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Evaluation of Effects of Stirring in a Melting Furnace for Aluminum

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Abstract

A new type of permanent magnet stirrer was installeted in an existing furnace and the effect of magnetic stirring on molten alloys was examined.

The end goal is to improve the quality of aluminum alloys through bath temperature homogenization, and to reduce energy usage and dross generation while providing a reduction in melt loss. Traditionally, molten aluminum has been mechanically or electromagnetically stirred; however the former is inefficient and dangerous while the latter requires excessive energy and complicated components. Using a permanent magnet stirrer, the temperature homogenization of the molten Al alloy was achieved safely and efficiently.

This report also discusses thoughts on more effective shapes of furnaces, compared to ordinary furnaces.

Purpose

This research report will examine the effects of stirring molten aluminum alloy by use of a permanent magnet based stirring technology. Using a permanent magnet stirrer solves problems associated with stirring mechanically. Some of these problems include maintenance, downtime and safety issues due to replacement and repair in a high temperature environment. There is also an electromagnetic method for stirring molten aluminum; however there are heavy energy consumption requirements as well as a supporting infrastructure and systems necessary to operate the stirrer. These issues have cost considerations as well as maintenance and other related complications. Permanent magnets, not requiring energy to generate a magnetic field, water for cooling nor other components not directly related to stirring, avoids these problems. Since a permanent magnet stirrer can be configured in various ways, there are implications on future furnaces that can be designed in order to fully maximize the benefits of this technology. This topic will also be discussed.

Method

Permanent magnets were set beside and beneath an existing furnace. The technology used for the purposes of this test was a Tsunami Series III™ permanent magnet stirrer from Zmag Japan, Ltd. The shape of the furnace was 1,500 by 1,500 mm, and the height of the molten aluminum was 500 mm. Aluminum alloy (AD4C) was melted by a burner attached to the furnace roof; the molten alloy was simultaneously stirred by rotating those magnets. The furnace was regulated to keep the temperature at a certain level, 740℃, in the furnace. When the temperature was less than 740℃, the burner fired, and when the temperature exceeded 740℃, the burner stopped.

The following tests were conducted:

- Temperature was measured at 21 points in the molten aluminum bath for evaluation of temperature homogeneity. The 21 points consisted of 7 locations, at 3 depths for each location. The depths were 25mm, 250mm (center), and 475mm from the bottom of the furnace. The temperature was measured and compared at each point both with and without rotating magnetic fields. In addition, the amount of gas consumption to keep the temperature constant was also measured.
- Samples were taken from various parts of the furnace and their chemical compositioins were then analyzed using ICP (Inductively Coupled Plasma), both with and without rotating magnetic fields.
- Content of hydrogen on the samples was measured by Gravi-Mass, an outgas measurement device, at NIKKIN FLUX INC.
- Mechanical properties of the cast samples (consisting of aluminum stirred by magnetic fields) were compared to the original ingot (prepared by conventional, non-stirring, means).

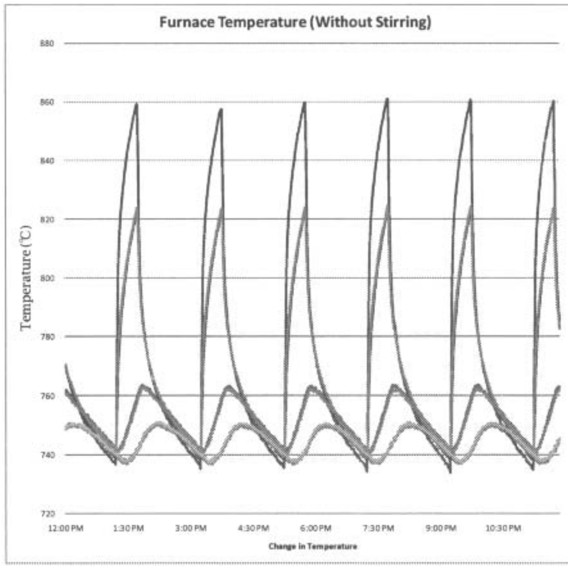

Figure 1

Result

1) Result of Stirring

(1) Temperature of molten aluminum alloy

Figure 1 indicates changes in temperature at each measuring point in the furnace where the temperature was kept at 740 ℃ for 12 hours without stirring by magnetic fields. When the temperature dropped under 740℃, the burner started, followed by a rise in temperature at each measuring point. A rise in temperature was highest at the upper layer of molten aluminum alloy, and the temperature lowered as the measuring point descended to the furnace bottom. When the temperature rose to 740℃, the burner stopped, followed by a fall in temperature in the molten aluminum. When the temperature dropped under 740℃, the burner started again. This cycle was repeated to keep 740℃ in the furnace. Figure 2 is an enlarged part of this cycle, and indicates changes in temperature on three points: 25mm (from the bottom), 250mm (center), and 475mm (top).

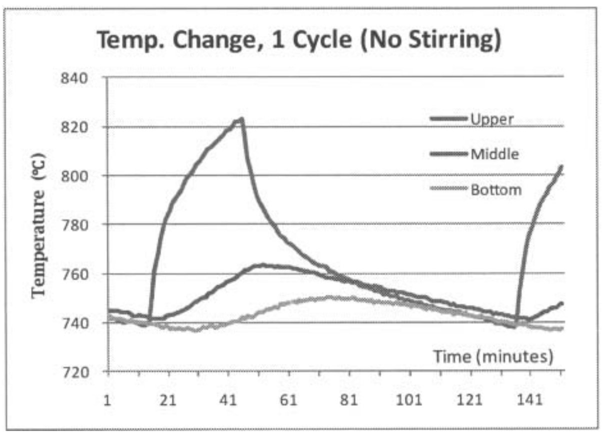

Figure 2

Once the burner started to work, the temperature rapidly rose in the upper layer of molten aluminum, followed by a rise in temperature in the center and bottom layers. When the temperature reached 740℃, the burner stopped and the temperature in the upper layer rapidly started to fall, followed by a gradual fall in temperature in the center and bottom layers. As time passed further, the temperature in the upper layer fell below the temperature of the bottom layer. At that point, the burner started again. One cycle took about 120 minutes, including 30 minutes to heat the furnace. When the temperature reached the maximum measured at 822℃, the upper layer in the center was measured at 764℃ and the bottom layer, 740℃. The difference was about 80℃ between the upper and bottom layers of molten aluminum.

With these results as a baseline, next a permanent magnetic circuit was set 250mm apart from the wall of the furnace, and rotated at a speed of 60rpm to stir molten aluminum. Temperature was measured in the same points. The result is shown in Figure 3.

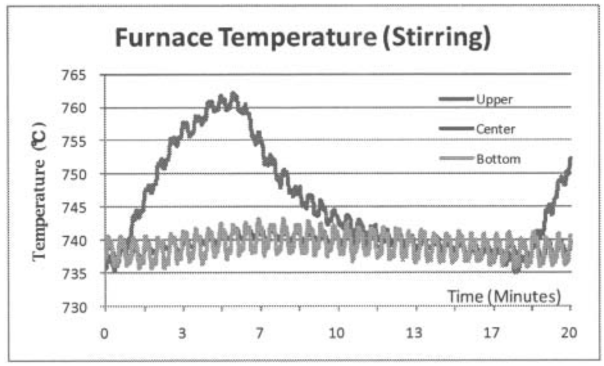

Figure 3

While rotating the magnetic fields, noise was observed on the thermometer due to the influence of magnetic fields. In this case, one cycle took 17 minutes, including 5 minutes to heat the furnace. This compares to a 120 minute cycle in the previous test without stirring. The highest temperature was 760℃ around the upper layer of molten aluminum. The temperature was kept about 740℃ around the center and bottom layers so no difference was shown between the center and bottom layers. The difference between the upper and bottom layers was at most 20℃, so it could be stated that the temperature in the furnace was very homogeneous compared with the case of no magnetic fields. At other measuring points, the results were similar. There were no noticeable differences according to the direction of the magnetic fields. Furthermore, there was no remarkable difference when the rotating speed was changed to 87rpm. The experiment above shows that homogeneity of temperature is caused by stirring molten aluminum through the rotation of the magnetic fields.

(2) Comparison of the amount of gas usage

Table 1 shows how much gas the gas burner used for an hour to hold the temperature in molten aluminum. When the magnetic fields didn't rotate, the amount of gas usage was 3.30 m^3. However, when the magnetic fields rotated at the speed of 60rpm, the amount of gas usage was reduced to 2.91 m^3, therefore leading to an expectation of energy savings. Energy savings is realized because the temperature is homogeneous due to the stirring of molten aluminum via rotating magnetic fields.

Rotation Speed	Gas Usage per Hour (m^3/h)
0 rpm	3.3
30 rpm	2.98
60 rpm	2.91
87.5 rpm	2.93

Table 1 Amount of gas usage per hour to keep temperature in furnace at 740℃

(3) Speed of the molten aluminum flow

To evaluate the flow speed of molten aluminum stirred by magnetic fields, the speed of a float placed on the surface of the molten aluminum was measured. When molten aluminum was stirred at a rate of 30rpm, 60rpm, and 87rpm, the speed of the float was respectively 0.05m/s, 0.2m/s, and 0.2m/s. However, a film of aluminum oxide was on the surface, interfering with the float, so molten aluminum flow may have been higher than indicated. In addition, the float moved fast near the stirrer, but slower further away from the stirrer. This is due to either magnetic fields that influenced the float or due to surface oxide that slowed the float. Whatever the case, a more accurate method of flow measurement needs to be considered, for example, measuring flow in an oxide free environment.

(4) Hydrogen content

Sample	Original Ingot	0 rpm	30 rpm	60 rpm	87 rpm
Hydrogen content (cc/100g)	0.616	0.691	1.123	0.938	1.155

Table 2 Hydrogen content in each test sample

Table 2 shows the amount of hydrogen in each test sample, measured by Gravi-Mass. As a basis of comparison, the amount of hydrogen in an original ingot before melting was measured. When magnetic fields weren't rotating, the amount of hydrogen was 0.69cc and as the rotation of magnetic fields increased, the amount of hydrogen tended to increase slightly. This increase could be due to the film of aluminum oxide breaking by the stirring action. However, the amount of hydrogen shown in Table 2 is quite low since, for example, AC2B and ADC12 alloys already include 1.20cc and 2.00cc respectively, according to Gravi-Mass. To reduce the amount of hydrogen, stirring should be done in a way that does not break the surface film of aluminum oxide. In addition, simultaneously degassing while stirring could be expected to lead to good results.

(5) Analysis of Chemical Composition

Table 3 shows a composition of Si and Mg measured by ICP Optical Emission Spectrometry in samples which were picked from points in the molten aluminum alloy. In the case of stirring a molten aluminum alloy, the difference in composition of Si between the upper and bottom layers of the molten aluminum alloy was less than the difference in the case of not stirring. However, because the ingot used for melting was an alloy, the difference was fairly small. It can be expected that stirring would be most effective in the following cases: Where an alloy element is being added to the molten aluminum. Where the molten aluminum contains a large amount of elements in the alloy. Where the specific gravity of the elements is high.

Sample	Si (wt%)	Mg (wt%)
0rpm Upper	4.48	0.25
Bottom	5.22	0.26
30rpm Upper	6.21	0.25
Bottom	6.63	0.27
60rpm Upper	5.02	0.25
Bottom	4.48	0.29
87rpm Upper	6.03	0.31
Bottom	5.90	0.26

Table 3 Composition of molten aluminum alloy sample

(6) Mechanical properties

The Vickers hardness of the cast sample which was stirred by magnetic fields was HV60. The Vickers hardness of the original ingot was HV61. Results are virtually the same.

The tensile strength and the elongation to fracture of an original ingot at room temperature were respectively 82MPa and 1.4%. This is in comparison to 95MPa and 2.4% for a cast sample which was stirred by magnetic fields. Therefore, it can be said that the strength and the elongation were improved because of stirring by magnetic fields. A possible reason for this improvement is that the elements in the sample became more homogenous.

Sample	Tensile Strength (MPa)	Elongation to fracture (%)
Ingot	82	1.4
Casting	95	2.4

Table 4 Mechanical properties of sample

(7) Microstructure

Figure 4 shows the optical microstructure of a cast sample stirred by magnetic fields. It is seen that the sample consists of a matrix of aluminum and preciptates, and the microstructure is not so different from an original ingot.

Optical microstructure of cast sample

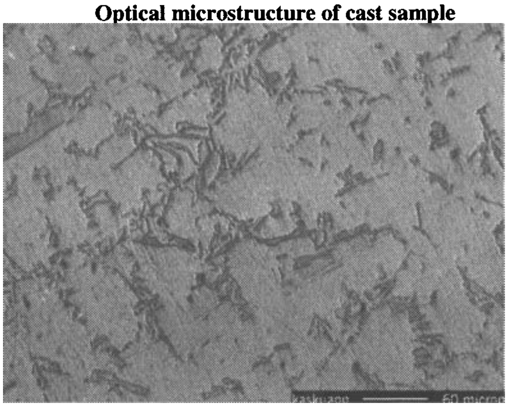

Figure 4

In summary, it was found that the temperature of the molten aluminum alloy was more homogeneous and the gas consumption was less with stirring by magnetic fields than in the case of ordinary stirring. These effects are clearly the result of stirring by magnetic fields. Furthermore, stirring by magnetic fields controls a rise in temperature of the surface of molten aluminum alloys. This effect could save energy and prevent the surface of molten aluminum from oxidizing.

2) Possibility of new furnace shapes

The contemporary melting furnace for aluminum is an open hearth furnace which melts aluminum by heating through the burner, placed above or on the side. The depth of molten aluminum is shallow in order to keep homogeneity of temperature between the top and bottom; in this research the depth was 50cm. Thus, when the amount of molten aluminum is increased, the furnace must be enlarged horizontally with a corresponding increase in the number of burners. In this research, it was found that stirring by magnetic fields resulted in an improvement in homogeneity of temperature. Given these results, the possibility of more efficient furnace shapes might well be considered. Here, the burner's heat contribution to melting aluminum is, for the purposes of this section, not considered. It is assumed there is sufficient available heat capacity.

The blue line in Figure 5 shows a difference of temperature from the upper to the bottom in the furnace without stirring by magnetic fields. The temperature is 820 ℃ around the surface, 760℃ around the center, and 740℃ around the bottom. On the other hand, the red line shows the temperature difference by stirring through magnetic fields. Due to the effects of stirring, the temperature around the upper layer of molten aluminum is held at 760℃ and at the bottom it is measured at 740 ℃. The difference in temperature is minimized.

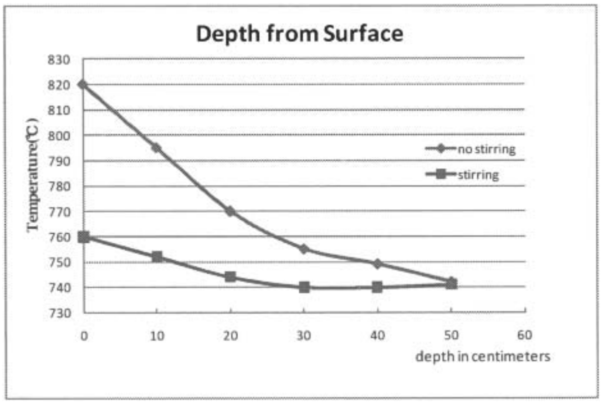

Figure 5

When the furnace is not stirred by magnetic fields, the temperature is 760℃ around the center layer (25cm from the surface). Therefore, it can be inferred that if stirring by magnetic fields is adopted for an existing furnace, the depth of molten aluminum can be increased by 25cm.

Building furnaces specifically designed for permanent magnet stirrers may be a way to maximize the benefits of stirring. A new shape of furnace, roughly illustrated, follows with approximate figures for the purpose of discussion.

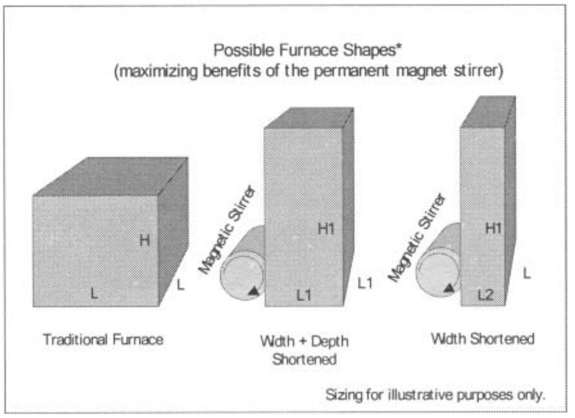

Figure 6

Figure 6 schematically shows the amount of molten aluminum alloy in the existing furnace and new furnaces with a magnetic stirrer. "L" shows depth and width, and the "H" shows height. Molten aluminum was 50cm high in the existing furnace without stirring by magnetic fields. The volume of the molten aluminum ("V") was as follows

$$V = 50 * L * L$$

In the case of stirring by magnetic fields, the molten aluminum can be increased by 25cm while maintaining the same volume, as shown in the following equation, with "L1" indicating depth and width.

$$(50 + 25) * L1 * L1 = 50 * L * L$$
$$L1 = \sqrt{2/3} * L = 0.81 * L$$

Therefore the size of the furnace can be reduced by 20%. Furthermore, if only the width is shortened in a vertical direction from the magnet ("L2"), the range of magnetic force could be maximized for efficiency. In this case, the width ("L2") can be reduced by two-thirds compared to an ordinary furnace. It follows then that a tall type furnace could be a more efficient configuration compared to a flat type furnace. An important comment is that these results were estimated as though the upper layer was not stirred by magnetic fields; however in reality there was a stirring effect in the upper layer so the width could be reduced further. Adjusting placement of the stirrer and adjusting the size and strength of the stirrer could allow a furnace to be taller still. The reduction in depth and width has some advantages including space savings for more flexible furnace placement. Also, the space reduction provides temperature homogeneity in a horizontal direction when the gas burner is on. This saves energy. Furthermore, when the reduced surface area is heated by gas burner, the amount of molten aluminum which contacts air and oxygen is reduced and the formation of oxides are also reduced. This reduction of oxides leads to lower melt loss. It can be expected that inclusions and hydrogen levels will drop, so mechanical properties of a cast are improved. Stirring by magnetic fields causes homogeneity of temperature, which controls excessive heat near the surface of molten aluminum. Consequently, the materials used in furnaces can be replaced by refractory for this lower temperature range; this change contributes to lower cost.

The results above show that by using a permanent magnetic stirrer, tall type furnaces could be used, the resulting space savings might also provide benefits in energy reduction through improvement in heat efficiency, improvement of production through controlling oxidization, and improvement in the metal quality through reduction of inclusions and hydrogen in molten aluminum. In addition, excessive heat can be minimized allowing for a change in ingredients used in the refractory. This contributes to lower the cost of furnaces.

Summary

It was found that stirring by magnetic fields led to excellent temperature homogeneity while simultaneously reducing the amount of gas consumption. Furthermore, surface heat could be controlled by stirring; reduced surface heat minimized oxidized dross while saving energy. Maintaining temperature homogeneity by stirring provides an opportunity to use tall type furnaces. Using a tall furnace, the area of molten aluminum surface is reduced, further reducing oxides and further saving energy. In addition, this change can improve production by reduction of melt loss, as well as an increase in material quality through the reduction of inclusions and hydrogen in the molten aluminum.