

## Torch brazing 3003 aluminum alloy with Zn–Al filler metal

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**Abstract:** Using Zn–Al filler metal with Al content of 2%–22% (mass fraction) and improved CsF–AlF<sub>3</sub> flux, wetting properties of Zn–Al filler metal on 3003 Al substrate were investigated. The mechanical property as well as the microstructure of the brazed joints was also studied. The results indicate that excellent joints can be produced by means of torch brazing when the Al content is less than 8%. The metallographic structure in the brazing seam is mainly composed of Al based solid solutions and Zn based solid solutions. The high hardness value of brazing seam of the 3003 aluminum alloy is higher than that of the base metal due to the effect of solid solution strengthening. The results also show that three microstructure zones could be found at the brazing interface; i.e., base metal, diffusing zone and interface zone. The distribution of the solid solution in the brazing seam is the main factor of the tensile strength rather than the diffusion zone width near the interface.

**Key words:** Zn–Al filler metal; torch brazing; mechanical properties; microstructure

## 1 Introduction

Because of the favorable strength property, excellent formability as well as good corrosion resistance, 3003 aluminum alloy has been widely used in the manufacturing of heat exchangers, where brazing and soldering is a feasible choice in the manufacturing process. The commercially available filler metal is usually based on an aluminum–silicon alloy system. Researchers [1–4] studied the microstructure of the Al–Si joints of AA3003 Al alloy brazed by the industrial Nocolok® controlled atmosphere brazing. However, in order to achieve a satisfactory bonding effect, it is necessary for the brazing operation to be conducted at the temperature around 640 °C [5]. The brazing temperature too close to the melting point of the workpieces would result in partially molten base metal or their mechanical properties may degenerate.

In order to solve this problem, many efforts were devoted to develop a low-melting-point filler metal. COOPER and JONES [6] introduced rapidly solidified technology to form a new Al–Si–Cu alloy, by changing the cooling rate, fine-grained microstructures were

obtained, but the industrialization still has a long way to go. CHANG et al [7] added 20% copper into the Al–12Si filler metal to lower the solidus temperature to 522 °C, and the liquidus temperature to 535 °C. Furthermore, a Zn-bearing Al–Si–Cu filler metal was reported by TSAO et al [8] by adding 20%–30% zinc into the Al–Si–20Cu filler metals to lower their liquidus temperatures to below 500 °C. But too much Cu in the filler metal generates a large volume fraction of the CuAl<sub>2</sub> intermetallic compound (IMC), and the intermetallic compound could produce brittleness [9], so, the processability of this alloy is restricted. Al–Ge system has a eutectic point of 424 °C, MOSHIER et al [10] found this alloy quite suitable for Al–Al brazing. Nevertheless, the high price of Ge restricts the prospect for extensive application. In addition to this, Zn–Al based filler metals have attracted great interest because of the low melting point and popular price. XU et al [11] studied the spreading phenomenon of Zn–Al based alloy on 6061 Al composite and pointed out that with ultrasonic vibration, the alloy metal could spread well on the composite.

The current investigation concentrates on the low-melting-point Zn–Al filler metal and its application

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on torch brazing 3003 aluminum alloys. The spreading performance, microstructure, and mechanical properties were also observed.

## 2 Experimental

The brazing filler metals were melted at  $(750 \pm 10)$  °C in a furnace with pure Zn(99.7%) and Al(99.9%). The composition of the filler metals is listed in Table 1.

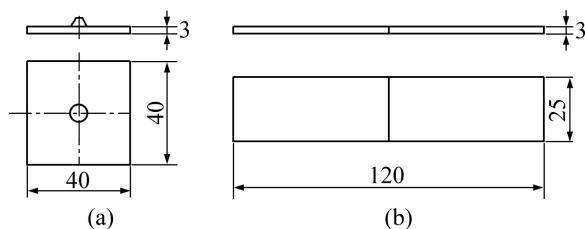
**Table 1** Composition of filler metals

Alloy No.	1	2	3	4	5	6	7
w(Al)/%	2	5	8	12	15	20	22
w(Zn)/%	98	95	92	88	85	80	78

The wetting and spreading performances were tested following China's National Standard GB/T 11364—2008 on a resistance furnace, in which the improved CsF-AlF<sub>3</sub> flux was used. The substrate was the 3003 plate with dimensions of 40 mm×40 mm×3 mm. The chemical composition of the 3003 alloy is listed in Table 2. Before brazing, the 3003 alloy plants were degreased with a powerful solvent and the surface oxide film was removed with SiC paper. The temperature was set as 500 °C when the melting point of the filler metal was under 470 °C (the melting point of the improved CsF-AlF<sub>3</sub> flux); when the liquidus temperature of the filler metal is higher than 470 °C, the furnace temperature was set as 30 °C, above the liquidus temperature; meanwhile, 0.16 g filler metals were used in this test. For the evaluation of bonding strengths with these filler metals, 3003 aluminum plate specimens shown in Fig. 1 were butted by torch brazing, and improved CsF-AlF<sub>3</sub> flux was also used. The strength of brazed joints were tested on a SANS electromechanical universal testing machine according to China's National Standard GB/T 11363—2008. And the average values of tested results were calculated and used. To ensure the accuracy of the results, five specimens were brazed under the same conditions with the same brazed alloy.

**Table 2** Chemical composition of specimen (mass fraction, %)

Si	Fe	Cu	Mn	Al
0.4	0.5	0.1	1.1	Bal.



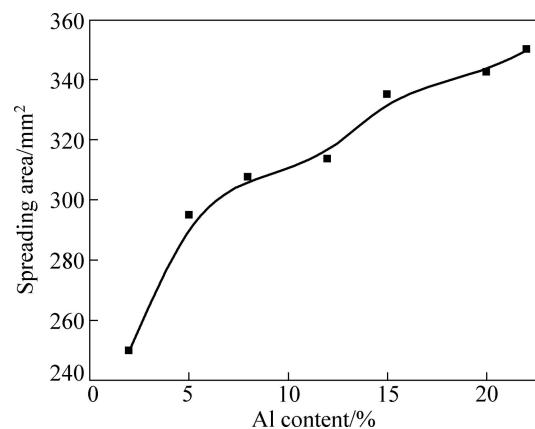
**Fig. 1** Dimensions of specimens (mm): (a) Spreading experiment; (b) Tensile experiment

The brazed specimens were then etched with 5% HNO<sub>3</sub> alcohol solution for 2–3 s after grinding and polishing. The microstructure observation was conducted on an optical microscope, a scanning electron microscope as well as an energy dispersive spectroscope.

## 3 Results and discussion

### 3.1 Wetting property of Zn-Al filler on 3003 Al substrate

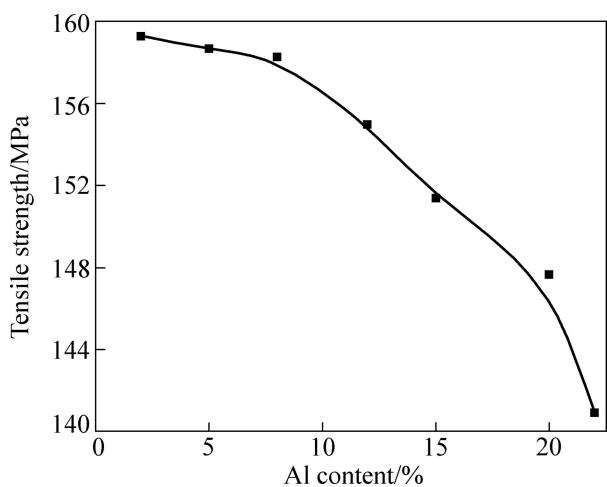
As we know, the wetting property of the filler metal is affected by the fluidity of the filler metal and the reaction between the filler metal and substrate. When the liquid filler dissolves in the base metal or reacts with the base metal to form the IMCs, its wetting property is usually better. However, the excessive solubility is harmful to the spreading performance. Due to the high dissolving rate of Zn in Al, the fluidity of filler metal on Al substrate is not good as that of Al–Si filler metal. It is found that the general trend of the spreading area is increased with increasing the content of Al, as shown in Fig. 2. And a reasonable explanation is that the large solid solubility of Zn in Al greatly impedes the wetting process.



**Fig. 2** Effect of Al content on spreading area of Zn-Al filler metal

### 3.2 Mechanical properties

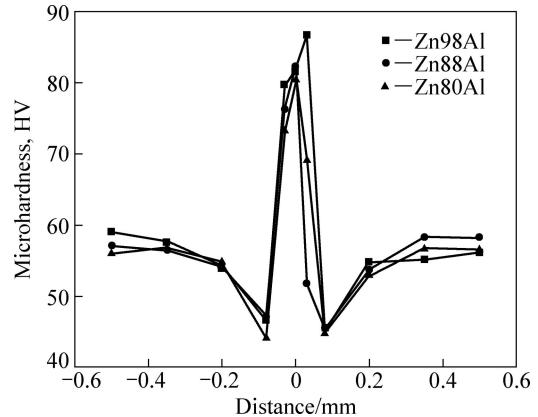
The effect of Al content on tensile strength can be seen from Fig. 3. Results indicate that sound joints could be obtained, and the tensile strength could be close to 160 MPa when the Al content varies in the range of 2%–8%; however, strength of joints degenerates when the content of Al exceeds 12%. Obviously, the Al content determines mechanical property of the joints, and the excessive Al in the filler metal is detrimental for the bonding strength of the joint. In this study, little Cu, Mg and Si were added in the filler metal, so the secondary crystalline phases such as CuAl<sub>2</sub>, Mg<sub>2</sub>Si were not found in the brazing seam [12], which increased the tensile strength of the joints.



**Fig. 3** Effect of Al content on tensile strength of Zn-Al filler metal

Figure 4 shows the microhardness values of 3003 aluminum alloy joints brazed with Zn-Al series filler. The average hardness value of the 3003 aluminum alloy is HV50–60. The microhardness of the Al based solid solutions is around HV50 [13]. The higher microhardness value in this study is mainly caused by the Zn element in

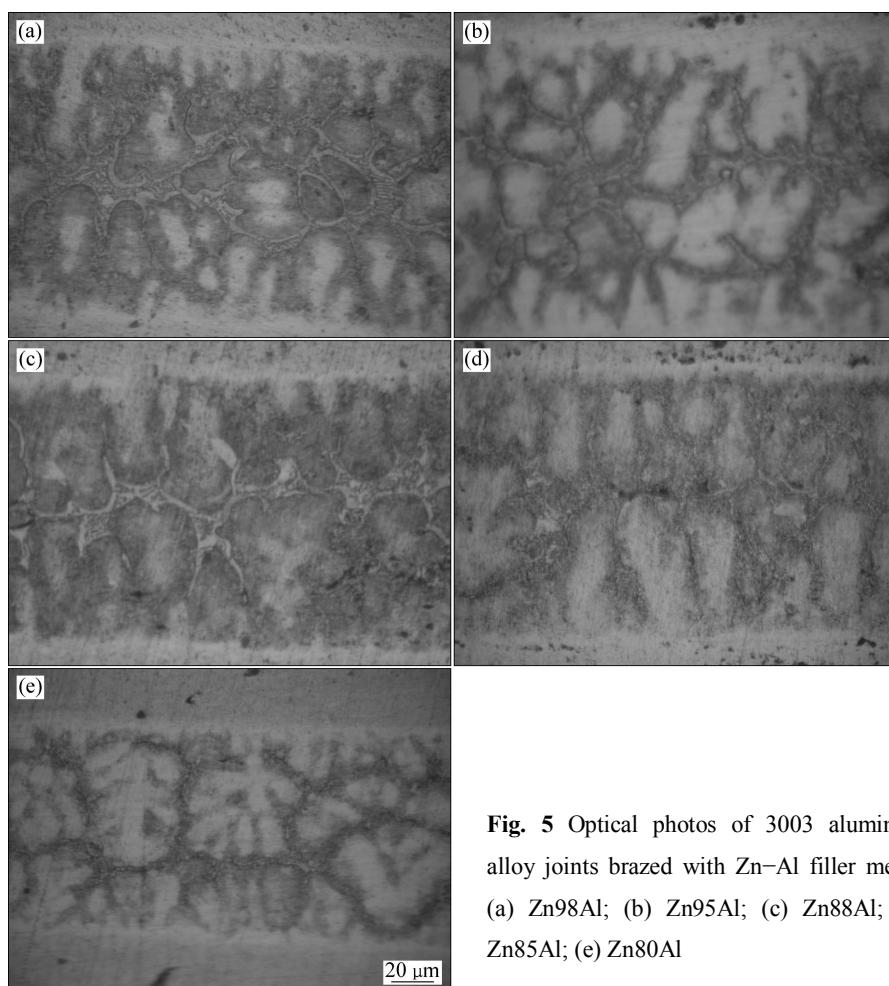
the filler metal. As the secondary phase formed, due to the solid solution strengthening effect, the hardness values in the brazing seam are HV70–90, and the hardness of Zn98Al joint is much higher than the other two.



**Fig. 4** Microhardness of brazing interface of 3003 alloy joint with Zn-Al filler metal

### 3.3 Microstructure observation

The microstructures of different joints are shown in Fig. 5. Along with the increase of the Al content, the



**Fig. 5** Optical photos of 3003 aluminum alloy joints brazed with Zn-Al filler metal: (a) Zn98Al; (b) Zn95Al; (c) Zn88Al; (d) Zn85Al; (e) Zn80Al

microstructures varies significantly. According to the Al–Zn binary phase diagram (Fig. 6), the Al substrate and the brazing alloy were bonded by the Al–Zn solid solution phase [14]. When the Al content is less than 5%, the solid solutions in visual field are much more than the high Al content ones. A significant mark appeared like a ‘dividing line’ in the middle of the brazing seam in Fig. 5(d). When Zn begins to dissolve into the base metal, the solid solutions grow, and the simultaneous intergrowth towards the center makes the ‘dividing line’ form. The large solid solution grains in the brazing seam may be harmful to the mechanical properties of the joints from the tensile test results. Another possible explanation of the performance deterioration is that during the solidification of the brazing joint, the simultaneous intergrowth pushes forward the impurities to the centre of the seam. With further increasing the Al content, the fish-bone phases appear (Fig. 5(e)). Combined with the tensile experiment result discussed before, the harmful fish-bone phases precipitated in the brazing seam should be avoided.

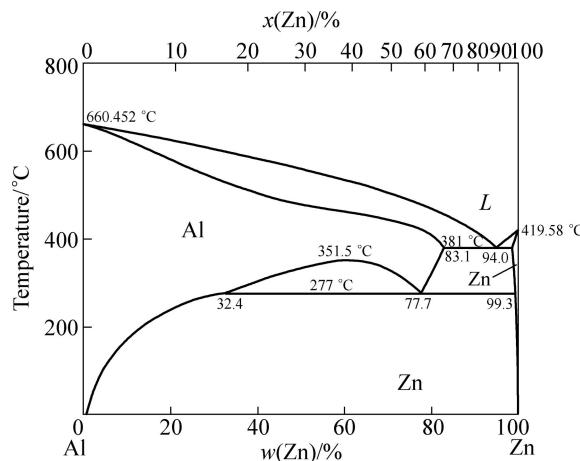


Fig. 6 Al–Zn equilibrium diagram

From the SEM image (Fig. 7), it is clear that the number of the solid solutions in the Zn98Al brazing seam is much more than that in the Zn80Al. However, from the EDS result of points A, B, C, D in Fig. 7 (Fig. 8), there is little change in the compositions of the solid solutions. While the Al content rises from 2% to 22% in the filler, the Al content in the Al-rich phase only increases by about 6%. From Fig. 8, it can be also found that during the brazing process, the base metal and the filler dissolved in each other. According to the Al–Zn equilibrium diagram (Fig. 6), the Al content around 30% (points A, D in Fig. 7) is in the eutectoid range. MOVAHEDI et al [15] found that the absence of eutectoid phases may be related to the nonequilibrium solidification during brazing. Qualitative analysis shows that points A, D in Fig. 7 are Al based solid solution ( $\alpha$  phase), and the points B, C are Zn based solid solution ( $\beta$  phase).

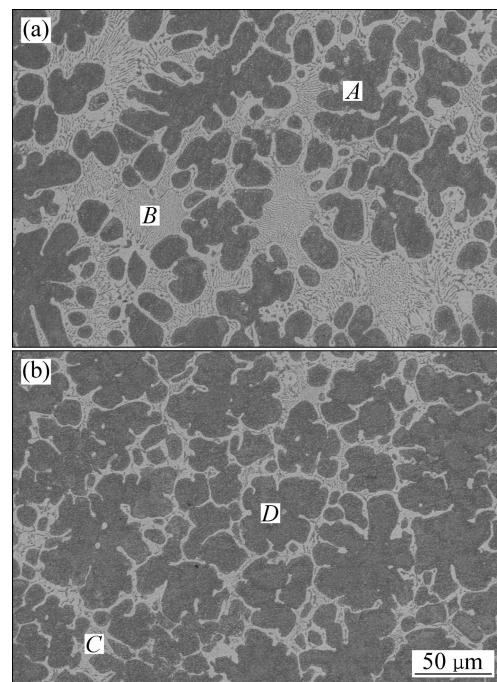


Fig. 7 SEM images of brazing seams: (a) Zn98Al; (b) Zn80Al

### 3.4 Zn penetration into base metal

In order to understand whether the filler/base metal interface was an influence factor of the joint strength, element line scanning was also adopted, as shown in Fig. 9. According to the element distribution at the interface, it is obvious that there are three regions, i.e., base metal, diffusing zone and interface. Along with the increase of the Al content, the width of diffusing zone raises. The width values of Zn98Al, Zn88Al, Zn80Al are 6.7, 12.0, 16.7  $\mu$ m, respectively.

The increase of the width could be explained by the diffusion behavior, and the diffusion coefficient as a function of temperature can be expressed as [16]

$$D = D_0 \exp\left(\frac{-Q}{RT}\right)$$

where  $D_0$  is the diffusion constant;  $Q$  is the activation energy;  $T$  is the thermodynamic temperature;  $R$  is the gas constant, 8.314 J/(mol·K). From the Al–Zn equilibrium diagram (Fig. 6), the melting points of Zn98Al, Zn88Al and Zn80Al increase progressively, so does the brazing temperature. Along with the brazing temperature increasing, the diffusion coefficient increases, and the width of the diffusion zone grows. MOVAHEDI et al [15] reported that the width of diffusing zone could largely affect the joint strength, and with the width increasing, a higher tensile strength was obtained. But the tensile strength of the Zn–Al joints in this study shows opposite (Fig. 3). So, the important affecting factor of the tensile strength is the distribution of solid solutions rather than the width of the diffusing zone.

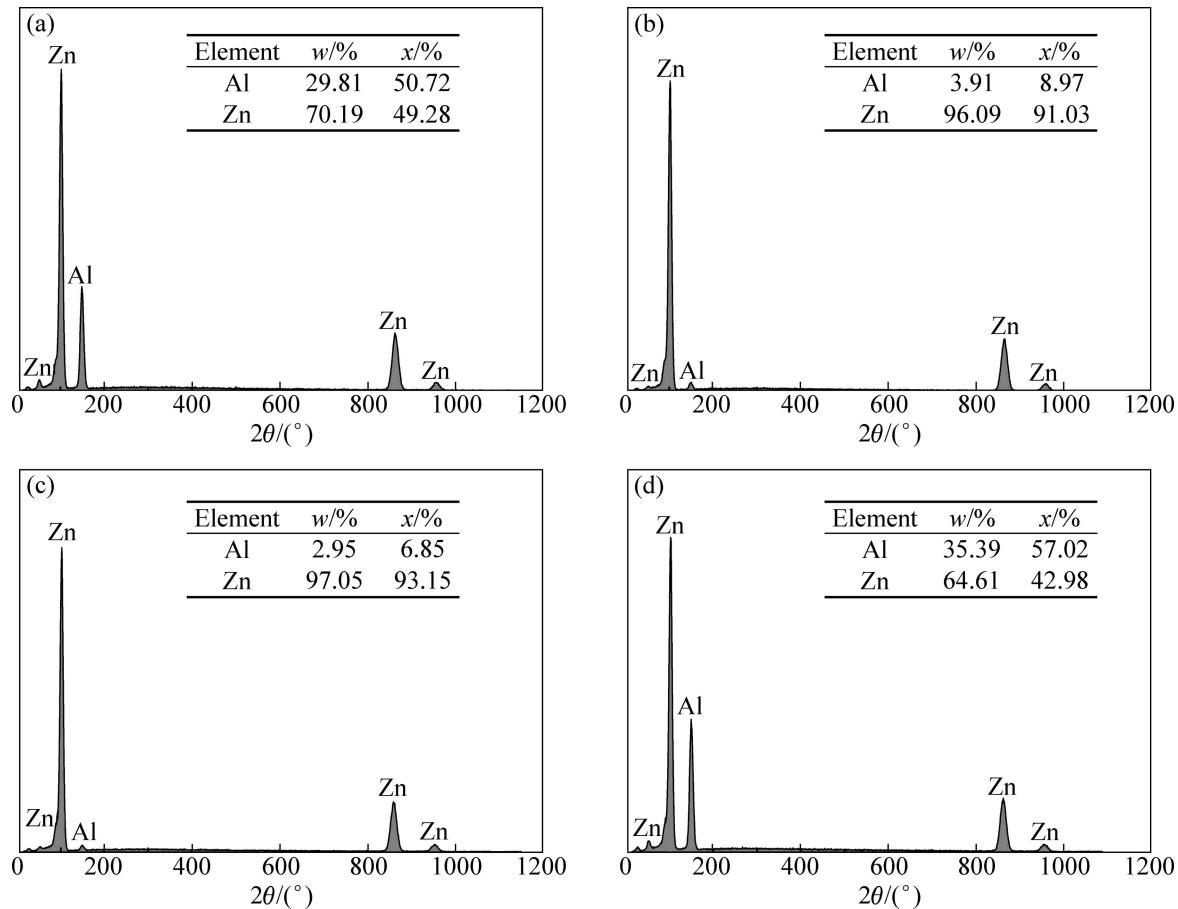


Fig. 8 EDX results of points A, B, C, D in Fig. 5: (a) Point A; (b) Point B; (c) Point C; (d) Point D

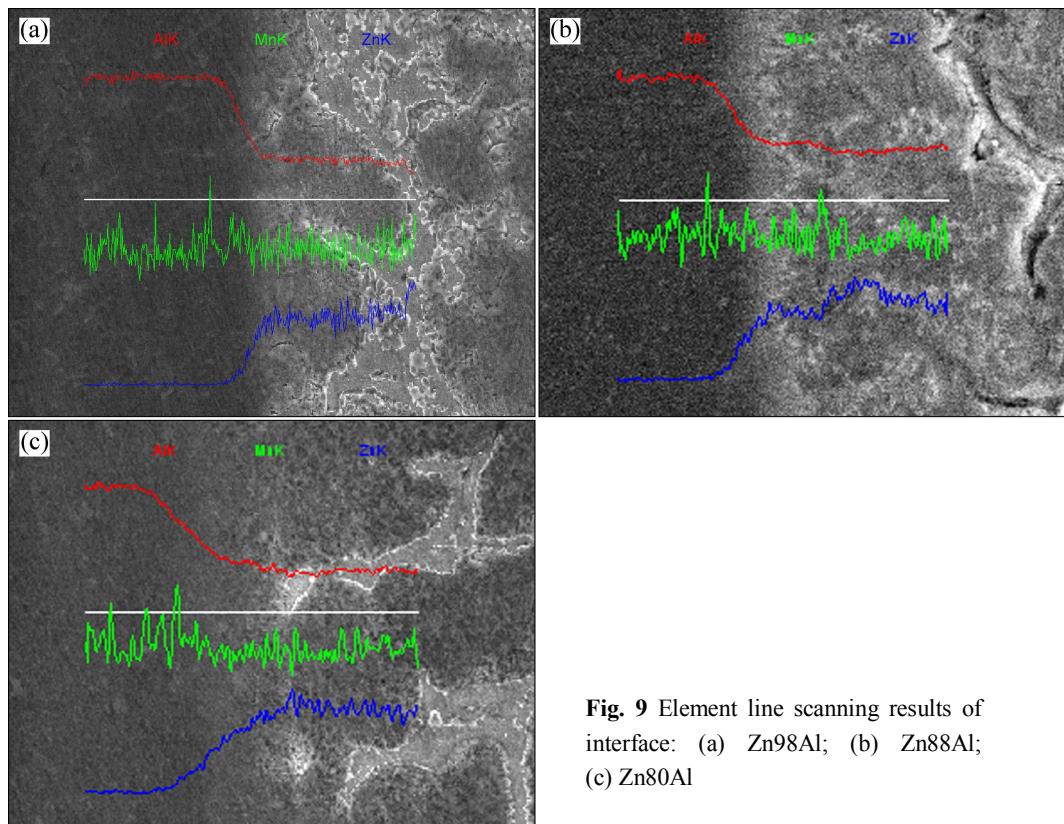


Fig. 9 Element line scanning results of interface: (a) Zn98Al; (b) Zn88Al; (c) Zn80Al

## 4 Conclusions

1) The tensile strength of joints changes with the increase of Al content in the filler metal. The maximum strength of the joint is obtained when Al content is 2%. Because of the solid solution strengthening effect, the microhardness value of the brazing seam is much higher than that of the 3003 aluminum substrate.

2) The microstructure of the Zn–Al joints contains an Al-based solid solution ( $\alpha$  phase) and a Zn-based solid solution ( $\beta$  phase). The brazing interface is mainly composed of three microstructure zones: base metal, diffusing zone, interface zone.

3) The tensile strength of the joint is mainly affected by the distribution of the solid solution in the brazing seam rather than the diffusion zone width near the interface.

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## 3003 铝合金 ZnAl 钎料的火焰钎焊

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**摘要:** 采用 Al 含量为 2%~22%(质量分数)的 ZnAl 钎料, 配合改进型 CsF–AlF<sub>3</sub>钎剂, 研究 ZnAl 钎料在 3003 铝合金板材上的铺展性能及钎焊接头的力学性能与显微组织。结果表明, 当 Al 含量低于 8%时, 3003 铝合金的火焰钎焊接头成形良好, 且抗拉强度较高。钎缝显微组织为 Al 基固溶体及 Zn 基固溶体。由于固溶强化作用, 钎缝的显微硬度比母材的高。钎缝界面由三部分组成, 母材、扩散区和界面区, 但影响接头强度的主要因素为钎缝内固溶体的分布情况, 而不是扩散区的宽度。

**关键词:** Zn–Al 钎料; 火焰钎焊; 力学性能; 显微组织