Light Metals 2012 *Edited by: Carlos E. Suarez*
TMS (The Minerals, Metals & Materials Society), 2012

A New Approach to Producing Large-Size AA7055 Aluminum Alloy Ingots

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

Abstract

In this paper, Low frequency electromagnetic field and air knife are applied simultaneously to produce large-size AA 7055 aluminum alloy ingots during DC casting. Moreover, the effects of low frequency electromagnetic field and air knife on the macro-physical fields during DC casting and the microstructure and crack in the ingots are studied and analyzed by the numerical and experimental methods. Comparison of the calculated results indicate that applying electromagnetic field can modify the direction and increase the velocity of melt flow and homogenize the distribution of temperature in the sump, and applying air knife can homogenize the distribution of temperature and decrease the stress and strain in the solidificated ingots. Further, the microstructure of the billet is refined remarkably and the crack is eliminated by applying electromagnetic field and air knife during DC casting because of modification of the macro-physical fields.

Introduction

AA7055 aluminum Alloys are targeted for the replacement of 7075-T6511 and 7178-T6511 alloy tempers, respectively, as well as other applications that require high tensile and compressive strengths and need excellent exfoliation corrosion and SCC resistance, such as upper wing structures, keel beams and longerons. Other applications include seat tracks, cargo tracks, fuselage frames and fuselage stringers[1,2]. But it is difficult for some aluminum plants to obtain ingots with high quality. The quality of ingots are determined by macro- and micro-structure, macro- and micro- segregation, macro- and micro- defects, such as hot tearing, cold crack and porosity. Moreover, the factors are controlled by the physical fields during solidification and then cooling procedure. Therefore, the ingots with high quality are obtained by controlling physical fields during solidification and then cooling procedure.

Cui and his colleagues [3-5] applied low frequency electromagnetic field to control melt flow, heat transfer and solidification procedure during DC casting of aluminum alloys. Results show that macro- and micro-structure is modified remarkable and macro- and micro- defects are reduced. Literatures [6,7] proposed to remove the water from the ingot surface at a point below that of initial impingement by means of wiper ring, which results in reducing or delaying the chilling action of water and then alleviates the crack problem. However, the electromagnetic field can only control the solidification procedure and the wiper ring can only control the cooling procedure of solidificated ingots. Therefore, electromagnetic field and wiper ring are used to control the physical fields during solidification and then cooling procedure in this paper.

Generally, the wiper ring comprises a sheet of rubber, so the high quality surface is demanded when this kind of wiper ring. If the ingot surface is bad, wiper ring can not contact tightly with the ingot and the cooling water can leak between them, which results in forming the crack easily during the casting process. In this paper, a type of non-contact wiper ring, air knife, is used and it utilizes compressed air to remove the water. Moreover, the air knife is not effected by the ingot surface quality and can remove the cooling water fully. Therefore, electromagnet-air knife DC casting process is used to produce AA7055 aluminum alloys and the macro-physical fields, the crack and the microstructure of ingots are studied by the numerical and experimental methods.

Numerical modeling and experiment

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 DC casting process of the ingots of 360mm by 1000mm in cross-section. Moreover, this detailed model can be found in reference [8,9].

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 process 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.

Experiments

Four AA7055 aluminum alloy ingots with cross-section of 360mm by 1000mm were cast by DC casting (DC), air knife DC casting (A-DC), electromagnetic DC casting (EM-DC) and electromagnet-air knife DC casting (EMA-DC) processes at melt temperature 1003K, and casting speed 55mm/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 EM-DC casting and EMA-DC casting process. The air knife is at 200mm below that of initial impingement.

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.

Results and discussion

The effects of electromagnetic field on microstructure

Fig.1 show the microstructure of the ingots cast in the conventional DC casting, A-DC casting, EM-DC casting and EMA-DC casting processes, respectively. By comparison Fig.1 (a)(b) and (c)(d), it is found that the microstructure of the ingots cast in the conventional DC casting and A-DC casting processes is usually coarse dendritic structure in the absence of the master alloy, but that in the EM-DC casting and EMA-DC casting processes is very fine equiaxed grain structure. From the present investigation, the reasons of generating the fine equiaxed grain structure are the modification of the macro-physical fields during the casting process, which results from applying electromagnetic field.

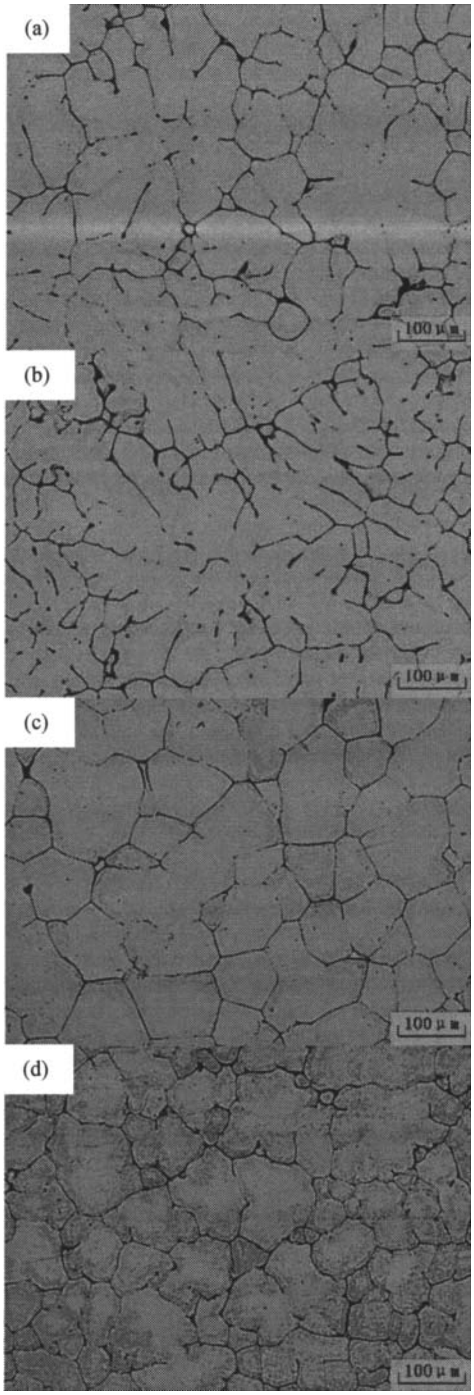
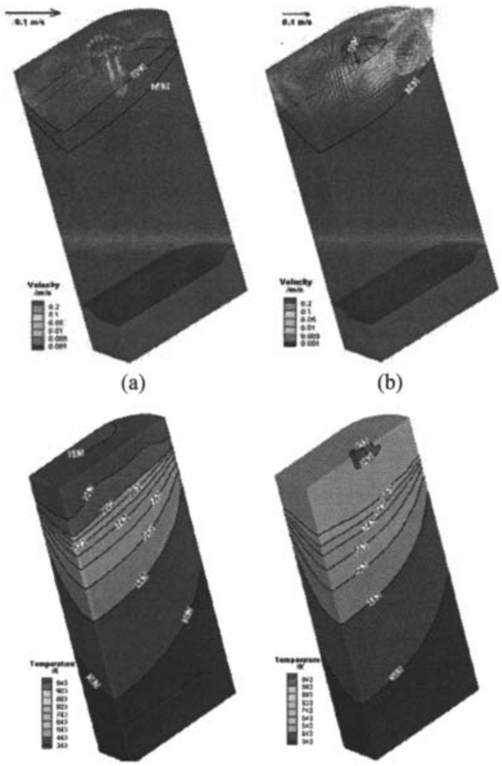


Fig. 1 Microstructure of ingots
(a) DC, (b) A-DC, (c) EM_DC and (d) EMA-DC

Fig. 2 (a) and (b) show the melt flow in DC casting and EM-DC casting processes, 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 EM-DC casting process, as shown in Fig. 2(b). The melt from A outlet in EM-DC casting 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. Therefore, 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.

Fig. 2 (c) and (d) shows the temperature profiles in the melt pool and ingot in DC casting and EM-DC casting process, respectively. As seen from the temperature profiles in Fig. 2 (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. 2 (d).

Moreover, 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. 2 (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 EM-DC casting process.



(a) (b)

(c) (d)

Fig. 2 Velocity vectors and temperature profile during DC casting (a)(c) and EM-DC casting (b)(d) process.

The effects of air knife on microstructure

By comparison Fig.1 (a)(c) and (b)(d), it is found that the microstructure of the ingots cast in the A-DC casting and EMA-DC casting processes is coarser and possess more apparent dendritic structure than that in the conventional DC casting and EM-DC casting processes which results from decrease of cooling rate and solidification rate after applying the air knife.

Fig. 3 shows the sump profiles in the DC casting, EM-DC casting, A-DC casting and EMA-DC casting processes. From this figure, it is found that the sump depth increases remarkably after applying the air knife, particularly in the A-DC casting process, because the ingots aren't cooled by the cooling water below the air knife which results from the cooling water being removed by the air knife. The increase of the sump and the weak cooling leads to the decrease of solidification rate, which results in the grain having enough time to grow up. With regard to the A-DC casting process, the sump root is below the air knife and the cooling is much weaker, so the microstructure is much coarser and the dendritic structure is much more apparent, as shown in Fig. 1 (a).

However, it is observed from Fig.1 (c) and (d) that the effects of the air knife on the coarsening of the microstructure and the dendritic structure is not obvious after applying electromagnetic field. Its reasons are as follows: increasing the number of nucleation is the main reason why the electromagnetic field leas to refining the microstructure and generating equiaxed structure. When applying the air knife, the melt flow and temperature field in the melt pool is not modified, as shown in Fig. 4, so the number of nucleation in EMA-DC casting is the same as that in EM-DC casting process, but the increase of the sump depth results in the grain having enough time to grow up. However, the number of nucleation is so enormous, which results in the gain having not enough space to grow up. Therefore, effects of the air knife on the coarsening of the microstructure and the dendritic structure is not obvious after applying electromagnetic field.

To sum up, applying electromagnetic field during DC casting can refine the grain effectively and promote the formation of equiaxed grain. Applying air knife can coarsen the grain and promote the formation of dendritic structure, but the electromagnetic field weakens remarkably the role of the air knife.

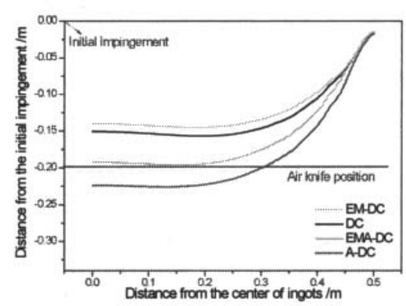


Fig. 3 Sump profiles

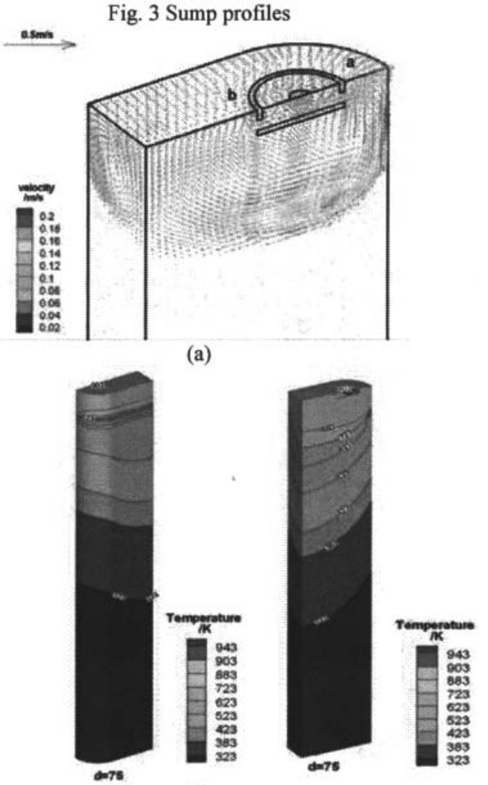


Fig. 4 Velocity vectors (a) and temperature profile (b) during EMA-DC casting process

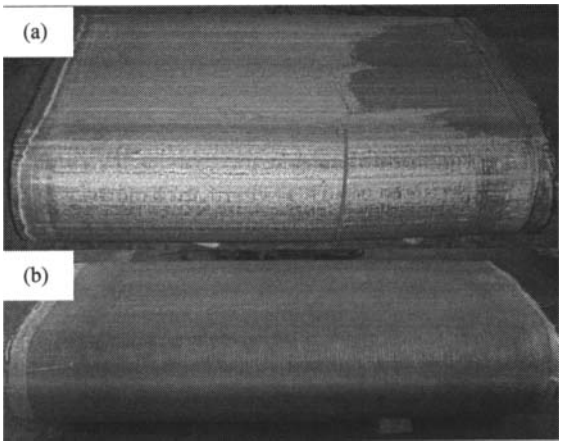


Fig.5 Photograph of LFEC (a) and DC (b) ingots

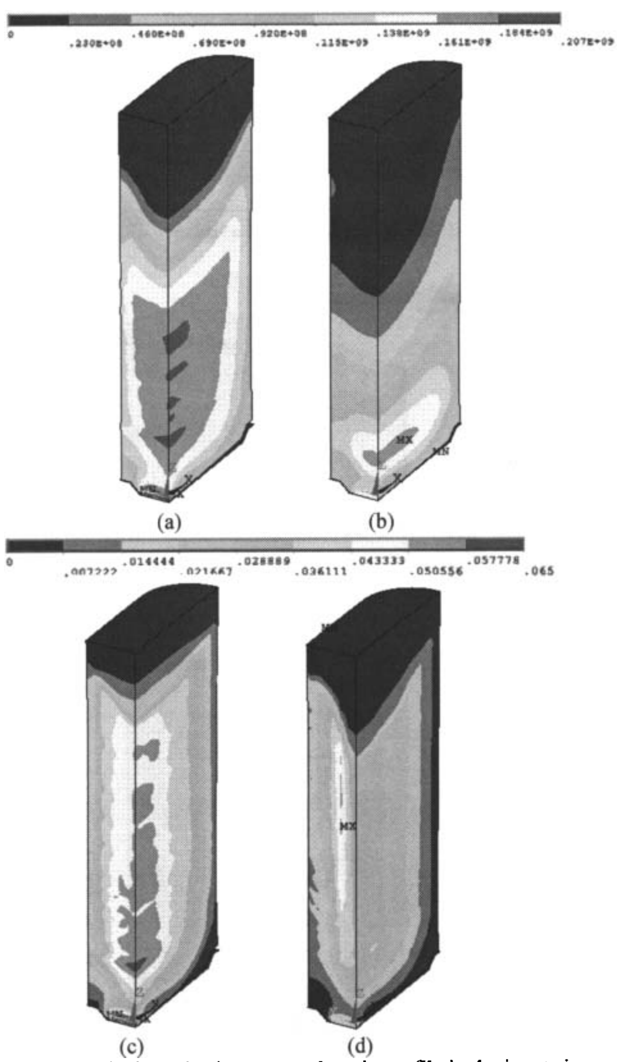
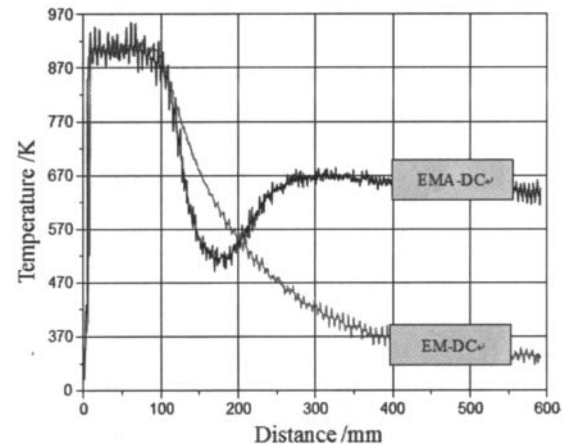


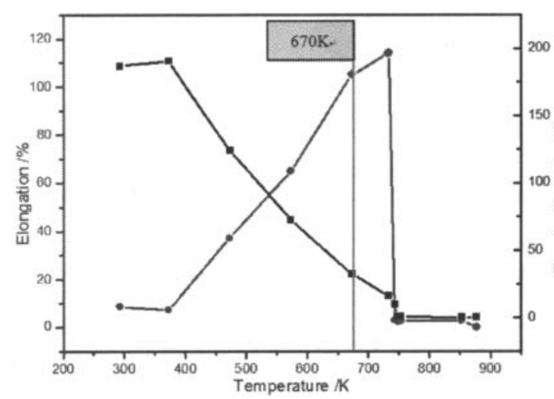
Fig. 6 Equivalent plastic stress and strain profile in the ingots in EM-DC casting (a)(c) and EMA-DC casting (b)(d) processes.

The effects of air knife on cold crack

As we know, a difficult problem for producing 7055 aluminum alloy ingots is cold crack and cold crack is very dangerous, particularly for the large-size ingots. Because cold crack occurs under the nonequilibrium solidus temperature, and the electromagnetic field take effect in liquid and semi-solid zone, therefore, the electromagnetic field has no help for restraining occurrence of cold crack. Fig. 5 shows the photograph of EM-DC and EMA-DC ingots. It is found that the crack is formed in EM-DC casting process, however, the ingot without the crack defects is obtained in EMA-DC casting process.



(a)



(b)

Fig. 7 The cooling curves on the ingot surface (a) and the tensile strength and elongation at the various temperature (b)

It is obvious from Fig. 5 that the cold crack can be effectively retrained by applying air knife because of two reasons, which is as follows:

a. The decrease of the stress and strain in the ingot.

Fig.6 shows the stress and strain profiles in the ingots in EM-DC casting and EMA-DC casting processes, respectively. It is found that the stress and strain generated in EM-DC casting process is bigger than that in EMA-DC process, which results from the temperature field modified by applying the air knife. By comparing Fig. 2 (d) and Fig. 4 (b), it is found that the temperature of ingot surface is increased and the temperature gradient along the casting direct and perpendicular to the casting direct is decreased after applying the air knife. As a result, the main reason of the decrease of stress and strain after applying the air knife is the decrease of temperature gradient along and perpendicular to the casting direct. Therefore, applying the air knife during the DC casting can reduce the stress and strain and then decrease the driver force for the crack occurring remarkable.

b. The plastic deformation of the ingot at the reheat temperature. In general, the cold crack occurs on the surface of ingots. Therefore, the reheated surface temperature after applying the air knife is important. Fig. 7 (a) shows the measured value of cooling curve on the ingot surface during the EM-DC casting and EMA-DC casting processes.it is found that the surface temperature after applying the air knife is reheated to about 670K. Moreover, Fig. 7 (b) shows the tensile strength and elongation of AA7055 aluminum alloy at the various temperature.it is observed from this figure that the elongation of this alloy is 100% and then it possesses the good plasticity at 670K. Therefore, the cold crack is retrained because the ingots generate the plastic deformation by the casting stress.

To sum up, applying the air knife can restrain the occurrences of cold crack effectively because the stress and strain in the ingots decreases and the plastic deformation occurs at the reheat surface temperature.

Conclusion

In this research, a new approach, Electromagnet-air knife DC Casting is used to produce large-size AA7055 aluminum alloy ingots and the macro-physical fields, the crack and the microstructure of ingots are studied by the numerical and experimental methods. The following conclusions are obtained:

1. Applying electromagnetic field during DC casting can refine the grain effectively and promote the formation of equiaxed grain. Applying air knife can coarsen the grain and promote the formation of dendritic structure, but the electromagnetic field weakens remarkably the role of the air knife.
2. Applying the air knife can restrain the occurrences of cold crack effectively because the stress and strain in the ingots decreases and the plastic deformation occurs at the reheat surface temperature.
3. The ElectroMagnet-Air knife DC casting (EMA-DC) process is an effective approach for producing large-size AA7055 aluminum alloy ingots.

Acknowledge

This study was supported by the national "973" foundation of china (grant number: 2005CB623707). The authors are grateful to Dr.Xiangjie Wang and Qingfeng Zu for their help in the experiment.

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