermocouple is perpendicular to the workpiece when spot-welding. A total of 8 thermocouples are installed. The position of the thermocouple is the stable heat source area in the middle of the weldment, The thermocouple installation position is shown in Fig. 1.

2 Numerical simulation model
2.1 Heat source model
In the simulation of laser-MIG composite Welding, the heat source is the coupling of MIG welding heat source and laser heat source. "Double ellipsoid heat source model" [26, 27] is adopted in MIG welding heat source model, and "three-dimensional cone heat source model" is adopted in laser heat source. The two heat sources are coupled in Simufact.Welding software, two welding guns are used to weld the workpiece, respectively corresponding to two heat sources.

2.2 Geometric models and meshing
The geometric model shown in Fig. 2a was built with SOLIDWORKS 2016 software. The model size was 150×120×6 mm. After the model is established, Hypermesh software is imported for mesh division. In order to ensure good efficiency and accurate results, uneven grid division was adopted in this simulation. The smaller the grid near the weld, the minimum mesh size was 1 mm, and then the transition to 2 mm, 4 mm and 6 mm successively. The grid type in the base metal area was hexahedral grid, and the weld area was tetrahedral and hexahedral mixed grid. The mesh size is 1 mm, with total nodes 82585 and total units 70168. The mesh division is shown in Fig. 2b, c.

3 Results and discussion

3.1 Simulation results and analysis of temperature field

3.1.1 Verification of welding thermal cycle curve
The welding parameters are MIG welding current 206 A, voltage 24 V, wire feed speed 12 m/min, laser power 3 KW, welding speed 15 mm/s, 0.8 mm welding gap. The position of tracking points selected in the simulation and experiment is the same relative position, as shown in Fig. 1. The simulation and actual welding thermal cycle curves are shown in Fig. 3. There is a horizontal area at the front end of both the simulation and experiment tracking points. The reason is that when the heat source first acts on the workpiece, the heat does not reach the tracking point area in time, and the temperature is still at room temperature. The temperature rises gradually as the heat source moves forward, reaching a maximum at the tracking point close to the heat source. As the heat source gradually moved away from the tracking point, the temperature dropped rapidly, and the temperature drop was particularly significant within 30 s after the end of 10 s welding, and the temperature began to drop slowly after 30 s. The simulated temperature drops more slowly than that measured by experiment, because the convection heat transfer coefficient used in the simulation is the convection heat transfer coefficient in the natural convection state, and the influence of the protective gas is ignored. In the actual welding, the protective gas and exhaust fan make the workpiece in a forced convection state, and the heat dissipation is faster, so the actual measured temperature changes faster. The overall change trend of experiment and simulation is consistent, indicating that the model is reasonable.

3.1.2 Dynamic change characteristics of temperature field
Figure 4 shows the temperature field variation characteristics of case 3 at different times during the welding heating process. As can be seen from Fig. 4a, the heat source just acted on the workpiece, the heating range is small, the high temperature region is mainly concentrated in the vicinity of the heat source, the heat source directly acting on the region of the metal quickly melted to form a molten pool, due to the shorter time, the temperature diffusion range is small, close to the heat source, the higher the temperature, away from the heat source of the region of the temperature does not have obvious changes. At the moment of 1.70 s, as shown in Fig. 4b, the heat source acts steadily. Due to the heat conduction effect of the workpiece, the heat gradually diffused around. With the movement of the heat source, the molten pool area leaving the center of the heat source gradually cooled, forming a weld. Then, as the heat source moves forward, the temperature "drag tail" is formed, and the temperature gradually diffuses to the parent metal around the weld, as shown in Fig. 4c. At 10 s, the temperature continues to spread, but the center of the heat source is far away from the weldment, at which point the heating process ends.

Figure 5 shows a cloud diagram of the characteristic distribution of the temperature field during the cooling process of case 3. The heat source center left the workpiece at 10 s, and at 11.84 s, the double ellipsoidal heat source did not completely leave the workpiece, and the temperature at the tail of the welded part was high. At this time, the molten pool formed may slowly flow out of the workpiece, resulting in defects such as depression. At 20.00 s, the heat source is completely detached from the workpiece. At this time, the temperature at the end of the weldment is the highest, 333.07 °C, which is higher than the temperature at other positions, and the overall temperature of the workpiece drops significantly. At 101.11 s, the maximum temperature drops to 97.44 °C, and the temperature along the weld is the highest. Until the time of 660 s, the workpiece temperature is basically cooled to room temperature, which is 20.24 °C.

3.2.3 Effect of welding speed on temperature field

Welding speed has the greatest influence on the temperature field, in order to investigate the effect of different welding speed on the temperature field, control the other process parameters remain unchanged, change the welding speed, designed as shown in Table 2 case 1-case 5 (different welding speeds) five sets of simulations. The temperature field distribution at the same time (quasi-steady state) under different welding speeds is shown in Fig. 6a, b, c, d, e. The molten pool corresponding to the highest temperature is the largest molten pool shape, which is taken as a reference object to avoid errors caused by manual determination of the molten pool position.

Figure 6 Temperature field cloud image at different speeds at 6s time. A 9 mm/s, b 12 mm/s, c 15 mm/s, d 18 mm/s, e 21 mm/s

As can be seen from Fig. 6, under the action of different welding speeds, the temperature field change characteristics are similar, are along the centre of the heat source, the temperature is a gradient distribution, the surface of the molten pool is "elliptic-like", and the smaller the welding speed, "ellipse" the larger, the weld more molten metal, and the larger the weld pool. The front part of the weld has high
energy density and high temperature, while the back part of the weld has low energy density and low temperature. The overall shape of the weld pool section is wide up and narrow down. When the welding speed is 9 mm/s and 12 mm/s, too much molten metal in the weld pool is easy to cause burning-through, pits and other defects. When welding at 15 mm/s, the weld is the best, while when welding at 18 mm/s and 21 mm/s, there are defects of incomplete welding.

Figure 7 shows the schematic diagram of tracking points. The established model is completely symmetrical and the left and right materials are consistent. The heat source stability area in the middle of the welding plate is perpendicular to the side of the weld, close to the weld, with the same distance between them, and five tracking points are taken.

Figure 8a shows the maximum temperature distribution of the five tracking points in the welding process at different welding speeds, and Fig. 8b shows the thermal cycle curve of tracking point 2 at different welding speeds. As can be seen from Fig. 8a, when the welding speed is increased from 9 mm/s to 21 mm/s, the highest temperatures at the tracking point 1 are 840.8°C, 685.1°C, 576.6°C, 508.6°C and 461.8°C, which indicates that the lower the welding speed, the higher the energy, the larger the molten pool area, and the higher the temperature at the corresponding tracking point. When the welding speed is 9 mm/s, the highest temperature of tracking point 1 is 840.8°C, and the highest temperature of tracking point 5 is 447.6°C, indicating that the closer to the weld, the higher the temperature and the more concentrated the energy density. With the increase of the distance from the weld, the energy density decreases, and the maximum temperature value that can be achieved also decreases rapidly, and the temperature difference of equidistant tracking point is smaller. According to Fig. 8b, under different welding speeds, the peak temperature reached at tracking point 2 is different from the required time. The faster the speed, the shorter the time to reach the peak temperature, and the lower the peak temperature, and there are characteristics of fast cooling in the high temperature region and slow cooling in the low temperature region.

Figure 8 Temperature distribution curve of tracking points. a The maximum temperature of the five tracking points, b Thermal cycle curve of tracking point 2

3.2 Simulation results and analysis of stress field

3.2.1 Effect of welding speed on residual stress

This section discusses the influence of welding speed on lateral and longitudinal residual stress. The tracking points shown in Fig. 9 are taken along the y axis (parallel to the weld) and the x axis (perpendicular to the weld) respectively. The tracking points obtained along the y axis (parallel to the weld) are 8 mm from the weld center, and the selected tracking points perpendicular to the weld direction are obtained in the heat source stability input region in the middle of the workpiece.

Figure 10 shows the transverse residual stress distribution of tracking points taken along the x direction (perpendicular to the weld direction) and the y direction (parallel to the weld analysis) at different welding speeds. The width of one side of the weld plate is 60 mm, from Fig. 10a, it can be seen that at both ends
of the workpiece away from the centre of the weld, the transverse residual stress value is almost 0 MPa, and the closer to the weld, the larger the transverse residual stress value is, and it reaches the maximum value at the edge of the weld, and then after the peak value, it decreases rapidly, and the centre of the weld reaches a very small value. The peak transverse residual stresses were 192.3 MPa, 172.2 MPa, 177.7 MPa, 164.3 MPa, and 145.7 MPa when the welding speed was varied from 9 mm/s to 21 mm/s. The peak transverse residual stresses in the vicinity of the weld seam were gradually reduced as the welding speed increased, and the overall value of the transverse residual stresses showed a tendency to decrease as well. As can be seen from Fig. 10b, the transverse residual stress in the middle of the welded plate is mainly tensile stress, while the transverse residual stress at both ends of the welded plate is mainly compressive stress, and the stress value presents a "cap-like" distribution with large at both ends and small in the middle. When the welding speed changes from 9 mm/s to 21 mm/s, the peak transverse residual stress is mainly concentrated at both ends of the workpiece, which are characterized by compressive stresses, and the maximum compressive stresses are −120.06 MPa, -120.86 MPa, -119.60 MPa, -116.21 MPa, -116.51 MPa, which are very close to each other, and the difference is very small. The transverse residual stress in the center of the workpiece is characterized by tensile stress. When the welding speed changes, the peak value of the transverse residual stress is 80.65 MPa, 72.84 MPa, 70.06 MPa, 62.72 MPa, 53.29 MPa, and the peak value of the transverse residual stress decreases with the increase of the welding speed. And the maximum tensile stress value appears near 90 mm-100 mm from the X-axis, slightly close to the back end of the workpiece (left end), not the absolute center, because the residual temperature of the welding part after the workpiece is higher, after the same time of cooling, the temperature difference of the latter part is slightly larger, leaving a greater residual stress. Overall, the transverse residual stress decreases with the increase of welding speed.

Figure 11 shows the longitudinal residual stress distribution of tracking points taken along the x direction (perpendicular to the weld direction) and the y direction (parallel to the weld analysis) at different welding speeds. It can be seen from Fig. 11a that the longitudinal residual stress perpendicular to the weld is manifested as compression at both ends and tension in the middle. As the compression stress at both ends decreases with the distance from the weld center, the compressive stress gradually decreases until it becomes 0 MPa and then becomes tensile stress, reaching the maximum value at the edge of the weld and gradually decreasing near the weld center. The smaller the welding speed, the greater the compressive stress and tensile stress of the parent metal and the heat affected zone, and the tensile stress of the weld and the near seam zone increases with the increase of welding speed. When the welding speed is from 9 mm/s to 21 mm/s, The peak value of longitudinal residual stress near the joint was 286.1 MPa, 303.3 MPa, 297.5 MPa, 304.9 MPa, and 305.0 MPa, which basically showed an increasing trend.

As can be seen from Fig. 11b, the longitudinal residual stress in the direction of parallel to the weld was "hat-shaped" distribution, weld plate on both sides of the near-zero, along the direction of the weld plate gradually increased in the middle of the position near the location of the weld plate to maintain a stable, mainly tensile stress characteristics of distribution. The welding speed has little effect on the peak value of longitudinal residual stress in this direction, which is basically about 140 MPa, but it has an effect on
the peak stress region of tensile stress. The greater the speed, the larger the peak stress region, that is, before reaching the stable stress value region, the greater the welding speed, the greater the longitudinal residual stress value at the same position.

3.2.2 Effect of laser power and welding current on residual stress

The transverse residual stress distribution of tracking points taken along the x direction (perpendicular to the weld direction) and the y direction (parallel to the weld direction) with different laser power and different welding current is shown in Fig. 12. From Fig. 12a, b, it can be seen that the effect of different laser power on the value of transverse residual stress perpendicular to the direction of the weld is not obvious, and the value of transverse residual stress at each position increases slightly with the increase of laser power. The value of transverse residual stress in each position perpendicular to the direction of the weld increases when the welding current becomes larger, and the magnitude of change is larger than that of the laser power, which indicates that the welding current has a greater influence on the value of transverse residual stress perpendicular to the direction of the weld within the range of welding parameters. The reason may be that the laser power mainly acts in the depth direction and has a small influence on the welding width, and the laser heat source has a smaller range of action, while the welding current has a greater influence on the welding pool width direction and a larger range of action, resulting in a larger range of existing temperature gradient, so the welding current has a more obvious influence on the residual stress value.

Figure 12c, d respectively show the influence of different power and current on the transverse residual stress parallel to the weld direction in laser-MIG welding of aluminum alloy. Parallel to the direction of the weld distribution of transverse residual stress is "cap-shaped", the middle of the tensile, the two ends of the pressure, and there is a relatively stable distribution of tensile stress in the middle of a section of the zone. The transverse residual stress in this direction increases with the increase of laser power and welding current, and the effect of welding current on residual stress is greater than that of laser power. In the stable stage of tensile stress, the residual stress value increases slightly, because in the latter part of the welding workpiece, due to the heat conduction, the temperature in the corresponding area is higher, resulting in a larger temperature difference, and the residual stress value is also slightly increased.

Under the action of different laser power and different welding currents, the longitudinal residual stress distribution of tracking points taken along the x direction (perpendicular to the weld direction) and the y direction (parallel to the weld direction) is shown in Fig. 13. As can be seen from Fig. 13a, b, with the increase of laser power and welding current, the longitudinal residual stress perpendicular to the weld direction increases slightly, with a small increase, and the welding current has a slightly greater impact. The workpiece is compressed at both ends, the middle is strained, and the maximum value appears in the weld edge area (about −6 mm and 6 mm), and the weld area is larger than the near seam area, which may be caused by the difference between the weld filler material and the base material elastic modulus and the coefficient of thermal expansion. From Fig. 13c, d can be seen, parallel to the weld direction distribution of longitudinal residual stress was "hat-shaped" distribution, mainly for the performance of
tensile stress characteristics, there is a stable tensile stress stage in the middle. With the increase of laser power and welding current, the longitudinal residual stress growth stage of the stress value is reduced, and the effect of welding current is more significant, the peak stress value has little effect, basically in the 140 MPa or so.

**Conclusion**

The effects of welding process parameters on the temperature and stress fields of laser-MIG welding of aluminum alloys were investigated by varying the welding speed, laser power and welding current, and the following conclusions were drawn:

1. The trend of thermal cycle curve and peak temperature measured by simulation and experiment are basically the same, which indicates that the simulation is accurate and reliable. In the process of welding heating, the temperature gradient is obviously distributed with the distance from the center of the heat source, and with the movement of the heat source, the molten pool area leaving the center of the heat source gradually cools, forming a weld. The heat source acts in the center of the weld in an "ellipsoid" shape. With the heat source moving forward, a "tailing" of temperature is formed, and the temperature gradually diffused to the parent metal around the weld. During the cooling process, the temperature changes dramatically in the first 20 s, rapidly cooling to about 330 °C, and basically cooling to room temperature at about 660 s.

2. Under different welding speed conditions, the temperature field change characteristics are similar, all along the center of heat source, temperature gradient distribution, the surface of the molten pool is "elliptic", and the smaller the welding speed, the larger the "elliptic surface", the more metal the weld melts, the larger the molten pool. When welding at 15 mm/s, the molten pool forming is the best, and the predicted results are in agreement with the experimental results. The closer the weld is, the higher the temperature is and the more concentrated the energy density is. With the increase of the distance from the weld center, the energy density decreases, and the peak temperature that can be reached at the corresponding position decreases rapidly, and the temperature difference of the tracking point with equal distance is smaller.

3. The transverse residual stress decreases with the increase of welding speed, and increases with the increase of laser power and welding current, but the change range is small, and the effect of welding current is slightly greater than that of laser power.

4. The longitudinal residual stress perpendicular to the weld shows the characteristic distribution of "pressing first and pulling later", and increases with the decrease of the distance from the weld center. The peak value of longitudinal residual stress in this direction is concentrated at the edge of the weld, and decreases with the increase of welding speed, and increases with the increase of welding current, and the laser power has little influence on it. The longitudinal residual stress parallel to the weld is a "cap" distribution, mainly manifested as tensile stress, and its value increases with the increase of welding speed, and decreases with the increase of welding current. The laser power has little influence on it.
Declarations

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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