Available online at www.sciencedirect.com
ScienceDirect
Trans. Nonferrous Met. Soc. China 20(2010) 2143−2147
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Effect of thermal-cooling cycle treatment on thermal expansion behavior of particulate reinforced aluminum matrix composites

CHEN Guo-qin(陈国钦), XIU Zi-yang(修子扬), YANG Wen-shu(杨文澍),
JIANG Long-tao(姜龙涛), WU Gao-hui(武高辉)

School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China

Received 23 October 2009; accepted 16 August 2010

Abstract: Two micron SiC particles with angular and spherical shape and the sub-micron Al_2O_3 particles with spherical shape were introduced to reinforce 6061 aluminium by squeeze casting technology. Microstructures and effect of thermal-cooling cycle treatment (TCCT) on the thermal expansion behaviors of three composites were investigated. The results show that the composites are free of porosity and SiC/Al_2O_3 particles are distributed uniformly. Inflections at about 300 °C are observed in coefficient of thermal expansion (CTE) versus temperature curves of two SiC_p/Al composites, and this characteristic is not affected by TCCT. The TCCT has significant effect on thermal expansion behavior of SiC_p/Al composites and CTE of them after 3 cycles is lower than that of 1 or 5 cycles. However, no inflection is observed in Al_2O_{3p}/Al composite, while TCCT has effect on CTE of Al_2O_{3p}/Al composite. These results should be due to different relaxation behavior of internal stress in three composites.

Key words: SiC; aluminum matrix composite; thermal expansion behavior; thermal-cooling cycle treatment

1 Introduction

Particle reinforced aluminum matrix composites have been considered as promising structural materials in the applications of space, aerospace, precise instrument and automotive sectors, for their high specific strength and stiffness, improved wear resistance as well as low density[1−2]. Especially, the coefficient of thermal expansion (CTE) of these composites is lower than that of aluminum alloys, while CTE could be designed via changing reinforcing particle type and its volume content[3−4]. This advantage makes them very attractive to be used in precise instrument, optical devices and electronic packing industry. The past researches on thermal expansion behavior and mechanism of the composites were mainly focused on the theoretical prediction[5−8] and the effect of heat treatment was rarely reported. It is well known that thermal-cooling cycle treatment (TCCT) is an important method to decrease residual stress and improve dimensional stability[9−10], which is very sensitive to precise instrument. However, the effect of TCCT on thermal expansion has not been reported.

In the present work, two micron SiC particles (with angular and spherical shape) and sub-micron Al_2O_3 particles (spherical shape) are introduced to reinforce 6061 aluminum by squeeze casting technology. The effect of TCCT on microstructure and thermal expansion behavior of three composites are tested and discussed.

2 Experimental

2.1 Material preparation

6061 Al alloy was selected as matrix alloy, whose chemical composition is listed in Table 1. Sub-micron Al_2O_3 particles (spherical shape) and two micron SiC particles (angular and spherical shape) were introduced to reinforce the 6061 aluminum by squeeze casting

Table 1 Chemical composition of 6061 Al alloy (mass fraction, %)

Si	Mg	Cu	Mn	Fe	Zn	Ti	Ni	Al
1.26	0.75	0.43	0.22	0.36	<0.15	<0.05	<0.05	Bal.

Foundation item: Project(20080430895) supported by China Postdoctoral Science Foundation; Project(2008RFQXG045) supported by Special Fund of Technological Innovation of Harbin; Project(HITQNJS.2009.021) supported by Development Program for Outstanding Young Teachers in Harbin Institute of Technology
Corresponding author: CHEN Guo-qin; Tel: +86-451-86402372-5058; E-mail: chenguoqin@hit.edu.cn
DOI: 10.1016/S1003-6326(09)60432-5

technology.

The composites were fabricated by squeeze casting technology[11]. Firstly, the Al_2O_3 or SiC particles were filled and pressed into a mold to produce a preform according to the given volume fraction. Then, the preform was pre-heated in a die. At the same time, the 6061 Al was melted, degassed, cleaned in a graphite crucible and heated to 750−760 °C. When the preform was heated to 550 °C, the molten 6061 Al was poured into the die and a vertical pressure up to 55 MPa was applied immediately to force the molten 6061 Al to infiltrate into the preform completely. The pressure was maintained for about 3 min until the solidification was complete. Three kinds of composites prepared for experiment, as shown in Table 2, are numbered as No.1, No.2 and No.3, respectively.

Solution and aging treatment and subsequent TCCT treatment (1, 3 and 5 cycles) were carried out using the parameters listed in Table 3.

2.2 Experimental procedure

Microstructure of as-fabricated composites was investigated by using Hitachi-S4700 scanning electron microscope (SEM). Further observation was carried out by Philips CM-12 transmission electron microscope (TEM). After heat treatment, the thermal expansion behavior of three composites were examined by Dilatometer 402C (NETZSCH Corp.). The cylindrical sample of 4 mm in diameter and 25 mm in length was used. During measurement, the temperature was heated from 0 °C to 500 °C with a heating rate of 5 °C/min. The helium atmosphere was maintained at a flow rate of 50 mL/min to ensure the equilibrium of temperature and prevent oxidation of samples. To diminish systematic errors, the dilatometer was calibrated by measuring a silica sample under identical condition.

3 Results and discussion

3.1 Microstructure of composites

Fig.1 reveals the SEM microstructures of as-cast Al_2O_{3sp}/6061, SiC_{ap}/6061 and SiC_{sp}/6061 composites, respectively. Al_2O_3 and SiC particles distribute uniformly in the composites, without any particle clustering. As a result of the high pressure employed during composite fabrication, the molten aluminum alloy infiltrates the particle preform entirely. Consequently, the composite material appears to be free of porosity. A dense microstructure is favorable to properties, which leads to the improvement in service life[12].

The interface and the existing of interface effect are the important factors that can affect the properties of the composites. Fig.2 illustrates the typical TEM micrographs of the interfaces in Al_2O_{3sp}/6061Al and SiC_{ap}/6061Al composite. A large amount of observations indicate that the Al_2O_3-Al and SiC-Al interfaces are clean, smooth and free from interfacial reaction products and amorphous layers, and no particles dissolved are observed.

3.2 Thermal expansion behavior

Fig.3 shows the variation of CTE with temperature of the three composites. It is obvious that TCCT has significant effect on the thermal expansion behavior of SiC particles reinforced Al composites (Fig.3(b) and (c)). For samples No.2 and No.3, CTE reaches minimum after 3 cycles. Moreover, inflections (pointed in Fig.3(b) and (c)) at about 300 °C are also observed, and this characteristic is not affected by TCCT. The inflections were also observed by other researchers[13−14].

However, TCCT shows little effect on CTE curves of Al_2O_{3sp}/6061. At the same temperature, CTE varies little with cycles. Furthermore, inflections (pointed in Fig.3(a)) at about 300 °C are not so clear as that of samples No.2 and No.3.

The inflections observed in CTE curves should be due to the thermal mismatch stress between SiC particles and Al matrix, which is generated by the addition of large particles. During the fabrication and solution process, thermal mismatch compressive and tensile stress would be generated on particles and matrix respectively due to large CTE difference between them[15−16]. For SiC_{ap}/6061Al and SiC_{sp}/6061Al, due to the large stress

Table 2 Composition and reinforcement's characteristic of three composites

Sample No.	Composites	Matrix	Reinforcement and its main characteristics			
			Formula	Shape	Size/μm	Volume fraction/%
1	Al_2O_{3sp}/6061Al	6061Al	Al_2O_3	Spherical	0.4	30
2	SiC_{ap}/6061Al	6061Al	SiC	Angular	2.0	45
3	SiC_{sp}/6061Al	6061Al	SiC	Spherical	2.0	45

Table 3 Heat treatment parameters employed

Solution temperature/°C	Aging temperature/°C	Cyclic temperature/°C	Cycles
525	160	−196, 160	1, 3, 5

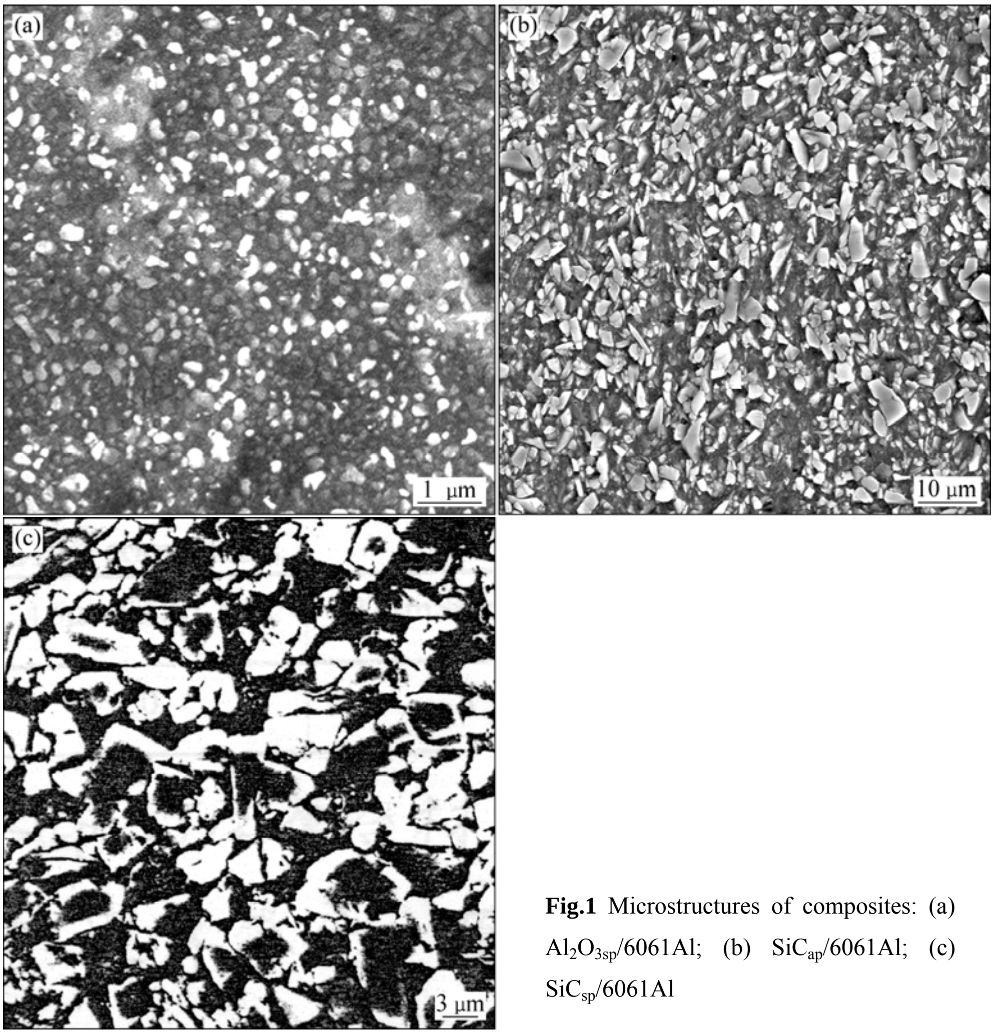

Fig.1 Microstructures of composites: (a) Al_2O_{3sp}/6061Al; (b) SiC_{ap}/6061Al; (c) SiC_{sp}/6061Al

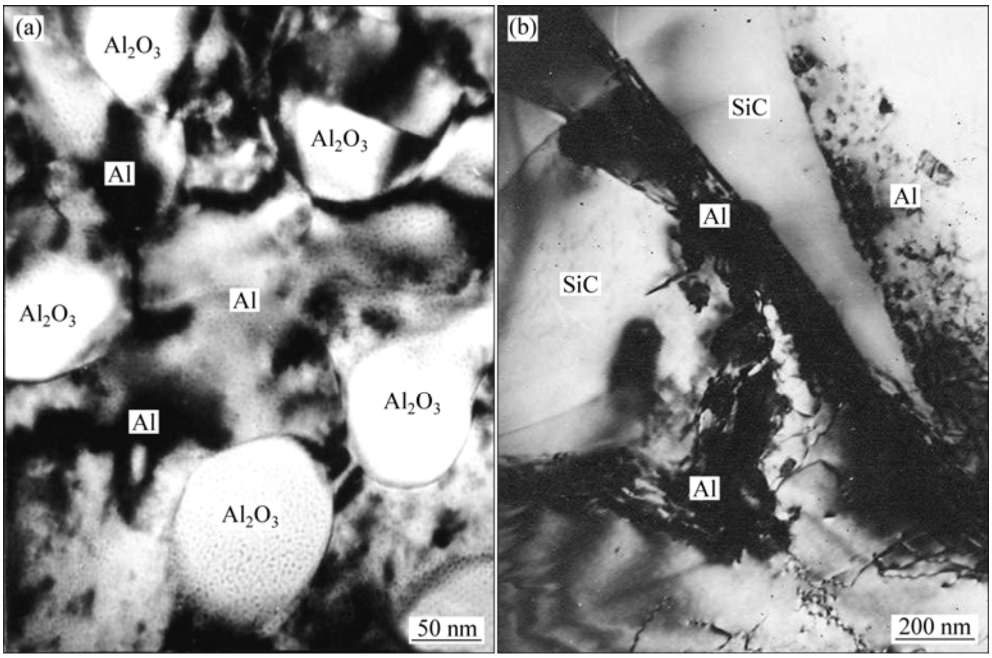

Fig.2 TEM micrographs of interfaces in composites: (a) Al_2O_3-Al; (b) SiC-Al

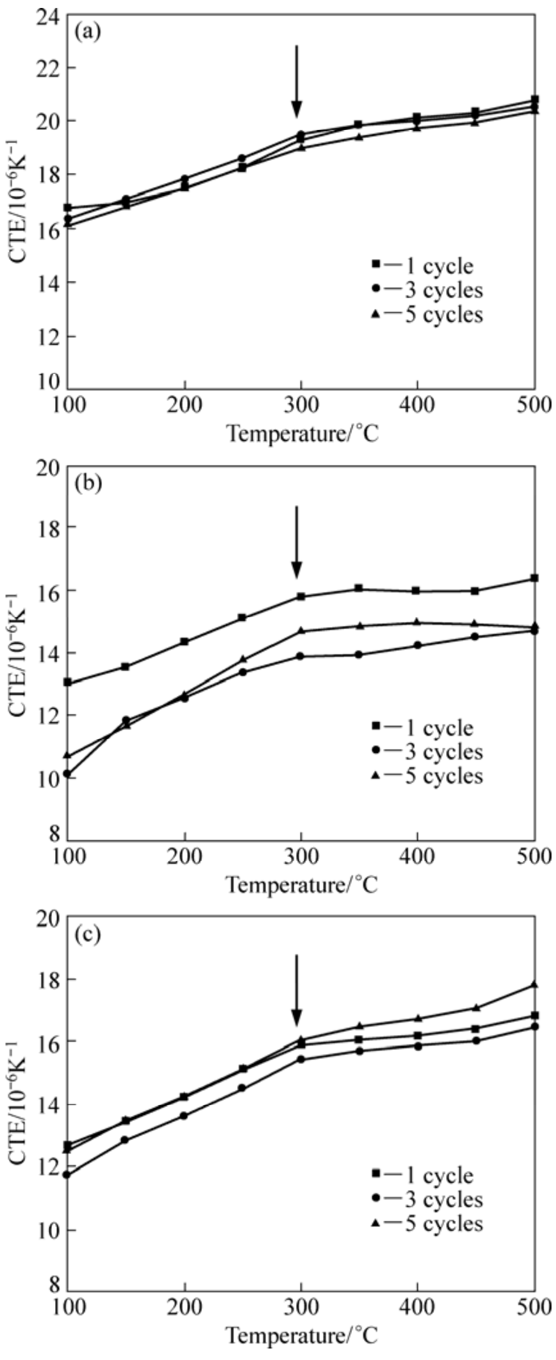

Fig.3 CTE curves of three composites: (a) Al_2O_{3sp}/6061Al; (b) SiC_{ap}/6061Al; (c) SiC_{sp}/6061Al

and dislocation density at SiC/Al interface, which are favorable for nucleation and growth of precipitation, precipitation process of aging could be fully completed at low temperature. As a result of precipitation of alloying elements, lattice constant of Al matrix decreases, which increases the lattice mismatch and following thermal mismatch stress significantly. Therefore, restraint of SiC particles under compressive stress on Al matrix under tensile stress is little when heating, which leads to fast increasing of CTE with temperature. However, to a certain temperature (at 300 °C in the present work), the stress of Al matrix and SiC particles swap with each other. Then, the restraint of SiC particles to thermal expansion of Al matrix increases with temperature. It slows the increasing ratio of CTE with temperature, which leads to inflections in the CTE curves.

For spherical sub-micron Al_2O_3 particle reinforced Al composite (Al_2O_{3sp}/6061), precipitation process is inhibited strongly by size and surface effect[12]. Thus, alloying elements maintain dissolving in Al matrix, and are even larger than that at Al_2O_3/Al interface. Contrary to the above discussion, it decreases the thermal mismatch stress, which increases the restraint to thermal expansion behavior. Therefore, although the stress would also swap with increasing of temperature, Al_2O_3 particles maintain large restrain effect at interface, leading to smooth CTE curve in Al_2O_{3sp}/6061Al.

The different effect of TCCT on SiC and Al_2O_3 particle reinforced Al composites may be due to internal stress relaxation during the cycling process. Thermal mismatch stress and macro-stress would change during temperature cycling. Superposition of the two stresses may exceed stress for initiation and activate dislocation in Al matrix, leading to relaxation of internal stress in composite. Moreover, aging at a certain temperature for long time is also contributed to stress relaxation [17−18]. Variation of internal stress leads to change of expansion behavior.

In the SiC_{ap}/6061Al and SiC_{sp}/6061Al composites, dislocations may be the most stable one with lowest internal stress after 3 cycles. Under the condition of less or more than 3 cycles, dislocation density, dislocation mobility and internal stress in matrix would increase. Thus, CTE after 3 cycles is lower than that after 1 or 5 cycles. However, TCCT has little effect on dislocation and internal stress in Al_2O_{3sp}/6061Al composite and CTE curve changes little.

4 Conclusions

1) Two micron SiC particles (angular and spherical shape) and sub-micron Al_2O_3 particles (spherical shape) are introduced to reinforce 6061 aluminium by squeeze casting technology. The composites are free of porosity and particles are distributed uniformly in composites.

2) Inflections at about 300 °C are observed in CTE versus temperature curves of angular and spherical SiC particles reinforced composites, and this characteristic is not affected by TCCT. No clear inflection is observed in spherical sub-micron Al_2O_3 particle reinforced Al composite.

3) TCCT has significant effect on thermal expansion behavior of SiC particle reinforced composites. CTE of

them after 3 cycles is lower than that after 1 or 5 cycles. TCCT shows little effect on CTE curve of Al_2O_3 particle reinforced composite. It should be due to different relaxation behavior of internal stress.

References

[1] MOLINA J M, NARCISO J, WEBER L, MORTENSEN A, LOUIS E. Thermal conductivity of Al-SiC composites with monomodal and bimodal particle size distribution [J]. Materials Science and Engineering A, 2008, 480(1/2): 483−488.

[2] WU G H, CHEN G Q, JIANG L T, LUAN B F, KONO N, HAITANI T. Aging behavior of AlN_p/2024Al composites fabricated by squeeze casting [J]. Transactions of Nonferrous Metals Society of China, 2006, 16: s1450−s1454.

[3] ELOMARI S, SKIBO M D, SUNDARRAJAN A, RICHARDS H. Thermal expansion behavior of particulate metal-matrix composites [J]. Composites Science and Technology, 1998, 58(3/4): 369−376.

[4] HUBER T, DEGISCHER H P, LEFRANC G, SCHMITT T. Thermal expansion studies on aluminium-matrix composites with different reinforcement architecture of SiC particles [J]. Composites Science and Technology, 2006, 66(13): 2206−2217.

[5] ROATTA A, BOLMARO R E. An eshelby inclusion-based model for the study of stress and plastic strain localization in metal matrix composites [J]. Materials Science and Engineering A, 1997, 229: 182−191.

[6] HSIEH C L, YUAN W H. Thermal expansion behavior of a model ceramic-metal composite [J]. Materials Science and Engineering A, 2007, 460/461: 453−458.

[7] ZHANG Q, WU G H, JIANG L T, CHEN G Q. Dimensional stability of Al-Si matrix composite reinforced with high content SiC [J]. Materials Chemistry and Physics, 2003, 82: 780−785.

[8] ISHIKAWA T, NAGASHIMA A, KANDORI K. Thermal cycling studies of across-piled P100 graphite fiber-reinforced 6061 aluminum composite [J]. Journal of Material Science, 1998, 26: 6223−6230.

[9] CHEN G Q, JIANG L T, WU G H, ZHU D Z, XIU Z Y. Fabrication and characterization of high dense Mo/Cu composites for electronic packaging applications [J]. Transactions of Nonferrous Metals Society of China, 2007, 17: s580−s583.

[10] CHEN N, ZHANG H X, GU M Y, JIN Y P. Effect of thermal cycling on the expansion behavior of Al/SiC_p composite [J]. Journal of Materials Processing Technology, 2009, 209(3): 1471−1476.

[11] WU G H. A submicro particulate reinforced aluminum matrix composites and fabrication method: China, ZL94117266.X [P]. 1994−10−14.

[12] DAYMOND M R, WITHERS P J. A synchrotron radiation study of transient internal strain changes during the early stages of thermal cycling in an Al/SiC_w MMC [J]. Scripta Materialia, 1996, 35(10): 1229−1234.

[13] WU G H, ZHAO Y C, MA S L, LI R H. Suppression effect of fine Al_2O_3 particulate on aging kinetics in a 6061 aluminum alloy matrix composites [J]. Transactions of Nonferrous Metals Society of China, 1999, 9(4): 818−821.

[14] CARREŇO-MORELLI E, URRETA S E, SCHALLER R. Mechanical spectroscopy of thermal stress relaxation at metal–ceramic interfaces in aluminium-based composites [J]. Acta Materialia, 2000, 18(18/19): 4725−4733.

[15] ZHANG J Y, ZOU J, ZHOU X L. Effect of particle on thermal residual stress in aluminum matrix composite [J]. Transactions of Materials and Heat Treatment, 2009, 30(1): 197−200.

[16] WANG X F, WU G H, JIANG L T. Effect of thermal-cold cycling treatment on dimensional stability of SiC_p/2024Al composite [J]. Transactions of Materials and Heat Treatment, 2006, 27(1): 23−27.

[17] ZHAO L Z, ZHAO M J, CAO X M, TIAN C, HU W P, ZHANG J S. Thermal expansion of a novel hybrid SiC foam-SiC particles-Al composites [J]. Composites Science and Technology, 2007, 67(15/16): 3404−3408.

[18] PARK C S, KIM M H, LEE C M. A theoretical approach for the thermal expansion behavior of the particulate reinforced aluminum matrix composite [J]. Journal of Materials Science, 2001, 36: 3579−3587.

(Edited by LAI Hai-hui)