Process optimization and thermo-plasticity analysis of laser welding-MIG for 6063 aluminum alloy

Yi Feng*
School of Automotive Engineering, Liuzhou Vocational & Technical College, Liuzhou, China
*Corresponding author e-mail: fy052011307@163.com

Abstract. The process of laser-MIG welding for 6063 aluminum alloy was optimized by the first regression orthogonal design method. Gleeble-1500 thermal simulator was used to check the thermo-plasticity. The brittleness temperature range of 6063 aluminum alloy was 470-620°C. On the basis of process optimization parameters, the welding currents: 150A, 180A and 210A, were selected for experiments. The types and causes of hot cracks were researched by means of SEM and EDS. The results show, with increasing the heat input, the welding thermo-plasticity decreases first and then increases. The crack is transformed from the liquefied crack to crystalline crack in the weld metal area. When the welding current is 180A, that is, the heat input is 3.0KJ/cm, the welding joint can obtain the best weld penetration. Its thermal plasticity is the smallest and the welding thermal crack is crystalline crack.

1. Introduction

As a super-hard alloy, 6063 aluminum has many merits. For example, it has lowly density, high intensity, good toughness and processing property. It is widely used in aerospace, transportation, naval vessels and weapons etc.[1] However, 6063 aluminum alloy has a high thermal conductivity and a large coefficient of linear expansion. In the process of welding, the molten pool metal presents a low melting point eutectic phase with cooling process, which leads to the cracking[2]-[4]. In recent years, a lot of research work has been carried out on metal welding technology of 6063 aluminum alloy at home and abroad. Zhen wen[5] used TIG welding technology to study the performance of 6063 aluminum alloy welding joint, determine the “over aging” phenomenon of the softening area of the joint, and put forward the improvement measures. Zou jiasheng[6] studied the heat treatment process of the welding joint of 6063 aluminum alloy, and improved the weld-ability of the 6063 aluminum alloy. Chen maojun[7] proposed the preventive measures of MIG on the defects of welded joints of 6063 aluminum alloy. Laser-MIG composite welding has the advantages of fast welding speed, stable welding process, no splash, little hole and grain etc. It has widely application perspective in the equipment manufacturing. By reasonably choosing welding parameters, the weld can be fully penetrated and well formed, and the hot crack can be effectively controlled[7]-[13]. In this work, a regression orthogonal design method is used to optimize the welding process parameters of 6063 aluminum alloy plate laser-MIG composite welding. On the basis of the optimized parameters, the thermal plasticity of 6063 aluminum alloy and its welded joint is evaluated through the welding hot crack experiment. Thus, the laser-MIG composite welding method is used in the on-board aluminum alloy. The application of car body manufacturing provides certain research basis.
2. Optimization of laser-MIG hybrid welding process based on orthogonal test

2.1. Orthogonal test conditions

6063-T6 aluminum alloy plate is used as the experimental parent material (see in Fig. 1). The thickness is 10 mm, the length and width is 50 × 200 mm. The laser-MIG hybrid welding robot system is used for automatic welding. The main parameters of MIG welding are used as evaluation indexes. The brand name of Er4043, an aluminum alloy welding wire with a diameter of 1.2 mm will be selected. The joint is 1 groove butt welding. The blunt edge and clearance are all zero, and the protective gas flow rate is 22~26 L/min. the chemical components of the parent material and welding wire is shown in Table 1.

![Figure 1. 6063-T6 aluminum alloy chart](image)

Table 1. Chemical components of 6063 aluminum alloy and welding wire (mass fraction, %)

| Number | name         | Si  | Fe  | Cu  | Mn  | Mg  | Cr  | Zn  | Ti  | Other | Al  |
|--------|--------------|-----|-----|-----|-----|-----|-----|-----|-----|-------|-----|
| 1      | base metal   | 0.2-0.6 | 0.35 | 0.1 | 0.1 | 0.45-0.9 | 0.1 | 0.1 | 0.1 | 0.5 allowance |
| 2      | Er4043 Welding wire | 0.4-0.6 | <0.8 | 0.3 | 0.05 | 0.05 | - | 0.1 | <0.02 | - allowance |

2.2. Parameter optimization results based on orthogonal test

According to the normality of parameters affected by welding process, the weld penetration and weld width are taken as the evaluation indexes, and the welding parameters are optimized by the orthogonal experimental method of one-time regression. The main influence parameters of weld penetration and weld width include MIG current, welding speed and laser power. According to the number of factors and levels, the L9(3^4) orthogonal table is selected, and 9 test plans can be determined.

Table 2. Orthogonal test factor level table

| level | A Electric current (A) | B welding speed (M/min) | C laser power (KW) |
|-------|------------------------|-------------------------|-------------------|
| 1     | 150                    | 2                       | 2500              |
| 2     | 180                    | 3                       | 3000              |
| 3     | 210                    | 4                       | 3500              |

The range analysis method is used to calculate the data. The results are shown in Table 3.
Table 3. Orthogonal test results

| Test number | 1  | 2  | 3  | Melting depth(I) | Melting width(II) |
|-------------|----|----|----|------------------|-------------------|
| 1           | 1  | 1  | 1  | 3.08             | 7.23              |
| 2           | 1  | 2  | 2  | 3.25             | 6.54              |
| 3           | 1  | 3  | 3  | 4.53             | 6.02              |
| 4           | 2  | 1  | 2  | 5.02             | 8.02              |
| 5           | 2  | 2  | 3  | 5.65             | 7.10              |
| 6           | 2  | 3  | 1  | 2.98             | 6.12              |
| 7           | 3  | 1  | 3  | 6.32             | 9.05              |
| 8           | 3  | 2  | 1  | 4.03             | 7.33              |
| 9           | 3  | 3  | 2  | 5.28             | 6.40              |

I Sum 1: 10.86 14.42 10.09 Optimization: A3B1C3
I Sum 2: 13.65 12.93 13.55
I Sum 3: 15.63 12.79 16.50
Range: 4.77 1.63 6.41

II Sum 1: 19.88 24.30 20.68 Optimization: A1B3C3
II Sum 2: 21.24 20.97 20.96
II Sum 3: 22.78 18.54 22.17
Range: 2.90 5.76 1.49

From table 2, it can be seen that, for the influence factors of welding depth, the maximum difference of laser power is the most important factor, and the other factors are welding speed, MIG welding current, and the best optimization scheme for obtaining better weld penetration is A3B1C3. That is to say, the MIG welding current is 210A, the welding speed is 2 m/min, and the laser power is 3500KW. For the weld width, in order to reduce the heat impact zone of the weld, the smaller value, the influencing factors are the welding speed, the MIG welding current and the laser power in turn. The best optimization scheme is: A1B3C3.

3. Experimental analysis of laser-MIG hybrid welding based on Parameter Optimization

3.1. experimental method

In order to ensure the reliability of the experiment, 6063-T6 aluminum alloy plate with thickness of 4 mm is selected for the experimental material. The supply state is solid solution and complete artificial aging treatment, that is to say, the thermal plastic test of 6063 aluminum alloy is heated to 470°C. The thermo-plastic experiment mainly analysis the section characteristics of the base material cooling stage, and takes the section shrinkage ratio as the evaluation index. That is, the sample is heated to 570°C at 10°C/s heating rate and 2s for heat preservation. Then the cooling rate of 10°C is cooled to different experimental temperatures. After 2s, the specimen is broken at the rate of 20mm/s, and the section shrinkage rate (Z) is measured at different experimental temperatures, and the Z-T curve of the cooling stage is drawn to determine the zero plastic temperature of parent material ((ND), T). The welding experiment was carried out by fishbone method. The shape and size of the specimen were shown in Figure 2. The thermal plasticity formula is as follows:

\[
A = \left( \frac{l}{l_0} \right) \times 100\% 
\]

In the formula, A is crack sensitivity, %; l is crack length, mm; l₀ is weld length, mm.

After welding the specimen with Keller reagent (2 mL HF+3 mL HCl+5 mL HNO₃+190 mL H₂O), the morphology and energy spectrum (EDS) of the joint were analyzed on the Supra 55 field emission scanning electron, microscope (SEM).
3.2. Experiment for Z-T results

Figure 2 is the Z-T curve of cooling stage. It can be seen that the shrinkage of the specimen is less than 5% when the cooling temperature is in the range of 470-550 °C, and when the cooling temperature is reduced to 460 °C, the plasticity of the parent material can be restored and the shrinkage rate of the section is over 10%. Thus, the zero plastic temperature of the parent material is determined at 470 °C. The SEM image of the fracture of the tensile specimen at 470 °C can be seen that the grain surface covers a layer of low melting eutectic film. It shows that the low melting eutectic between the grain boundaries exists in the liquid form at this cooling temperature, thus significantly reducing the high temperature plasticity.

![Z-T curve and SEM image of fracture surface during cooling stage](image)

3.3. Experiment for thermo-plastic results and analysis

In the light of the laser-MIG composite welding, the MIG current has the most significant effect on the weld penetration. On the basis of the optimum welding parameters, we choose laser power is 2500 KW, voltage 32V and the welding speed 2M/min. Then, we choose the MIG welding currents with 150, 180 and 210A respectively to check the welding hot crack. This is equivalent to 2.5 kj/cm, 3.0 kj/cm and 3.5 kj/cm heat input.

The results of the thermo-plastic test for welding are shown in Table 4. With the increasing of MIG current, and the increasing of heat input, the thermo-plasticity of laser-MIG hybrid welding presents a change law of first decrease and then increase. When the heat input is 2.5 kj/cm and 3.5 kj/cm respectively, the welding thermo-plasticity is higher, and when the heat input is 3.0 kj/cm, the thermal plasticity of the joint decreases by about 47%.

| Welding process | Heat input (kJ/cm) | Cracking sensitivity (%) | Mean Cracking sensitivity (%) |
|-----------------|-------------------|--------------------------|-----------------------------|
| Plasma-MIG      | 2.5               | 72.92                    | 86.39                       |
|                 | 3.0               | 39.58                    | 45.14                       |
|                 | 3.5               | 84.58                    | 85.14                       |

From Figure 3, it can be seen, when the heat input is less than 2.5 kJ/cm, no thermal crack is found in the weld metal area, while a large number of hot cracks are distributed along the grain boundary in the partial melting zone of the parent material, and the thermal plasticity of the welding is higher. Because the Zn/Mg atom ratio is about 1, it shows that there is a Mg/Zn low melting point eutectic phase in the grain boundary of PMZ. The local liquefaction occurs in the grain boundary under the heat cycle of welding, and the tensile stress causes the cracking of PMZ along the grain boundary during the solidification shrinkage of the molten pool. Obviously, this crack is a liquid crack in the
partial melting zone of the parent material, and the fracture of the liquefied crack is rough. The features of the smooth and convex strip shape.

Figure 3. Microstructures of WZ of hot cracking at the heat inputs

When the heat input is 3.5 kJ/cm, the welding thermo-plasticity is higher, and all cracks along the center of the weld, but there is no crack in the base metal partial melting zone. The hot crack fracture of the weld is characterized by uneven cobblestone fracture morphology, smooth grain boundary surface and relatively large equiaxed grain. It can be concluded from the fracture surface that the crack forms in the solid liquid phase during the cooling and solidification process of the weld metal. At this stage, as the crystallization process continues, the low melting point eutectic liquid phase is squeezed between the dendritic grains and cannot flow freely to form a liquid film. The crystallization crack is formed along the intergranular liquid film under the tensile stress of the weld shrinkage is shown in Fig.4.

Figure 4. Microstructures of fracture surface of samples at the heat input

When the welding heat input is 3.0 kJ/cm, the welding hot crack also shows longitudinal cracking along the weld center, the base metal part. Although there are no hot cracks in the melting zone, there are discontinuous spot pits in the local area. This phenomenon shows that welding under this heat input condition. The hot crack tendency of the joint is approximately in the critical state between the crystalline crack of the weld and the liquefaction crack of the base metal fusion zone, and the macroscopic behavior is relatively low Welding thermo-plasticity. The micro fracture of welding hot crack is also cobblestone shape, the equiaxed grain is relatively small, the surface of grain boundary is relatively smooth, and it is also a typical weld crack.

It can be seen that, with the increase of welding heat input, the type of welding hot crack gradually changed from the liquefied crack in the part of the parent material to the crystal crack in the weld metal area, and the reason for the gradual increase of the tendency of the weld crystal crack is that the increase of the welding heat input, the growth of the dendrite grain of the weld and the increase of the eutectic at the low melting point in the grain boundary, and the scattered state along the grain boundary, gradually change to the intermittent distribution of the concentration along the grain boundary. At the same time, the tensile strain of the weld metal increases with the heat input. When the heat input reaches a certain threshold, the tensile strain of the weld is greater than the minimum alloy, that is, the crystallization crack is produced along the grain boundary, and the weld crack is released near the partial melting zone of the base metal. When the tensile strain from the weld crystallization cracking is not enough, the tensile strain in the adjacent parts of the parent material is
not enough to produce a liquefied crack, but some discontinuous micro-pits will be formed. It is obvious that by reasonable control of the welding heat input, it can reduce the crack sensitivity of the weld metal at the same time, while it does not produce the liquefied crack in the partial melting zone of the parent material.

4. Conclusion

(1) The brittleness temperature range of 6063 aluminum alloy base metal is 470-620°C, and the width of the range is about 150°C, indicating that it has a high tendency of welding hot cracking.

(2) When the thickness of 4 mm 6063 aluminum alloy laser-MIG composite welding, with the increase of heat input, the thermal plasticity of the welding first decreased and then increased, and the type of thermal crack changed from the liquefied crack in the partial melting zone of the parent material to the crystal crack in the weld metal area, but all of them showed characteristics of the intergranular cracking, among which the heat input was 3.0 kJ/cm, the thermal plasticity of welding is the smallest.

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