Journal of Alloys and Compounds 503 (2010) 92–95

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jallcom

An experimental investigation of the interface characteristics of aluminium/silicon carbide

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ARTICLE INFO

Article history:
Received 6 January 2010
Received in revised form 22 April 2010
Accepted 28 April 2010
Available online 5 May 2010

Keywords:
Metal–ceramic bonding
Interface
Metal matrix composites

ABSTRACT

The interface bonding characteristics of metal–ceramic joints were investigated using bonded Al–SiC joints prepared in different processing conditions. Interface microstructures and chemistry were studied using scanning electron microscope (SEM), energy dispersive spectroscope analysis. The results revealed that the segregation of Si was increased with increasing holding time and temperature. The reported microhardness values were also increased towards the interface. The concentrated Si at the interface alters the interface characteristics positively.

1. Introduction

The properties of ceramic–matrix interfaces are among the key factors limiting the potential applications of various metal–ceramic joints and composites [1]. There are numerous obstacles for successful joining, the most important of which is the relative inertness of ceramic and the coefficient of thermal expansion (CTE) mismatch. Temperature changes induced during cooling from the joining temperature and during subsequent service can generate high internal stresses due to the CTE mismatch and lead to poor joint strength or failures. While our understanding of the mechanical behavior of the interface in metal–ceramic bonding has grown over the last few decades, the study of the interface bonding strength and metallurgical nature at the interface remains in its infancy.

The interface and interphase regions play a vital role in limiting the properties of composite materials. Interfaces are narrow regions separating well designed domains and are primarily responsible for a range of key properties including stiffness, strength and fracture behavior [2]. The interface strength in the metal–ceramic joints depends in a very complex way on the residual stress state, interface microstructure, interface chemistry, etc. [3]. In the Al/SiC metal ceramic system, the chemical reaction products Al_4C_3 ensure the chemical reaction at the interface, but this product tends to weaken the bond at the interface. This reaction happens due to the segregation of C from SiC. Hence, the reaction kinetics should be altered to control the reaction, but without affecting the bonding nature. In the recent past, many models were developed to study the interface effect on the mechanical properties and reported [4,5]. Basically, the interaction between a liquid metal and a ceramic substrate during processing may give rise to either physical or chemical bonding between them. For chemical bonding two main effects may be distinguished, one related to the formation of a solid solution and another leading to the formation of a reaction product. However, it is very difficult to understand the formation of metal–ceramic bonding during liquid state processing, owing to the formation of oxide films and intermetallic compounds at the interface, and also it is difficult to analyze the interface bond strength between the matrix and the reinforcement.

The consequences of such interfacial reactions are the chemical degradation of the reinforcing material associated with a decrease of its mechanical properties. The formation of brittle reaction products at the interface as well as the release of elements initially part of the reinforcing material toward the matrix may generate inopportune metallurgical phases at the vicinity of the reinforcing materials. In the present work, the interface nature and segregation of elements to the ceramic–matrix interface in different processing conditions received particular attention. The aim is to understand how the processing parameter influences interface bonding between matrix and reinforcement. The interface was characterized using the scanning electron microscope (SEM) fitted with energy dispersive spectroscopy facilities.

2. Experimental procedure

SiC plates of $75 \times 100 \times 6\,mm^3$ were prepared by a sintering process with 1900 °C at 3000 psi for 2 h. These samples were fully dense SiC particles with a den-

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doi:10.1016/j.jallcom.2010.04.209

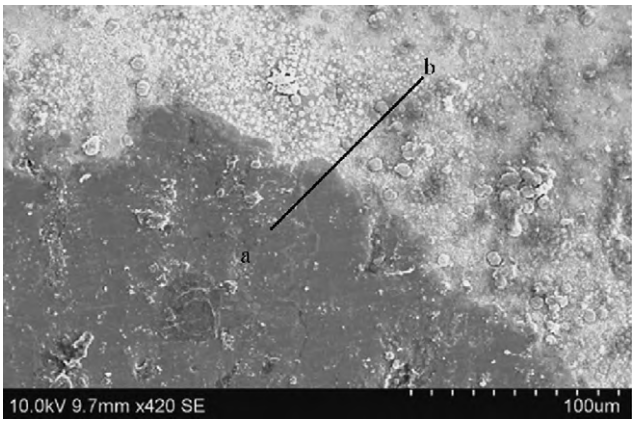

Fig. 1. Scanning electron microscope image of interface of Al/SiC.

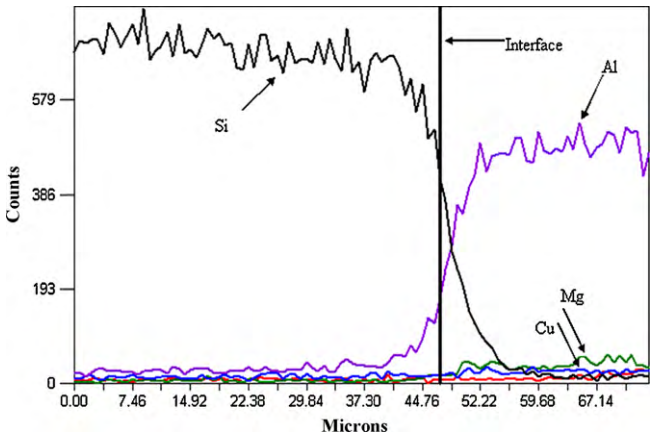

Fig. 2. EDS analysis of interfacial compounds at the interface of Al/SiC.

sity of 3.2 g/cm^3 and an elastic modulus of 410 GPa. The bonding surface of SiC was ground with SiC paper from 320 to 1000 grit and the polished surfaces cleaned by using acetone before being kept in steel mould. The SiC plate was kept in a special steel mold and a clay graphite crucible was kept over the mold which contains Al alloy. A provision is arranged in the crucible with a stop rod to allow the liquid Al melt to flow to the mould. The whole setup was kept inside the furnace. The heating rate in the furnace varies between 8 and 15 °C. The experiments were conducted at different temperatures such as 700, 750, 800, 850 and 900 °C, with different holding times of 10, 20, 30 min. During the holding time, liquid aluminium contacts with the SiC plate without any force (natural contact). After it has been allowed for chemical reaction at different holding times, the mould was taken out and cooled at room temperature. The cross sections of the bonded Al/SiC sample were cut from the specimen for the metallographic analysis by standard polishing techniques. The interface structure of the bonded Al/SiC was examined by the SEM equipped with an EDS. The interface compounds at the interface were evaluated by the EDS. The interface strength of the bonded joints was quantified by means of a tensile test using the FIE tensile machine. The strength of the Al/SiC bonds fabricated at various temperatures using solid state diffusion bonding was measured and correlated to the interfacial microstructure. The microhardness was measured at the interface by using the Wilson Wolpert hardness tester with 500 g load at different locations across the interface region.

3. Results and discussion

3.1. Interface structure of Al/SiC

The microstructures of the metal–ceramic interfaces have been studied on a transverse section by the SEM and EDS analyses. All metallographic sections show a very sharp interface. On viewing the micrographic structure shown in Fig. 1, good interface bonding is apparent. This SEM image shows the interface of the Al/SiC fabricated at 850 °C in 20 min holding time. The compositions at the interface were evaluated by using the EDS analysis is shown in Fig. 2. The interdiffusion of aluminium and silicon can be seen from Fig. 2 and it can be approximately determined from their concentration profile as marked by the dashed line in the SEM image shown in Fig. 1. When the liquid Al matrix contacts with the solid SiC, two kinds of reaction take place: the first one is, the solid SiC segregated into the Si and C [6–8] elements at higher temperature. The segregated Si element was dissolved in the liquid Al matrix and diffused. The dissolving rate of Si was faster than that of C. The second reaction is: C reacts with the liquid Al to form the Al_4C_3. When the processing temperature increases, the segregation level of SiC was increased. Hence, the concentration of Si was increased at the interface region of the matrix and it altered the composition of the matrix. The Al–Si eutectic phase was formed at the interface region in the matrix due to the higher concentration of the Si element at the interface. Therefore, the higher concentration of Si may reduce the formation of alumina carbide at the interface [9]. The higher concentration of Si increases the wettability of liquid Al and it creates the strong interface bond between the matrix and the reinforcement.

3.2. Effect of processing temperature on interface bond strength

The interfacial bond strength was analyzed by using a tensile test. The strain rate is fixed at 10^{-3} s^{-1}. The dimensions of the specimen were prepared as per the standard of ASTM E-338. Fig. 3 shows the influence of the processing temperature and holding time on effective bonding strength. The interfacial bond strength was varied with respect to the processing temperature and holding time, and can be seen from Fig. 3. When the processing temperature increases, the interface bonding strength was increasing gradually, despite the fact that the concentrations of silicon at the interfaces was increased and it creates the strong interface bond and minimizes the Al_4C_3 formation at the interface. When increasing holding time from 10 to 20 min the interface bond strength was increased. Further, the interface strength was decreased when holding time at above 20 min because the presence of reaction products. The reaction products (alumina carbide) are formed during prolonged contact between liquid Al matrix with solid SiC. This reaction product does not allow or transmit the load from matrix to reinforcement properly. The segregated Si was low at the interface at low temperature. An increase in the processing temperature can cause a nonwetting to wetting transition for liquid metals in contact with ceramics. Therefore, the bond strength is very low at lower temperatures compared to that at higher temperatures. Simultaneously, the bonding strength was increased whereas the increase in holding time results in altering the matrix composition; this modifies the reaction kinetics between the matrix and the reinforcement. Thus, a higher concentration of silicon at the interface increased the wettability around the surface of the reinforcement,

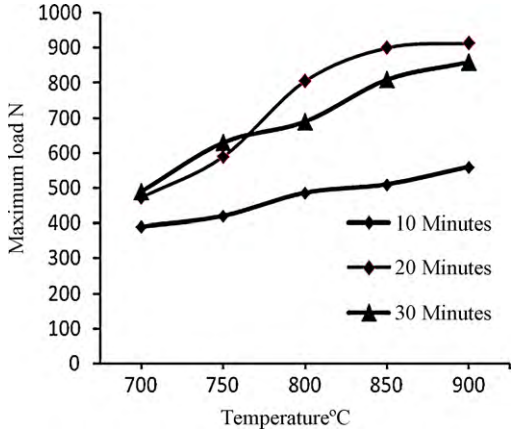

Fig. 3. Load vs displacement of Al/SiC bonding.

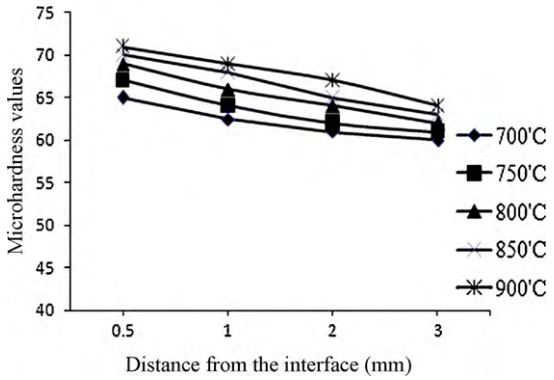

Fig. 4. Microhardness values of Al/SiC system at near the interface with various processing temperatures and holding time.

and improved the strong interface bond between aluminium and silicon carbide. From Fig. 3, the bonding strength was slightly decreased at a holding time of 30 min at the higher temperature due to more segregation and chemical reaction that takes place between the matrix and the reinforcement.

3.3. Effect of microhardness distribution at the interface in the matrix region

The objective of the microhardness measurement experiments was to assess the changes in the matrix properties near the interface after the Al matrix joined with solid SiC reinforcement at higher temperature with the holding time. This analysis is used to study the effect of the interfacial behavior of composites in the interface region, as well as the influence of the segregation element at the interface. The microhardness value was measured along the interface of the joined specimen at different intervals of 0.5, 1, 2, and 3 mm. Fig. 4 shows the microhardness distribution in the bond regions for the Al–SiC samples at different processing temperatures.

Fig. 5 shows the microhardness values at 0.5 mm near the interface with various holding times. A comparison of the different samples with different bonding times and temperatures shows that the hardness is higher near the interface than that away from the interface, when the bonding time is short. However, it increases close to the level of the interface in matrix metal values as the bonding temperature increases. The increase of hardness in the matrix metal is probably ascribable to the diffusion of elements like C, Si, etc. from the solid SiC to the matrix, while the parent metal adjacent to the interlayer was melting temporarily as a result of the melting point depressant effect of Si (due to formation of eutectic). It seems reasonable to consider the diffusions of Si forming Mg_2Si, C forming Al_4C_3, etc., at the interface. Diffusion of Si at the interface subsequently strengthens the matrix. Also, the increase of the bonding holding time will allow diffusion and dissolve the Si elements at the interface as reflected in thinning the diffusion region and make the hardness values increase to the level of the interface in the matrix metal.

The higher concentrations of Si at the interface in the matrix aluminium alloy have a satisfactory effect in improving the hardness strength of the matrix near the interface region. This is to be expected since aluminium is a soft material and the Si being hard, contributes positively in improving the hardness strength of the composite. The presence of stiffer and stronger Si element resists plastic deformation near the interface during the microhardness test. The absence of Si elements just away from the interface region shows a remarkable change in the hardness values in the samples. The highest hardness value is obtained near the interface where the segregation element accumulation is more, and lower values are obtained just away from the interface where the segregation element concentration is lower and is almost equal to the matrix alloy content. The microhardness measurement in the samples is conducted to understand the distribution of the Si element in the aluminium matrix in different processing conditions.

3.4. Effect of holding time

The interface bonding strength of the Al–SiC system has been increased with increasing holding time. The silicon elements were segregated from the SiC and diffused into the liquid Al alloy more efficiently as the holding time was prolonged, which enhances the contact between the solid SiC and the liquid Al alloy. Therefore, the concentration of the silicon increases gradually at the interface with increasing holding time, (as shown in Fig. 6) which decreased the formation of alumina carbide at the interface of Al/SiC [10]. The diffusion rate of Si is often satisfactorily expressed by the Arrhenius equation [11]. $D = D_0 \exp(-E_a/RT)$, $E_a = (E_{al,int} - E_{al})$ where E_a – the activation energy of Si at the interface, D – diffusion coefficient or diffusivity, D_0 – pre-exponential coefficient, $E_{al,into}$ – activation energy for Si in Al, E_{al} – activation energy of vacancy formation in Al, R – universal gas constant. The Arrhenius equation is used to determine the length of diffusion of the Si elements in the Al alloy matrix. The length of diffusion [12]: $L = \sqrt{4Dt}$, where L – diffusion length of Si, t – time of diffusion between the matrix and the reinforcement. It has been found that the rate of diffusivity of Si increases with an increase in the temperature [13] and time. Hence, the diffusion rate

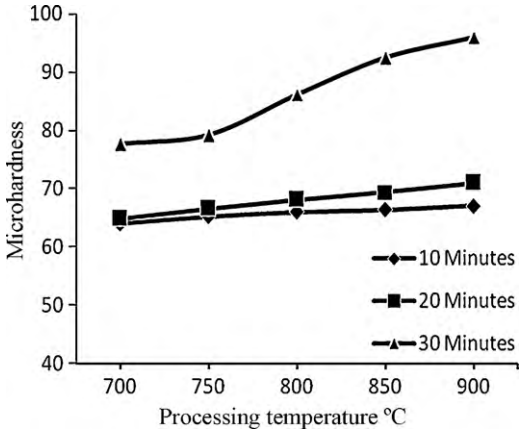

Fig. 5. Microhardness values at 0.5 mm near the interface regions with different holding time.

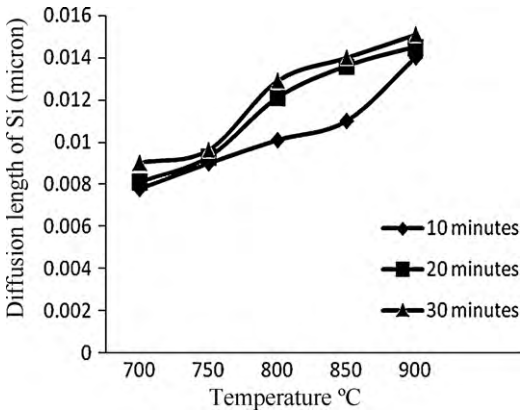

Fig. 6. Diffusion length of sillicon at the interface region at various temperarue.

of Si in the matrix region depends on the holding temperature and time.

4. Conclusions

The characteristics of the interface compounds of the Al/SiC system have been studied. The following observations could be drawn from this investigation:

- The segregation of the elements of Si and C increased with an increase in the processing temperature and holding time.
- The concentration of Si at the interface increases with an increase in the holding time at higher temperatures.
- The fracture strength of the interface increases with an increase in the processing temperature. However, the bonding strength gradually decreases after 20 min holding time due to presence reaction products at the interface.
- The diffusion length of silicon increased with increasing holding time.

References

[1] G. Levi, W.D. Kaplan, Mater. Sci. 41 (2006) 817–821.
[2] K. Jayaraman, K.L. Reifsnider, R.E. Swain, Compos. Technol. Res. 15 (1993) 14–22.
[3] Y. Lee, J. Yu, Ceram. Int. 21 (1995) 395–398.
[4] N. Chandra, H. Li, C. Shet, H. Ghonem, Int. Solids Struct. 39 (2002) 2827–2855.
[5] L. Mishnaevsky, K. Derrien, D. Baptiste, Compos. Sci. Technol. 64 (2004) 1805–1818.
[6] S. Ren, X. He, X. Qu, Islam S. Humail, Y. Li, Compos. Sci. Technol. 67 (2007) 2103–2113.
[7] J.K. Park, J.P. Lucas, Scripta Mater. 37 (1997) 511–516.
[8] J.C. Romerio, R.J. Arsenault, Acta. Metall. Mater. 43 (1995) 849–855.
[9] J.C. Lee, J.Y. Byun, S.B. Park, H.I. Lee, Acta Mater. 46 (1998) 1771–1775.
[10] A.C. Ferro, B. Derby, Acta Metal. Mater. 43 (1995) 3061–3073.
[11] E. Ogris, A. Wahlen, H. Luchinger, P.J. Uggowitzer, Light Met. 2 (2002) 263–269.
[12] A. Bukaluk, Vacuum 63 (2001) 119–126.
[13] G.G. Sozhamannan, S. Balasivanandha Prabu, Mater. Chart. 60 (2009) 986–990.