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The Mechanism Research of Electric Current Pulse and Electromagnetic for Grain Refinement of 6181 Aluminum Alloys During Two-roll Casting

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Research Article

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ABSTRACT

6181 aluminum alloys sheets were produced by two-roll casting with electric current pulse and magnetic fields, and the microstructures were observed. The experimental results show that application of composite fields (ECP and EM field) during TRC process refines the microstructures of sheets more evenly and effectively by comparison with individual application of ECP or EM field. For visually explaining the phenomenon, the distribution and amplitude of the magnetic induction intensity B and electromagnetic force F were obtained by numerically simulated. In addition, an obvious improvement of tensile strength by physical fields was measured. But the maximum elongation was from action of magnetic field and reached 10.9%.

INTRODUCTION

Recently, the topic of saving energy and environment protection has been paid more and more attention. In the field of materials, in the interest of reaching the above requirements, the research of light alloy and new methods of production has been a consequent trend. 6XXX aluminum alloys, which have been known as a kind of automotive materials, due to their low density, high specific strength, excellent plasticity, and good electrical conductivity [1-3]. However, how to reduce the manufacture costs and the improve formability of aluminum alloys sheets is required. In this research, the 6181 aluminum alloys sheets are produced by the two-roll casting. The twin-roll casting (TRC) is manufacturing process that makes crystallization, solidification, deformation combine into a whole, and it has been confirmed as a simple economical and effective method for production of aluminum [4,5]. In 2000, during twin roll casting of aluminum alloys, various macroscopic defects such as surface bleeds and deformation segregates were observed by Yun [6]. In 2005 and 2006, Gras [7] and Forbord [8] investigated also respectively twin roll casting of aluminum alloys and found the micro defects formation. With the development of computer, combination of simulation and test become an effective method for TRC. Chen Shou-dong [9] built the analytical model of twin-roll continuous casting aluminum thin strip solidification and provided some theoretical direction. Lee Ys [10] researched the influence of different processing parameters (symmetric nozzle and symmetric roll speed) and roll separation force for the temperature and liquid fraction, and found a good quality of the strip was experimentally obtained at a roll separation force of 6-8t. From here we see that the TRC process has attracted a batch researchers' interest.

However, how to decrease the defection and columnar crystals, enhance the mechanical property has not been well solved. In the process of cast ingot, in order to reduce the inhomogeneity of structure, refine grain sizes and improve the mechanical property, electromagnetic fields (EM) and electric current pulse [ECP] are applied to the solidifications of organization. Cui Jian-zhong [11] suggested that the magnetic fields can refine the microstructures and improves the surface quality. Ma Jianhong [12] offered some experimental evidence that the solidification structure can be refined and the proportion of equated area can be raised by the electric current pulse. So it is a good idea to explore the effect of the EM fields and ECP for the structures in TRC process.

MATERIALS AND METHODS

The 6181 aluminum alloys are composed by 97.1% Al, 1.2% Si, 1.0% Mg, 0.5% Fe and 0.2% Mn. The experimental procedure of TRC process without and with EPC field and EM field as shown as **Figure 1.** First of all, the 99.85wt% pure Al ingot and Al-Si alloys (Silicon accounted for the proportion of 20% in alloys) were let into resistance furnace that manually set up to 750°C.

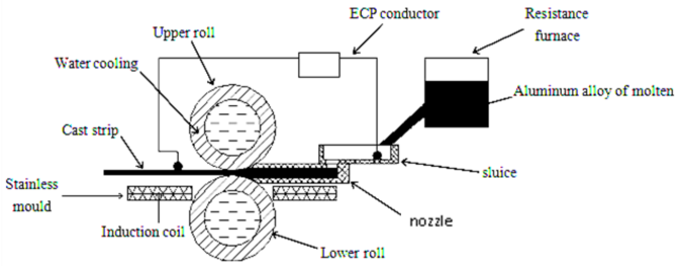


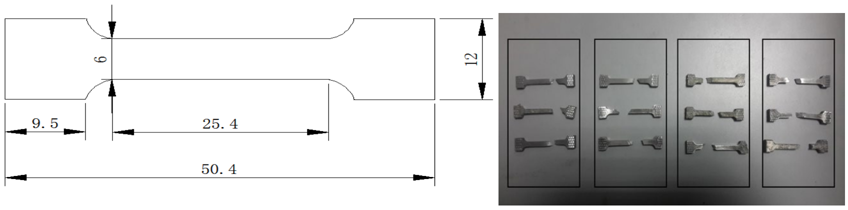
Figure 1. Schematic diagram of the TRC process with ECP and EM fields.

About 2 hours later, the Al and Al-Si alloys were melted into liquid. And then the furnace temperature was reduced to720°C; the 99.95% pure Mg blocks were added to the homogeneous melt and stirred until complete disappearing. And the furnace temperature was reduced once more to 690°C (It is the pouring temperature). 30 min later, the solution was slagged off and degassed. At the beginning of TRC experiments, the molten aluminum alloy was poured into the sluice and nozzle which were pre-heated to 400°C. At the same time, cooling water was passed through the twin rolls to reduce melt temperature, and the EPC and EM fields were added to the TRC process. The EPC parameters were optimized as follows: 20 Hz frequency and 400 I peak current. A static magnetic field with a nominal value of 0.02-0.25T was applying at cast-rolling areas. The velocity of experimental rolling is 0.7m $min^{-1.}$ The diameter of experimental rolling is 500mm.

Four sheets were manufactured under different forming conditions. The first sheet was formed by non-field TRC process, the second under ECP condition. The third sheet was manufactured under EM field's condition. The last one was produced under combination of ECP and static magnetic field condition.

Rectangular specimens of 20mm×10mm×5mm were cut out from the strips along the rolling direction. The surfaces of specimens were mechanical polished and coated film by 3.4ml HBF4 and 96.6ml H2O. The optical microscope (OM) was used to observe grain organization of specimen.

Multiple sample tensile testing was performed using a SHIMADZU AG-X100KN Material Testing Machine along the rolled direction at room temperature under constant deformation speed of 0.5 mm $min^{-1.}$ The dimension for the tensile specimen and specimens of fracture are shown in **Figure 2**. And the morphology of fracture was observed by a SSX-550 scanning electron microscope (SEM).



(a) (b)

Figure 2. Diagrammatic sketch of pinch force

RESULTS

The distribution of grains for 6181 aluminum alloys sheets is shown as **Figure 1.** In order to observe the changes of grains, the whole area is divided into Ⅴ parts. Ⅰ and Ⅴ corresponds with chilling area in the surfaces; Ⅱ and Ⅳ are the columnar crystals zone; Ⅲ is the equiax crystal zone at the centrality. The arrows point out the direction of solidification and pressure. The morphology of surfaces without the physical fields is typical broken grains, and they distribute along a 5° - 10° angle difference with horizontal direction. The length of slope with the ECP or EM field has a little increase. However, when the ECP and EM field are together applied to TRC process, the slope disappears nearly **(Figure 3)**. At the columnar crystals zone, the physical fields make the grain distribution more uniformity. Based on the fundamentals of solidification, the dendritic/cellular crystals grow coincident with solidification direction; but in the TRC process, the crystals are flattened by the pressure from two rolls. Moreover, under the action of physical fields, fat grains become gradually thin. And the quiax crystal zone is amplified and grain sizes are refined obviously with ECP and EM field. And effect of the composite fields is better than them alone for grain refinement.

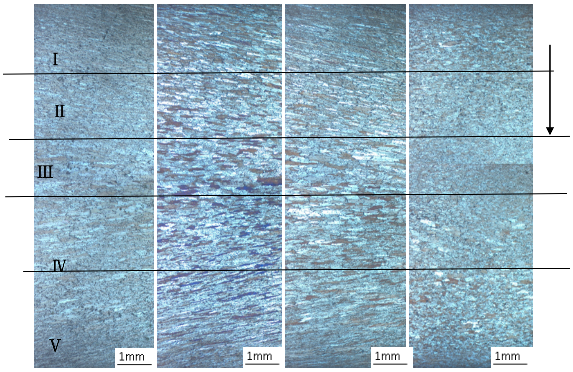


Figure 3. Microstructure of the strip obtained from TRC process. Micrograph (a) corresponds to the conventional TRC strip, and micrograph (b), (c) and (d) corresponds respectively to with ECP, EM and complex fields.

To visualize directly the influence of magnetic force for grains growth during TRC process, the distribution of magnetic induction intensity B and distribution of electromagnetic force F are simulated by the Ansoft Maxwell soft. **Figure 4** shows the distribution of magnetic induction intensity B from melt, mushy zone to solidity. According to right-hand screw rule, the B1 is generated by current in the magnetic fields, and their direction point out vertical up, and the numerical value is about 13.8 – 29.0 mT, which conforms to the actual measured value. The magnetic induction intensity B2 generated by ECP is alone the clockwise direction, and their values decrease gradually from external to internal. Due to the lesser values from ECP, therefore, when the ECP and EM field together act on TRC process, values of the magnetic induction intensity B3 change little compared with B1 from magnetic alone. But their direction occur incline to the -z axle. **Figure 5** indicates distribution of electromagnetic force F1, which is related with magnetic induction intensity B and current I. In the magnetic fields, the direction of electromagnetic force F is outward. The electromagnetic force F2 that is produced by ECP points out interior at the time. Here, it should be emphasize that the F2 is different with F1, with change of times, direction of F1 is almost constant, but direction of the F2 turns towards inside and outside alternate change. This means that electromagnetic force F3 has some change in the direction when ECP and EM field meet. And the F3 is greater than F1 and F2.

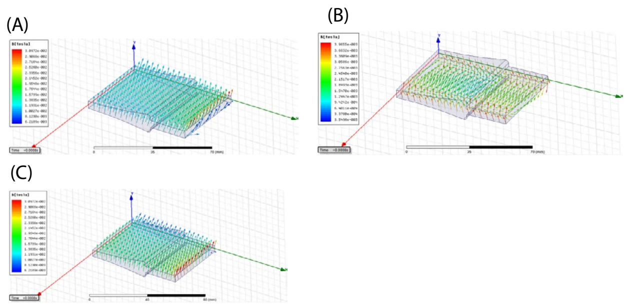


Figure 4. Distribution of magnetic induction intensity B from (a) EM field (b) ECP (c) complex fields

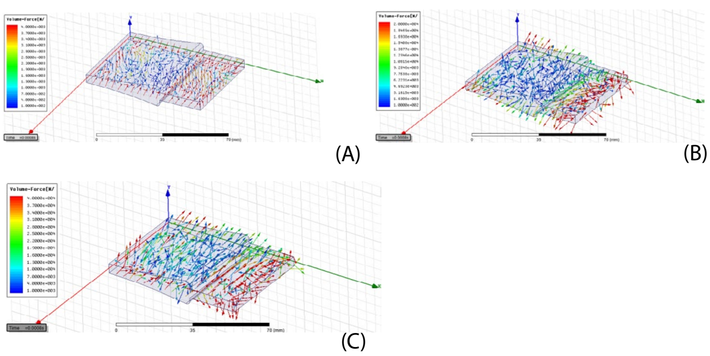


Figure 5. Distribution of electromagnetic force F produced by (a) EM field (b) ECP (c) complex field

In the presence and absence of the physical fields, the mechanical properties of 6181 aluminum alloys, including the ultimate tensile strength σb (UTS), yield strength $\sigma 0.2$ (YS) as well as the elongation, are shown in the **Figure 6a and 6b**. As observed in the **Figure 6a** the UTS under the physical fields are superior to one of materials prepared in the normal TRC process. And the composite fields are more effective than separate them. The YS change little. However, curve of the elongation that has been obtained from cracked samples are different from the rule of UTS and YS. The maximum elongation is from with magnetic field and reaches 10.9%.

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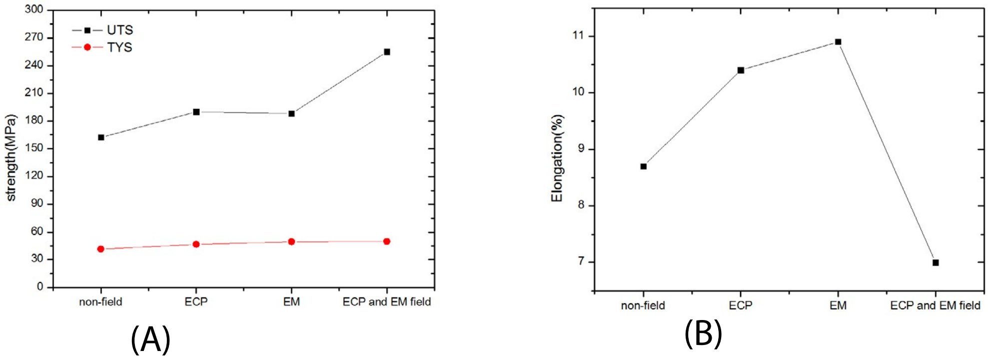

Figure 6. The variation trends of the elongation, UTS and TYS values of tensile specimens: (a) Elongation (b) UTS and TYS values

Figures 7a and d shows the fracture surface morphology of tensile sample in the longitudinal direction. All these specimens show the typical ductile fracture. The depth and sizes of **(Figure 7b and c)** dimple is greater than others. However, the fracture surface morphology of tensile sample with composite field is small and low.

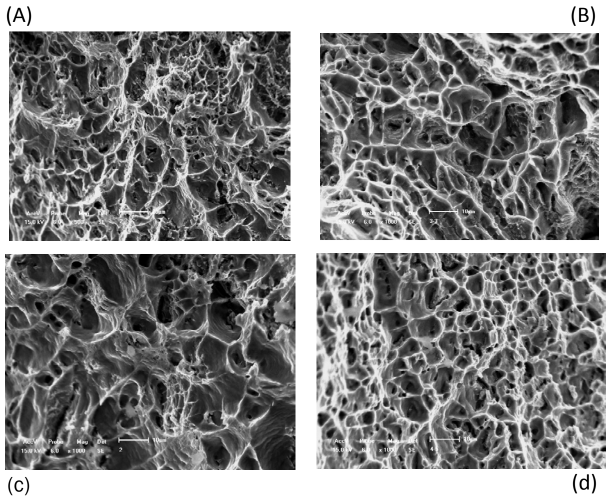

Figure 7. SEM micrographs of the fracture surface morphology: (a) the non-field sheets (b) ECP sheets (c)EM field sheets (d) complex field sheets

DISCUSSION

First of all the effect and mechanism of ECP on the grain refining should be discussion. The above experimental result **(Figure 3b)** shows that the application of ECP during TRC process can modify the morphology and sizes of grains. The result should be attributed to two reasons. One of the reasons is explained in the aluminum alloy melt stage.

A great deal of atom groups of short-range order and meeting and parting changing consist in metal melt. Gather of them depend on electrostatic effect [13]. When the ECP acts on the metal melt, the pinch force F2 is produced as **Figure 5b**. Under action of the force F2, the adjoining free atoms and small short-range order atom groups are possible to come into being great atom groups as shown as **Figure 8a**. When the great atom groups reach a particular size, the stable embryos will be taken shape, and they enhance nucleation probability [14]. When direction of the F2 points out outside, the instability atom groups are broken as free atoms as **Figure 8b**, but the rate of gather overtops the rate of dispersed The other one reason comes from solidification stage. According to Barnak the pinch force F2 can be expressed as the following formula [15].

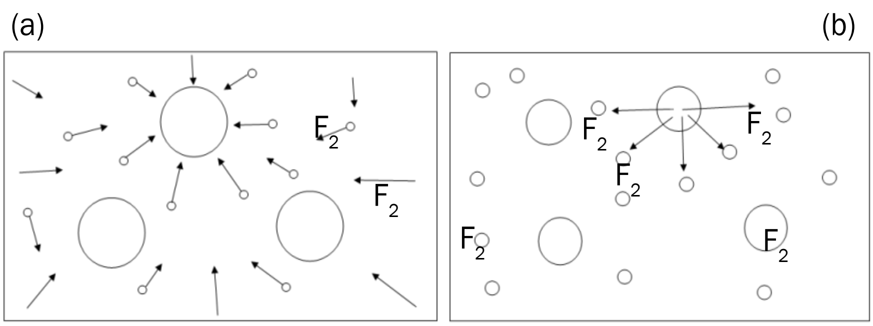

Figure 8. The dimension of the tensile specimen, and specimen of fracture

$$\sigma = \nu[\mu J^2 (r^2 - a^2)/4] \quad (1)$$

Where v is Poisson's ratio, μ the permeability, J the current density, r the specimen radius and a distance from an arbitrary point to centrality of sample. The maximum pinch force F2 can be only 1 KPa by their compute, which accord with the result of simulation. They are enough strong to stir the melt. The crystal nuclei formed in the surface of two rolls are brought to melt and become new nucleation points. Therefore, the grains are refined. Secondly, in the EM fields, the convection is the main reason to refine grains. The dendrite begins growth from surface of two rolls to the inside of melt. According to the magnetic force F1 as **Figure 5a**, their direction is perpendicular to direction of dendrite growth. When the melt is stirred by the F1, the strong convection is produced. The shearing force is formed under the convection acting on liquid - solid interface; when their strength exceeds resistance of dendrite arms, the dendrite arms can be broken. Fragments of dendrite arms are brought into the inside of melt as **Figure 9**. A part of fragments is remelted; the other part becomes neterogeny cores of equiax crystal.

The magnetic mechanism had been proved by a large number of researchers [16-19]. Moreover, the dendrite growth and break with magnetic field are further observed and certified by experiments [20]. However, when the ECP and EM fields are together added to the TRC process, the ECP and EM fields arises reaction, and the magnetic force F3 are generated, which can be expressed as following formula

F=J*B

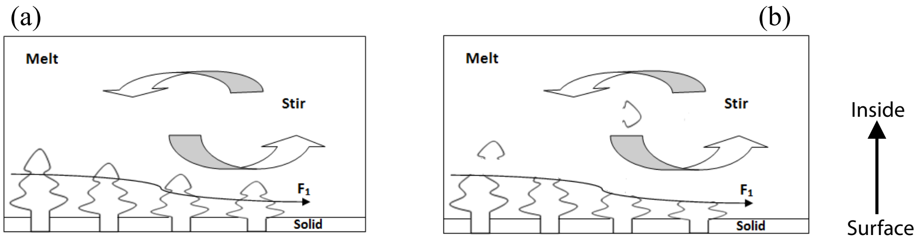

Figure 9. Diagrammatic sketch of dendrites break and melt stirring

Where B is magnetic induction intensity and J is the current density. The melt and liquid - solid interface suffer not only F1 and F2 but also F3. Besides, the value of F3 exceeds F1 and F2, and the shake of convection is more violent. Therefore, the rate of nucleation is increased. Grains are refined and equiaxed. As is well known, the tensile strength increases with the decrease of grain size [21]. Gao [22] indicated that the refinement of grains could suppress deformation by twinning and sliding. Obviously, for comparison these UTS and YS values, it is contrary to the sizes of grains.

CONCLUISON

The influence of electric current pulse and magnetic field for grain refining and distribution of 6181 aluminum alloys during two-roll casting was investigated. The experimental results show that application of composite fields (ECP and EM field) during TRC process refines the microstructures of sheets more evenly and effectively by comparison with individual application of ECP or EM field. Distribution and amplitude of the magnetic induction intensity B and electromagnetic force F were numerically simulated. The results reveal that melt and liquid- solid interface suffer more force from composite fields than individual one. And the tensile strength was enhanced when physical fields were applied to TRC process. However, effect of EM field for elongation is best and the value reaches 10.9%.

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