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ARTICLE

Effects of Silicon on Microstructures and Properties of Al-40Zn-*x*Si Filler Metal

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Abstract: The effect of Si on the brazability and the microstructures of Al-40Zn-*x*Si filler metals were studied, and the microstructures and the mechanical properties of the joints brazed with Al-40Zn-*x*Si filler metals were investigated. The results indicate that the Al-40Zn-*x*Si filler metal presents the best wettability on 6061 aluminum alloy when Si content is and 4.0 wt%. The microstructure of the filler metal indicates that the primary silicon particles could be found when the silicon content exceeds 4.0 wt%. Al-Si eutectic mixed with Zn-Al eutectoid is located at α-Al interdendritic regions in the brazed seam after cooling with water. Moreover, the Al-40Zn-4Si joint possesses the optimum shear strength of 142.28 MPa. However, the excess of Si would increase the amount of brittle eutectic structure and primary silicon particles in the brazed joints, and thereby the mechanical properties will be deteriorated.

Key words: Al-40Zn-*x*Si filler metal; brazing; microstructure; mechanical property

Aluminum is regarded as one of the most promising lightweight materials for its superior mechanical properties, excellent corrosion resistance and relatively low density. Increasing demands for the joints of aluminum and its alloys have promoted the development of aluminum brazing. So far, a variety of brazing alloys have been researched and developed, such as Al-Si, Al-Si-Cu, and Zn-Al systems. Brazing for the most commercial aluminum alloys with Al-Si eutectic filler metal often becomes difficult because of its high melting point (577 ℃). The relatively high brazing temperature would cause the localized melting of base metal and deteriorate the mechanical properties. In the previous investigations, the ternary Al-Si-Cu alloy was selected as the promising filler metal for aluminum brazing because of its lower melting point [1, 2]. Nevertheless, Cu is easy to react with Al base metal to form Cu-Al compounds. The excessive intermetallic compounds would lessen the mechanical property and reliability of the brazing joint[3, 4].

The brazability of Al-40Zn-4.2Si eutectic alloy was studied by Suzuki et al[5]. The sound joint was obtained at the brazing temperature of 563 ℃. Dai et al[6] studied a series of Al-42Zn-6.5Si-*x*Sr alloys, which indicated that the melting point of Al-42Zn-6.5Si alloy was around 520 ℃ and the addition of Sr could enhance the properties of the alloys. However, the effects of silicon on properties of Al-Zn-Si alloy have been rarely reported. In the present paper, the influences of silicon on microstructures and brazability of Al-40Zn-*x*Si filler metals were studied. In addition, the microstructures and mechanical properties of 6061 aluminum alloy brazed joints were investigated.

1 Experiment

A series of Al-40Zn-*x*Si (*x*=2, 3, 4, 5, 6) alloys were prepared in the present work. The chemical compositions of filler metals are listed in Table 1. Pure Zn, Al (99.9% purity) and Al-12Si master alloy were melted in a crucible electrical resistance furnace. A graphite rod was used to stir the liquid brazing alloy every 10 min to ensure composition uniformity. KCl/NaCl eutectic mixture was used over the surface of the liquid alloy to prevent oxidation. All the cast

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ingots were fabricated into wires with 2 mm in diameter for brazing.

The test plates of 6061 alloy used in the present work were processed into specimens with dimensions of 40 mm × 40 mm × 3 mm for spreading test, and 60 mm × 25 mm × 3 mm for shear test, as shown in Fig.1. Before the brazing, all the specimens were degreased in acetone and ground by SiC paper, and then cleaned in alcohol. The spreading test was carried out according to China's National Standard GB 11364-2008[7]. 0.2 g filler metal was placed on the specimen covered with a modified CsF-AlF_3 flux. The heating temperature was 570 ℃, and the holding time was 1 min. The brazing process was performed in an electrical resistance furnace. The specimens with an overlap length of 3 mm were heated at 570 ℃, then retained at the temperature for 10 min, and finally cooled in water.

The melting temperatures of the filler metals were investigated by differential thermal analysis (DTA). The microstructures of Al-40Zn-*x*Si alloys and brazing joints were observed by the scanning electron microscope (SEM) including energy dispersive X-ray (EDS).

2 Results and Discussion

2.1 Brazability of filler metals

The melting points of Al-40Zn-*x*Si filler metals are listed in Table 2. The results show that the solidus and liquidus temperatures of the alloys increase with the increase of Si content. Compared with the Al-40Zn-2Si filler metal, the solidus and liquidus temperatures of Al-40Zn-6Si filler metal are higher by 3.1% and 2.9%, respectively. Nevertheless, the melting points of Al-40Zn-xSi filler metals still gives a remarkably decrease compared to that of Al-12Si filler metal.

Usually, the wettability is described by the spreading area of a filler metal on the substrate, and as reported, the lager the spreading area, the better the wettability[8]. Fig.2 shows the spreading test results of Al-40Zn-*x*Si alloys. It can be seen that the wettability of Al-40Zn-*x*Si filler metals are improved by adding an appropriate amount of Si. The spreading area of Al-40Zn-4Si filler metal is about 157.19 mm^2, enhanced by 49.69% and 31.74%, respectively, compared to that of Al-Zn-2Si and Al-Zn-3Si filler metals. The spreading area decreases when Si addition increases up to 5.0wt% and 6.0 wt%.

The results presented in Fig.2 suggest that appropriate amount of silicon is beneficial to the spreading performance. According to the Zn-Al binary phase diagram, the solubility of liquid Zn in Al is about 50wt% at 500 ℃. The excessive solubility would go against the spreading performance on the substrate[9-11]. The amount of Al-Si eutectic gradually increases with the increase of Si content, as shown in Fig.3a~3c, which is conducive to enhancing the spreading ability. However, when the content of Si exceeds 4 wt%, the primary Si appears in the filler metal. Meanwhile, the liquidus temperature of the filler metal increases with the increase of addition of silicon, as shown in Table 2. The higher liquidus temperature may lessen the fluidity of the

Table 1 Chemical compositions of filler metals (wt%)

No.	1	2	3	4	5
Al	Bal.	Bal.	Bal.	Bal.	Bal.
Zn	40	40	40	40	40
Si	2	3	4	5	6

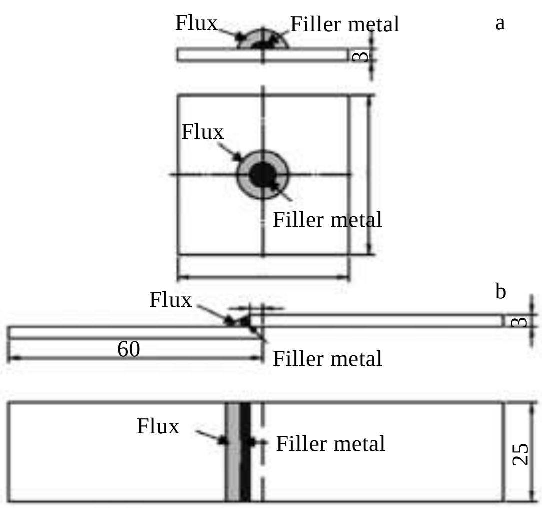

Fig.1 Schematic illustration of the experimental set up: (a) spreading test and (b) lap joint for shear testing

Table 2 Melting points of the filler metals (℃)

No.	1	2	3	4	5
Solidus	507.72	510.69	516.26	520.01	523.61
Liquidus	529.21	531.21	538.42	541.39	544.64

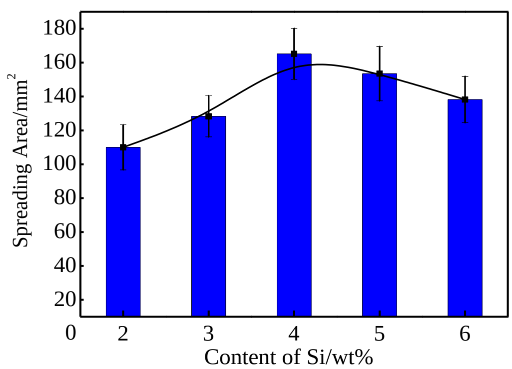

Fig.2 Spreading areas of Al-40Zn-*x*Si on 6061 substrates

filler metal at the heating temperature of 570 ℃[12]. So the excessive content of Si addition to the filler metal would deteriorate the wettability of Al-40Zn-*x*Si alloys.

2.2 Microstructures of filler metals

In order to clarify the phase constitution of Al-40Zn-*x*Si alloys, X-ray diffraction (XRD) analysis was carried out under certain conditions. Fig.4 shows the XRD patterns of Al-40Zn-2Si, Al-40Zn-4Si, Al-40Zn-6Si. The XRD results suggest that the Al-40Zn-*x*Si alloys consist of three phases including Si phase, α-Al phase and η-Zn phase. The diffraction peaks of η-Zn phase and α-Al phase decrease with the increase of Si content.

The solidification process of Al-40Zn-*x*Si alloys could be summarized in three stages. At the first, α-Al phase is formed, then the Al-Si eutectic phase is formed, and Zn-rich phase is developed at the end [13]. Fig.3 shows SEM images of as-cast Al-40Zn-*x*Si filler metals. It should be noted that the microstructures of Al-40Zn-*x*Si alloys change obviously with the different additions of Si. As shown in Figs.3a-3b, the needle-like eutectic Si is observed in the interdendritic regions. When Si is added up to 4.0 wt%, the bulk Si particles appear in the filler metal. The bulk Si particles are recognized as the primary Si particles[14]. The silicon atoms are easy to segregate and form Si-Si clusters, which lead to the formation of primary silicon even in hypoeutectic Al-Si alloys[15]. In addition, the segregation and gathering of bulk primary silicon particles are observed when the content of Si exceeds 5.0wt%, as shown in Fig.3e (point E). The chemical compositions of different points in Fig.3 were analyzed and are listed in Table 3. The results indicate that the dark areas A, D are α-Al phase. The white points B and C consist of 29.87 wt%Al, 70.13 wt%Zn and 22.21 wt%Al, 77.79 wt%Zn, respectively. According to the Al-Zn equilibrium diagram and previous investigations, points B, C are eutectoid Zn-Al phase[16].

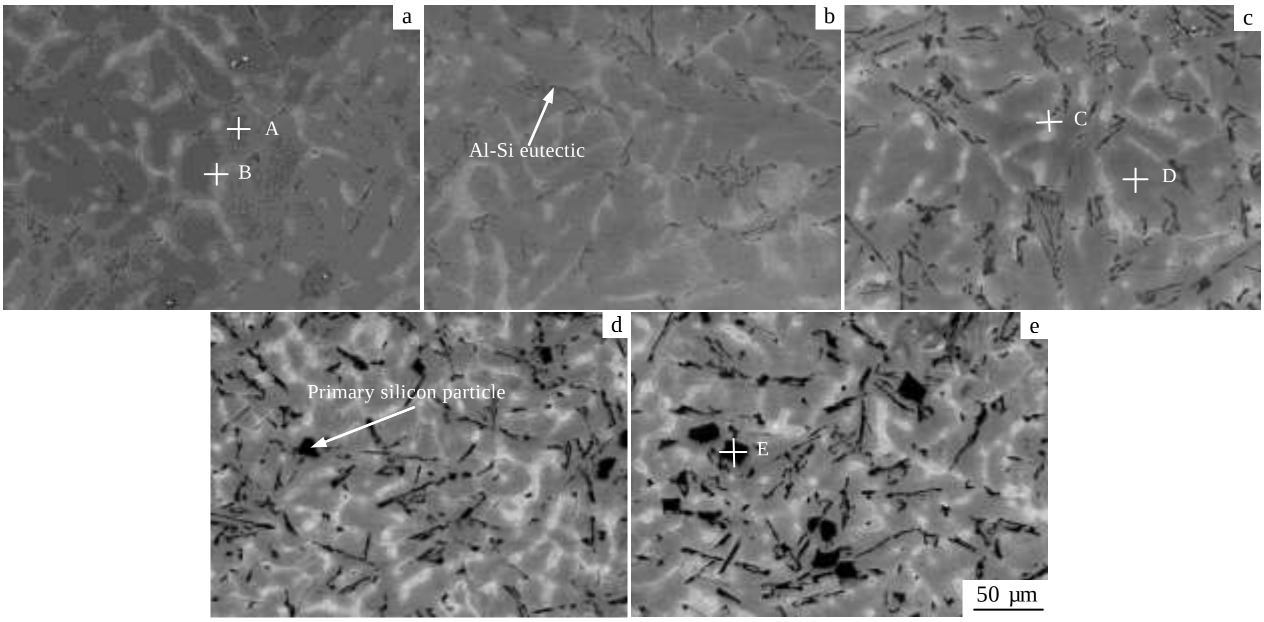

Fig.3 Microstructures of Al-40Zn-*x*Si filler metals: (a) Al-40Zn-2Si, (b) Al-40Zn-3Si, (c) Al-40Zn-4Si, (d) Al-40Zn-5Si, and (e) Al-40Zn-6Si

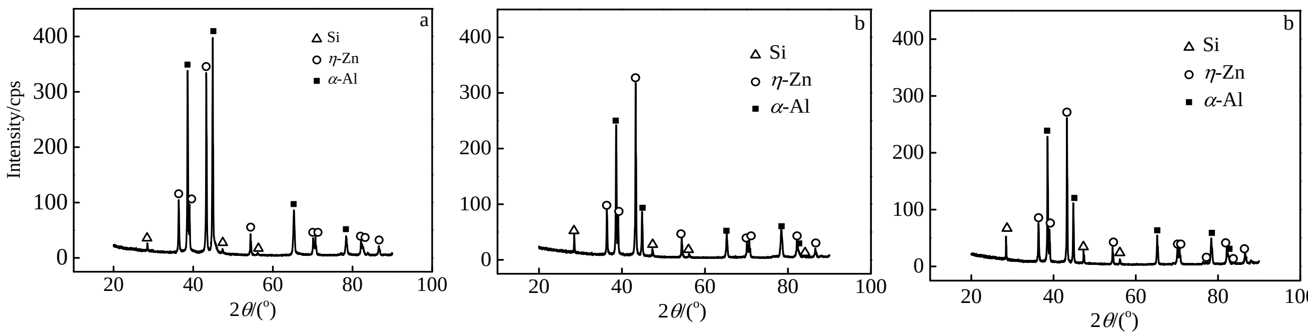

Fig.4 X-ray diffraction patterns for filler metals: (a) Al-40Zn-2Si, (b) Al-40Zn-4Si, and (c) Al-40Zn-6Si

Table 3 EDS results of points indicated in Fig.3 (wt%)

Point	A	B	C	D	E
Al	73.99	29.87	22.21	74.09	0.79
Zn	25.26	70.13	77.79	24.61	1.80
Si	0.75	-	-	1.31	97.40

2.3 Microstructures of brazed joints

The scanning electron micrographs of 6061 aluminum brazed joints with water cooling are shown in Fig.5. It can be seen from Fig.5a that the brazed seam is composed of the dark α-Al phase and net-like white phase. When the content of Si is 4.0 wt%, the size of α-Al phase is smaller and the net-like white phase turns to be more concentrated, as shown in Fig.5b. For the Al-40Zn-6Si brazed joint, the size of Al-Si eutectic phase is somewhat coarser and the primary silicon can be found, as shown in Fig.5c. It is well known that the large silicon particles in the brazed seam could be the stress source when the deformation occurs and deteriorate the mechanical properties of the brazed joints. The EDS analysis results of points F and G are listed in Fig.5d and 5e, which indicate that the chemical compositions of the areas are significantly different from Al-Si eutectic or Zn-Al eutectoid. According to Ref.[17], the researchers reported that under high cooling rate, such as water cooling, the reactions of the eutectic and eutectoid would occur at the same time, and it would be difficult to figure out these two phases in the microstructures. Hence, the white area in Fig.5b is assumed as the mixture of Al-Si eutectic phase and Zn-Al eutectoid phase, while point G is assumed to be the mixture of Al-Si eutectic phase, Zn-Al eutectoid phase and primary silicon particles.

2.4 Mechanical properties of brazed joints

Fig.6 shows the microhardness profile of 6061 aluminum joints brazed with Al-40Zn-*x*Si filler metals. The microhardness of the brazed joints was measured by the Wilson-wlopert microhardness meter at a 10 g load and for 10 s loading time. It can be seen that the average hardness value of 6061 base metal is around 500 MPa. The hardness values in the brazed seam side are in the range of 1100~1500 MPa, much higher than those of the base metal and diffusion seam sides. Moreover, the hardness value increases linearly when the amount of silicon increases from 4.0 wt% to 6.0 wt%, which could be attributed to the large amount of Al-Si intermetallics and bulk-like primary silicon in the brazed joints, as shown in Fig.5.

The shear strength of the brazed joint is gradually enhanced when the content of silicon increases from 2.0 wt% to 4.0 wt%, as shown in Fig. 7. The fracture occurs in the brazed joints of the brazed specimens in all cases after shear tests. Results show that the peak value of 142.28 MPa is acquired at x=4, which increases by 135.8% compared to that of Al-40Zn-2Si. However, the joint strength drops when the content of Si exceeds 5.0 wt%. When the content

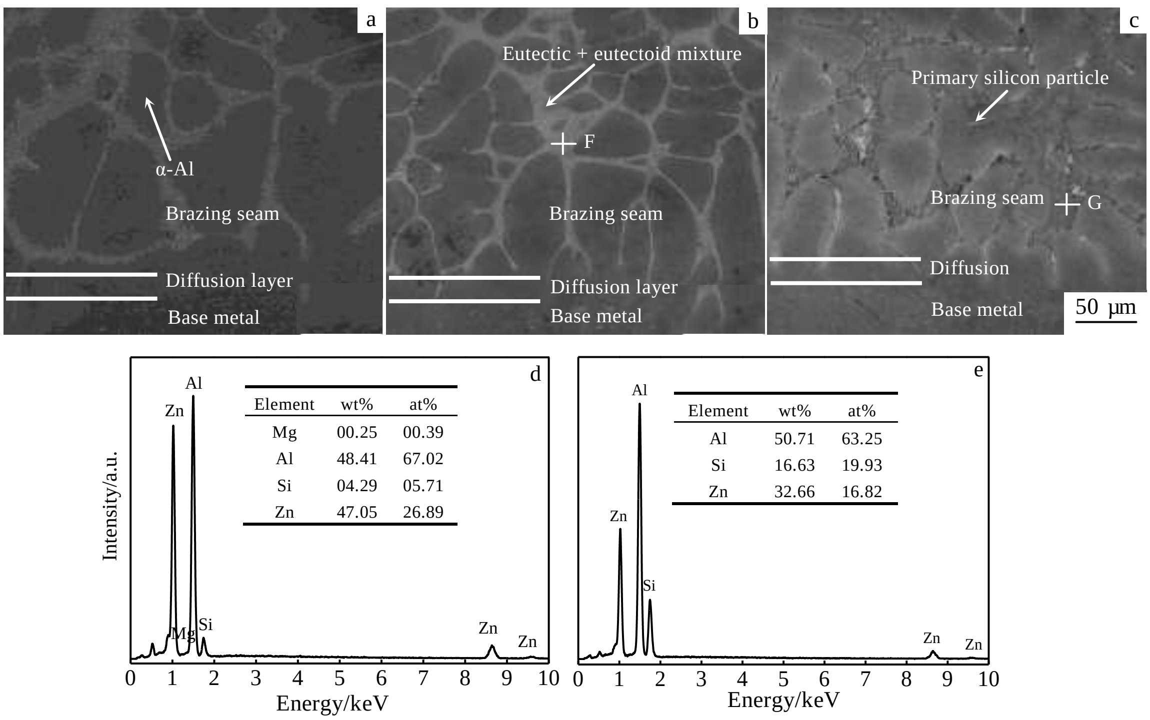

Fig.5 Interface microstructures and EDS spectra of brazed joints: (a) Al-40Zn-2Si/Al, (b) Al-40Zn-4Si/Al, (c) Al-40Zn-6Si/Al, (d) EDS analysis of point F, and (e) EDS analysis of point G

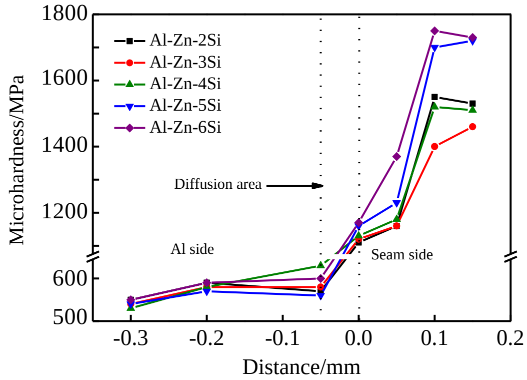

Fig.6 Microhardness of the brazed joints with different Al-40Zn-*x*Si filler metals

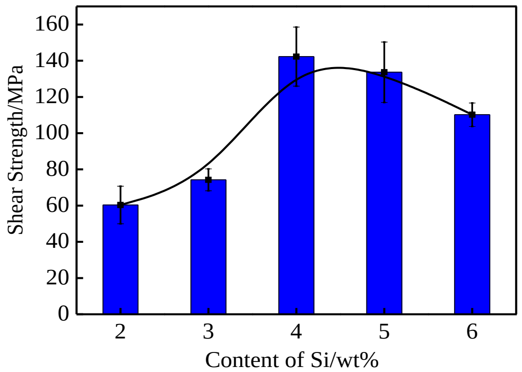

Fig.7 Shear strength of 6061 aluminum alloy brazing joints

of Si is 6.0 wt%, the shear strength of the joint is still much higher than that of Al-40Zn-2Si and Al-40Zn-3Si filler metals. The changes in the shear strength of the brazed joints are attributed to the amount, the size and the distribution of silicon particles in microstructure[18]. It has been reported that the homogeneous distribution of silicon is helpful to improve the mechanical property of alloys[19]. Therefore, the appropriate content of silicon is beneficial to increase the shear strength of aluminum joints. The degradation of mechanical property could be explained by the formation of excessive Al-Si eutectic and large bulk-like primary silicon, leading to the cracking tendency among the brazed joints.

3 Conclusions

1) The spreading areas of Al-40Zn-*x*Si filler metals can be significantly improved by adding appropriate amount of silicon. The microstructures of Al-40Zn-*x*Si filler metals consist of α-Al, Al-Si eutectic, Zn-Al eutectoid, and the primary silicon particles could be found when the silicon content exceeds 4.0 wt%.

2) In Al-40Zn-*x*Si brazed joints after water cooling, Al-Si eutectic is located at the interdendritic regions, and mixed with Zn-Al eutectoid. The excessive amount of silicon will lead to the formation of primary Si particles of the brazed joint.

3) The mechanical properties of the brazed joints are significantly improved when the addition of silicon increases from 2.0 wt% to 4.0 wt%, and the optimum value of the shear strength is obtained when Si content is 4.0 wt%.

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Si 元素对 Al-40Zn-*x*Si 钎料组织和性能的影响

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摘　要：研究了Si元素对Al-40Zn-*x*Si 钎料的钎焊性能，显微组织的影响以及不同Al-40Zn-*x*Si钎料对铝合金钎焊接头的显微组织和力学性能的影响。结果表明：当Al-40Zn-*x*Si中Si元素含量为4% (质量分数) 时，钎料具有最好的润湿性能。显微组织分析表明：当Si元素含量超过4%后，钎料中开始出现块状初生硅；铝合金钎焊接头水冷后，Al-Si共晶组织和Zn-Al共析组织共存于焊缝中α-Al 的枝晶间区域。当钎料中Si元素含量为4%时，焊后水冷的铝合金钎焊接头的抗剪强度达到最大值142.28 MPa。但是，当钎料中Si元素含量为5%以上时，焊缝中会形成较多的脆性共晶组织和初生硅颗粒，影响接头力学性能。

关键词：Al-40Zn-*x*Si 钎料；钎焊；显微组织；力学性能

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