

Multi-functional SiC/Al Composites for Aerospace Applications

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Abstract

Multi-functional Al-matrix composites with high volume fraction (55%–57%) of SiC particles are produced with the new pressureless infiltration fabrication technology. X-ray detection and microscopic observation display the composites which are macroscopically homogeneous without porosity. The investigation further reveals that the SiC/Al composites possess low density (2.94 g/cm^3), high elastic modulus (220 GPa), prominent thermal management function as a result of low coefficient of thermal expansion ($8 \times 10^{-6} \text{ K}^{-1}$) and high thermal conductivity ($235 \text{ W/(m}\cdot\text{K)}$) as well as unique preventability of resonance vibration. By adopting a series of developed techniques, the multi-functional SiC/Al composites have managed to be made into near-net-shape parts. Many kinds of precision components of space-based optomechanical structures and airborne optoelectronic platform have been turned out. Of them, several typical products are being under test in practices.

Keywords: composites; multi-function; infiltration; SiC; aluminum; aerospace applications

1 Introduction

With unabated rapid development in aerospace optoelectronic detecting systems, proper option of structure materials have become most vital to the success of advanced designs. Traditional metallic structure materials including Al alloys and Ti alloys and steels, etc., could no longer meet all the requirements, especially, pertinent to those set by the military specifications for satellites and aircraft in reducing weights, increasing reliability and stability as well as extending their lifetime. For example, in the airborne optoelectronic platform, application of Al alloys is unacceptable because it is deficient in precision stability of structure because of high coefficient of thermal expansion (CTE), low elastic

modulus and resonance frequency. Ti alloy in possession of high density, the most common material for space-based optomechanical structures, is inherently poor in thermal conductivity and unfavorable for weight reduction. The poor heat diffusivity leads to significant decrease in thermal management effects, generally resulting in weak reliability of the system. The aforesaid drawbacks of conventional metallic structure materials have, of course, induced strong interest to search for new alternatives and, as a potential candidate, SiC particle reinforced Al-matrix (SiC/Al) composites have attracted strong interest from designers. Of them, over the past decade, high volume fraction Al-matrix composites with SiC particle contents typically ranging from 40 vol% to 70 vol% have become the focus of research because of their possibility to achieve excellent combination of demanded properties inclusive of high thermal conductivity, low tailorable CTE,

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high modulus, low density, etc. Furthermore, they might be manufactured from inexpensive raw materials^[1-4].

However, popularization of high volume fraction SiC/Al composites is still hampered by the concerns about the easiness of manufacture and production expansion and cost reduction. In detail, the production of composites through the traditional methods, including powder metallurgy, pressure infiltration, etc., still faces some technical necks in practices, in particular, of producing large-sized composites and shaping them into end products due to the needs for expensive special processing equipment. A solution to this problem is to fabricate composites into near-net-shape or net-shape components with cost-saving methods on inexpensive equipment^[5-7].

More recently, Beijing Institute of Aeronautical Materials (BIAM) has developed a novel pressureless Al-melt infiltration processing, which obviates the need for pressurizing or vacuumizing devices and makes it possible to fabricate rather complicated components out of high volume fraction SiC/Al composites with a wide range of size. This article will, apart from a brief description of the cost-effective BIAM-developed pressureless infiltration fabrication technology of high volume fraction SiC/Al composites, present microstructures and properties of the multi-functional SiC/Al composites, manufacturing technologies of typical composite components for aerospace applications.

2 Fabrication of Multi-functional SiC/Al Composites

The first step of the pressureless infiltration fabrication processing is to prepare densely packed powder beds or precisely formed preforms of SiC particles. The SiC particles used here are of an abrasive grade. To make densely packed powder beds, loose SiC particles should be poured into a refractory container and then packed by vibrating for about 10 min to attain a density of 55%-57%.

An aluminum alloy ingot with specified composition, which has been placed on the densely

packed powder beds or preform of SiC particles with about 55%-57% density is loaded inside a refractory container. The loading is heated to the required temperature in the range of 790-810 °C and maintained for 2-12 h depending on the thickness of SiC powder beds or preform under the protection of nitrogen and at atmospheric pressure without the need for vacuum or extra measures in the self-developed retort furnace. Then, the loading is cooled to about 500 °C in nitrogen and removed from the furnace.

On the self-developed special-purpose equipment, the maximum size of SiC/Al composite ingot could reach 725 mm × 655 mm × 65 mm with the weight of 91 kg. On the processing conditions under study, the infiltration velocity is up to 8-12 mm/h. X-ray inspection indicates the composite ingots which are macroscopically homogeneous without any pores, porosity or cracks. The results have confirmed that the metallurgical quality of SiC/Al composite ingots meets the requirements of I-class Al alloy casting by Chinese aeronautical standard.

3 Microstructures of Multi-functional SiC/Al Composites

Fig.1 shows scanning electron microscope (SEM) metallographic micrograph of the 55 vol%-57 vol% SiC/Al composites obtained in this work, which illustrates a very homogeneous microstructures free of porosity.

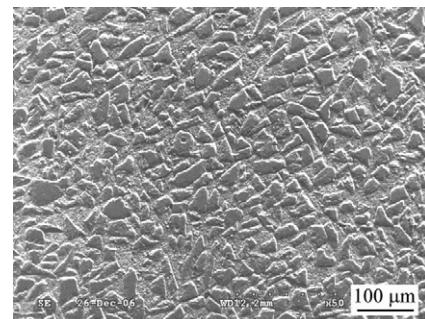


Fig.1 SEM micrograph of SiC/Al composites.

Fig.2 and Fig.3 show the representative transmission electron microscope (TEM) and high resolution transmission electron microscope (HRTEM) micrographs of atomic bonding interface in the

SiC/Al composites. Despite the favorable thermal dynamic environment ($\sim 800^\circ\text{C}$) for the reaction in SiC-Al or SiO_2 -Al-Mg system during relatively long process, it can be seen from Fig.2, Fig.3 and Fig.4 that no detectable quantity of reaction products could be discovered on the interfaces in composites, such as MgAl_2O_4 , Al_4C_3 , etc. The absence of Al_4C_3 , which is considered as one of the most detrimental reaction products that may occur during the fabrication of SiC/Al composites, is attributed to the unique Al-matrix which has higher level of silicon.

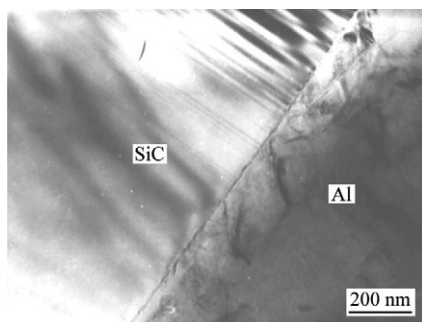


Fig.2 TEM micrograph of SiC/Al interface.

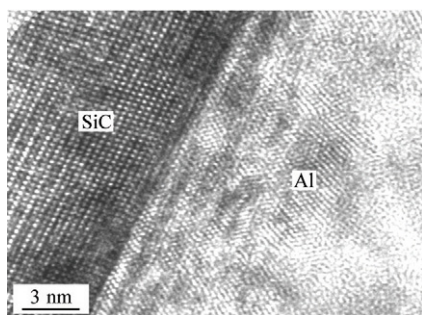


Fig.3 HRTEM micrograph of SiC/Al interface.

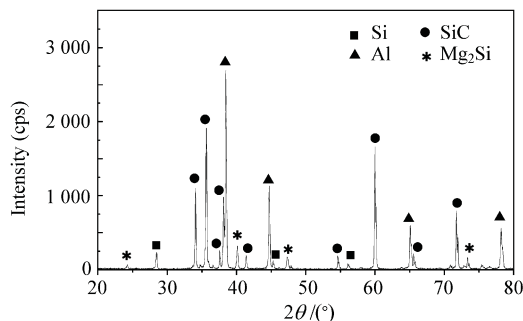
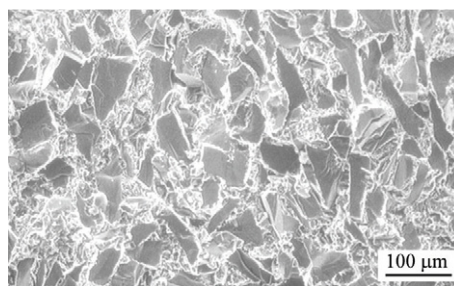


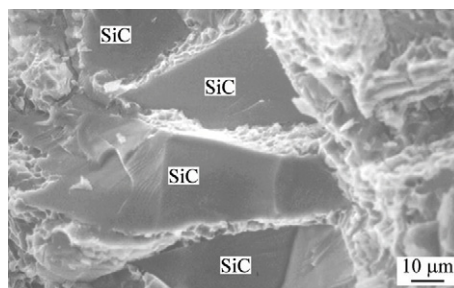
Fig.4 X-ray diffraction (XRD) spectrum for SiC/Al composites.

Examination of the fracture surfaces produced during three point flexural strength testing (see Fig.5) revealed that the cracks pass through the SiC

particles and Al-matrix without observation of debonding of SiC-Al interface. The fractographs (Fig.5) clearly show that almost all the particles on the fractured surface belong to cracked particles rather than debonded ones. On the metallographic section, the fraction of SiC particles is found to be similar to that on the fracture surface. Almost all fracture planes (facets) of particles run in parallel to the fracture surface of the composites. Fig.5 indicates that the failure is dominantly caused by SiC particle fracture and Al-matrix dimple rupture rather than by interface debonding. The fracture mode indicates that the bonding between SiC and Al-matrix is sufficiently strong.



(a) Low magnification



(b) High magnification

Fig.5 Typical SEM fractographs of SiC/Al composites.

4 Properties of Multi-functional SiC/Al Composites

Table 1 lists the typical properties of the 56 vol% multi-functional SiC/Al composites determined in the study. Table 2 compares the properties of the composites under study and other structural alloys.

A number of property parameters affect the choice of materials for aerospace optoelectronic detecting systems, but the specific modulus and

thermal properties might be the most important. As shown in Table 1 and Table 2, the SiC/Al composites exhibit very high elastic modulus and specific modulus—the composites have a elastic modulus approximately three times as high as Al alloys, twice as Ti alloys and same as steels. The specific modulus of the composites is much higher than that of the traditional structure alloys—nearly three times as high as Al alloys and Ti alloys and steels. Since the resonance frequency of materials is known to be proportional to the square root of their specific modulus, the resonance frequency of the SiC/Al composites is expected to be about 70% higher up on that of Al alloys and Ti alloys. In addition, superior to other structure alloys, the multi-functional composites provide an ultra-high thermal conductivity of 235 W/(m·K), for instance, more than 33 times over that of Ti alloys commonly used in space-based optomechanical structures, resulting in more uniform thermal management and increased operating stability of optical and electronic components.

Table 1 Properties of the multi-functional SiC/Al composites

Properties	Value
Density/(g·cm ⁻³)	2.94
Elastic modulus/GPa	220
Sepecific modulus/(10 ⁵ m)	74.8
Flexure strength/MPa	405
CTE/(10 ⁻⁶ K ⁻¹)	8.0
Thermal conductivity/(W·m ⁻¹ ·K ⁻¹)	235.0
Poisson's ratio	0.23
HV hardness/(N·mm ⁻²)	200

Table 2 Comparison of properties of SiC/Al composites under study and other structural alloys

Properties	Al (2024)	Ti (TC4)	Steel (45#)	SiC/Al
ρ /(g·cm ⁻³)	2.78	4.44	7.81	2.94
E /GPa	70	109	200	220
$\frac{E}{\rho}$ /(10 ⁵ m)	25.2	24.5	25.6	74.8
λ /(W·m ⁻¹ ·K ⁻¹)	120.0	6.8	48.0	235.0
α /(10 ⁻⁶ K ⁻¹)	22.7	9.2	11.6	8.0

Additionally, compared with Al alloys and Ti alloys, the composites provide a better CTE match

to optical and electronic components, such as SiC mirror, for low CTE improves dimension stability of structure when the environmental temperature changes.

Flexure strength of the SiC/Al composites prepared with pressureless infiltration is close to that with squeeze casting (for details see Ref.[8]). The standard deviation of flexure strength is 2.43 MPa, accounting for 0.59% of average, which further indicates the quite uniform microstructures of SiC/Al composites free of porosity.

5 Manufacturing SiC/Al Composite Components

In the present work, near-net-shape SiC preforms were made with precise hot injection moulding at about 70 °C out of slurry consisted of SiC particles, liquid carrier (paraffin) and a small quantity of binder. After removal from the mould, the preforms were heated to 1 000 °C at a controllable rate of 1.5 °C/min under the protection of atmospheric nitrogen, held at 1 000 °C for 5 h, and then slowly cooled in the closed furnace.

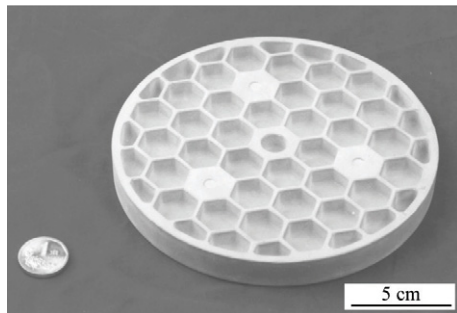
Additionally, special coatings on SiC preforms were developed to prevent the molten alloy from over-infiltration beyond the surface boundary during processing so as to ensure the desired shape and the surface smoothness of the resultant composites. All surfaces of SiC preforms, except those in contact with the alloy ingot, were painted with the gas-permeable coating composed of the colloid graphite powders and ethanol. Subsequently, the preform with coating on it was baked in vaccum at 200 °C to volatilize ethanol. For the components with sophisticated configuration, the above mentioned coating is particularly necessary to fabricate successful near-net-shape or net-shape composites.

Afterwards, the prepared preform was loaded into the proprietary retort furnace to carry out the pressureless melt infiltration processing at 790-810 °C under the protection of atmospheric nitrogen. Fig.6(a) shows a typical example of SiC preform prepared with precise hot injection moulding. It contains 56 vol% (calculated) SiC particles and has

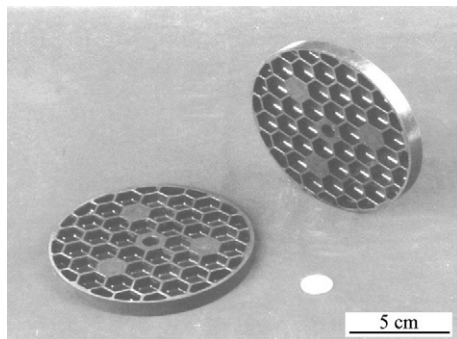
a structure of tens of thin-walled (about 2 mm) honeycombs.

As shown in Fig.6(b), in the process of manufacture, the Al-melt infiltration can be locally stopped when a part of the front comes in contact with the infiltration restrictive coating, and totally stopped when all the front contacts the coating-barrier. Still further, the formed composite body has an outer shape in substantial agreement with the inner shape of the barrier.

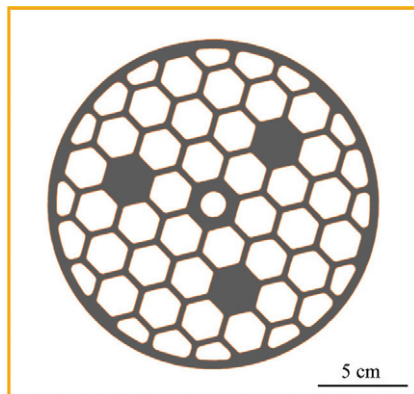
Fig.6(c) shows the results of CT inspection, which demonstrates that the final SiC/Al composite component has the configuration quite as identical



(a) Precisely-formed SiC preform



(b) SiC_p/Al composite components



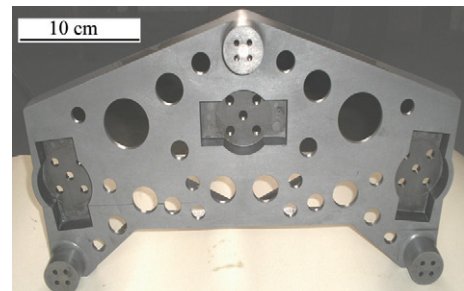
(c) CT image of the SiC_p/Al composite component

Fig.6 Near-net-shape SiC_p/Al composite components.

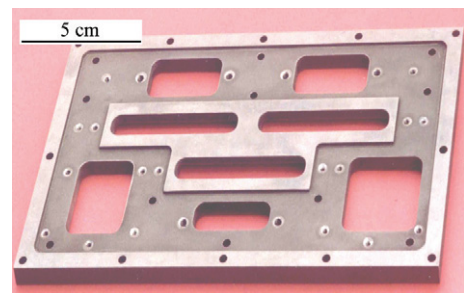
as that of SiC preform with dimensional deviation controlled within 0.2%. All honeycombs are quite regular and meet the demands of the designers. Moreover, it is noted that refining the powder from which the barrier is made could promote the surface smoothness of composite components up to 3.2 μm (R_a).

At BIAM, many kinds of precise multi-functional SiC/Al composite components for space-based optomechanical structures and airborne optoelectronic platform, such as optical mirror substrates and frame, have been fabricated with near-net-shape configuration, and then further processed for end use by means of electric spark machining, grinding and abrading as well as ultrasonic soldering, etc. After precision machining, the components have surface smoothness up to 0.4 μm .

Fig.7(a) shows a SiC/Al composite optical mirror substrate, Fig.7(b) shows an installation substrate for the optoelectronic components of space-based optomechanical systems.



(a) Optical mirror substrate



(b) Installation substrate for an optoelectronic component

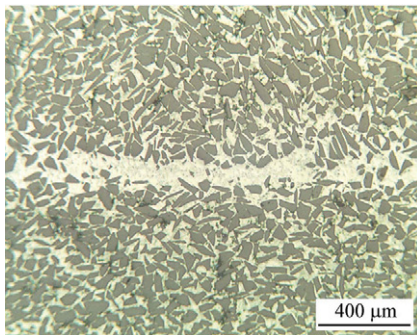
Fig.7 A SiC/Al composite component for space-based optomechanical structures.

Fig.8(a) shows an ultrasonic soldered SiC/Al composite frame for an airborne optoelectronic platform, and Fig.8(b) and 8(c) metallographic micrographs of a weld-line. From the micrographs, it

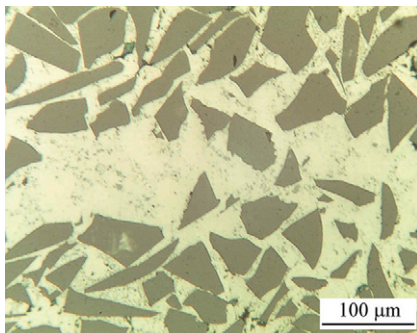
is observed that some SiC particles have migrated into the region of weld-line thus forming a unique “composite” weld-line which improves the strength and stiffness of weld-line. The results of rupture tests revealed the strength of weld-line quite as identical as that of SiC/Al composites.



(a) An ultrasonic soldered SiC/Al composite frame



(b) Low magnification metallographic micrograph of weld-line



(c) High magnification metallographic micrograph of weld-line

Fig.8 An ultrasonic soldered SiC/Al composite frame for an airborne optoelectronic platform and metallographic micrographs of weld-line.

6 Aerospace Applications of Multi-functional SiC/Al Composites

In aerospace vehicle, weight reduction is a key problem. The multi-functional SiC/Al composites

with low density and ultra-high specific modulus approximately three times as high as Al alloys, Ti alloys and steels, are undoubtedly prime candidates. For example, adopting SiC/Al composites instead of Ti alloys to make the optical mirror substrates for a satellite would be expected to cut weight down by 10 kg, which leads to a further reduction in the weight of supporting structures and savings of fuel. At the same time, compared with Ti alloys, the SiC/Al composites would provide the mirror substrates with doubled stiffness and better precision stability under mechanical loadings thanks to elastic modulus approximately twice as high as that of Ti alloys.

For aerospace optoelectronic detecting systems working in a severe vibration environment, such as airborne optoelectronic platform, a high natural frequency is always required for long-term mechanical reliability. The multi-functional SiC/Al composites have a very high resonance frequency which is expected to be about 70% higher than Al alloys and Ti alloys. This is very important, for it can prevent resonance vibration, ensure the reliability of optoelectronic device as well as extend its lifetime.

The results of applying typical components out of SiC/Al composites in some advanced optoelectronic detecting systems of satellite and pilotless aircraft, such as those shown in Fig.7 and Fig.8, have testified that substituting the multi-functional SiC/Al composites for Ti alloys in the optomechanical structures of space-based systems could reduce the weight by more than 30% and improve thermal management effect of the structure significantly. Using the composites instead of Al alloys in the airborne optoelectronic platform could also remarkably improve the natural frequency and precision stability of the structure.

7 Summary

BIAM now has the capability of producing multi-functional SiC/Al composites with excellent metallurgical quality, of which the largest size amounts to 725 mm × 655 mm × 65 mm weighing 91 kg. The composites have homogeneous micro-

structures free of porosity, thus having sufficient strong atomic bonding interfaces. The specific modulus of the composites is about three times as high as that of the traditional metallic structure materials, such as Al alloys, Ti alloys, and steels. The elastic modulus could reach as high as 220 GPa. In addition, the composites provide an ultra-high thermal conductivity of 235 W/(m·K), more than 33 times over that of Ti alloys. The composites are also superior to Al alloys in this respect, which lead to more uniform thermal management and increase operating stability of optical and electronic components. Compared with Al alloys or Ti alloys, lower CTE ($8 \times 10^{-6} \text{K}^{-1}$) of the composites improves dimensional stability of structures in aerospace optoelectronic detecting systems when the environmental temperature changes.

Many kinds of precise multi-functional SiC/Al composite components for space-based optomechanical structures and airborne optoelectronic platform have been produced successfully and are now being under test in practical uses.

References

- [1] Jin S. Advances in thermal management materials for electronic

applications. JOM 1998; 50(6): 46-51.

- [2] Zweben C. Metal-matrix composites for electronic packaging. JOM 1992; 44(7): 15-24.
- [3] Rawal S. Metal-matrix composites for space applications. JOM 2001; 53(4): 14-17.
- [4] Cui Y. Aerospace applications of silicon carbide particulate reinforced aluminium matrix composites. Journal of Materials Engineering 2002(6): 3-6. [in Chinese]
- [5] Maruyama B, Hunt W H. Discontinuously reinforced aluminium: current status and future direction. JOM 1999; 51(11): 59-61.
- [6] Kunze J M, Bampton C C. Challenges to developing and producing MMCs for space applications. JOM 2001; 53(4): 22-25.
- [7] Zufia A, Hand R J. The production of Al-Mg alloy/SiC metal matrix composites by pressureless infiltration. Journal of Materials Science 2002; 37(5): 955-961.
- [8] Hwu B K, Lin S J, Jahn M T. Effects of process parameters on the properties of squeeze-cast SiC_p -6061 Al metal-matrix composite. Materials Science and Engineering A 1996; 207(1): 135-141.

Biography:

Cui Yan Born in 1969, he is a professor. He received his Ph.D. degree from Harbin Institute of Technology in 1997. His current researches focus on the design, fabrication and application of metal matrix composites.

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