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A New Approach to Producing AA7055 Aluminum Alloy Slab Ingots

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Low frequency electromagnetic casting (LFEC) process is used to produce AA7055 aluminum alloys in this research. Moreover, the effects of low frequency electromagnetic field on the macro-physical fields (flow field, temperature field and stress-strain field) during the semi-continuous casting process of aluminum alloys and the microstructure and crack in the ingots are studied and analyzed in detail by the numerical and experimental methods. Comparison of the results for the macro-physical fields in the LFEC process with that in the conventional DC casting process indicate the following characters due to the application of electromagnetic field: a vigorous forced convection of the melt; an entirely changed direction of melt flow; a remarkably increased velocity of melt flow; a uniform distribution of temperature; a decreased gradient of temperature; the elevated isothermal lines; the reduced sump depth; the decreased stress and plastic deformation. Further, the microstructure of the ingot is refined remarkably and the crack in the ingots is eliminated in LFEC process because of modification of the macro-physical fields induced by the application of low frequency electromagnetic field.

Keywords: *AA7055 aluminum alloy, low frequency electromagnetic field, DC casting, macro-physical field.*

1. Introduction

Superhigh strength aluminum alloys are important materials to the aerospace industries, because of their low density, high strength, and good hot work ability. Demand in the aerospace industry for higher strength, higher toughness, and high corrosion resistance motivates continuing research on these alloys [1,2]. AA7055 aluminum alloy is a major candidate for such applications. Although the properties of AA7055 aluminum alloys are clearly attractive, the processing of the alloy is difficult because of its high alloying element content, and the processing details of the alloy are unavailable in these literatures, especially for DC casting process. In general, increased alloying element content makes it more difficult to cast the alloy because the crack susceptibility is also increased remarkably. In particular, when the Zinc content in the aluminum alloy is more than 8%, it is very difficult to obtain ingots without crack defects by the conventional method. Therefore, in order to obtain the ingots without crack defects, some special methods are used, such as spray forming process and LFEC, etc. LFEC process is the attracted among these methods because this process is based on the conventional DC casting. LFEC was developed by Cui and his colleagues [3,4], and low frequency electromagnetic field is used to control the macro-physical fields in the casting process. In this research, Low frequency electromagnetic casting process is used to produce AA7055 aluminum alloys and the macro-physical fields, the crack occurring in casting process and the microstructure of ingots are studied by the numerical and experimental methods.

2. Numerical modeling and experiment

2.1 Numerical modeling

In the paper, a coupled model is used to describe the interaction of the multiple macro-physical fields-electromagnetic field, fluid flow, temperature field, solidification and stress-strain field in the conventional DC casting and LFEC processes of the ingots of 200mm by 600mm in cross-section and the casting process parameters are listed in Table 1. Moreover, this detailed model can be found in reference [5,6].

Table 1. Casting process parameters in the DC casting and the LFEC processes

	Casting temperature	Casting speed	Water flow rate	Electromagnetic frequency	Electromagnetic intensity
DC	1003 K	65 mm/min	70 l/min	None	None
LFEC	1003 K	65mm/min	70 l/min	20 Hz	12000 At

In order to model the interaction of the multiple physical fields in the two processes, the model used in this paper is implemented by the commercial software package Ansys and Fluent. Further, this modeling procedure of DC casting and LFEC processes is: firstly, the electromagnetic field is calculated by Ansys and the Lorentz force is obtained simultaneously; then, the Lorentz is added to the conservation equation of momentum as the momentum source term during solving flow field which is coupled with temperature field and solidification and these physical filed are calculated by Fluent; lastly, the calculated temperature is inputted into Ansys to calculate the stress-strain field which is carried by Ansys.

2.2 Experiments

Two AA7055 aluminum alloy ingots with cross-section of 200mm by 600mm were cast by LFEC process and conventional DC casting process at melt temperature 1003K, and casting speed 65mm/min, respectively. The electromagnetic field was applied by an 80 turns water-cooling copper coil surrounding the mold made of aluminum alloy. The current frequency in the coil is fixed at 20 Hz and the current intensity is 150A in the LFEC process.

3. Results and discussion

3.1 The effect of electromagnetic field on fluid flow and heat transfer

The method of two-distributors is used in the paper. There are two outlets in every distributor and two outlets are different in size. One (referred as A outlet) is larger and faces to the center of ingot, the other (referred as B outlet) is smaller and face to the end face of ingot. Moreover, the area ratio of the outlets is 3 to 2. Fig. 1 (a) and (b) show the melt flow in DC casting and LFEC process, respectively. As seen from this figure, it is found that the direction and magnitude of the melt flow is modified entirely because the present of electromagnetic field. With regard to the conventional DC casting, as observed in Fig. 1(a), the melt from A outlet is led to the end face and return to A outlet through the solidification front, which results in the formation of the big circle parallel to the rolling face. At the same time, it generates another circle in free surface. Moreover, the melt from B outlet also generates a circle parallel to the rolling face and contrary to the circle induced by the melt flow from A outlet. By comparison with DC casting process, the flow velocity in the melt pool increases remarkably in LFEC process, as shown in Fig. 1(b). The melt from A outlet in LFEC process generates two circle too. Moreover, their direction is same as that in DC casting process but the intensity increases greatly as compared with DC casting process. The melt from B outlet bypasses the distributor directly and blend into the circle induced by the melt flow from A outlet. To sum up, the great changes in the melt flow in the present with electromagnetic field are explained by the forced convection resulted from the rotational component of the electromagnetic force.

Fig. 2 (c) and (d) shows the temperature profiles in the melt pool and ingot in DC casting and LFEC process, respectively. As seen from the temperature profiles in Fig. 1 (c) and (d), the distribution of the temperature field has been markedly modified. Firstly, it is observed that the temperature contours in the right part are shifted upwards relative to the left part, which must result in the sump shape being modified and the sump depth being reduced. In addition, compared to that in the absence of the electromagnetic field, the temperature in the bulk liquid is lower and more uniform in the presence of the electromagnetic field. The reason for the great modification of the temperature field is the vigorous forced convection induced by the electromagnetic stirring and that the heat flux along the longitudinal direction is increased due to the vigorous forced convection in the solidification front. In addition, the heat transfer manner in the melt pool is mainly the conductive and convective heat transfer due to the vigorous forced convection induced by the electromagnetic stirring, therefore, the uniform temperature distribution within the sump is seen in Fig. 1 (d).

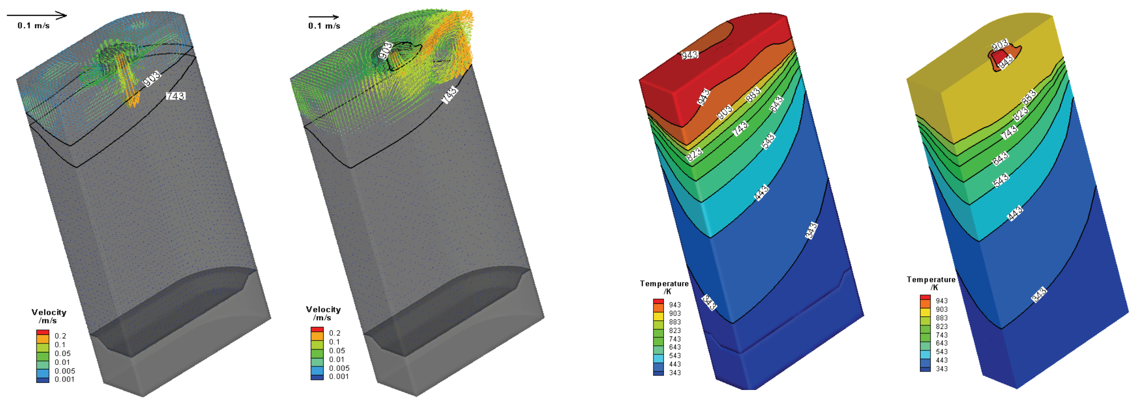


Fig. 1 Velocity vectors and temperature profile during DC casting (a)(c) and LFEC (b)(d) process.

3.2 The effect of electromagnetic field on stress-strain field

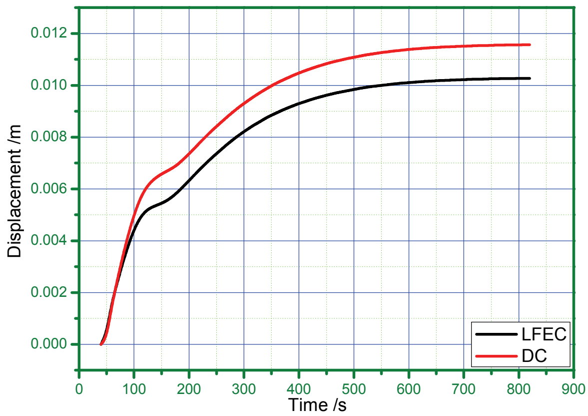
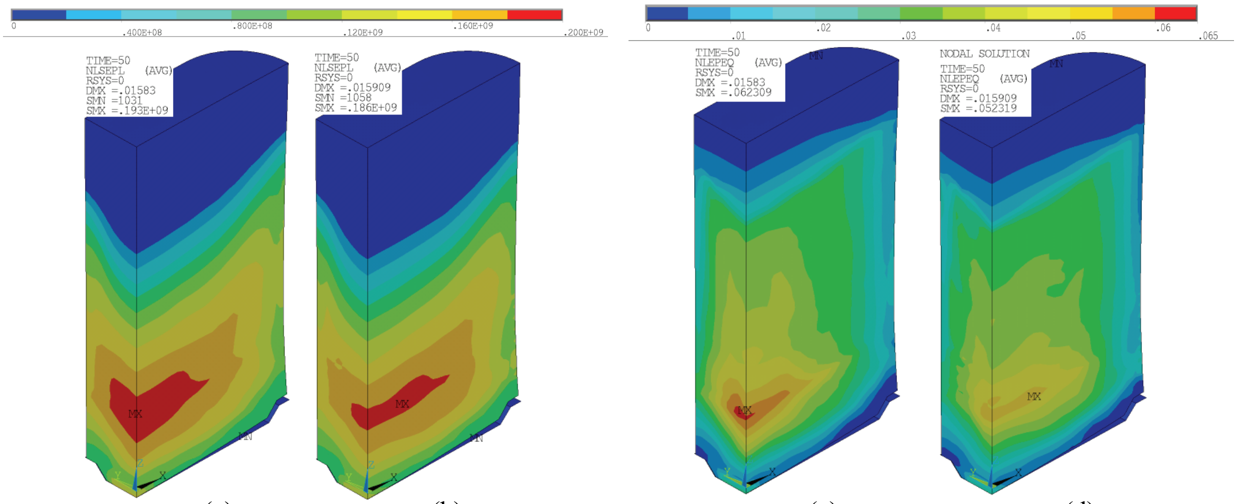


Fig. 2 the variation of butt curl with time.

Fig. 2 shows the variation of butt curl with time in DC casting and LFEC process, respectively. In general, the formation of butt curl is explain as the torque moment resulting from the contract force at the spray point of second cooling water based on the center of ingot as the support point[7]. The calculated value of butt curl for DC casting and LFEC process are 11.8mm and 10.2mm, and the experimental value are 12.4mm and 10.5mm. Moreover, there is a good agreement between them. From this figure it is found that butt curl grows fast at first and then slowly reaches a constant value. In rapid growing period, torque moment is strong enough to cause a butt curl motion at fast rate. Moreover, in saturated period butt curl is suppressed by hardening of withdrawn large bottom shell. In addition, from seen in the figure, it is found that the butt curl generated in LFEC process is smaller than that in DC casting process because of the thicker and stronger bottom shell caused by the increased heat transfer between the ingot and the bottom block in the present of electromagnetic field.

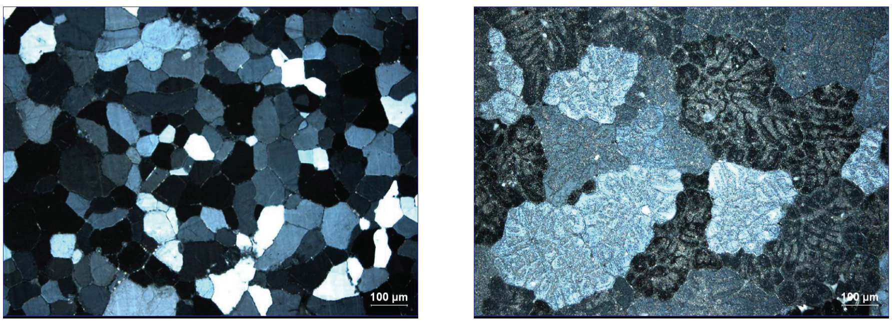
Fig.3 shows the stress and strain profiles in the ingots in DC casting and LFEC processes, respectively. It is found that the stress and strain generated in DC casting process is bigger than that in LFEC process, which results from the temperature field modified by applying electromagnetic field. Further, when electromagnetic field is applied in casting process, the temperature contours shifted upwards and the temperature difference is induced, which results in the cast stress and plastic strain reducing remarkably in the casting process.



(a) (b) (c) (d)

Fig. 3 Equivalent plastic stress and strain profile in the ingots in DC casting (a)(c) and LFEC (b)(d) processes.

3.3 The effect of electromagnetic field on microstructure



(a) (b)

Fig.4 Microstructure of LFEC (a) and DC (b) ingots;

Fig.4 (a) and (b) show the microstructure of the ingots cast in the conventional DC casting and LFEC processes, respectively. It is observed from this figure that the microstructure of the ingots cast in the conventional DC casting process is usually coarse dendritic structure in the absence of the master alloy, but that in the LFEC process is very fine equiaxed grain structure. From the present investigation, the reasons of generating the fine equiaxed grain structure are as follows:

As shown in Fig. 1 (d), the temperature in the sump pool is very uniform and is lower than the liquidus temperature in the presence of electromagnetic field, which must result in the high undercooling and low temperature gradient. As seen from the temperature profile in Fig. 1 (d), the whole melt within the sump keeps the large undercooling state, which must increase the nucleation rate and number. Therefore, such uniform temperature field generated by the electromagnetic stirring is one of the main reasons for obtaining the fine equiaxed structure of the ingot cast in the LFEC process.

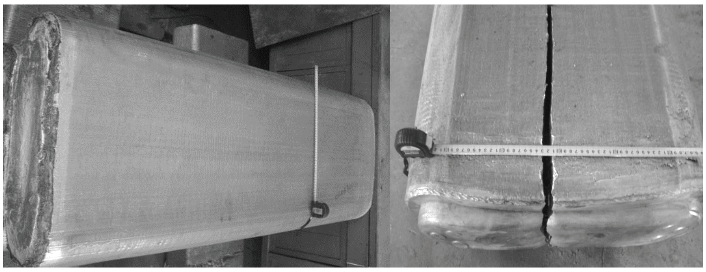
As given in Fig. 1 (b), due to the vigorous forced convection caused by the electromagnetic stirring, the dendrite fragments are detached from the solidification front, the mold and the free surface of the melt. The causes of the dendrite detachment include as: dendrite arm fracture due to shearing action, dissolution of dendrite arms and the separated grain from the mold and the free surface of the melt. When these fragments are detached into the sump and move within the sump with the melt flow, each of them will all become a crystal nucleus. It is reason for such phenomenon that these fragments will survive and not be remelt due to the melt as the large undercooling state and the low thermal gradient when they move freely in the melt pool, and then they are captured by the high viscous melt or the dendritic net at the solidification front and form a new nuclei when they sedimentate at the solidification front, which can not be observed in the conventional DC casing process. Therefore, the vigorous forced convection induced by the electromagnetic field can promote the formation of the fine equiaxed grain structure of the ingot.

3.4 The effect of electromagnetic field on crack

The photograph of DC and LFEC ingots are shown in Fig5. it is found that the crack is formed in DC casting process, however, the ingot without the crack defects is obtained in LFEC process. In order to study the crack occurring, the numerical method is used in this paper. Firstly, a criterion for crack occurring must be built. In this paper, a cracking damage index (CDI) and is as followed:

$$CDI = \varepsilon_\theta / \varepsilon_f$$

Where ε_θ and ε_f are the equivalent plastic strain and fracture strain at the different temperature, respectively. The crack can occur when CDI more than 1. Contrariwise, the crack can not occur.



(a) (b)
Fig.5 Photograph of LFEC (a) and DC (b) ingots

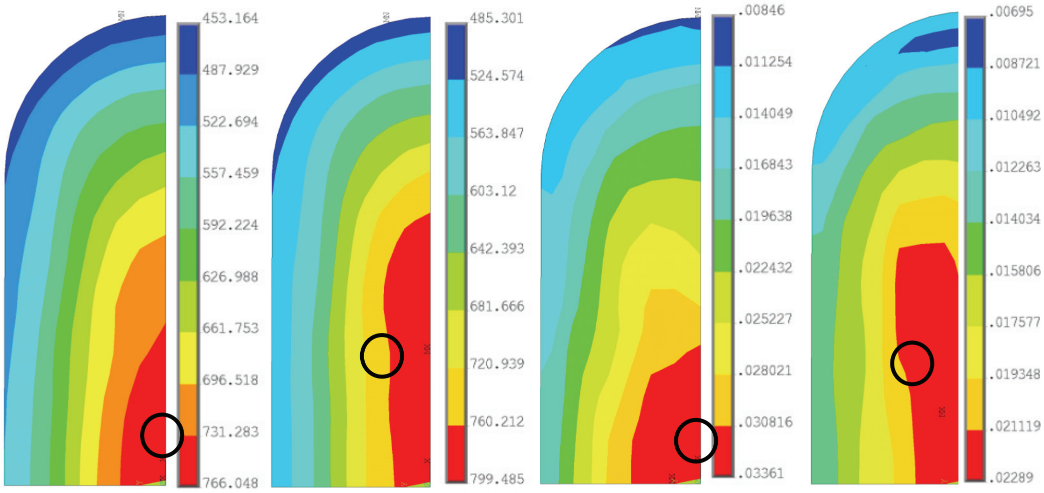
The coordinate, temperature and equivalent plastic strain at the time and location, when and where the maximum CDI (*MCDI*) generate in DC casting and LFEC processes, is listed in table.2. Moreover, this time and location are called as the dangerous time and node, respectively.

Table. 2 Calculated results of MCDI

process	time	node	coordinate	temperature	Equivalent plastic strain	MCDI
DC	210s	12324	(0.0429, 0.0162, 0.15)	749.105K	0.0303	1.23967
LFEC	210s	13104	(0.0857, 0.0311, 0.15)	748.500K	0.022	0.90909

It is found in this table that the crack occurs in DC casting process and it does not in LFEC process based on the criterion used above. Further, the reasons why applying the electromagnetic field can retrain the crack occurring are as follows:

Fig.6 shows the equivalent plastic strain and temperature profile on the cross-section including the dangerous node at the dangerous time in DC casting and LFEC processes. It is observed in the fig.6 (c) and (d) that the dangerous node move toward the end face of the ingot because of applying the electromagnetic field. In addition, the maximum equivalent plastic strain (0.0303) in DC casting process is so bigger than that (0.022) in LFEC process because the temperature difference between the inner and outer of ingot, which is because of the elevated isothermal line in the center of ingot induced by applying electromagnetic field. As shown in fig.5 (a) and (b), the temperature difference between the inner and outer of ingot are 296.105K and 263.5K, respectively. Therefore, applying electromagnetic field in the casting process can reduce the casting stress and the driver force for the crack occurring remarkably.



(a) (b) (c) (d)

Fig. 6 Calculated results on the cross-sections including the dangerous position; (a)temperature profile, (c) equivalent plastic strain during DC process, (b)temperature profile, and (d) equivalent plastic strain during LFEC process.

4. Conclusion

In this research, a new approach – Low Frequency Electromagnetic Casting is used to produce AA7055 aluminum alloy. Comparison of the results for the macro-physical fields in LFEC process with that in the conventional DC casting process indicate the following characters due to the application of electromagnetic field: a vigorous forced convection of the melt; an entirely changed direction of melt flow; a remarkably increased velocity of melt flow; a uniform distribution of temperature; a decreased gradient of temperature; the elevated isothermal lines; the reduced sump depth; the decreased stress and plastic deformation. Further, the microstructure of the ingots is refined remarkably and the crack in the ingots is eliminated in LFEC process because of modification of the macro-physical fields induced by the application of low frequency electromagnetic field. Therefore, LFEC process is an effective approach for producing AA7055 aluminum alloy.

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