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EFFECT OF Al/Cu WEIGHT FRACTION ON THE MECHANICAL AND ELECTRICAL PROPERTIES OF Al-Cu CONDUCTORS FOR OVERHEAD TRANSMISSION LINES

In the past few years, overhead copper transmission lines have been replaced by lightweight aluminum transmission lines to minimize the cost and prevent the sagging of heavier copper transmission lines. High strength aluminum alloys are used as the core of the overhead transmission lines because of the low strength of the conductor line. However, alloying copper with aluminum causes a reduction in electrical conductivity due to the solid solution of each component. Therefore, in this study, the authors attempt to study the effect of various Al/Cu ratios (9:1, 7:3, 5:5) to obtain a high strength Al-Cu alloy without a significant loss in its conductivity through powder metallurgy. Low-temperature extrusion of Al/Cu powder was done at 350ºC to minimize the alloying reactions. The as-extruded microstructure was analyzed and various phases (Cu_9Al_4, $CuAl_2$) were determined. The tensile strength and electrical conductivity of different mixing ratios of Al and Cu powders were studied. The results suggest that the tensile strength of samples is improved considerably while the conductivity falls slightly but lies within the limits of applications.

Keywords: transmission line, aluminum, lightweight, extrusion, intermetallic, tensile

1. Introduction

For many years, the aluminum wire has been developed for manufacturing of Aluminum Conductor Aluminum Reinforcement (ACAR), Aluminum Conductor Steel Reinforcement (ACSR), and All Aluminum Alloy Conductor (AAAC) in order to reduce various disasters caused by sagging and prevent environmental hazard [1,2]. Aluminum has replaced many Copper-Clad Steel designs due to its various advantages such as high electrical conductivity compared to the same weight of copper and has twice the power transmission efficiency which makes it more cost-effective, for its widespread use in the overhead power line industry.

As a result, the vast majority of overhead line conductors made from either copper-based or aluminum-based alloys which leads to a tradeoff of conductivity and strength [4]. In order to reduce this tradeoff, various research activities have been performed in the past to increase the strength and retain good conductivity in aluminum [5-7].

Aluminum-based composites are produced by several methods such as casting and powder metallurgy [8,9]. Among these methods, powder metallurgy is a potential candidate to fabricate high strength Al-Cu alloys. Conceptually, the copper powder provides good electrical conductivity while the aluminum powder provides specific strength. We can tailor the strength and composite conductivity by varying the weight fraction of each powder. In addition, the effect of lowering in electrical conductivity can be reduced by minimizing the alloying reaction during hot extrusion [10].

Therefore, in this study, the authors have mixed Al and Cu powders with various weight fractions to enhance the mechanical properties while minimizing the reduction in electrical conductivity. Also, hot extrusion of the mixed powders was performed in an inert atmosphere and lower temperature to minimize the generation of intermetallic compounds (IMCs). The mechanical and electrical properties were investigated for the high strength Al-Cu conductors, and the correlation between these physical properties and microstructure is discussed in detail.

2. Experimental

The aluminum powder used in the experiment was obtained from Changsung Co., Korea (mean size: 20 µm, purity 99.99%).

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The copper powder was obtained from Duksan, Korea (mean size: 30 μm, purity 99.99%). The Al and Cu powder were mixed in a sealed container using a Turbula mixer in various ratios of 9: 1, 7: 3, and 5: 5.

The mixed powder was charged into an aluminum can and sealed by welding for hot extrusion process. Prior to the hot extrusion process, a graphite lubricant was applied to the can and extruded in a ratio of 15:1. The hot extrusion temperature was set at 2/3 of the melting temperature of pure aluminum, i.e., at 350°C.

Electrical conductivity was measured using a portable instrument (Fischer, SIGMASCOPE SMP10) at room temperature according to the DIN EN 2004-1 and ASTM E1004 method, and it was displayed as percentage ratio to the International Annealed Copper Standard (IACS). Tensile strength was evaluated via a universal testing machine (Daekyung Tech & Testers, Korea) according to the ASTM B557 method. The tensile test was performed at room temperature and in a crosshead speed of 2 mm/mim which corresponds to a strain rate of 10^{-2} s^{-1}.

The microstructure was investigated via X-ray diffraction (XRD, SHIMADZU, XRD-6100) and scanning electron microscope (SEM, JEOL, JSM IT500HR) equipped with energy dispersive X-ray spectroscopy (EDS, OXFORD Instruments, AZtecGSR).

3. Results and discussion

Figure 1 shows the results of the XRD pattern of the as-extruded samples with different Al/Cu ratios. In all the samples, the aluminum peak appeared as the main peak due to the high volume fraction of aluminum. Initially, at 9:1, there is no IMCs in the XRD pattern. However, when the proportion of copper is increased from 9:1 to 7: 3, Cu_9Al_4 and $CuAl_2$ were found to appear and continue to increase up to Al: Cu = 5:5. Aluminum is a fast diffuser in the copper matrix due to its higher thermal diffusivity than copper. The above results show that aluminum is more thermally diffused than copper forming more Cu_9Al_4 [11]. Since there are several Al/Cu couples are available at the Al/Cu = 5: 5, the diffusivity of Al leads to the presence of numerous IMCs as shown in Fig. 1.

Figure 2 shows the hot extruded microstructure of Al-Cu alloys with various Al/Cu weight ratios. Initially, at Al/Cu = 9:1, the aluminum-rich phase is seen all over the surface. As the mixing ratio of Al/Cu increases, the copper-rich areas in the microstructure increases gradually. Defects of powder metallurgy, such as pore and prior particle boundaries were not observed in the microstructure of all samples. This may be due to the fact that aluminum particles in the mixed powder were filled between the copper powder particles during hot extrusion and a good extruded sample was obtained.

Figure 3 shows the electrical conductivity of the extruded samples with various Al/Cu ratios. The conductivity of the samples was compared to the standard high purity Al. The electrical conductivity of all samples was slightly lower than pure aluminum. As the mixing ratio copper component increased, the electrical conductivity of the samples decreases with a minimum at 5: 5. The conductivity at 9:1 decreases down to 8% IACS at 5:5. In general, the alloys under investigation show low electrical conductivity as compared to pure Al due to the solid solution and the formation of intermetallic compounds (IMCs).

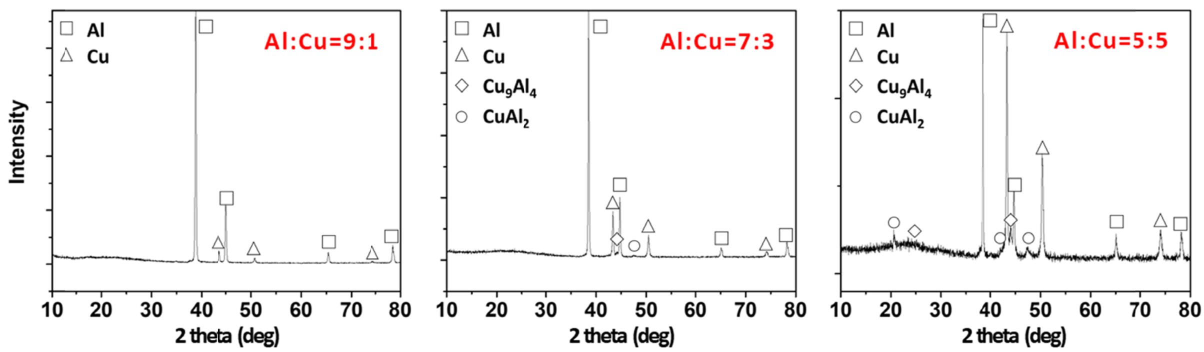

Fig. 1. XRD pattern of hot extruded Al-Cu alloy with various Al/Cu ratios

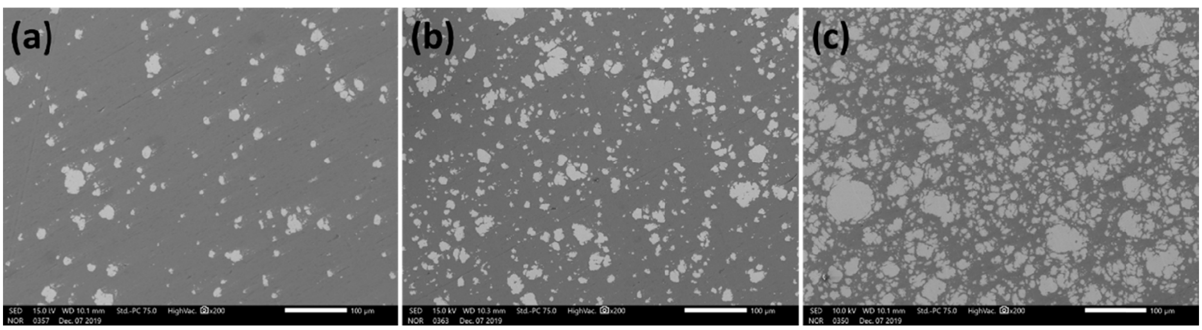

Fig. 2. SEM images of the extruded Al-Cu powder with various Al/Cu ratios; (a) Al9: Cu1, (b) Al7: Cu3, and (c) Al5: Cu5

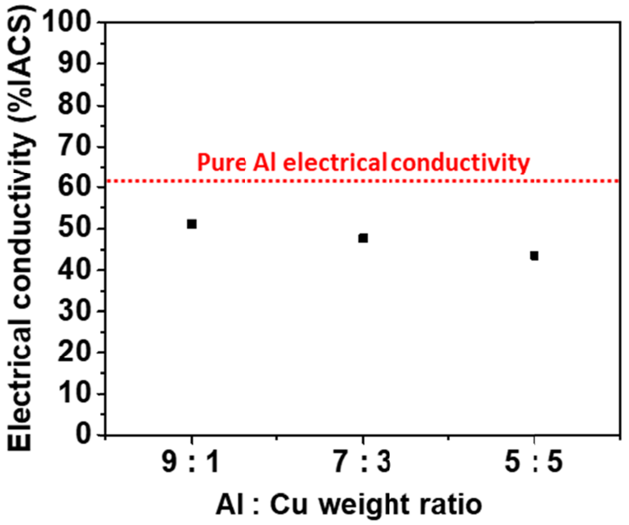

Fig. 3. Electrical conductivity of hot extruded materials for various Al/Cu ratios. Dashed line indicates the conductivity of pure aluminum

Figure 4 shows the stress-strain curves of hot extruded samples and corresponding ultimate tensile strength as a function of their mixing ratios. The ultimate tensile strength of the extruded Al/Cu system was highest at a 5:5 ratio. This can be due to the presence of numerous IMCs at this Al/Cu = 5:5 ratio. It is also seen that the tensile strength of the hot-extruded samples increases slowly from 9:1 to 7:3 and then rapidly from 7:3 to 5:5 with an increasing Al/Cu mixing ratio. The reason was ascribed to the presence of several Al/Cu reaction couples at 5:5 due to higher volume ratio Al: Cu that resulted in high fractions of IMCs.

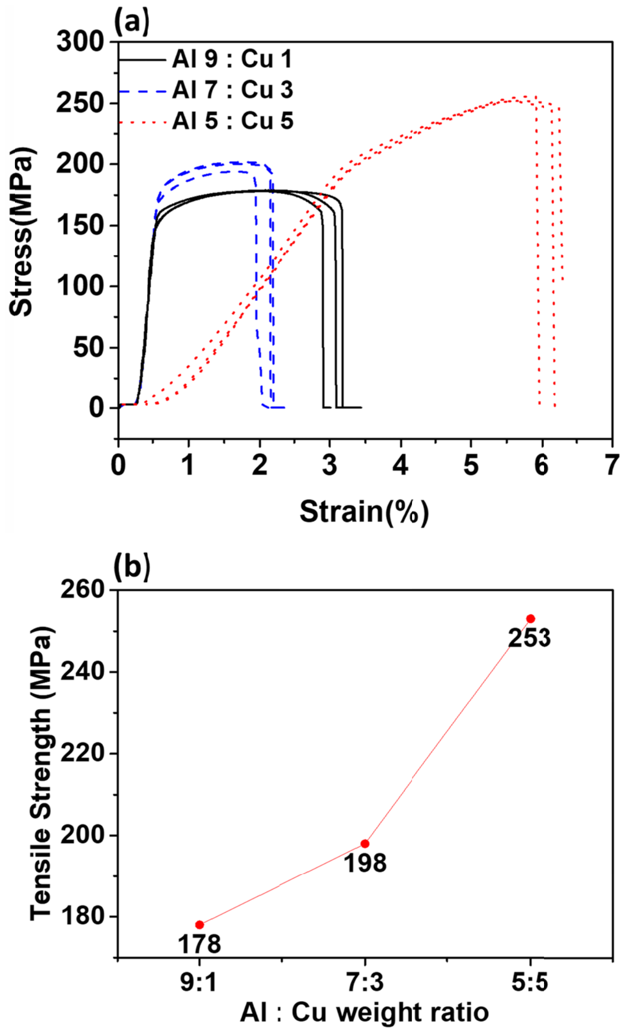

Fig. 4. Hot extruded materials with various Al/Cu ratios; (a) stress-strain curves and (b) tensile strength

Figure 5 shows the results of SEM-EDS of each extruded Al/Cu powder samples. The EDS mapping shows the overlapping of the surrounding areas near IMCs (Fig. 5a). The presence of IMCs was observed in the contact areas of aluminum and copper. In Figure 5(b), the size of the IMCs was measured to be about 2 µm thick. It is reported that the mechanical properties improve when the IMCs are grown to a thickness of 2.5 µm [12]. From the linearity results of the elemental components, it was not possible to define specific regions as $CuAl_2$ and Cu_9Al_4 phases. The various IMCs exist on the matrix surface due to the fast thermal diffusion rate of aluminum. The aluminum rapidly escaped from the aluminum matrix and diffuse towards copper matrix to form Cu_9Al_4 and the place from which the aluminum escapes forms a $CuAl_2$ due to diffused copper [12,13]. The hot extrusion process of the mixed powder is a high-pressure and high-temperature sintering process. However, due to the short time of the hot extrusion process, the IMCs were formed only at the matrix surface.

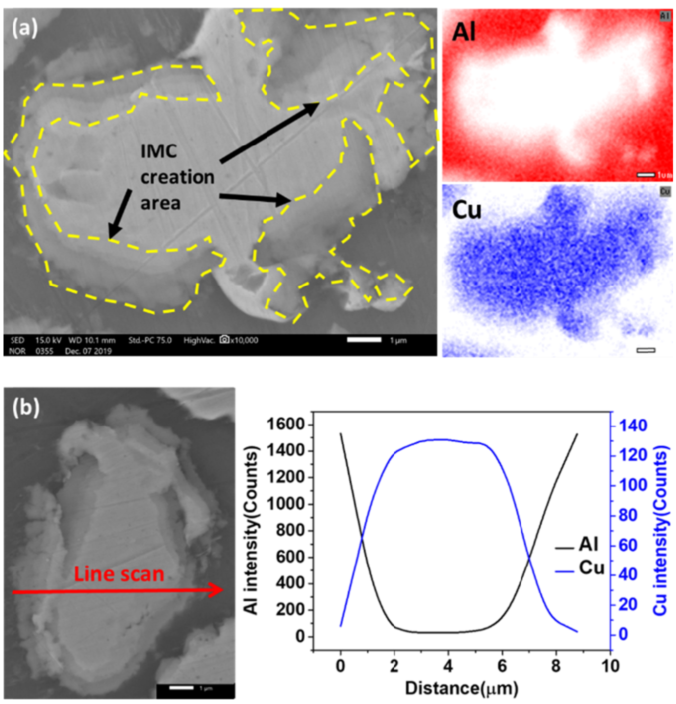

Fig. 5. EDS results of extruded Al/Cu powder; (a) elemental mapping of 5:5 Al/Cu ratio and (b) line scanning of 7:3 Al/Cu ratio

The hot extruded sample of the mixed Al/Cu powder not only overcome the electrical conductivity reduction caused by metal alloying but also has a high mechanical property. The sample with a 5: 5 mixture ratio exhibited the highest tensile strength due to the presence of numerous IMCs in the matrix.

However, aluminum used as a transmission line is considered to be an important factor of specific strength. All of the extruded samples had a specific strength of about 30% higher than that of pure aluminum. The extruded sample with 9: 1 mixing ratio has slightly reduced electrical conductivity compared to pure aluminum, but could be applied to transmission lines due to its greater mechanical properties.

4. Conclusions

This study confirmed the electrical conductivity and strength characteristics of the aluminum and copper mixed powder after hot extrusion to improve the strength of the aluminum ACSR transmission line conductor.

(1) After hot extrusion, $CuAl_2$ and Cu_9Al_4 IMCs were generated on the matrix surface. Cu_9Al_4 phase was formed on the copper matrix surface by rapid thermal diffusion of aluminum, while $CuAl_2$ phase appeared on the aluminum matrix.

(2) More IMCs were formed by increasing the copper mixing ratio resulting in enhancing the mechanical properties. Therefore, although the conductivity of aluminum-copper conductors was slightly lower than that of pure aluminum, they are potentially applicable to transmission line conductors because of the significantly greater strength than pure aluminum.

Acknowledgments

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