Test and Analysis of Superconducting Electromagnetic Tornado Stirring System

Hirofumi KASAHARA
CRIEPI
kasa@criepi.denken.or.jp

Abstract :
There are many benefits that can be achieved to uniformly refine and concentrate the components of crystals through stirring systems in material processing. Among the stirring systems that are available, electromagnetic stirring systems are known to be highly effective, especially electromagnetic tornado stirring systems, because they can control the flow of fluids three dimensionally. The application of electromagnetic stirring systems using conventional copper magnets is minimal due to high operation costs caused by the large Joule losses that occur. By replacing the copper magnets with AC superconducting magnets, manufacturing of highly concentrated Si aluminum alloy capable of miniaturization as engine materials in automobiles and airplanes becomes possible through energy conservation and powerful Lorentz force.

The performance of a tornado stirring system was evaluated by producing a superconducting electromagnetic stirring system for electromagnetic stirring that has rotational stirring, vertical stirring, and tornado stirring which combines both rotational and vertical stirring. In addition, the analysis results for the magnetic field and electromagnetic force produced using JMAG-Designer 10.3 by modeling the molten metal and superconducting magnets was compared to the test results.

The effects of rotational stirring, vertical stirring, and electromagnetic tornado stirring were evaluated using metal gallium, which are melting at room temperature, with an electromagnetic tornado stirring system.

This showed conclusively that the analysis results obtained in JMAG and the test results matched.

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1. Preface

Research in material processing using electromagnetic force started long ago in the fields of iron and steel as well as non-ferrous metal manufacturing and resulting in commercial viability. Material processing using electromagnetic force is called Electromagnetic Processing of Materials, or EPM.

Products such as electromagnetic breaks using DC magnetic fields and electromagnetic stirring using AC magnetic fields have become commercially viable[1)] and further innovations for higher quality and more efficient material processes is expected. Electromagnetic stirring provides the added value of refining and concentrating the components of crystals in an environment free of impurities by stirring materials via electromagnetic force. Conventionally, electromagnetic stirring was realized by water cooling copper magnets, but operation costs such as the electromagnetic force to drive and cool the magnets were high. In addition, there are limitations in large scale applications because the magnetic field required cannot be attained. Our research investigates superconducting AC coils and attempts to utilize superconductors for electromagnetic stirring[2)]. A powerful rotational stirring that could not be attained conventionally was realized by applying rotation force using superconducting magnets.

However, the stirring force weakens because the rotational force increases the material rotates as a rigid body. There are also limitations to the rotational force added by the change in the fluid level caused by centrifugal force. A prototype for an electromagnetic tornado stirring system that combines rotation and vertical stirring by adding electromagnetic force in the vertical direction of the liquid metal along the walls to restrain the liquid metal was built and tested as well as analyzed using JMAG-Designer version 10.

2. Conventional Electromagnetic Processing

The continuous casting process is indicated in Fig. 1[3)]. The most important role of the continuous casting process is removing any 'inclusions'. Inclusions are removed by floating as much of the inclusions as

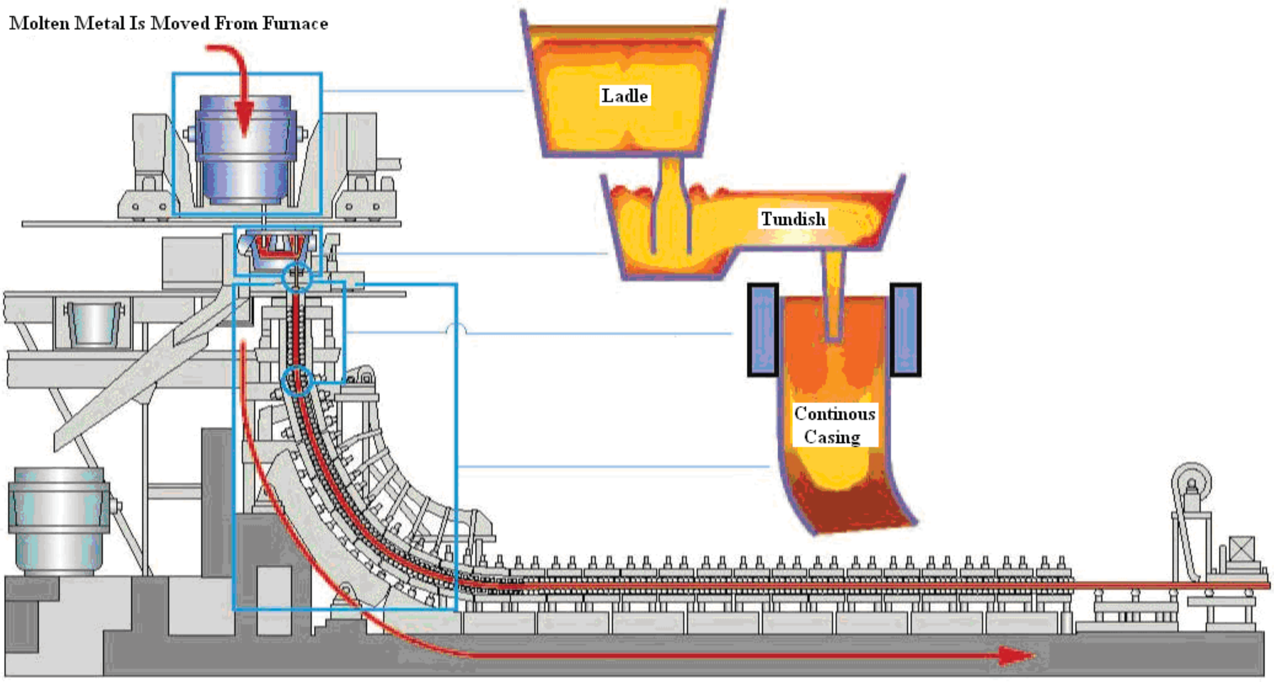


Fig. 1. Assembly of a continuous casting system[3)]

Molten metal from the furnace is poured into the mold and the solidified liquid is pulled from the bottom of the mold while removing inclusions from the steel.

possible to the top of the molten metal because they can cause impurities such as oxidation, lack of or breakout from the refractory materials, or powder in the tundish.

A continuous casting system combining electromagnetic stirring is indicated in Fig. 2. The solidification of molten steel flowing from the tundish is indicated in the figure. There are three areas that a rotating magnetic field is applied; M-Stirring, S-Stirring, and F-Stirring. The frequency of the rotating magnetic field utilized for the rotational stirring magnets varies with the depth of solidification. For example, the rotating magnetic field applied to F-Stirring has a lower frequency than M-Stirring. The crystals are refined by making the solidifying metal particles collide using the most powerful stirring process at the point of solidification.

The ASEA-SKF furnace used by JFE and Kobe Steel, Ltd. is indicated in Fig. 3 as an example of electromagnetic stirring in secondary smelting. Vertical stirring is used in this example. The ASEA-SKF furnace combines vertical magnetic field stirring with a 64 ton circular coil and 48 ton figure 8 coil. A 0.06 T magnetic field is applied with frequencies lower than 1.3 Hz and an excitation current of 1200 A. Water-cooled copper pipes are used as the coils.

Secondary smelting is a process to reduce the level of oxygen which increases when the level of carbon monoxide decreases as the molten metal finishes smelting. Si, Mn, and Al deoxidizing agents are added to the molten steel to reduce the level of carbon monoxide and physically separate inclusions (separate by floating inclusions to the top of the molten steel) or govern the quality by adding an alloy. Electromagnetic stirring is used regardless of the cost because it is necessary to both promote the smelting response via

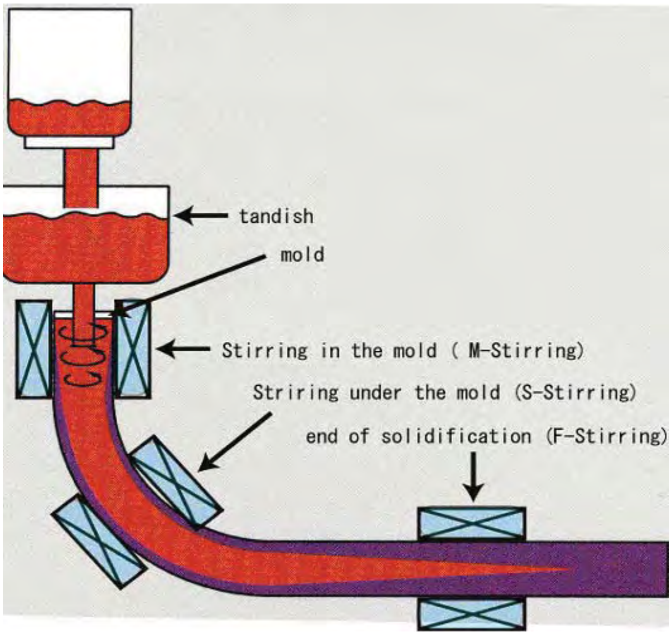


Fig. 2. Electromagnetic stirring applied to a continuous casting system

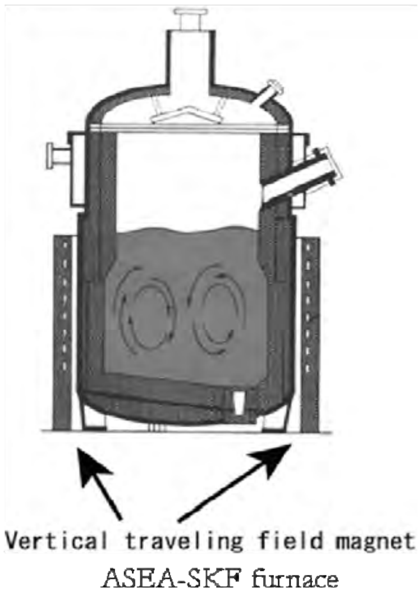


Fig. 3 ASEA-SKF furnace utilizing vertical stirring

powerful stirring and prevent splashing fluid.

The actual electromagnetic stirring system for brass bar manufacturing at OHKI BRASS & COPPER CO., LTD is indicated in Fig. 4 and Fig. 5.[4)] The right side of each figure is a conventional manufacturing system without stirring and the left side of each figure is a manufacturing system

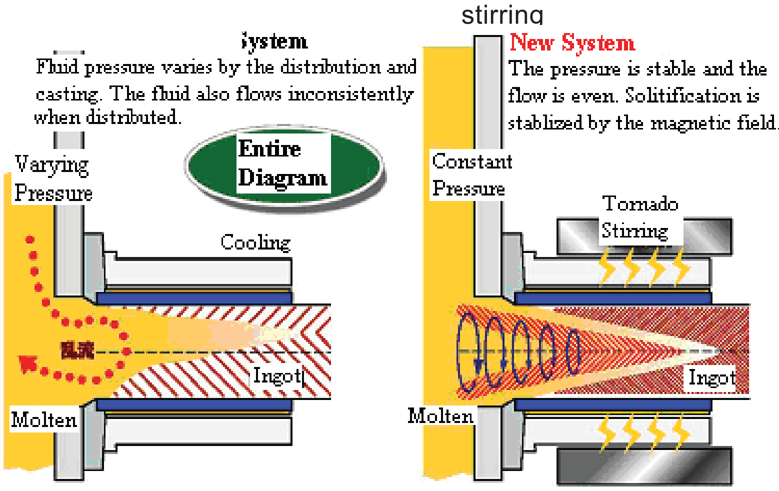


Fig. 4. Electromagnetic stirring during casting[4)]

that utilizes electromagnetic stirring.

Electromagnetic stirring is performed by applying a magnetic field from the center to the exterior of the liquid when the molten solidifies as ingot, as indicated in Fig. 4.

A cross-section of material processed using electromagnetic stirring is indicated in Fig. 5. The cross-section on the left of the figure is a conventional material processed without stirring and the image on the right of the figure is a material using electromagnetic stirring. The structure of the material on the left is random with large clumps, but the material on the right processed using new casting methods with electromagnetic stirring has refined crystals and is uniform from the center to the exterior of the material. Therefore, products that improve degasification caused by uniform solidification and enhance air leakage efficiency can be achieved by adding optimal stirring at the point of solidification.

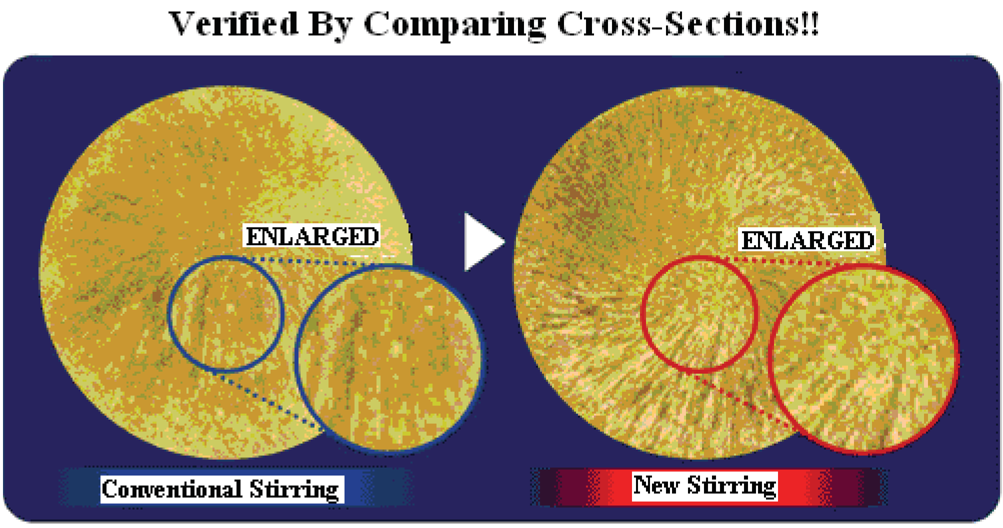


Fig. 5. Effect of stirring during solidification (example)[4]

3. Developing Superconducting Electromagnetic Stirring Systems

The loss of the magnets is miniscule because the superconductive wire has no resistance which produces no Joule losses during excitation. However, AC losses are produced by interaction with the magnetic field when an alternating current is used. The AC loss is proportional to the square of the magnetic field which is proportional to the frequency. Cooling is necessary to eliminate the heat produced by the AC loss and maintain superconductivity. The cooling uses a refrigerant (liquid helium, etc.). Innovations to the thermal design (thermal diffusion = cooling conditions) are necessary when constructing the system.

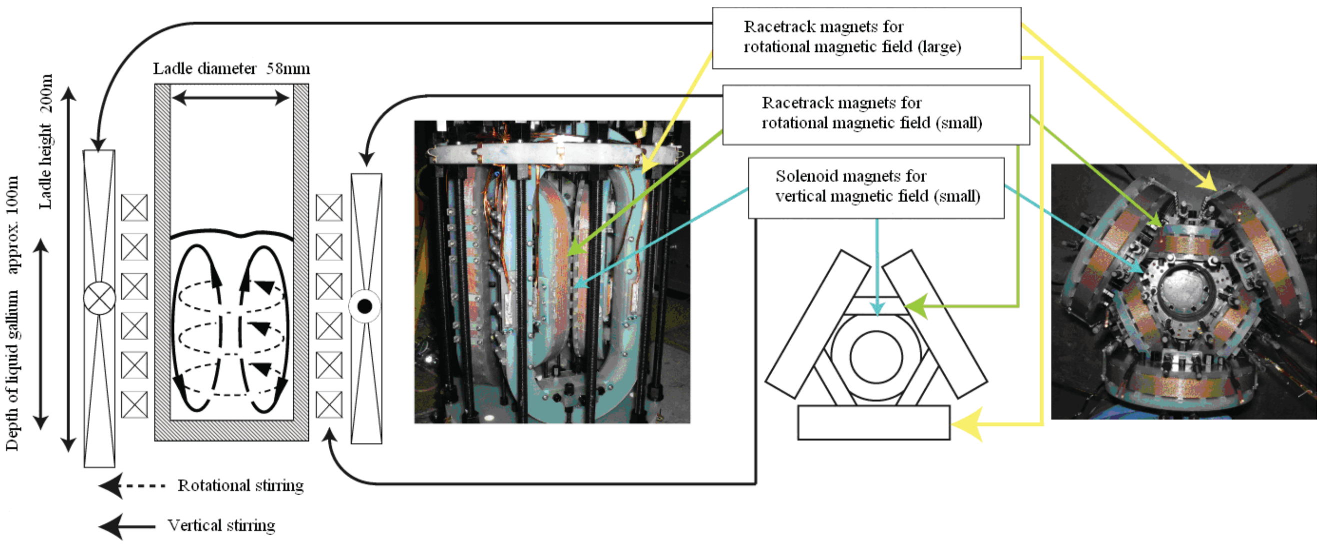
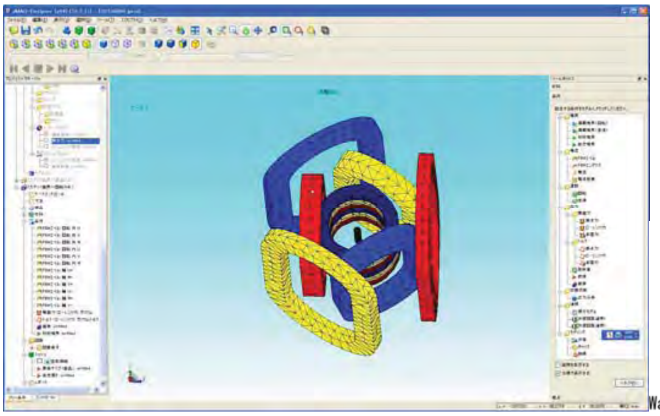


Fig. 6. Superconducting electromagnetic stirring system



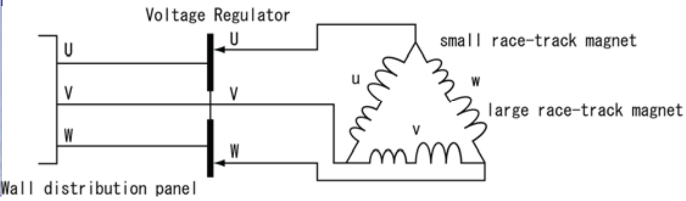


Fig. 7. Magnets producing rotating magnetic field Fig. 8. Connection of magnets

3.1 Rotating Magnetic Field

The prototype of the superconducting electromagnetic stirring system is indicated in Fig. 6. Racetrack magnets assembled cylindrically and linearly should be used because superconductive wires are not very flexible and using magnets with a lot of freedom such as copper magnets is difficult. Large and small racetrack magnets (geometry resembles a racetrack for athletic competitions) are used to keep the poles as close to the molten metal as possible and the rotating magnetic field is produced using 3-phase AC by assembling three groups of magnets as indicated in Fig. 7. The wire connection of the power supply is indicated in Fig. 8. The system is excited by a 3-phase delta connection by connecting the large and small racetrack magnets in series at a frequency of 50 Hz through a volt slider from a wall switchboard. The number of turns for the large racetrack magnets and the small racetrack magnets are adjusted by taking into account the geometry of each racetrack magnet and the distance from the center of the molten metal to manipulate the magnetic field to produce.

3.2 Vertical Magnetic Field

The stirring may rotate the liquid molten like a rigid body depending on the physical value of the molten metal when a strong rotating magnetic field is applied. Therefore, six solenoid coils are arranged in the racetrack magnets to achieve more powerful stirring by applying stirring force in the vertical direction. The arrangement of the solenoid coils and the excitation method of each layer are indicated in Fig. 9. The stirring force is applied from top to bottom by exciting u, -w, v, and then the solenoid magnets.

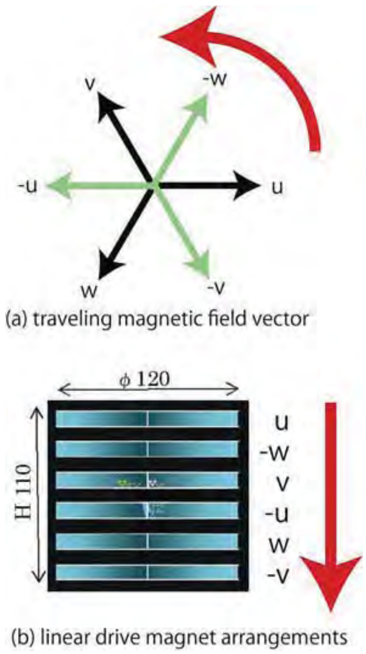


Fig. 9. Magnet applying the vertical magnetic field and the method of excitation

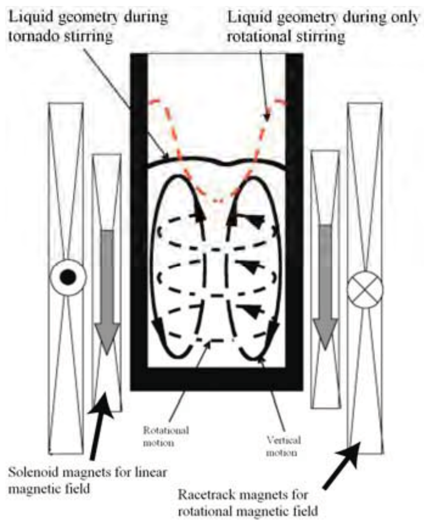
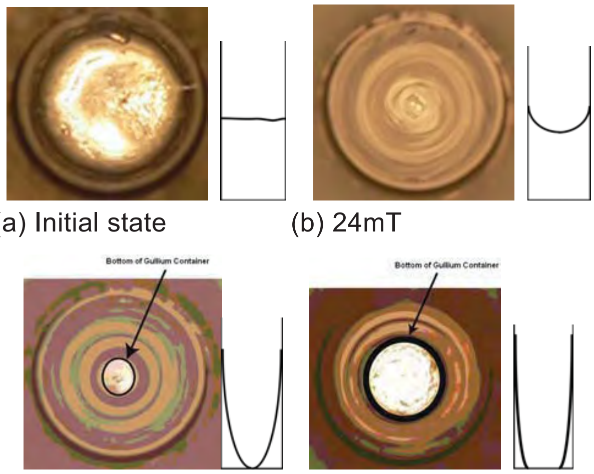


Fig. 10. Tornado stirring

3.3 Tornado Stirring

Professor Shoji Taniguchi from Tohoku University proposed generating a spiraling flow by combining the rotational stirring in 3.1 and the vertical stirring in 3.2, as indicated in Fig. 10.[5] This type of spiral stirring is called tornado stirring in this presentation. A more effective stirring should be achieved because the motion of the fluid can be controlled three dimensionally in tornado stirring systems. Vertical stirring is used to restrict the deformation at the liquid's surface resulting from the centrifugal force generated by the strong rotating magnetic field.

Manufacturing for aluminum alloy of highly concentrated Si which allows miniaturization as engine materials in automobiles and airplanes may be possible using this powerful stirring during solidification. Furthermore, material processing can be preformed in a weightless environment by applying electromagnetic force that is larger than the mass of the metal.



(a) Initial state (b) 24mT

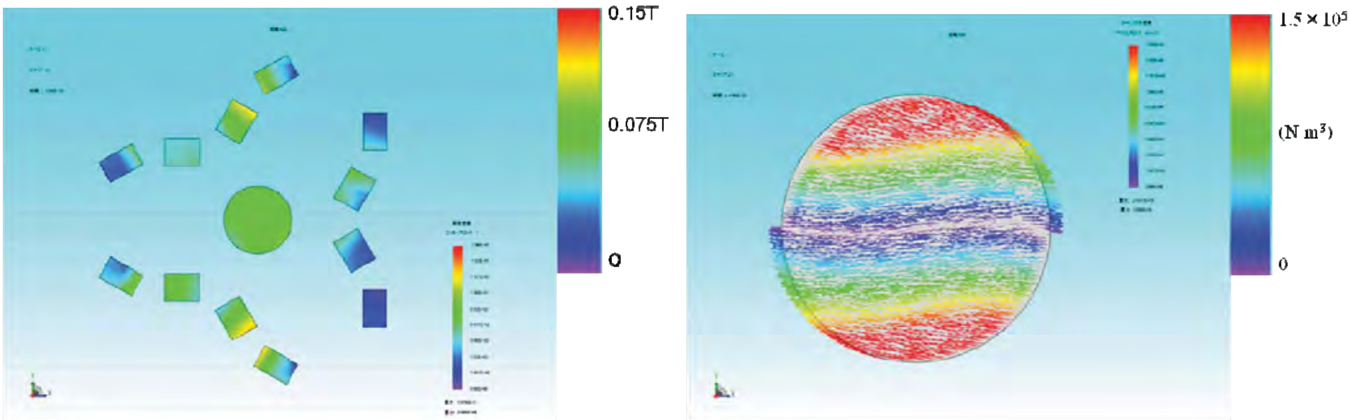
(c) 48mT (d) 60mT

Fig. 11. Changes in the level of Gullium caused by electromagnetic stirring

4. Testing and Analysis Using JMAG-Designer

Gullium was used as the liquid metal for the stirring tests. Gullium has a mass of 6 g/cc^3 and is a liquid at room temperature with a melting point of 30 degrees Celsius. The conditions the rotational stirring was performed are indicated in Fig. 11. Stirring using superconductors powerful enough to expose the container and hold the liquid to its walls was applied.

A rotational stirring simulation was performed by modeling the magnetic system from the design, as indicated in Fig. 7. The analysis results of the magnetic flux density acting on the magnets and the electromagnetic force density added to the molten metal is indicated in Fig. 12.



(a) Magnetic flux density distribution (b) Magnetic force density

Fig. 12. Rotational stirring simulation

The rotating magnetic field measured by the hall effect sensor is 0.06 T for the Gullium at the wall. The analysis results approximately match at 0.7 T. The electromagnetic force produced by this magnetic field of 1.5 x 10^5 N/m^3 can rotationally stir the Gullium which requires a gravitational force larger than 7.71 x 10^4N/m^3.

The magnetic flux density distribution for vertical stirring is indicated in Fig. 13. The vertical stirring raises the center of the fluid until it hits the lower circumference of the container by applying a traveling magnetic field downward into the container. Therefore, frequency is applied to the traveling magnetic field only at the surface to account for the skin effect. 700 Hz for a depth of approx. 10 mm was used for this analysis. The magnetic field at the surface of the Gullium measured by the hall effect sensor is 0.098 T. The analysis results indicated in Fig. 14 show the magnetic field is approximately 0.2 T. The magnetic field is under calculating using the hall effect sensor because of the position and angle of the hall effect sensor used to measure the magnetic field.

The tornado stirring is performed by adding a rotating magnetic field of 50 Hz and a traveling vertical magnetic field of 700 Hz. Changes in the level of Gullium were measured to evaluate the effect of tornado stirring. The changes of the level of Gullium are indicated in Fig. 14. The black line indicates the actual rise of the fluid level circumferentially in the container from the centrifugal force caused by rotational stirring. The blue line indicates a rise at the center of the fluid when a traveling magnetic field is applied vertically. The red line indicates a restricted rise in the level of fluid circumferentially caused by centrifugal force when tornado stirring is performed. The electromagnetic force that is applied is indicated in Fig. 15. The rotating magnetic filed is 50 Hz and the vertical magnetic field is 700 Hz.

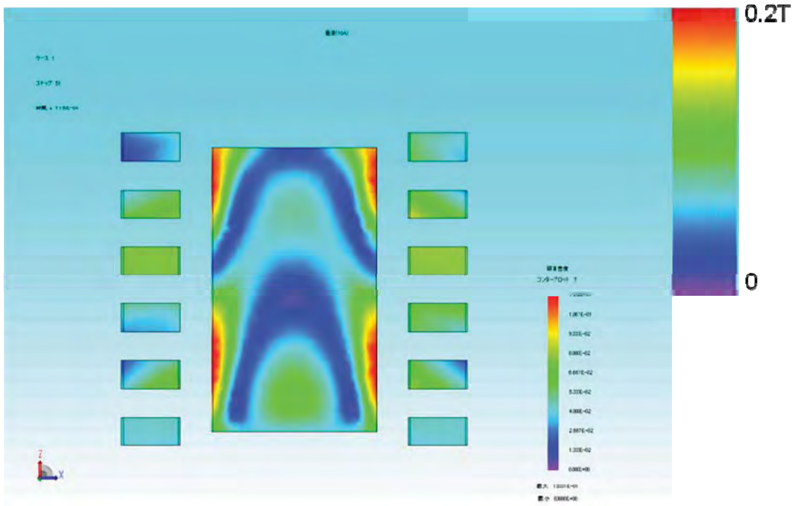


Fig. 13. Magnetic flux density distribution of vertical stirring (0 to 0.15 T)

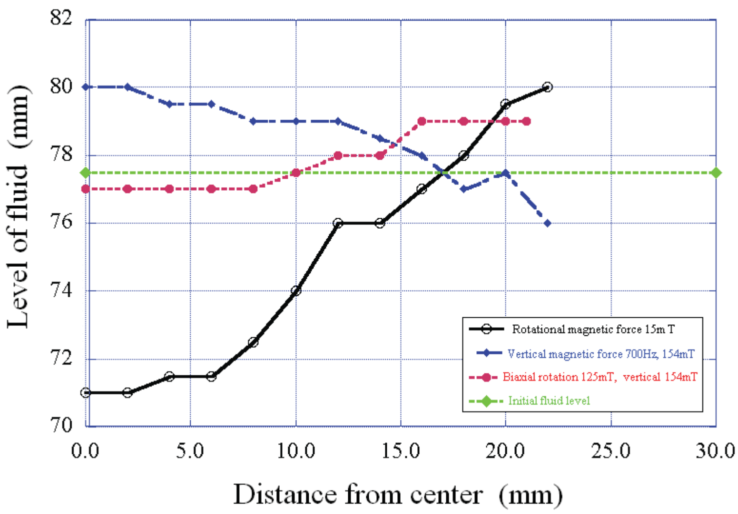


Fig. 14. Variations in the geometry of the fluid

5. Conclusion

Fundamental testing using a prototype for a tornado electromagnetic stirring system was performed aiming to apply superconducting technology to the material manufacturing field. Analysis was also implemented simultaneously using JMAG and the results that were obtained approximately match the results from actual testing.

Design parameters such as the necessary electromagnetic force, size of magnets, number of turns, frequency, and current could be determined from the analysis results.

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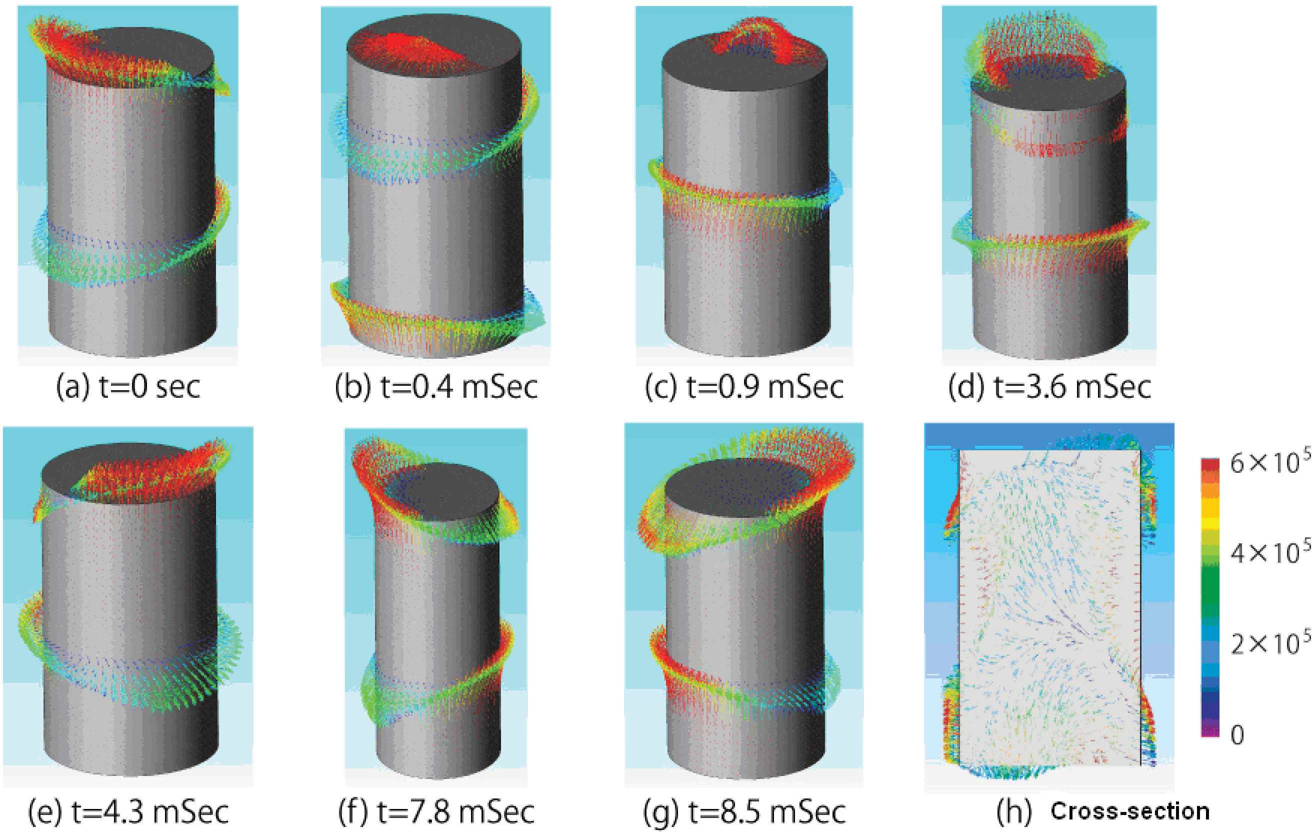

Fig. 15. Electromagnetic force density distribution for tornado stirring