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**Abstract**
Aluminum and copper clad ingots have gained great attention because its versatility to wide application areas, such as brazing sheet, light weight electrical wire and clad plate. In general, clad sheet and wire can be fabricated by rolling bonding or adhesive bonding. However these processes require complicated pre-treatment and processing and its processing cost is high. In this study, casting of aluminum and copper clad ingot was suggested and integrated by modification of direct chill casting and horizontal casting. Key parameter for successful interface bonding was precise control of cooling rate in the mould divider. To improve the bonding behavior and microstructure of clad ingot, electromagnetic stirring was applied during continuous casting process. By applying electromagnetic stirring, the interface bonding of clad ingot was improved with refined microstructure. In result, uniform and strongly bonded aluminum and copper clad ingot was fabricated under electromagnetic field. Finally preliminary study of rolling and extrusion of clad ingots were conducted and it shows promising results for fabrication of clad sheets and wire.

**Key words:** continuous casting, aluminum, cooper, clad ingot, electromagnetic stirring

## Introduction
It is desirable for many purposes to fabricate aluminum and copper sheets made of two or more alloy layers. There are large potential markets for clad products consisting of two or more layers of different alloys. Such products are used to produce clad sheets and wire for various applications such as brazing sheet, aircraft plate where two or more combined properties is required. In the manufacture of those products, a large portion is produced by methods employing roll cladding or bonding. It is reliable process but has a disadvantage in the interface between the layers which is not metallurgically clean and bonding of the layers can often be a problem. An alternative approach of fabricating clad products is a novel and inexpensive method of casting composite metal bodies suitable for further processing by conventional metal working methods. Conventional aluminum and copper alloy ingots have been cast by continuous casting process known as direct chill (DC) casting. In this process, molten metal has been poured into the top of open ended mould. Such a system is commonly used to produce monolithic ingots for rolled and extruded products. There has been an interest in casting layered ingots to produce a clad ingot from 1950s. This has typically been carried out using modified direct chill casting of simultaneous or sequential solidification of two alloys.
In Robinson's patent, a casting system is suggested where an internal partition is placed within the mould cavity to substantially separate areas of different alloy compositions. In Binczewski's patent, a method is suggested for producing a composite ingot by DC casting where an outer layer of higher solidus temperature is cast about an inner layer with a lower solidus temperature. Recently Mark Douglas Anderson from Novelis Inc. has integrated clad ingot casting technology so called Fusion Technology as a commercial scale successfully.
This study includes a method and apparatus for direct chill casting two aluminum and copper layers at one time to form a composite ingot with electromagnetic stirring technique. For a good adhesion between the two layers, it is desirable to ensure that the layers, while being cast together in a single mould, are formed sequentially so that molten metal of one layer contacts previously cast semi solid metal of another layer. The appropriate control of interface cooling may also prevent harmful oxide formation at the interface between the metal layers, again improving mutual adhesion of the layers. Clad ingots were subjected to further specialized metal working such as hydrostatic extrusion and differential speed rolling. Finally it is confirmed that clad wire and sheets were successfully fabricated from aluminum and copper clad ingots.

## Experimental Method
Casting experiments were performed using and AA1050, AA6061 and pure Cu alloy. A part of the raw AA6061 alloy was modified with 400 ppm Ti by adding AlTiB1 during ingot preparation. The experimental setup is schematically

depicted in Fig. 1. The copper mould with slit and AA1050 and AA6061 were used in vertical slab casting. The vertical casting machine was equipped with direct cooling water spray into mould and billet. The mould has same structure of monolithic casting however divider was installed inside mould. The divider has water and air cooling auxiliary parts to control the solidification behaviour of the interface between two layers. The graphite mould and AA1050 and pure copper were used in horizontal billet casting machine. Indirect cooling was applied to horizontal casting machine. Casting speed was varied up to 150 mm/min and 1500mm length billet and slab were fabricated with two casting machines. The rotating magnetic field equipment was installed around mould and low frequency magnetic field was applied to generate the melt rotation. The cast samples were cut and polished to reveal the microstructure. The microstructure was observed with low magnification camera and optical microscope. The grain size, interface microstructure and adhesion properties were estimated to find the effect of melt stirring. Finally slab was cut into designated size for rolling. In case of two layered aluminium slab, differential speed rolling was applied to get sound sheet sample. Rolling process was in done in 300 $^{o}$C and differential speed ratio was 1.6. In case of aluminium and copper clad billet, hydrostatic extrusion process was applied to obtain enhanced clad wire.

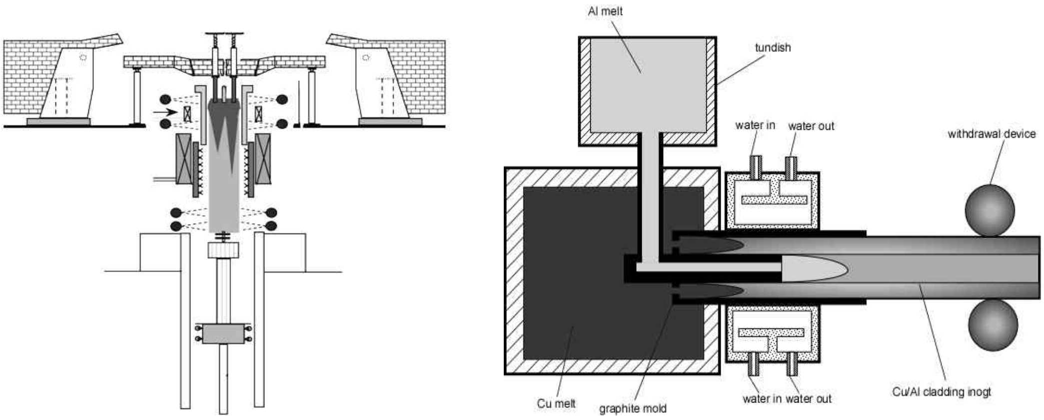


Fig. 1: Schematics of the vertical and horizontal continuous casting of clad ingot with electromagnetic stirrer

**Results and Discussion**

The slab clad ingot casting is done successfully by adjusting processing parameters such as melt temperature, melt level, casting speed, and cooling water. In order to find optimal processing parameters, numerical simulation study was done and checked with several experiments. The most important parameter for slab clad ingot casting was the cooling of divider by cooling water and air. If the cooling water and air cools too much, the interface adhesion is poor and occasionally separated. If the cooling is not enough, two melt is mixed and layered structure was not obtained after casting. After establishment of sound casting condition, rotating magnetic field was applied to observe the effect of magnetic field.

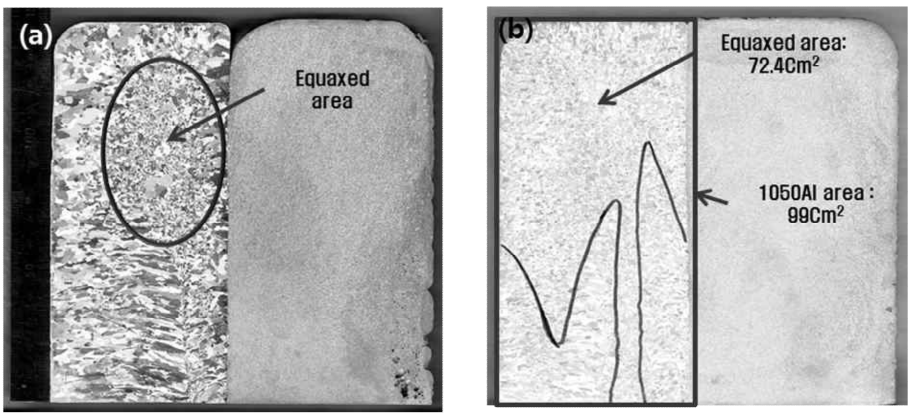


Fig. 2: The cross section images of AA1050/AA6061 clad ingots (a) without EMS, (b) with EMS

The solidification structures of slab clad ingot were shown in Fig. 2. AA6061 side shows refined grain size due to addition of grain refiner. However AA1050 side shows coarse and columnar structure in Fig. 2(a) and it is observed in typical aluminum casting sample. If rotating magnetic field was applied during casting, microstructure was changed as refined structure.  The equiaxed area of EMS applied sample is around 72% of total area and its grain size is greatly reduced. The rotating magnetic field induces shear flow ahead at the dendrites. Also interface adhesion shows difference between two samples. Around edge region of interface, large shrinkage gap is found in Fig. 2(a) however no gap at edge interface was found in Fig. 2(b). The difference of melt temperature between center and edge region during casting process is large without EMS. The EMS induces melt stirring and uniform temperature was obtained. Therefore uniform solidification was happened along the interface. The adhesion properties were evaluated with tensile and bending test. Stress-strain curve for clad ingot sample shows good agreements with microstructure.

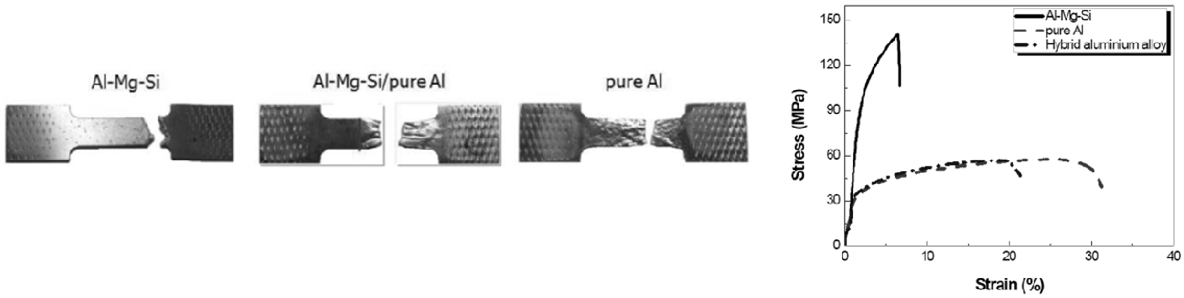


Fig. 3: The tensile test of AA1050/AA6061 clad ingots and its stress-strain curve

Fig. 3 shows the tensile test samples of AA1050/AA6061 samples and its stress-strain curve. As shown in Fig. 3, the failure is occurred at the AA1050 side, which means the strength of interface is enough to endure the failure. Each sample of AA1050, AA6010 monolithic and AA1050/6061 clad was tested and its stress-strain curve were compared. Two monolithic samples show typical values of yield strength and elongation. Clad sample shows low yield strength and elongation but these values are not directly related to clad sheets. The tensile test along sheet rolling direction shows mid values of two monolithic materials. It was possible to fabricate different aluminum alloy combination with adjusting casting conditions. AA1050/AA2024, AA4004/AA5052 were fabricated with same casting machine.

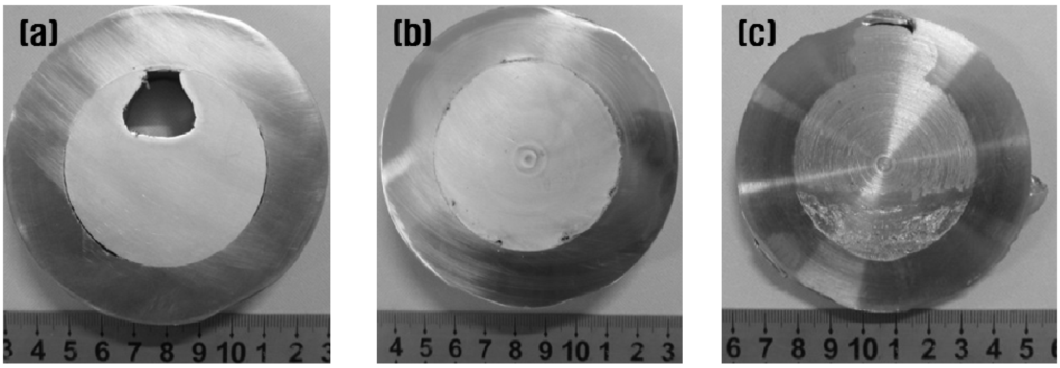


Fig. 4: The cross section images of Cu/Al clad ingots,  (a) low melt temperature
(b) optimum temperature and (c) high temperature with EMS applications

Clad billet casting was done with horizontal casting machine. Out region is cooper and inner region is aluminum as shown in Fig. 4. The melt temperature of aluminum was main parameters to obtain clad sample. Low melt temperature of aluminum induces fast solidification before filling the hollow copper but high melt temperature generates re-melting of copper outer billet. Precise control of melt temperature was needed to obtain fully filled clad billet. Also casting speed, cooling water intensity and cooling water temperature were important factors to determine billet casting process. Fig. 4(b) shows good interface bonding due to processing parameter control and EMS application. In horizontal casting of clad billet, bottom interface shows good adhesion but top interface shows shrinkage gap with EMS. If EMS is applied during casting, aluminum melts circulated the inner region and fills uniformly. Casting defects at interface region still exist but it can be removed by severe plastic deformation such as extrusion. However large defects of non-EMS samples exhibits as large crack or process instability during plastic deformation. It also shows grain refinement effect aluminum alloy by applying EMS. It was also possible to fabricate clad billet of AA3003/AA4004 alloy combinations with vertical casting machine.

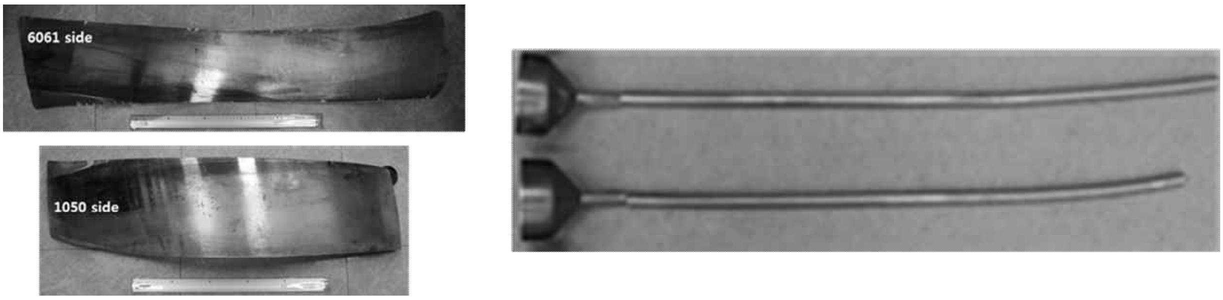

Fig. 4: The AA1050/AA6061 clad sheet from clad slab ingot and Cu/Al wire from clad billet

Clad slab was rolled and the results were shown in Fig. 4. The significant difference of flow stress between AA1050 and AA6061 induces bending of rolled sheet. The thickness ratio of AA1050/AA6061 was changed to suppress the bending behavior. Differential speed rolling was also applied as same purpose. Clad sheet was successfully fabricated by optimizing rolling condition and it shows no significant rolling defect. If more differential speed ration is applied, bending will be adjusted as normal condition. Al/Cu billet was extruded by hydrostatic extrusion method. Uniform stress distribution around billet eases the extrusion process even though each clad layer has different physical properties. The electrical properties were checked after extrusion and its values were comparable to monolithic copper wire.

## Conclusion

This study demonstrates the clad ingot casting with vertical and horizontal casting machine. The impact of electromagnetic stirring on microstructure and interface adhesion was evaluated and forced convection influences significantly the macrostructure. Finally clad Al/Al slab was subjected to differential speed rolling and sound clad sheet was fabricated. Cu/Al billet was subjected to hydrostatic extrusion process and clad wire was fabricated successfully.

## Acknowledgment

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