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ARTICLE

Review on Brazing of High Volume Faction SiC_p/Al Composites for Electronic Packaging Applications

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Abstract: High volume faction (HFC, ⩾50%) SiC_p/Al composites are becoming increasingly popular as the electronic packaging materials, and the brazing of them is therefore of great practical importance. Recently, some new filler metal alloys and processes have been developed for effectively brazing the HFC SiC_p/Al composites. Starting from a survey of physical and mechanical properties and fabrication process of the HFC SiC_p/Al composites, the filler metal, brazing process as well as the corresponding joint microstructures and strength are reviewed for understanding their relationships in order to improve the joining technique and joint reliability. The additions of Cu, Mg and Ni into Al-Si based alloy can contribute to improve the performances of filler metal and/or joint, such as the operating temperature of filler metal, interfacial bonding and brazing seam strength. Two assisted procedures involving surface metallization and ultrasonic vibration can optimize the brazability by avoiding or removing the inevitable oxide films (Al_2O_3 and SiO_2) on the surface of HFC SiC_p/Al composites. The need of further investigations, covering optimization design of filler metal, surface metallization process as well as wettability and interfacial behavior of filler-coating-SiC_p/Al substrate system are strongly underlined.

Key words: high volume faction SiC_p/Al composite; filler metal; surface metallization; brazing; interface; joint mechanical properties

Electronic packaging refers to the packaging of integrated circuit (IC) chips (dies) in a narrow sense, which can support and protect the circuits and other components from environmental factors such as moisture, contamination, hostile chemicals and radiation, while at the same time removing the heat generated during the operation of the devise[1,2]. With the rapid and continuous advances in microelectronics, the devices, such as the multichip modules including several devices in close proximity, are becoming miniaturization, increased functional density, high powder and light weight. To meet the requirement arising from the issues, the packaging substrate materials must be given several physical and mechanical characteristics, such as high thermal conductivity (CT), low weight, low and tailorable coefficient of thermal expansion (CTE), good hermeticity and appropriate mechanical properties[3-5]. The conventional materials applied for the electronic packaging are broad; however, these materials having respective disadvantages cannot meet all of the performance requirements. For instance, both pure Al and Cu have high CT value, while large residual stress will emerge due to the high CTE difference in device based on Si or GaAs substrate. The W-Cu and Mo-Cu composites can provide available thermal conductivity and compatible CTE, while they have high density and high price. Kovar alloy has been used in the field of electronic packaging for a long time, but there are also

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some restrictions of the low CT and high density. These issues of the conventional materials have led to increasing focus on the metal matrix composite (MMC), especially on the Al matrix composites with SiC particle reinforcement (SiC_p/Al composites) due to the variety of advantages (including tailorable CTE, high CT, low weight and compatible strength) suited to the requirement of advanced electronic packaging[6-8]. Moreover, joining is an indispensable process for application of the SiC_p/Al composites in the electronic packaging. Among a variety of joining techniques, brazing is most commonly adopted as a reliable and economical one for the SiC_p/Al composites.

The purpose of this paper is to provide a brief overview focusing on the filler metal and the brazing process of the HFC SiC_p/Al composites. What is more, the potential solutions to improve the brazability of the HFC SiC_p/Al composites and some fundamental researches that need to be strengthened are put forward.

1 SiC_p/Al Composites

The SiC_p/Al composites present many distinct advantages compared to the conventional packaging materials, and their physical and mechanical properties are determined by the individual performances of the matrix and reinforcement, as well as the details of the microstructure when they form a composite. The SiC particle is a suitable and versatile option for the reinforcement due to the low density (3.2 $g \cdot cm^{-3}$), low CTE (4.7×10^{-6} K^{-1}), high Young's modulus (450 GPa), low cost and alternative CT (80~200 $W \cdot m^{-1} \cdot K^{-1}$)[1,3,9]. While, in a contrast, the Al metal also offers a series of advantages in the electronic packaging except for the high CTE (23×10^{-6} K^{-1}) which is intolerable for this application. However, a range of attractive advantages can be obtained when the SiC particles and Al metal are composited together. Table 1 lists the physical and mechanical properties of the SiC_p/A6061Al composites with the different volume factions of the SiC particle. As demonstrated in Table 1, it is possible to tailor the properties of the SiC_p/Al composites by altering the concentration of the SiC particle. For instance, the CTE of the composites presents a reduction due to the addition of the low-expansion SiC particles, which can make a low stress between the composite and semiconductor materials or ceramic substrates in the electronic packaging. Meanwhile, the modulus and tensile yield increase with the volume faction of SiC particles increasing, and only a little enlargement is induced in the density of the SiC_p/Al composite. However, the CT presents a decreasing trend with increasing the SiC particle volume fraction in the composite, which is mainly governed by the thermal performance, content, type and distribution of each component, as well as the defects, such as micro-pores in the composite[10,11].

Due to the outstanding performances of the HFC SiC_p/Al composites compared to the low volume faction SiC_p/Al composites, they have received substantial attention in the last decade. Nowadays, diverse processes have been successfully applied to fabricate the HFC SiC_p/Al composites, such as pressureless infiltration[12-14], pressure infiltration[10,15-17], squeeze casting[11,18,19], powder metallurgy[20] and semi-solid powder process[21], and all the SiC_p/Al composites fabricated by these processes show good physical properties, especially the thermal properties (Table 2). Fig.1 shows the typical optical microstructure of the SiC_p/Al composite with 55% volume faction particles fabricated by the pressureless infiltration. It is inevitable that many gaps are located at the SiC/Al or SiC/SiC interface due to this pressureless infiltration process.

2 Filler metals for HFC SiC_p/Al Composites

2.1 Demands for filler metal

As we know, the brazing temperature of SiC_p/Al composites in the electronic packaging application should be limited because the Al metal matrix will melt, the mechanical properties of SiC_p/Al composites will be compromised and the interface reaction between SiC and Al will happen when the operating temperature is higher than 650 ℃[22]. Moreover, the Au-Si alloy with a melting temperature of 430~450 ℃ is constantly used as filler metal between the electronic chip and substrate, and the joining temperature between the packaging shell and the pins or other component should be higher than that of the chip level packaging. Thus, the requirement for the joining temperature range of 500~600 ℃ is put forward for the brazing of SiC_p/Al composite. The available brazing temperature range is severely limited since the melting temperatures of filler metals must be located in this temperature range and they can be produced in the form of foil or wire. So, the main constituent of filler metals had better aluminum metal and some other constituents which can moderately decrease the melting temperature have to add.

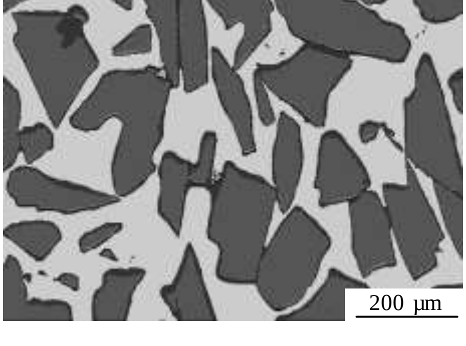

Fig.1 Typical optical micrograph of the SiC_p/Al composite fabricated by pressureless infiltration[10]

Table 1 Physical and mechanical properties of SiC_p/6061Al composites with different SiC volume fractions[4]

Properties*	Particle volume fraction/%			
	0	25	55	70
Modulus/GPa	69	114	186	265
Tensile yield/MPa	275	400	495	-
Elongation/%	15	3.80	0.60	0.10
CTE/$\times 10^{-6}$ K^{-1}	23	16.40	10.40	6.20
CT/$W\cdot m^{-1}\cdot K^{-1}$	238	~160	~123	~107
Density/$g\cdot cm^{-3}$	2.77	2.88	2.96	3.00

* T6 heat treatment applied on the composite

Table 2 Thermal properties of HFC SiC_p/Al composites fabricated by diverse processes

Thermal properties	52%, 62%SiC_p /AlSi7Mg[12]	55%SiC_p /pure Al[10]	70%SiC_p /pure Al[15]	70%SiC_p /pure Al[11]	50%, 58% SiC_p /pure Al[19]	66.3%SiC_p /Al-11Si[20]
	Pressureless infiltration	Pressure infiltration	Pressure infiltration	Squeeze casting	Squeeze casting	Powder metallurgy
CTE*/$\times 10^{-6}$ K^{-1}	9.24, 8.45	—	9.18	9.14	9.5, 7.89	—
CT */$W\cdot m^{-1}\cdot K^{-1}$	136, 118	193	165	165	177, 172	212±2

* Values under room temperature

Bonding is a very important process for the application of SiC_p/Al composites in the electronic packaging. The disparate nature of the Al matrix and SiC reinforcement materials greatly affects the bonding of the SiC_p/Al composites and makes it more complex than bonding between homogenous materials due to the presence of the tenaciously and chemically stable Al_2O_3 film and the exposed SiC particles on the surface of SiC_p/Al composite[23,24].

The Al_2O_3 film and exposed SiC particles were considered to be the two main brazing barriers of the SiC_p/Al composites. Aluminum, as indicated by its position in the electromotive force series[25], is considered to be a thermodynamically reactive metal. An Al_2O_3 film (about 3~5 nm) is easily formed on the surface of the SiC_p/Al composites and it is sufficiently tenacious to limit the fluidity of the molten alloy and to prevent the direct contact between the molten filler metal and the SiC_p/Al composites, resulting in a poor joint quality. Meanwhile, a poor wettability of filler metal in contact with the exposed SiC at the brazing temperature is also presented. According to Liu's review[26], few pure metals or inactive alloys have a good wettability on SiC at a relatively low temperature. Moreover, the presence of SiO_2 layer on the surface of SiC particles also can reduce the wettability and prevent brazing the SiC_p/Al composites. In short, the intrinsic poor wettability derived from the SiC_p/Al composite substrate (the two oxide films and the exposed SiC) make the filler metal seriously present a capacity of removing or destroying the oxide films. In addition, taking into account that the brazing filler metal need to achieve a metallurgical and electrochemical compatibility with the SiC_p/Al composites, the additional constituents into the filler metal should involve some elements which can improve the wettability and itself physical and mechanical performances, such as Cu, Ni, Mg, Ti, and Zn.

2.2 Current investigations

The binary Al-Ag, Al-Cu and Al-Si alloys possess eutectic temperatures of 567, 548 and 577 ℃, respectively[27], which are fit for the joining temperature of 500~600 ℃. In the systems of Al-Ag and Al-Cu binary eutectic alloys, the brittle intermetallic compounds Ag_2Al and Al_2Cu (which can reduce the mechanical performances of the filler metal) often emerge; however, no intermetallic compounds form in the Al-Si eutectic alloy, but its melting temperature of 577 ℃ is somewhat high. Based on these issues, it is necessary to develop ternary or multi-element alloys with good mechanical properties and relatively low melting temperature. According to the works reported[28-31], the quaternary Al-Si-Cu-Ni alloy has a relatively low melting temperature. What is more, the Ni and Cu elements can form solid solutions with each other and improve the ductility and toughness of the filler metal. Moreover, previous researches reported extensively the mechanisms of removal of the tenaciously stable Al_2O_3 film that involves physical and chemical effects. The Mg element introduced in the Al-Si-Cu-Ni filler metal can not only remove the remaining oxygen and moisture in the furnace[32], but also disrupt the oxide film by the reaction with the Al_2O_3 film[31-33]. In addition, Teffill et al[34] investigated the effect of a series of elements (Mg, Li, Sr, Nd, Be, Ca, etc) on the vacuum brazing of the aluminum alloy, indicating that the Mg element has the most positive effect on the removal of Al_2O_3 film.

Simultaneously, the Ti or Zn as a trace element was also added to the Al-based alloys as the filler metal for brazing the HFC SiC_p/Al composite before or after the electroless Ni plating[35,36], where an obvious difference of the existing forms of Ti was observed in the solidified ingot and the rapidly solidified one in the Al-12Si-1.5Mg-4Ti filler metal[35]. The Ti mainly existed as a needle-like $Ti(AlSi)_3$ compound in the solidified ingot, while numerous Ti was present within the supersaturated aluminum matrix in the rapidly solidified ingot, which allows the thermodynamically unstable Ti easy to react with the Al_2O_3 film. The Zn-Al alloy was used in the ultrasonic brazing of 55 vol. % SiC_p/A356 composite in air[37], while its melting temperature of ~375 ℃ is too low.

3 Brazing of HFC SiC_p/Al Composites

Presently, fusion welding (TIG welding[38], MIG welding[39], electron beam welding[40]), diffusion bonding[41] and friction stir welding[42] techniques were applied to join low volume faction SiC_p/Al composites. However, they possess respective disadvantages especially for joining of the HFC SiC_p/Al composites. For instance, the significant deformation can be produced during the diffusion bonding and friction stir welding, while the segregation or inhomogeneous distribution of SiC particles and the undesirable deleterious phase like Al_4C_3 at the interface will emerge during the fusion welding due to the high energy input and sharp temperature change, resulting in bad welding performance. Compared with the three joining techniques, brazing should be the most appropriate process to join the HFC SiC_p/Al composites due to the moderate interfacial reactions and low deformation. According to the reports on the brazing of HFC SiC_p/Al composite, the brazing process can be roughly divided into three types.

3.1 Direct brazing

Many researchers investigated the brazing of the low volume faction SiC_p/Al composite and obtained good results; however, few works were reported on the direct brazing of the HFC SiC_p/Al composites. Table 3 and Fig. 2 show the direct vacuum brazing process of HFC SiC_p/Al composites and the corresponding joint shear strength. It is noted that the melting temperature of filler metals ranges from 525 ℃ to 579 ℃ and the element Mg as a trace-element is added to the filler metal. The difference between the melting temperature and the brazing temperature is usually controlled at 20~40 ℃ since too high brazing temperature can bring about the grain coarsening in the Al matrix and the formation of undesirable Al_4C_3, while too low brazing temperature can make the molten filler metal short of good fluidity, resulting in unsatisfactory filling-in of the filler metal in the brazing seam. Certain brazing pressures have to apply due to the un-spreading of the Al-based brazing filler on the HFC SiC_p/Al composites derived from the inevitable oxide films on both the filler metals and the SiC_p/Al composites. As shown in Fig.2, the

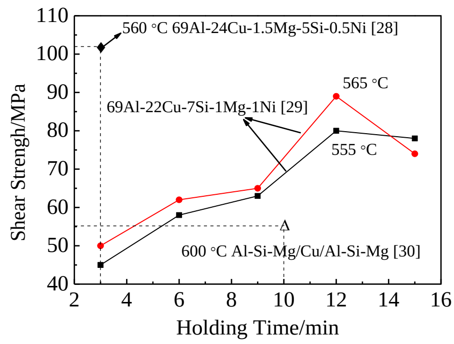

Fig.2 Shear strength of brazed joints at different brazing parameters using different filler metals

joint shear strength of over 100 MPa is obtained only under the conditions of using the 69Al-24Cu-1.5Mg-5Si-0.5Ni as filler metal and of brazing at 560 ℃, which can be attributed to the dissolution of the bright precipitation phases containing Cu and Ni located in the brazing interlayer at the higher temperature (Fig.3). Moreover, the joint shear strength increases with the holding time increasing from 3 to 12 min and then declines while using the 69Al-22Cu-7Si-1Mg-1Ni as filler metal, and the joint strength values obtained at the higher brazing temperature (565 ℃) is always higher than that of those obtained at the lower brazing temperature (555 ℃) except for with the longest holding time of 15 min.

3.2 Brazing after metallization

Surface metallization is an effective way to improve the wetting and brazing of HFC SiC_p/Al composites because the filler/composite interface changes from the metal/ceramic system (the Al_2O_3 film and the exposed SiC) into the metal/metal system. Up to now, the electroless Ni(-P) plating and Cu electroplating are the two main surface metallization processes of HFC SiC_p/Al composites. Several typical investigations on the electroless Ni(-P) plating on HFC SiC_p/Al composites were made to get dense and uniform coating[43-45]. For instance, Zhao et al[45] obtained a nodular, dense and uniform Ni-P coating by electroless plating (Fig. 4). However, the CT value of the SiC_p/Al composites declines after the electroless plating since the Ni-P coating is amorphous and the movement of electrons and phonons is scattering.

Table 4 lists the brazing processes of HFC SiC_p/Al composites after the electroless Ni(-P) plating, Cu electroplating and magnetron sputtering of Ti and the corresponding maximum joint strength. Obviously, the brazing temperature of 280 ℃ is undesirable while using the Sn-Ag-Ni filler metal. As expected, the brazing temperatures using the Al-based filler metals are located in the range of 550~600 ℃. Compared with the direct brazing

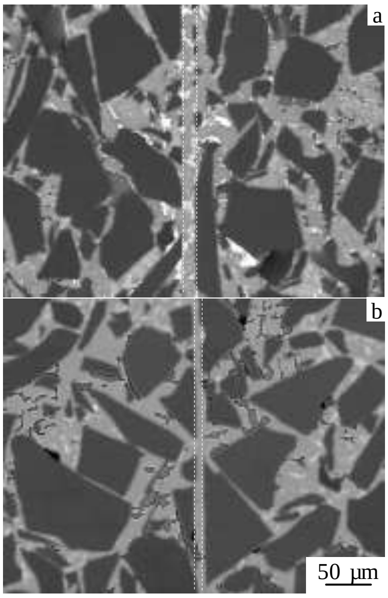

Fig.3 Cross-section microstructures of brazed joints of 55 vol% SiC_p/A356 composite using the 69Al-24Cu-1.5Mg-5Si-0.5Ni as filler metal at 550 ℃ (a) and 560 ℃ (b)[28]

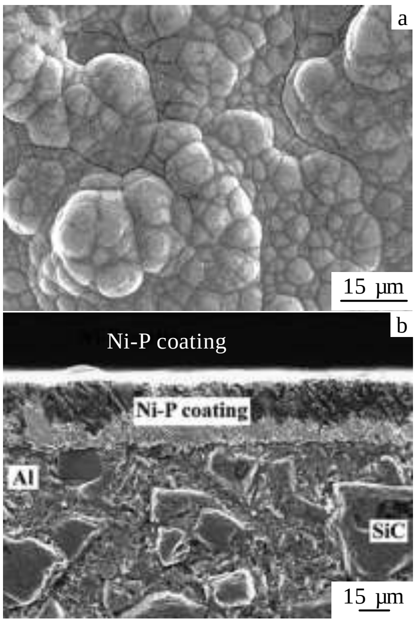

Fig.4 Surface (a) and cross-section (b) morphologies of Ni-P coating electroless plated on a HFC SiC_p/Al composite[45]

processes and the corresponding maximum joint strength, most of the optimal holding time is prolonged and all the maximum joint shear strength values are enhanced to over 100 MPa except for using the Sn-Ag-Ni filler metal. This sharp decrease of joint strength obtained by the Sn-based filler metal can be attributed to the undesirable interfacial layer involving Ni-Sn-P, Ni_3P and Ni-P phases derived from the chemical reactions between the Sn-Ag-Ni filler metal and the Ni(-P) coating[50]. In particular, the maximum or average joint strength increases by 20%~40% after the electroless Ni plating while using the Al-12Si-1.5Mg(-4Ti) filler metal, which can be attributed to the stronger interface mutual interactions (diffusion and metallurgical reaction) among the Al-based filler metal, the Ni film and the SiC_p/Al composite and to the inhibition of SiC particles into the brazing seam (Fig. 5)[35]. However, the joint strength decreases to a certain extent after the electroless Ni plating while using the Al-12Si-1.5Mg-4Ti filler metal since the formed intermetallic compounds of $AlTi_3$ and $Ti(AlSi)_3$ cannot interact well with the Ni coating. Meanwhile, the formed intermetallic compounds as the framework lead to a bit wider brazed seam using the Al-12Si-1.5Mg-4Ti as filler metal than the other filler. So, the joint strength can be affected by not only the chemical reactions but also the thickness of brazed seam.

3.3 Ultrasonic-aided brazing

Up to now, ultrasonic vibration is widely applied in the field of the metal joining, and it is fit to braze the SiC_p/Al composites due to the disruption of the Al_2O_3 film. For instance, Yan et al[37,51,52] performed the ultrasonic-aided brazing of 55 vol% SiC_p/A356Al composite using the 89.3Zn-4.2Al-3.22Cu alloy in air, and investigated the joint microstructures, mechanical performance and strengthening mechanism. An continuous oxide layer formed at the interface when applying the ultrasonic vibration for 0.5 s at 420 ℃ (Fig. 6a), while the oxide layer completely disappears as the ultrasonic acting time increases to 5 s at the same working temperature, and the SiC particles enter into and are distributed uniformly in the filler layer (Fig. 6b). The shear strength of joints brazed at 420 ℃ increased from 54.3 MPa to the maximum value of 165.5 MPa and then decreased to 152.5 MPa with the ultrasonic acting time increasing from 0.5, 5 to 10 s[37]. This result was mainly attributed to the removal of the residual oxide layer, the interdiffusion between the filler metal and the Al matrix, and in particular the volume faction of the SiC particles in the brazing seams (Fig. 6). The volume faction of SiC particles in the brazing seams increased with the increase of ultrasonic acting time, and the SiC particles can hinder or delay the propagation of microcracks and deflect cracks along the surface of the SiC particles. However, the shear strength of brazed joints slightly decreases owing to the excessive mass transfer during interaction (such as the diffusion of Zn from the 89.3Zn-4.2Al-3.22Cu brazing filler layer into the SiC_p/A356 composite matrix) when the ultrasonic acting time climbs to 10 s.

Table 3 Direct brazing processes of HFC SiC_p/Al composites and joint maximum strength

Material	Filler metal/wt%	Melting temperature/ ℃	Brazing temperature/ ℃	Time/ min	Applied pressure/kPa	Maximum strength/MPa	Ref.
55%SiC_p/A356	69Al-24Cu-1.5Mg-5Si-0.5Ni	525~542	550, 560	3	-	102	[28]
60%SiC_p/6063Al	69Al-22Cu-7Si-1Mg-1Ni	530~543	555, 565	3~12	3～5	89.6	[29]
45%SiC_p/2024Al	86.5Al-12Si-1.5Mg/Cu/ 86.5Al-12Si-1.5Mg	559~579	600	10	-	54.3	[30]

Table 4 Brazing processes of HFC SiC_p/Al composite after electroless Ni(-P) plating, Cu electroplating and magnetron sputtering of Ti

Material	Metallizing coating	Filler metal/wt%	Brazing temperature/ ℃	Time/min	Maximum strength/MPa	Ref.
60%SiC_p/6063Al	Ni	Al-12Si-1.5Mg	580	30	123.4	[35]
60%SiC_p/6063Al	Ni	Al-12Si-1.5Mg-4Ti	580	30	109.3	[35]
65%SiC_p/6063Al	Ni-P	66Al-5Si-6Cu-Zn-1Ti	565, 570, 575	10, 20, 30	155	[36]
SiC_p/Al	Ni-P	Sn-2.5Ag-2Ni	280	4	26	[46]
SiC_p/Al	Ni-P	73Al-20Cu-2Ni-5Si	550	6	105	[47]
60%SiC_p/6063Al	Cu	Al-Cu-Mg-Sn	580	30	145.6	[48]
60%SiC_p/Al	Ti	89.5Al-10Si-0.5Mg	580	40	110	[49]

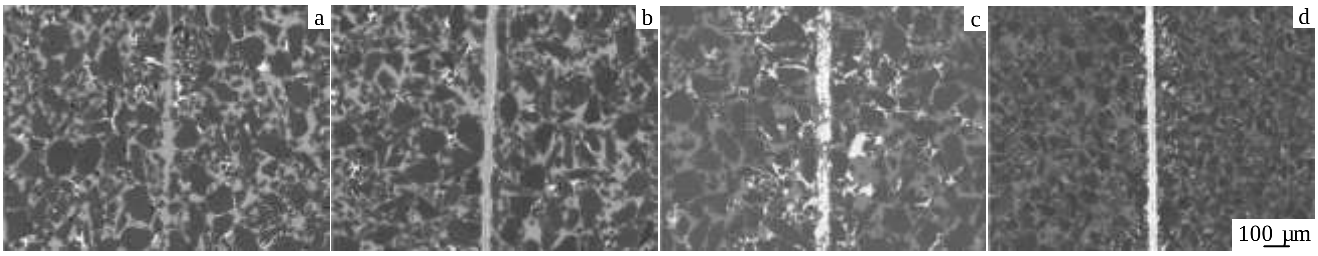

Fig.5 Cross-section microstructures of brazed joints of 60 vol% SiC_p/6063Al composite using the Al-12.5Si-1.5Mg(-4Ti) filler metal before and after electroless Ni plating: (a) Al-12.5Si-1.5Mg, no plating; (b) Al-12.5Si-1.5Mg, plating; (c) Al-12.5Si-1.5Mg-4Ti, no plating; (d) Al-12.5Si-1.5Mg-4Ti, plating[35]

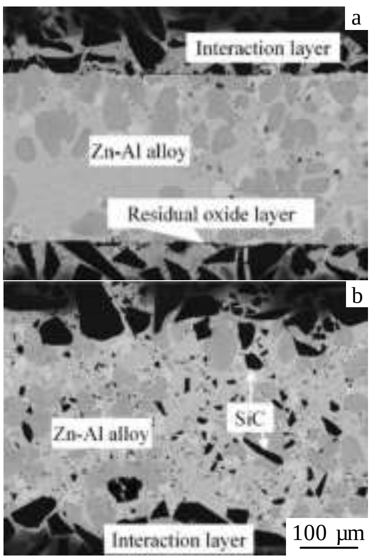

Fig.6 Cross-section microstructures of SiC_p/A356 composite joints brazed by applying ultrasonic vibration for 0.5 s (a) and 5 s (b) [37]

4 Summary

Significant work for the brazing of HFC SiC_p/Al composite have been done in the design of the filler metal, surface metallization, optimization of brazing processes and mechanical behavior of brazed joint. Indeed, some issues still exist and need to be further considered.

The filler metals for brazing of the HFC SiC_p/Al composite are mainly limited in the Al-based alloys and their compositions are involved in Si and Cu and other trace-elements like Ni, Sn, Zn, Mg and Ti. Due to the easy oxidation characteristic of Al, the Al-based filler metals cannot spread on the SiC_p/Al composites; as a result additional pressure has to apply in the brazing of the SiC_p/Al composites. Moreover, in the limited temperature range of 500~600 ℃, the ability of Mg element to remove or destroy the Al_2O_3 film and the reactive activity of Ti element with the exposed SiC particles are markedly insufficient, so the brazability of the Al-based filler metals on the SiC_p/Al composites cannot be improved substantially as active brazing of ceramics. Perhaps, glass solder is a kind of potential candidate filler because of its appropriate melting temperature and good interface compatibility with the SiC_p/Al composite adhering to the inevitable Al_2O_3 and SiO_2 films. In this case, a pre-oxidation treatment of the SiC_p/Al composite may enhance the wettability and brazability of the HFC SiC_p/Al composites.

Indeed, the surface metallization of the HFC SiC_p/Al composites can markedly enhance the brazability of the SiC_p/Al composites. Presently, the electroless plating and electroplating are commonly adopted; however, the two metallization processes can reduce the CT of the SiC_p/Al composites and induce complex interface reactions and great thermal mismatch. Taking into account these issues, other surface metallization processes, such as magnetron sputtering and ion implantation, should be introduced. Moreover, the fundamental research on the surface and interface characteristics of coating/substrate system, and the wetting of filler on the metalized SiC_p/Al composites, as well as the relationships among the metallization and brazing process, joint interface microstructures and joint properties should be strengthened.

For the brazing of the HFC SiC_p/Al composites, a pressure of 3~5 kPa is often applied due to the un-spreading of Al-based filler metals on the SiC_p/Al composites. If the glass solder or/and the reducing atmosphere (H_2) is introduced, the low-pressure or pressureless brazing process (which is very practical in the electronic packaging) may be achieved. In a word, the brazing of HFC SiC_p/Al composites is quite complicated and the multi-interfaces involving the filler material, metallization coating and the SiC_p/Al composites should be carefully considered.

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高体积分数 SiC_p/Al 电子封装复合材料的钎焊综述

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摘　要：高体积分数SiC_p/Al复合材料作为电子封装材料使用日益流行，其钎焊具有重要的实际意义。近来，一些新钎料合金和工艺被开发用于高体积分数SiC_p/Al复合材料的钎焊。本文回顾了SiC_p/Al复合材料的物理力学性能和制备工艺，综述了应用于高体积分数SiC_p/Al复合材料的合金钎料、钎焊工艺及其接头微结构与性能，旨在进一步理解它们之间的关联性，以优化接头性能与可靠性。往Al-Si合金中添加Cu、Mg、Ni等合金元素有助于提高钎料合金和钎焊接头的使用性能，如可优化钎料合金的应用温度、接头界面结合和焊缝强度。而表面金属化和超声波振动两种钎焊辅助工艺可通过避免或去除复合材料表面的Al_2O_3和SiO_2氧化膜来改善合金钎料的钎焊性。最后指出，需要进一步加强对合金钎料的优化设计、表面金属化工艺以及焊料/涂层/基材体系之间的润湿性和界面行为的研究。

关键词：高体积分数SiC_p/Al复合材料；钎料；表面金属化；钎焊；界面；接头力学性能

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