Microstructure and Hardness Analysis of 2A14 Aluminium Alloy Join By Pulsed Electron Beam Welding

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Abstract. Microstructure and hardness Analysis of 2A14 Aluminium Alloy Join by pulsed electron beam welding. Study on microstructure appearance and hardness analysis of 2A14 Aluminium Alloy Join by Pulsed Electron Beam Welding was carried out. The results show that the micro-structure of the weld zone was fine equaxied grains and the pulsed electron beam changed crystal morphology. The HAZ was the weakest hardness area of the joint.

1. Introduction
2A14 aluminium alloy belongs to Al-Cu-Mg-Si high strength aluminium alloy. It has high room temperature strength, good high temperature and ultra-low temperature properties, and is widely used in the development and production of launch vehicle propellant tanks. Due to its unique physical and chemical properties, such as low melting point, high linear expansion coefficient, good thermal conductivity and strong chemical activity, the weldability of the alloy is poor, which limits its application to a certain extent. The weldability of aluminium alloys is affected by the content of main alloy elements Cu. The content of Cu with high hot cracking tendency corresponding to brittle temperature range is 2.0%~4.0%, and the content of copper in 2A14 aluminium alloy is 3.9%~4.8%. It basically falls into the tendency zone of hot cracking composition. The addition of other auxiliary alloying elements Mg, Si and Mn in the alloy makes the ternary and quaternary alloys formed in the welded joints more complex, which is characterized by strengthening. With the increase of eutectic phase and low melting point, 2A14 aluminium alloy is sensitive to various welding process factors, poor welding performance, severe hot cracking tendency, brittle weld, sensitive to stress concentration and softening of heat affected zone of base metal [1, 2, and 3].

When high strength aluminium alloy is welded by common welding method, multi-layer and multi-pass welding is needed because of the small amount of heat transfer. It is easier to form high melting point (2050 C) of A12O3, which results in slag inclusion in the weld, and the hot crack after welding is more serious than that of thin plate welding. The strength of the weld is not high, and when the welding temperature is high, the residual stress and deformation of the post-weld structure are larger. Electron beam welding (EBW) is a kind of welding method that uses the heat energy produced by the high-speed convergent electron flow bombarding the joint of workpiece to make metal fuse. EBW has the characteristics of high power density, fast welding speed, large depth-width ratio and narrow heat-affected zone [4].
Compared with the continuous beam, the pulsed electron beam welding process will not be continuous, but will bombard the welded workpiece in the form of pulses to achieve intermittent heat input. Pulsed electron beam (PEB) can adjust the pulsed beam current by using a pulsed bias power supply. The pulse frequency and duty cycle can vary within a certain limit. Due to the unique energy transfer and conversion mechanism of pulsed electron beam welding technology, it has many characteristics different from continuous beam welding. The thermal shock provided by each pulse is several times higher than that provided by continuous electron beam welding method. On the one hand, the average temperature of welding position is lower than that of continuous electron beam welding method, so as to reduce heat input; on the other hand, it will aggravate molten pool gold. Vibration and stirring can promote nucleation, effectively inhibit dendrite growth and promote equiaxation [5]. Therefore, pulsed electron beam welding is expected to solve the welding problem of this kind of aluminium alloy.

2. Test Method

The experimental material 2A14 aluminum alloy is heat-treated and strengthened aluminum alloy, and its chemical composition is shown in Table 1. The sample sizes are 100 mm x 60 mm x 3 mm.

| Table. 1 Chemical composition (mass percentage) of 2A14 aluminum alloy sheet |
|-----------------------------------------------|
| component | Al  | Cu   | Mg    | Si    | Mn    | In   |
| content   | rest| 39~48| 0.4~0.8| 0.6~1.2 | 0.4~1.2 | <0.25 |

Medium pressure and high vacuum electron beam welding machine was used to carry out experiments. Before welding, the surface of the specimens was mechanically polished, then soaked in sodium hydroxide solution for 100S, and then soaked in nitric acid solution for 30S at room temperature to remove the oxide film in the welding zone.

The experiment was carried out on the pulsed electron beam welding equipment. The vacuum degree of electron gun is 2.0 * 10^-3 Pa, and that of welding chamber is 3.8 * 10^-3 Pa. The acceleration voltage is 60 Kv, the focusing current is 580 mA, the welding speed is 5.0 mm/s, the pulse frequency is 20 Hz, and the duty cycle is 0.2. After welding, the specimens are placed in the vacuum chamber to be cooled and taken out. The welded joints are made by wire cutting along the direction perpendicular to the weld bead. After inlaying, grinding and polishing, the welded joints are corroded by corrosion reagent (HF: NHO3:H2O is 1:3:6). The microstructure of the welds is observed and analyzed under OLYMPUS-PMG3 optical microscope. The microhardness of the welded joints is measured by HXS1000A microhardness tester and along the weld seam. The heat affected zone (HAZ) and base metal were tested successively, with an interval of about 0.5mm, a load of 0.49N and a loading time of 10S. The hardness distribution of the joints was analyzed.

3. Test Results and Analysis

3.1. Microstructure Distribution of Weld

As can be seen from Fig. 1, the solidification and crystallization characteristics of liquid metal in molten pool of 2A14 aluminum alloy have not changed under the action of electron beam. From fine equiaxed grains of base metal to coarse columnar grains at the boundary of molten pool, the center of weld is fine equiaxed grains.
The solidification process of weld pool starts from the boundary of weld pool and is a kind of heterogeneous nucleation. The weld metal grows from semi-melted parent metal grain to weld pool in the form of columnar crystal. The temperature gradient in the vertical direction of the molten pool boundary is the largest, which is the direction of the fastest heat dissipation. Therefore, the grains perpendicular to the molten pool boundary grow preferentially and form columnar grains. When the grains grow to the center of the weld, the temperature gradient is the smallest and the crystallization speed is the highest. These grains can grow freely and form equiaxed grains.

The heat affected zone (HAZ) is usually the area where the microstructure and properties of welded joints are poor. The metallographic structure of HAZ is shown in Figure 2. Under the action of welding thermal cycle, the grain coarsening phenomenon appears in the heat affected zone (HAZ) of joints.

3.2. Crystalline Morphology under Pulsed Beam Conditions

There is only one region of columnar crystal structure in the common continuous electron beam welding joint of aluminum alloy, but under the pulse condition, the crystallization of molten pool is multi-layered first. As shown in Figures 2 and 3.
The analysis shows that 2A14 aluminium alloy has good thermal conductivity and is very sensitive to welding heat input. Under the intermittent heat input condition of pulsed electron beam, on the one hand, the weld metal will form an uneven temperature field, and the liquid metal in front of the solid-liquid interface will be supercooled due to the solute, which together leads to the crystal growth of weld metal in different regions [6, 7]. On the other hand, due to the oscillation and stirring of pulsed beam, the dendrite fracture is caused and the weld structure is refined.

3.3. Microhardness Analysis
The diagonal length of the indentation on the surface of the specimen is measured by using a diamond indenter with a regular quadripyramid, which is pressed into the surface of the specimen under the action of the test force, and the test force is removed after holding the prescribed time.

The quotient of the test force divided by the indentation surface area is the Vickers hardness value. Vickers hardness is calculated according to the following formula:

\[ HV = \text{constant} \times \frac{\text{test force}}{\text{indentation surface area}} = 0.1891 \frac{F}{d^2} \]

In formula: \(HV\)--Vickers hardness symbol; 
\(F\)--Test Force, N; 
\(d\)--The arithmetic mean value of \(d\)-indention diagonals D1 and d2, mm

In practice, the Vickers hardness value is obtained by looking up the table according to the diagonal length D.
According to the national standard, the diagonal length of Vickers hardness indentation ranges from 0.020 mm to 1.400 mm.

According to Vickers Hardness Measuring Principle, as can be seen from Fig. 5, the hardness of base metal is the highest, followed by weld, and the hardness of HAZ is the lowest in the three regions of the joint.

![Microhardness Distribution of Joints](image)

**Fig. 5 Microhardness Distribution of Joints**

The hardness of HAZ is the lowest because it has experienced sufficient thermal cycle during welding, resulting in over-aging and grain coarsening to varying degrees, resulting in a decrease in hardness [8]. However, due to the concentrated power density and small heat input in pulsed electron beam welding, the area is narrower, the time of overaging is shorter, and the hardness of the joint decreases slightly. The hardness of weld metal also softens to a certain extent. It is believed that most solute atoms, such as Cu and Mg, are squeezed into liquid phase [9] under the action of pulsed beam because of the precipitation of a-Al solid solution with low solute content during solidification of weld metal. At the same time, the burning loss of alloy elements in the weld reduces the supersaturation and the precipitation of strengthening phases in the weld, which may cause the hardness of the weld to decrease.

### 4. Conclusion

1. Pulse electron beam welding (PEB) of 2A14 aluminium alloy is characterized by typical weld structure, coarse columnar grains near the weld fusion line and fine equiaxed grains at the weld center. The grains in the heat affected zone (HAZ) of the joints are superheated and grow due to the welding thermal cycle.
2. Under the condition of pulsed electron beam welding, there are inhomogeneous temperature field and component undercooling in the weld pool, and the crystalline morphology of the weld joint presents zonal stratification. At the same time, the grain structure of weld is refined by the oscillation of pulsed beam.
3. HAZ is a weak area of joint structure and performance. During welding, HAZ experienced sufficient thermal cycle, which resulted in over-aging and grain coarsening to varying degrees, leading to the decrease of hardness.

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