Aluminium-Silicon-Magnesium Filler Metal for Aluminium Vacuum Brazing
Wettability and Characteristics of Brazing Microstructure

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Mg2Si composite was added to Al-Si filler metal for aluminium alloy vacuum brazing via in situ synthesis. Spreading area method was used to measure the wettability of the brazing alloy on the parent metal in vacuum. The filler metal wetting area increased with increasing Mg2Si content. The compound within the interface was examined with an electron probe and the following results were obtained: Mg2Si content of the brazing interface was lower than that of filler metal, Mg2Si was distributed into both sides of the interface and arranged in block, grain and short rod-like shapes. Si crystal had a primarily needle-like structural arrangement. The elemental distribution on both sides of the interface was analysed using thread scanning method. A solid solution of Mg was formed in the interior parts of the grain in the parent metal. The solid solution content decreased as the distance from the interface increased.

Keywords: composite filler metal, activity of filler metal, interface of brazing seam

1. Introduction

Mg vapour enhances the effectiveness of Al-Si filler metal and thus, is a key component of vacuum aluminium brazing1–4. However, it is only useful when used in large quantities, which causes contamination in the vacuum equipment, and requires regular cleaning and oil replacement, leading to a high maintenance cost. To reduce the contamination, a craft box must be used to wrap up the workpiece and evaporation source. However, the box isolates the workpiece from the heat source, and increases the heating time. In addition, the operation is sensitive to the location of the magnesium powder block, and thus technologically more complex than the other methods5). In recent years, addition of magnesium to Al-Si filler metals has been studied to improve the filler activity in aluminium vacuum brazing6,7). Zhang and Zou have proposed that the surface oxide film on the parent metal cracks during brazing above 673.15 K, and magnesium vapour infiltrates through the cracks into the parent film, forming an eutectic mixture of silicon and magnesium with low melting temperature. At the same time, the filler metal wets the parent metal surface spreading along the aluminium alloy substrate.8,9) However, the solubility of magnesium in aluminium solid solution is low, and thus the oxide film stripping is not effective after vacuum brazing. Thus, alternative metals, such as zinc or copper, have been proposed to reduce the melting point of filler and improve the filler activity10–17). However, the evaporation rate and harmful effects of zinc are higher than those of magnesium.

In this study, Mg2Si is studied as an additive into the filler metal. The filler is tested for brazing a joint of LF21 aluminium alloy at 5 × 10−3 Pa. Effects of changing contents of compounds on wettability of the filler metal are studied. The compounds are melted and decomposed within a specific temperature range, which produces Mg vapour. The vaporization loss is small, and the quantity of vaporization can be controlled by the composition of vapour. The amount of contamination is small, and no waste is produced.

2. Experimental Procedures

2.1 Experimental materials

The filler metal was produced via in situ synthesis. The projection of Al-Si-Mg ternary alloy phase diagram is shown in Fig. 1. For the filler metal sample 1#, (Al-Si14.1-Mg4.8), law of gravity-centre was used to obtain the weight percentages of microstructure as α-Al+Si11.6%+Mg2Si7.73%. For the filler metal sample 2#, (Al-Si13.6-Mg2.9), Lever rule was used to obtain the weight percentages of microstructure as (Al+Si) + (Al+Si+Mg2Si)56.92% with a Mg2Si content of 4.4%. For the filler metal sample 3#, (Al-Si13.1-Mg1.9), Lever rule was used to obtain the weight percentages of microstructure as (Al+Si) + (Al+Si+Mg2Si)33.64%, with a Mg2Si content of 2.6%. The filler metal composition and the calculated compound contents are presented in Table 1.

2.2 Experimental process

Si and Mg powders were coated with aluminium foil. An aluminium block was heated to 1023.15 K until it melted in the crucible and then, was protected with a coating agent. The wrapped Si and Mg powders were inserted into the crucible using a cup cover. After melting, the temperature was kept constant at 1023.15 K for 15 min, which produced a uniformly mixed structure. Finally, the melt was poured and shaped into strips. Due to the burning loss and oxidation in the preparation process, the actual composition of the filler metal was different than the initial composition. Thus, the alloy metals were refined more than once and the final content of the alloy elements in the filler metal was tested, to make sure that the actual and initial compositions of filler metal were the same. Finally, the gas was removed with CH2CCl4, and the filler metal was processed into foil. As the filler metal in the form of foil tape was thin, the metallographic observations were performed on the bulk filler metal.

Three filler metal samples at different compositions were used. Oil contamination was prevented by treating the sam-
samples with acetone. 0.2 g of filler metal was used in the spreading and wetting experiments. The parent metal was LF21, which is similar in performance to International Brand 3003. Parent metal components are shown in Table 2. The samples had a thickness of 2 mm and dimensions of 30 mm × 30 mm.

Rust was cleaned from the samples at 323.15 K with NaOH (10%). The filler metal was polished with HNO₃ (50%). The filler metal was inserted into the parent metal, and then was placed into the vacuum furnace, which was followed by the wettability experiment. The wetting areas of the filler metals were measured, and the results were compared. The brazed specimen was placed on the recording paper and photographed. Cumulative grid method was used to calculate the spreading area of the filler metal. Each specimen was tested for three times and the average of the measurements was recorded as the final result.

The filler metal foil is used in lap brazing experiment. The aluminium alloy LF21 had dimensions of 80 mm × 24 mm × 2 mm. Filler metal thickness was 0.1 mm. Lap length was 2 mm. The pressure in vacuum chamber during the brazing was 2.3 × 10⁻³ Pa. The brazing temperature was 873.15 K and the brazing time was 8 min. The heating rate was 15 K/min. Figure 2 shows a schematic diagram of lap joints.

After the melting, the weight loss at the filler metal was measured with differential scanning calorimetry. The metallographic specimen was produced by crosscutting and sampling the brazing. The line scanning method was used to check the distribution of each component in the interface. Secondary electron imaging was used to observe the structural arrangement in the interface. The scanning electron microscope was an EVO 18 of ZEISS (EHT = 20 KV, WD = 10.5 mm.) The differential scanning calorimetry instrument was STA409Pc of NETZSCH (rate of warming and cooling = 15 K/min, flow of argon gas = 25 ml/min.)

3. Results and Discussions

3.1 Morphology of filler metal organisation

The original microstructure of the filler metal is shown in Fig. 3.
The three filler metal microstructures at different compositions shown in Figs. 3(a), (c) and (e) are α-Al, Si crystal and Mg2Si, respectively. α-Al morphology had a primarily eutectic crystal arrangement, whereas the Si crystal was needle shaped. The morphology and distribution state of α-Al and the Si crystal corresponded to the traditional composition of the Al-Si filler metal. Mg2Si was the active phase explored in this study, and its morphology depended on the contents of the filler metal. In Figs. 3(b), (d) and (f), the distribution of the Mg2Si phases in the matrix are clearly demonstrated. The interfaces between α-Al and the Si crystal are not clearly seen due to the absence of etching in the preparation. The Mg2Si content of 1# filler metal was 7.73%, and the morphology of Mg2Si appeared primarily as block shapes, along with a small amount of relatively small sized bone shapes. The Mg2Si contents of 2# and 3# filler metals were approximately 4.4% and 2.6%, respectively, i.e. lower than that of 1#. The morphologies of #2 and #3 appeared as primarily small sized bone shapes, along with a smaller amount of small size block shapes.

3.2 Wettability of filler metal

The grid method was used to measure the wetting area of filler metals with different Mg2Si contents. The results are presented in Table 3.

No magnesium powder or block was used as active solvent during the brazing process. The wetting of the filler metal on the parent metal was controlled by the melting properties of the compounds in the filler metal. A comparison of the surface wetting of three filler metals at the brazing spot indicated, that the wetting area of 3# was the smallest and that of 1# was the largest.

As the filler metal melted, Mg2Si soluted. Subsequently, the Mg element vaporized and reacted with steam, which caused a weight loss at the filler metal. As the Mg2Si content in the filler metal was increased, the rate of Mg vaporization was also increased. The thermally induced weight loss of the filler metal after the melting process is presented in Table 4.

Mg vapour has a direct effect on the surface of the brazing...
area. As the rate of vaporization decreases, the wetting properties are improved. Excessive Mg vapour damages the seam surface of the parent metal causing pock marks and wrinkles near the brazing line. It also clears the oxide film and diffuses into the parent metal. Oxide film removal starts at the surface near the seam and proceeds with the stripping of the film from the rest of parent metal surface. As no filler metal floats on the surface, pock marks and wrinkling are effected. The contents of the filler metal can be changed through reducing a portion of the compounds to increase the surface cleaning efficiency. The highest degree of surface cleaning is obtained at the liquid-gas interface when the filler metal melts and Mg vaporizes. According to physical chemistry principles, the surface tension and viscosity of the filler metal in liquid phase decreases because of the Mg vapour. The surface tension, on the other hand, decreases because of mass transfer through diffusion at the liquid-solid interface. The mass transfer enhances the wetting on the parent metal. According to the Al-Si-Mg alloy phase diagram, the ternary eutectic point of (α-Al+Si+Mg2Si) can be found at a (Al:Si:Mg) composition of (18.1:14.1:4.8). If the Mg element is added at the right concentration, the filler metal composition approaches the eutectic point. Consequently, the melting point is reduced and the flow of the filler metal on the parent metal is facilitated.

### 3.3 Elemental distribution in interface

The elemental distribution at the interface was analysed with an electron probe. The results are shown in Fig. 4. No chemical reagent was used to prevent erosion at the brazing seam, ensuring the accuracy of the scanning results. The line scan images of the brazing zone are shown in Fig. 4(a), (c) and (e). The results showed that Mg and Si existed not only in the filler metal at the brazing seam but also in the parent metal. The parent metal is LF21 aluminium alloy, which is composed of Al and Mn. The filler metal is mainly composed of Al-Si-Mg. This result indicated that Mg and Si diffused to the parent metal during brazing.

The Map analysis of the brazing seam is shown in Figs. 4(b), (d) and (f). After diffusing into the parent metal, Si

<table>
<thead>
<tr>
<th>Filler metal</th>
<th>Mg2Si content %</th>
<th>Mass of sample/g</th>
<th>Mass of remaining/g</th>
<th>Weight loss %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1#</td>
<td>7.73%</td>
<td>10.5312</td>
<td>10.2789</td>
<td>2.39%</td>
</tr>
<tr>
<td>2#</td>
<td>4.4%</td>
<td>10.5338</td>
<td>10.3811</td>
<td>1.45%</td>
</tr>
<tr>
<td>3#</td>
<td>2.6%</td>
<td>9.4916</td>
<td>9.4013</td>
<td>0.95%</td>
</tr>
</tbody>
</table>

Fig. 4    Elemental distribution at brazing area. (a) Line scan data of 1# brazing area; (b) Map data of 1# brazing area; (c) Line scan data of 2# brazing area; (d) Map data of 2# brazing area; (e) Line scan data of 3# brazing area; (f) Map data of 3# brazing area;
was arranged in the form of needles and grain shapes near the seam, and was distributed in depth along the grain boundaries of $\alpha$-Al. The needle shapes belonged to a monatomic Si crystal morphology, and the large grain shapes belonged to Mg with compound morphology. Mg appeared more dispersed and granular near the seam area of the parent metal. The dispersed structure belonged to the solid solution state, and the large granular structures belonged to the compound state.

As the rate of diffusion at the interface increased, the solid-liquid interfacial tension decreased and the size of the wetting area of the filler metal on the parent metal increased. Mg and Si contents decreased from the brazing seam to the parent metal, because of the concentration gradient in the diffusion process. According to Fick’s second law, the distance and velocity of diffusion are controlled by the concentration gradient. Thus, high Mg and Si contents of the filler metal leads to a large diffusion distance. In brazing, when there is a large difference in the concentrations of active elements between the filler and parent metals, the parent metal dissolves into the filler, and diffusion starts from the filler to the parent metal, causing corrosion at the parent metal and making a corrosion mark on the brazing seam edge. Corrosion becomes more easily detectable as the brazing time increases. Thus, the length of time when the filler is maintained in liquid state before the cooling at the seam is started should be strictly controlled.

4. Conclusions

$\text{Mg}_2\text{Si}$ can be added to the Al-Si filler metals for aluminium vacuum brazing to activate the parent metal surface and improve the wettability of the filler metal on the LF21 aluminium alloy.

In the process of brazing, a large amount of $\text{Mg}_2\text{Si}$ in the melting filler metal diffuses to the interface and subsequently forms compounds at the crystal boundary. A small amount of $\text{Mg}_2\text{Si}$ vaporizes. Mg content of the filler metal is higher than that of the brazing seam. Mg compounds primarily appear as bone shaped particles and have arborisation shaped morphology.

REFERENCES