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Effects of Direct Current on the Wetting between Molten Al and a Graphite Substrate

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Abstract: Graphite fiber attracted much attention in the area of aluminum based composite due to its low density and high strength. However, one of the major drawbacks in fabricating graphite reinforced metal matrix composites (MMCs) is that aluminum generally does not wet graphite. Therefore, it is difficult to impregnate the graphite fiber in molten aluminum. The application of external electric power has been recently reported as a promising way to improve the wettability. The effect of an electric current on the wettability of molten Al on graphite has not been investigated. The effects of electric current, density of sample and heating time on wettability, thickness of product, and microstructure were investigated. The wettability remarkably improved utilizing electric current due to a larger formation of Al_4C_3 per unit time from electromigration. The wettability of molten Al on graphite substrate is better with an applied negative current and with lower relative density of sample.

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Keywords: wettability, Al_4C_3, electric current, aluminum, graphite

1. INTRODUCTION

Graphite fibers have been used extensively as reinforcement materials in polymer and epoxy based composites due to their excellent properties. These properties include low density and high strength. The unique properties of graphite fibers also attracted much attention in the area of aluminum based composite. However, one of the major drawbacks in fabricating graphite reinforced metal matrix composites (MMCs) is aluminum generally does not wet graphite. Therefore, it is difficult to impregnate the graphite fiber with molten aluminum. To solve the difficulty, Oh *et al.* [1] reported that the wettability of molten Al can be remarkably improved by coating graphite particles with Cu. In addition, the applications of external electric power have been recently reported as a promising way to improve the wettability [2]. The effect of an electric current on the wettability of molten Al on graphite has not been investigated. In this communication, we report the effects of electric current, density and heating time on wettability, thickness of product (Al_4C_3) and microstructure.

2. EXPERIMENTAL PROCEDURE

In this study, in order to enhance the wettability of the Al melt on graphite, its wetting behavior on graphite was observed using the sessile drop test, by which its wetting angle was measured. Graphite plates were polished using diamond paste, and then cleaned in ethanol using ultra-sonication. Aluminum ingot (99.999% purity) was used as a liquid drop material. Figure 1 displays a schematic diagram of the device used for the sessile drop test. To observe the wetting behavior of Al droplets, the graphite substrate was placed on the alumina crucible horizontally to the CCD camera. The furnace was evacuated under the vacuum of 10^{-5} torr and heated to 1050 °C at a heating rate of 5 °C/min. When the temperature reached to 1050 °C, a droplet of Al was made to fall onto the graphite substrate. After the molten Al was dropped, the wetting behavior was captured by a high

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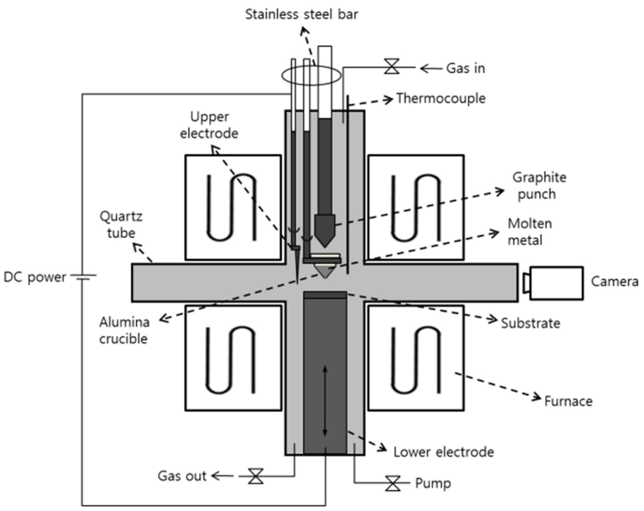


Fig. 1. Schematic representation of the device used for the sessile drop test..

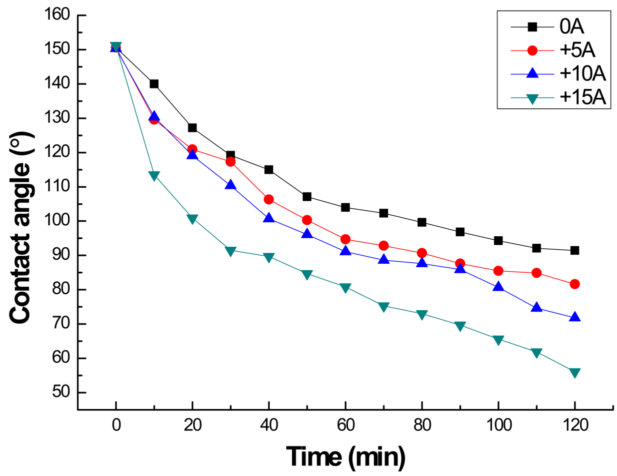


Fig. 2. The variation of the contact angle (θ) with time for molten Al on graphite substrate during isothermal exposure at 1050 °C under various electric current.

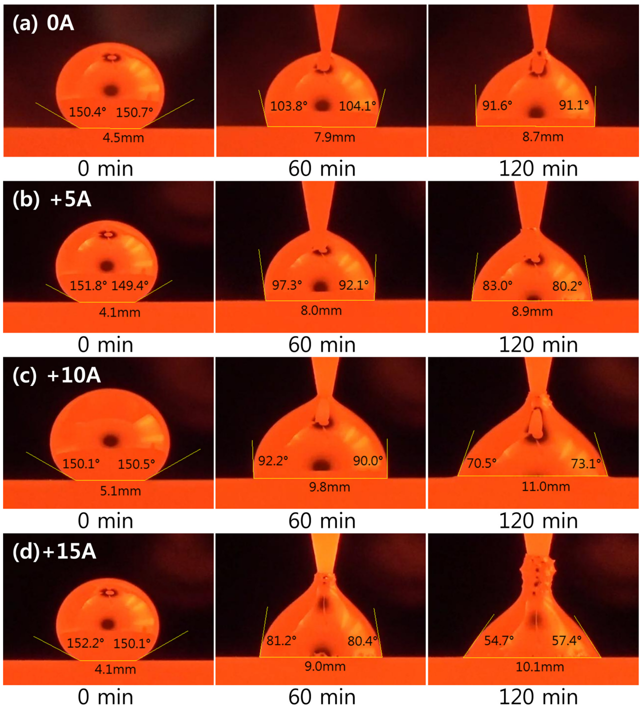
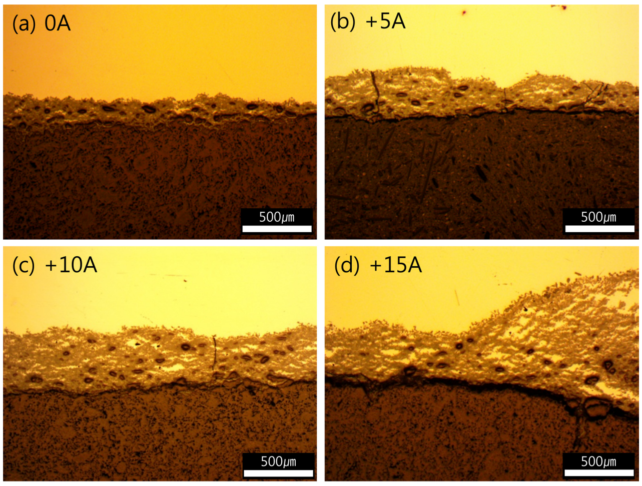


Fig. 3. The droplet image during isothermal exposure at 1050 °C for molten Al on graphite substrate with heating time and electric current : (a) 0A, (b) 5A, (c) 10A and (d) 15A.

resolution CCD camera. The captured images were used to evaluate the contact angle. An electric current (0, 5, 10 and 15 A) was applied through the molten Al bead and graphite substrate. In this study, we defined the electric current flowing from an Al droplet to CNT substrate as the positive current (+), otherwise as the negative current (−). Compositional and microstructural analyses of the products were conducted through optical microscopy and electron probe micro-analysis (EPMA).

3. RESULTS AND DISCUSSION

Figure 2 displays the variation of the contact angle (θ) with heating time for molten Al on a graphite substrate during isothermal exposure at 1050 °C. The wettability of molten Al on graphite without an applied current is initially poor and the contact angle continuously decreases with heating time due to formation of Al_4C_3 [3]. Contact angle decreases markedly with increases of applied currents. The droplet image during isothermal exposure at 1050 °C for molten Al on graphite substrate without applied current and with an applied of 5A, 10A and 15A are shown in Fig. 3. Contact angle of molten Al on graphite substrate is decreased with applied electric current. An applied current may accelerate the wetting of molten Al on graphite and decrease remarkably the contact angle. Figure 4 shows the optical micrograph of a cross-section perpendicular to the interface of pure Al on graphite after wetting at 1050 °C, for various electric current. It can be found that the



	0A	+5A	+10A	+15A
Thickness(μm)	164	230	527	612

Fig. 4. Optical micrograph of cross-section perpendicular to the interface of pure Al on graphite after wetting at 1050 °C for 120 min with various electric current.

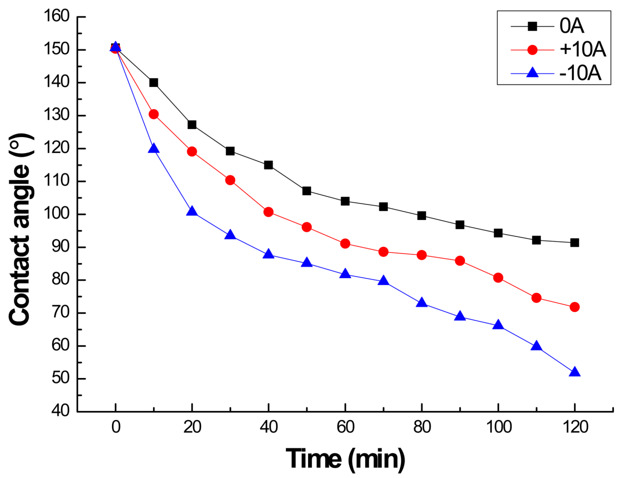


Fig. 5. The variation of the contact angle (θ) with time for molten Al on graphite substrate during isothermal exposure at 1050 °C under various electric current.

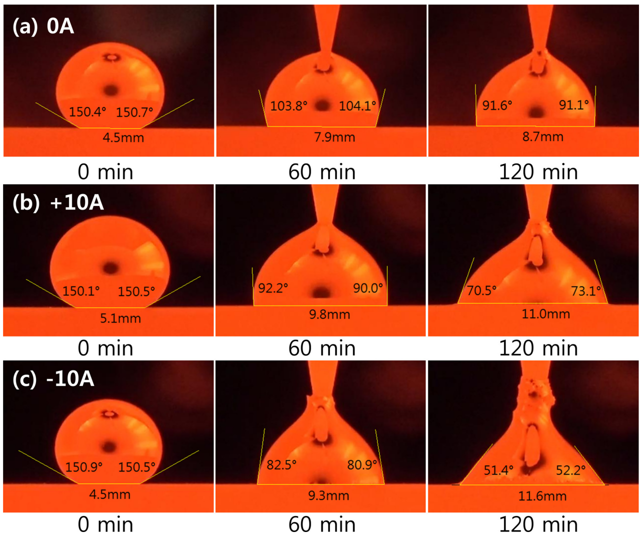


Fig. 6. The droplet image during isothermal exposure at 1050 °C for molten Al on graphite substrate with heating time and electric current : (a) 0A, (b) 10A and (c) -10A.

thickness of the product, which was analyzed as Al_4C_3 using EPMA, increases with applied current.

Variation of contact angle of molten Al on graphite under the different direction of current (+10A and -10A) is shown in Fig. 5. The contact angle is considerably reduced with heating time in the case of an applied negative current of -10 A. Evolution of the droplet image during isothermal exposure at 1050 °C for molten Al on graphite substrate without and with an applied current of +10 A are shown in Fig. 6. The direct current direction has an obvious influence on the spreading rate and contact angle of molten Al on graphite substrate. But Xu *et al* [4] has reported the contact angle of molten Bi on Cu substrate with an applied positive current of +2 A is smaller than that with an applied negative current of −2 A. This result is in opposite with our result.

Figure 7 displays the optical micrograph of a cross-section perpendicular to the interface of pure Al on graphite after wetting at 1050 °C for 2 h under the electric current of 10 A. It can be found the thickness of a product, which was analyzed as Al_4C_3 using EPMA increases with applied current. Figure 8 displays the interaction between carbon and aluminum is thermodynamically feasible.

$$3C + 4Al \rightarrow Al_4C_3 \qquad (1)$$

The contact angle of molten Al on graphite depends on an applied current, a direction of current and a heating time, To understand the variation of wettability, two factors may be considered. One is the effect of surface energy between molten Al and Al_4C_3 according to formation of Al_4C_3 during heating.

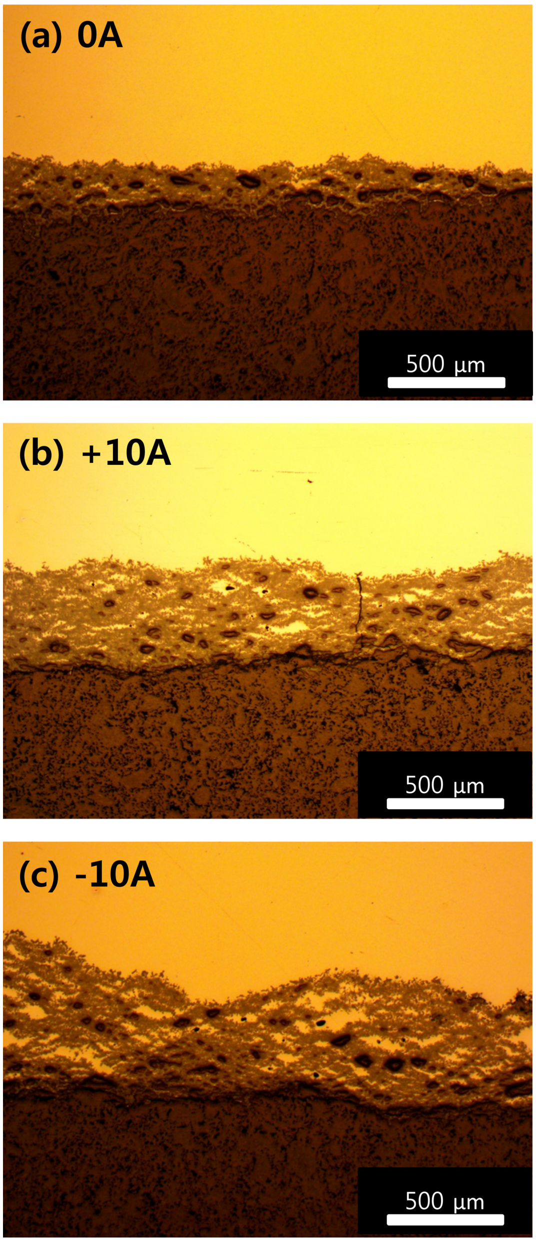


Fig. 7. Optical micrograph of cross-section perpendicular to the interface of pure Al on graphite after wetting at 1050 °C for 120 min with various electric current.

Unfortunately, surface energy between molten Al and Al_4C_3 was not reported. However, the interface reaction product (Al_4C_3) promotes wetting in this study. This behavior matches well with another study [3]. From this result, surface energy between molten Al and Al_4C_3 may be lower than that of molten Al and graphite. The other would be the role of heat energy produced from the formation of Al_4C_3 on the

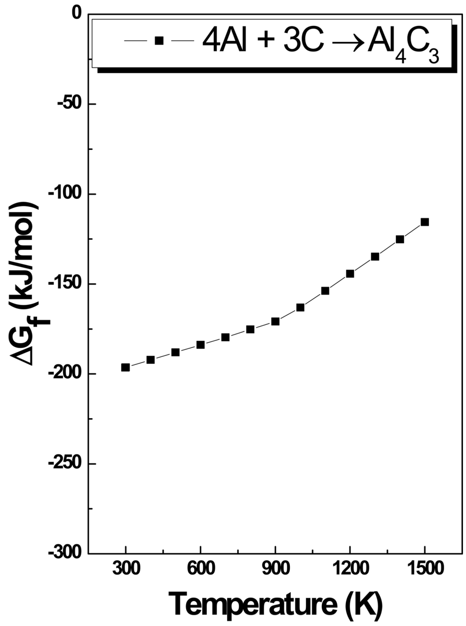


Fig. 8. Temperature dependence of the Gibbs free energy variation by interaction between 4Al and 3C.

wettability. The temperature of molten Al can increase due to the heat energy (enthalpy change) according to the equation (2). The calculated adiabatic temperature is 2020 °C.

$$\Delta H_f^0(Tig) = \int_{Tio}^{Tad} C_{Ps(p)} dT \qquad (2)$$

Where, $\Delta H_f(T_{iq})$ is formation enthalpy change of Al_4C_3 at 1050 °C, T_{ad} is adiabatic temperature, T_{ig} is ignition temperature, and $C_{Ps(p)}$ is heat capacity of Al_4C_3. Surface tension of molten Al continuously decreases with heating temperature [5]. This can enhance wettability of molten Al on graphite. The thickness of the interfacial reaction layer increases remarkably due to the enhanced diffusivity of the atoms. This could be related to the electromigration effect [6]. Wettability can be enhanced under an electric current which may be related to the thickness of the interfacial reaction layer. This means that more heat per time can be produced. Therefore, the temperature of molten Al, when applying an electric current, may be higher than that of non-electric field, and wettability can be enhanced under the electric current.

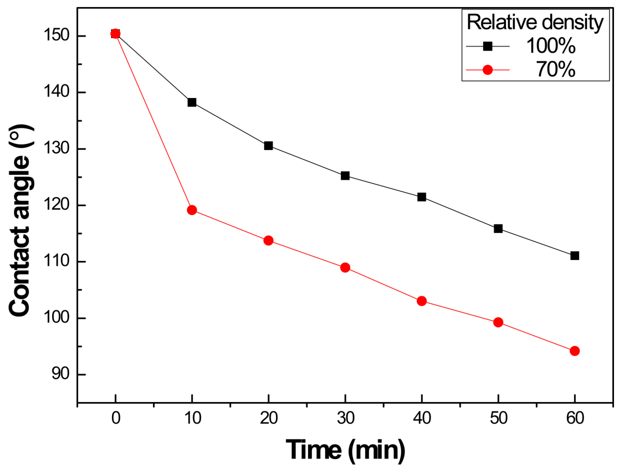


Fig. 9. The variation of the contact angle (θ) with time for molten Al on graphite substrate during isothermal exposure at 1050 °C under different relative density of graphite.

Figure 9 shows the variation of the contact angle (θ) with heating time for molten Al on a graphite substrate with different relative density measured using Archimedes method during isothermal exposure at 1050 °C. The wettability of molten Al on graphite with relative density of 70% is better than that of graphite with relative density of 100%. The reaction site of molten Al and graphite to form Al_4C_3 increases with an increase in porosity. This means that more Al_4C_3 in graphite of lower relative density can be produced at the same heating time. Figure 10 displays the optical micrograph of a cross-section perpendicular to the interface of pure Al on graphite with different relative density after wetting at 1050 °C for 1 h. It can be found that the thickness of the product, which was analyzed as Al_4C_3 using EPMA, is thicker in graphite of lower relative density. More heat per time can be produced. Therefore, the temperature of molten Al, when applying a low relative density of graphite, may be higher than that of high relative density of graphite and wettability can be enhanced under the low relative density.

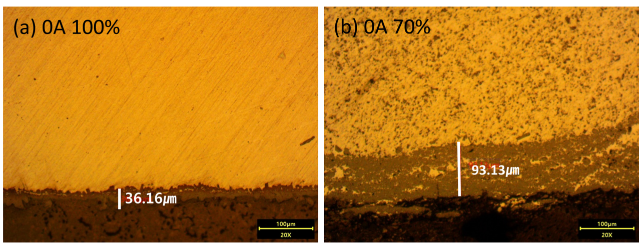


Fig. 10. Optical micrograph of cross-section perpendicular to the interface of pure Al on graphite after wetting at 1050 °C for 60 min under different relative density of graphite.

4. CONCLUSION

The wettability of molten Al on graphite without an applied current is poor, and the contact angle continuously decreases with heating time. Contact angle of molten Al on graphite substrate is decreased with applied electric current. An applied current may accelerate the wetting of molten Al on graphite and decrease the contact angle considerably. Wettability can be enhanced under an electric current which may be related to the thickness of the interfacial reaction layer (Al_4C_3). This means that more heat per time can be produced. The wettability of molten Al on graphite substrate is better under an applied negative current and with lower relative density.

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