Microstructure and Physical Properties of Alloy Brazed with Filler by Mapping Scanning Analysis and Wettability Test

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Abstract. In this paper, a new type of AlSiMgCuNiAg filler metal was developed. The solidus temperature of the filler metal is 509.1℃ and the liquidus temperature is 531.3℃. The filler metal has a good wetting and spreading effect on the surface of 6061 aluminum alloy. The CuAl$_2$ phase in the brazing seam was greatly aggregated after brazed, while the CuAl$_2$ phase was reduced and Mg$_2$Si strengthening phase was formed when the brazed joints with heat treatment. The average shear strength of the brazed joint without heat treatment was 47.1MPa, and the average shear strength of the brazed joint with heat treatment reached to 108.7Mpa. The strength of the brazed joint with heat treatment was increased by about 131% relative to the strength of the brazed joint without heat treatment.

Keywords: Aluminum alloy, Brazing, Shear strength, Heat treatment.

1. Introduction
Aluminum is one of the most abundant and widely distributed elements in the earth's crust, accounting for about 8% of the weight of the earth's crust, ranking third only to silicon and oxygen. Aluminum and its alloy thermal conductivity, low density and high conductivity (only behind gold, silver, copper), Therefore, in order to reduce energy consumption, reduce weight, enhance mobility and improve efficiency in the manufacture of missiles, satellites, aircraft, rockets, ground radar, microwave components, air conditioning radiators and car water tanks, the production require as much as possible with aluminum instead of copper, even replace steel [1-3].The aluminum profiles developed in industry are mainly concentrated in the container profiles, rail vehicle profiles, electric power industry profiles and radiator profiles, which account for more than half of the total consumption of industrial aluminum profiles, among which the development of radiator profiles is earlier. The main alloy elements of 6061 aluminum alloy are magnesium and silicon, and form Mg$_2$Si phase, which is a kind of heat-treatable strengthened phase, with high specific strength, small density, fatigue strength and fracture toughness, corrosion resistance, excellent thermal conductivity and good molding and many other advantages, so it has become the first choice of radiator materials [4-7].

The increasingly wide application of 6061 aluminum alloy constantly puts forward new requirements for the connection method[8]. At present, the main welding methods are fusion welding (MIG, TIG, laser welding, vacuum electron beam welding) and pressure welding (friction stir welding and spot
welding)[9-14]. However, for the welding structure with large area, such as micro-channel aluminum radiator and plate aluminum radiator, a large number of fins and cover plates need to be welded, and the welding method mentioned above cannot meet the welding needs[15]. Brazing is an important connection method of aluminum and aluminum alloy. Compared with pressure welding and fusion welding, brazing has the following advantages: large area brazing can be realized, beautiful appearance, smooth joint, the brazing deformation is small, the precision of the brazing size is easy to control, it can connect various parts of different shapes and thicknesses, and the process is easy to realize automation and mechanization[16].

The biggest characteristic of brazing is that the welding temperature is lower than the solidus of base material but higher than the liquidus of the filler metal. The connection is completed in the solid state of the base material, which has little influence on the base material. The solidus temperature of 6061 aluminum alloy is 582-595°C, and the liquidus temperature is 605-652°C. In order to prevent the base metal from overburning the brazing temperature should not be higher than 595°C in theory At present, the commercially available aluminum alloy brazing filler metals are mainly AlSi and AlSiMg brazing filler metals, which have a relatively high melting temperature and over-burning defects may occur when brazing 6061 aluminum alloy. Moreover, with the continuous thinning of aluminum tubes, the problem of overburning has become more serious. Therefore, it is particularly important to explore the filler metal and brazing process with lower melting temperature.

In this paper, a new type of aluminum alloy filler metal Al-7Si-1.5Mg-15Cu-2Ni-0.5Ag was developed. The addition of Cu element can reduce the melting point, but too much copper will lead to the increase of brittle phase in the brazed joint. The addition of nickel element can replace part of copper element to reduce the melting point and improve the corrosion resistance of the joint. The addition of silver element can promote the precipitation of strengthening phase in the brazed joint. The microstructures and mechanical properties of brazed 6061 aluminum alloy joint with Al-7Si-1.5Mg-15Cu-2Ni-0.5Ag filler metal were investigated.

2. Experimental section
The new Al-7Si-1.5Mg-15Cu-2Ni-0.5Ag filler metal was used to vacuum braze 6061 aluminum alloy tokens with dimensions of 50×10×2mm. The filler metal was smelted in the high purity graphite crucible under atmosphere with the high frequency induction heating method. During the smelting process, the calculated master alloys such as AlCu, AlSi, AlNi and the silver wrapped with aluminum foil were added into the preheated graphite crucible and covered with covering agents. After the above metals were melted, the Mg wrapped with aluminum foil was added and stirred for two minutes, then the melted alloy were put to stand for two minutes and then pour it into the mold. After smelting the ingots were cut using a precision mill and subsequently grinded into foils with a thickness of 200 µm.

After removing the oil stain on the surface of 6061 aluminum alloy base metal with acetone, it was washed in 15% NaOH solution for 15s. After being washed with clear water, it was washed with 15% HNO₃ solution for 10s to remove the alkali on the surface of the base metal. After being washed with clear water, it was washed with anhydrous ethanol and then dried naturally.

The wetting experiment and brazing process were conducted in the vacuum furnace. The heating rate of the brazing cycle was 5°C/min, the test temperature was 570°C with a holding time of 10 min. afterwards, and the components were cooled down to room temperature through vacuum cooling. The vacuum degree during the heating process is not less than 8×10⁻³Pa. During the test, 2g magnesium blocks were placed in the vacuum furnace to remove the oxide film on the aluminum alloy surface. The brazing joints obtained by vacuum brazing were treated with heat treatment. The solution process was 510°C with a holding time of 2h, and then cooled in water. The aging process was 200°C with a holding time of 8h, and then cooled in air.

The NETZSCH STA 449 F3 differential scanning calorimeter was used to test the melting temperature of the filler metal, the wetting test and the brazing test were carried out in the WZQH-60 aluminum alloy vacuum brazing furnace. Phenom Pro scanning electron microscope was used to analyze
the microstructure of brazed joints. The mechanical performance test was carried out on the MTS E45.105 million ability test machine.

3. Results and Discussion

3.1. Microstructure analysis of filler metal
SEM images and EDS maps of the filler metal are shown in Figure 1. It can be seen that the Al element is uniformly distributed, which indicates that the matrix of AlSiMgCuNiAg filler metal is α-Al phase, and the Si phase is agglomerated in the matrix. Mg and Ni elements are dispersed on the matrix. According to the metallographic manual, Al and Cu elements are easy to form θ phase (Al$_2$Cu), and Al, Cu and Ni elements are easy to form Al$_6$Cu$_3$Ni phase. These metal compounds can improve the strength and hardness of the filler metal, but reduce the plasticity of the filler metal.

![Fig 1. Mapping scanning analysis results of filler metal.](image)

3.2. Melting characteristic analysis of filler metal
Figure 2 shows the melting temperature curve of the filler metal. It can be seen that the solidus temperature of the filler metal is 509.1°C and the liquidus temperature is 531.3°C. The solidus and liquidus of the filler metal alloy are lower than the traditional Al-Si and Al-Si-Mg based filler metal. Because the addition of Cu element can form Al-Cu-Si ternary eutectic with Al and Si elements, the ternary eutectic has a low melting temperature at 525°C, thereby reduces the melting point of the filler metal. And the relatively narrow range of melting temperature is conducive to the rapid melting of the filler metal on the base metal and the rapid spreading in a short time.  

![Fig 2. The DTA analysis result of the filler metal.](image)
3.3. Wettability test of filler metal

Figure 3 shows the wetting and spreading morphology of the filler metal on the surface of 6061 aluminum alloy. It can be seen from the figure that the filler metal has good wetting and spreading effect on the surface of the base metal.

![Image of wetting and spreading morphology](image)

**Fig 3.** The spreading morphology of the filler metal.

3.4. Microstructure analysis of brazed joints

Figure 4 shows the microstructure of the brazed joint without heat treatment and with heat treatment. As shown in Figure 4(a), the brazing seam of the brazed joint without heat treatment is mainly composed of dark grey matrix phase (spot A), gray massive phase (spot B) and grey skeleton phase (spot C). The element of EDS analysis shows that the grey massive phase as CuAl$_2$ phase, the CuAl$_2$ phase will decompose at a certain temperature, which can have a certain aging strengthening effect on the filler metal alloy. However, a large amount of CuAl$_2$ phase gathered will increase the brittleness of the brazed joint, and then reduce the mechanical properties of the brazed joint. The main components of grey skeleton phase are Al, Cu and Si elements. According to the phase diagram, it should be Al-Si eutectic phase, Si-rich phase and CuAl$_2$ phase. The main component of the dark gray matrix phase is Al element, presumably α-Al phase.

Figure 4 (b) shows the microstructure of brazed joints after heat treatment. It is evident from the figure that the block and skeleton phases were reduced, the results of EDS energy spectrum analysis was carried out on the massive phase show that the contents of Al element and Cu element were decreased, this indicates that Al and Cu elements were further diffused into the matrix during the heat treatment process, and then the brittle phase in the brazing joint was reduced, and the mechanical properties of the brazed joints were increased. Compared with the brazed joint without heat treatment, part of dark gray block microstructure was added to the bulk phase of the joint after heat treatment. The results of EDS energy spectrum analysis of the joint showed that Mg element aggregated here and formed Mg$_2$Si strengthened phase with Si element. The presence of Ag element in the filler metal could promote the precipitation of the strengthened phase during heat treatment.

3.5. Mechanical properties of brazed joint

The shear strength test of brazed joints without heat treatment and after heat treatment were measured. The brazed joints were all fractured at the braze seam. The results show that the average shear strength of brazed joints without heat treatment was 47.1 MPa, and the average shear strength of brazed joints with heat treatment was 108.7 MPa. It can be seen that the strength of the brazed joint with heat treatment was increased by about 131% relative to the strength of the brazed joint without heat treatment.

Figure 5 shows the shear strength fracture morphology of the brazed joint. As shown in the figure, the filler metal flows uniformly at the lap joint and has a high brazing rate. Figure 6 presented the microstructure of the tensile fracture of the brazed joints without heat treatment and with heat treatment.
It can be found from the figure that the fracture of the braze seam without heat treatment was flat and there are some lamellar tears along the grain boundary, indicating that the fracture mode of the brazed joint was brittle fracture. After heat treatment, the fracture surface of the brazed joint has a relatively flat, shiny crystalline section, and a large number of dimples with different sizes. Therefore, it can be seen that the fracture has both brittle fracture morphology with cleavage fracture as the main mechanism and partial ductile fracture morphology. This is also the reason why the shear strength of the brazed joints with heat treatment is greatly improved.

![Microstructure of brazed joint without and with heat treatment](image1)

(a) Without heat treatment                         (b) with heat treatment

**Fig 4.** The microstructure of brazed joint without and with heat treatment.

| Sample                        | Microzone | Al  | Si  | Mg  | Cu  | Ni  | Ag  |
|-------------------------------|-----------|-----|-----|-----|-----|-----|-----|
| Sample without heat treatment | A         | 91.62 | 1.31 | 1.06 | 4.01 | 0.31 | 1.69 |
|                               | B         | 70.31 | -   | -   | 29.69 | -   | -   |
|                               | C         | 65.12 | 9.29 | -   | 25.59 | -   | -   |
| Sample with heat treatment    | A         | 92.49 | 0.69 | 1.10 | 3.21 | 0.25 | 2.26 |
|                               | B         | 50.14 | 12.10 | 0.15 | 20.31 | -   | -   |
|                               | C         | 57.68 | 9.52 | 7.51 | 12.9 | 8.21 | 4.18 |

**Table 1.** Chemical composition at different regions of the brazed joint.

![Macro morphology of the shear strength fracture of brazed joints](image2)

(a) Without heat treatment.                  (b) With heat treatment.

**Fig 5.** The macro morphology of the shear strength fracture of brazed joints.
4. Conclusion

The microstructure, melting properties and wettability of the AlSiMgCuNiAg filler metal prepared by test were studied. And the vacuum brazing of 6061 aluminum alloy using the AlSiMgCuNiAg filler metal was investigated. The microstructure and shear strength of the brazed joints without heat treatment and with heat treatment were compared. The specific conclusions are as follows:

(1) The matrix of AlSiMgCuNiAg filler metal is αAl phase. The solidus temperature of the filler metal is 509.1℃ and the liquidus temperature is 531.3℃. The solids and liquidus of the filler metal alloy are lower than the traditional Al-Si and Al-Si-Mg based filler metal. Because the addition of Cu element can form Al-Cu-Si ternary eutectic with Al and Si elements, the ternary eutectic has a low melting temperature at 525℃, thereby reducing the melting point of the filler metal.

(2) AlSiMgCuNiAg filler metal has good wetting and spreading effect on the surface of 6061 aluminum alloy. The CuAl$_2$ phase in the brazing seam was greatly aggregated when the brazed joints without heat treatment, while the CuAl$_2$ phase was reduced and Mg$_2$Si strengthening phase was formed when the brazed joints with heat treatment.

(3) The average shear strength of the brazed joint without heat treatment is 47.1MPa, and the average shear strength of the brazed joint with heat treatment is 108.7MPa. The strength of the brazed joint with heat treatment was increased by about 131% relative to the strength of the brazed joint without heat treatment.

Acknowledgments

This work was financially supported by Major Science and Technology Innovation project fund of Zhengzhou (2019CXZX0060).

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