Simulation Study of Magnetic Shielding to Address Heat Generation in Rollers for Clamping Aluminum Rod Heated by HTS DC Induction Heater

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Abstract. The roller is the connect structure between the gripper and main or auxiliary gearbox, which rotates simultaneously with the aluminum billet. When preheating short aluminum billet, a part of the roller is in the air-gap, which will be heated during preheating the aluminum billet, and the increase in the temperature of the roller can affect the gearbox. To address the roller heat, a magnetic shielding method has been proposed. And the effect of the magnetic shielding of the magnetic field in the roller and the air-gap has been analyzed. The weakening effect of the magnetic shielding on the heating power also has been evaluated. At the same time, the electromagnetic force of the magnetic shielding is also been carried out. The results show that the magnetic shielding can effectively reduce the heating power of the roller. Evidently, adding a magnetic shielding around the roller is feasible to alleviate or solve the problem of roller and gripper heat.

1. Introduction

The HTS DC induction heater is proposed to improve the efficiency of heater. The efficiency of the traditional AC induction heater is about 50% because the copper coil itself will heat up under the action of AC. The superconducting coils was firstly proposed to instead of the copper coil in the AC induction heater, but the efficiency of the heater is comparable to that of AC induction heaters due to the AC loss of the superconducting coil. In order to avoid the AC loss and take advantage of the zero resistance characteristics of the superconducting to improve the efficiency of the heater, the HTS DC induction heater concept was proposed. In the concept, the aluminum billet rotates in the DC magnetic field generated by the HTS magnet. Because the HTS magnet excited by DC has almost no losses, the efficiency of the heater can be up to above 80% [1-3].

Many researches about HTS DC induction heater has been done, and some HTS DC induction heaters has been commercialized. The first commercial HTS DC induction heater with a rated power of 360kW has been put into operation at the Weseralu aluminum extrusion plant in Germany since 2008 [4]. In Korea, an HTS DC induction heater with a rated power of 300kW had been designed since 2014, and commercialized by Superecoil Company Ltd. in 2017 [5-6]. A 1-MW HTS DC induction heater has been proposed years ago and assembled in China in 2019, and many tests have been done [7-9].

At present, a new 500kW HTS DC induction heater has been manufactured, and is now undergoing final commissioning, which will be put into production at the aluminum extrusion plant upon completion. The HTS DC induction heater can preheat aluminum billet with a diameter of 410mm and...
a length of 1500mm. However, the grippers clamping the aluminum billet and the rollers connected to the gripper and gearboxes are also heated when the HTS DC induction heater heats a short billet, which is not conducive to the safe operation of the main and auxiliary gearboxes. And the ability of HTS DC induction heater to continuously preheat the short billet is also limited.

In order to solve the above problem, this paper proposes a magnetic shielding method that can reduce the heating power in the rollers during the aluminum billet heating process. And the effect of the magnetic shielding on the magnetic field and the heating power in the rollers has been analyzed. The electromagnetic force of the magnetic shielding has also been assessed. The magnetic shielding will be applied in the HTS DC induction heater.

2. About the HTS DC induction heater

2.1. Specifications of the HTS DC induction heater

Fig.1 shows the HTS DC induction heater, which is designed for preheating the aluminum billet with a diameter of 410mm and a length ranging from 650mm to 1450mm. The specifications of the heater are given in Table.1. This heater consists of four main parts: the power supply system, the magnet system, the iron core, and the drive system. The power supply system is used to provide the energy to devices that require electricity. The magnet system including the cooling system, which is used to generated the magnetic field in the heating area, namely the iron core air-gap. The iron core is used to direct the magnetic field to the air-gap, and the movable iron core can regulate the magnetic field distribution to achieve the desired temperature distribution by some linear actuators. The drive system is used to drive the aluminum billet to rotate in the heating area, which can make the aluminum billet heated by the eddy current generated in the billet. And the main and auxiliary gearboxes are applied to solve the peak torque that appears in the lower speed [10]. The rollers and grippers are connected to the gearboxes to clamp the aluminum billet.

| Items                          | Specifications                      |
|-------------------------------|------------------------------------|
| Metal billet type             | Aluminum alloy (6061)              |
| Temperature deviation         | ≤±25K                               |
| Rotating speed                | 500rpm                             |
| Billet size (max)             | φ410mm, L650-1450mm                 |
| Rated power                   | 500kW                              |
| HTS tape (YBCO)               | Shanghai Superconductor             |
| Operating current             | 120A                               |
| Magnetic field at the billet center | 0.45T          |
| Operating temperature         | 25-30K                             |
| Inner/outer diameter of HTS magnet | 1426/1486mm                     |

2.2. Challenge and solution

The rollers are the connect structure between the gripper and main or auxiliary gearbox, and are made by titanium alloy that has a low thermal conductivity. The gripper is also made of the titanium alloy with high strength, which is contacted directly with the aluminum billet. The gripper and the roller rotate simultaneously with the aluminum billet at the same speed, and will also be heated during the operation of the heater, especially heating the short aluminum billet, which will take the challenges to the gearboxes because the gearboxes can not withstand the temperature higher than 100℃.
grippers and partial rollers will enter into the air gap, and the temperature in these parts is higher than in the parts that do not enter the air gap. Therefore, certain measures need to be taken to alleviate or solve the problem of roller and gripper heat.

The indirect method is to adopt the metal with the low thermal conductivity to reduce the heat transfer rate along the roller, which is one reason that the rollers and grippers adopt the titanium alloy. At the same time, the titanium alloy has a great resistivity, which can reduce the heating power of the gripper and rollers during the operation of the heater.

The direct method is to reduce the magnetic field in the grippers and rollers by add magnetic shielding that can divert some the magnetic flux away from the gripper and roller. Due to the limitations of the air gap space that can be used to set the magnetic field shielding, the magnetic shielding uses a ring ferromagnetic block, which only covers the roller. And the magnetic shielding is fixed on the gearbox and move together with the gearbox when the grippers clamp the aluminum billet. And the magnetic shielding has three cases including semi-shielding, full-shielding, and the combination of both semi-shielding and full-shielding, which can be seen in Fig.2. The semi-shielding does not enter the air-gap and cover the partial roller, but can has greater thickness; the full-shielding has part into the air-gap and cover the whole roller, but the thickness is limited; the compound-shielding consists of two rings of different thicknesses, the thicker ring not entering the air-gap and the thinner ring entering the air-gap.

In order to verify the feasibility of the magnetic shielding, the focus is to reduce the heating power during rollers rotation by weakening the magnetic field in the rollers in the subsequent analysis. The study is done using simulation, and experimental validation will be done in subsequent work.

3. Numerical Method

Fig.3 shows the models with the semi-shielding, full-shielding, and compound-shielding, respectively, which is built based on the HTS DC induction heater in Fig.1. In these models, there are only the iron core, HTS magnet, rollers, and magnetic shielding, other parts are not included. The air-gap in Fig.2 is used to preheat the aluminum billet with a diameter of 410mm and a length of 650mm to achieve a gradient distribution of the temperature along the billet axial. And these models do not consider the coupling of the electromagnetic field and the thermal field because here just to evaluate the change of the magnetic field and the heating power in the roller caused by the magnetic shielding. The degree of improvement in roller heating can be reflected by evaluating the change in heating power. The electromagnetic parameters of the titanium alloy are from the software. And the rotation speed of the rollers is 500rpm, the operating current is 120A. Here the analysis focuses on the situation when preheating the short aluminum billets because the challenge described above does not exist when preheating long aluminum billets.
4. Results and discussion

4.1. Semi-shielding

Fig. 4 shows the magnetic flux density distribution in the rollers with different semi-shielding. The semi-shielding has a length of 180mm, and the roller has a length of 480mm. As the thickness of the semi-shielding increases, the magnetic field distribution in the rollers decreases, especially in the shielding-covered areas, where the magnetic flux decreases significantly. In the unshielded area, the decrease in magnetic flux is smaller. The minimum magnetic field in the roller decreased by 67% from 0.12T without a shielding to 0.04T with a shielding that has a thickness of 70mm. The maximum magnetic field in the roller decreases by 2.3% from 0.43T without a shielding to 0.42T with a shielding that has a thickness of 70mm. Evidently, the magnetic shielding has a significate effect on reducing the magnetic field in the rollers.

![Figure 4](image)

**Figure 4.** Magnetic flux density distribution in the rollers with semi-shielding of varying thickness.

In order to better compare the effect of the thickness of the shielding on the magnetic field distribution of the rollers, the magnetic field distribution of the intersection line between the surface of the roller and the shielding end plane is compared, as shown in Fig.5(a) (the left roller). And the corresponding percentage decline in magnetic field is given in Fig.5(b). As can be seen, the presence of the shielding does significantly reduce the magnetic field strength in the roller. And the magnetic field decreases with the thickness of the shielding, and with an average reduction of 40% for a shielding thickness of 70mm compared to without shielding. The magnetic field distribution of the left roller end line is also given in Fig.6(a), and the corresponding percentage decline in magnetic field is given in Fig.6(b). The presence of the shielding has little effect on the magnetic field distribution in the part of the roller that enters the air gap of the core, and the magnetic field decrease with the thickness, with a decrease of 2%-5% at a thickness of 70 mm compared to without shielding.
Figure 5. Magnetic flux density at the intersection line and the end line, and the percentage decline in magnetic field.

The change of the magnetic field in the right roller is similar as the left roller. The magnetic field at the intersection line between the surface of the roller and the shielding end plane has an average reduction of 48% for a shielding thickness of 70mm compared to without shielding. And the magnetic field at the right roller end line has a decrease of 1.5%-6% at a thickness of 70mm compared to without shielding. The magnetic field in the right roller has a greater decline than that in the left roller because the right air-gap has a greater width than in the left.

In order to evaluate the influence of the exist of the shielding on the magnetic field in the air-gap, a comparison of the magnetic field in the centerline of the air-gap is performed, which can be seen in Fig.6. When the thickness of the shield is 70mm, the magnetic field in the center line of the air gap for a 650mm aluminum billet decreases within 3% compared to without shielding, which is too small to ignore. Evidently, place a semi-shielding around the roller is a feasible method to reduce the heating power in the roller. And the magnetic field for a 1450mm aluminum billet has a greater decline at the end of the air-gap than in the middle, and the closer it is to the end, the more it decreases, and with a decrease of 34% at the end of air-gap, which is an important reference for the design of magnetic shielding. And the decrease of 34% is greater than the decrease in magnetic field caused by shielding when the 1450mm billets are preheated, because the air-gap is much smaller when preheating the 1450mm billets than when preheating the 650mm billet.

Figure 6. Magnetic flux density at the axis of the heating area and percentage decline compared to without shielding.
4.2. Full-shielding

Fig. 7 shows the magnetic flux density distribution in the rollers with different full-shielding. The full-shielding has a length of 480mm, and the part entering the air-gap is 240mm. The roller length is the same as the shielding. As the thickness of the full-shielding increases, the overall magnetic field in the rollers shows a significant decreasing trend. The minimum magnetic field in the roller decreased by 50% from 0.12T without a shielding to 0.06T with a shielding that has a thickness of 30mm. The maximum magnetic field in the roller decreases by 16% from 0.43T without a shielding to 0.36T with a shielding that has a thickness of 30mm. Evidently, the magnetic shielding also has a significant effect on reducing the magnetic field in the rollers.

![Magnetic Flux Density Distribution](image)

**Figure 7.** Magnetic flux density distribution in the rollers with full-shielding of varying thickness.

![Magnetic Flux Density at Intersection and End Lines](image)

**Figure 8.** Magnetic flux density at the intersection line and the end line, and the percentage decline in magnetic field.
In order to better compare the effect of the thickness of the shielding on the magnetic field distribution of the rollers, the magnetic field distribution at the middle line of the roller surface, as shown in Fig.8(a) (the left roller). And the corresponding percentage decline in magnetic field is given in Fig.8(b). As can be seen, the presence of the shielding does significantly reduce the magnetic field strength in the roller. And the magnetic field decreases with the thickness of the shielding, and with an average reduction of 26% for a shielding thickness of 30mm compared to without shielding. The magnetic field distribution of the left roller end line is also given in Fig.8(c), and the corresponding percentage decline in magnetic field is given in Fig.8(d). The presence of a full-shielding also has a significant effect on the magnetic field distribution in the part of the roller that extends into the air-gap. The magnetic field decreases with the thickness of the shielding, and with an average reduction of 20% for a shielding thickness of 30mm compared to without shielding.

The change of the magnetic field in the right roller is similar as the left roller. The magnetic field at the middle line of the right roller surface has an average reduction of 42% for a shielding thickness of 30mm compared to without shielding. And the magnetic field at the right roller end line has an average decrease of 31% at a thickness of 30mm compared to without shielding. The magnetic field in the right roller has a greater decline than that in the left roller because the right air-gap has a greater width than in the left.

In order to evaluate the influence of the exist of the shielding on the magnetic field in the air-gap, a comparison of the magnetic field in the centerline of the air-gap is performed, which can be seen in Fig.9. When the thickness of the shield is 30mm, the magnetic field in the center line of the air gap for a 650mm aluminum billet decreases within 10% compared to without shielding. Evidently, place a full-shielding around the roller is also a feasible method to reduce the heating power in the roller, but the full-shielding has a greater influence on the magnetic field in the heating area than the semi-shielding. And the magnetic field for a 1450mm aluminum billet has a greater decline at the end of the air-gap than in the middle, and the closer it is to the end, the more it decreases, and with a decrease of 40% at the end of air-gap, which is an important reference for the design of magnetic shielding. And the decrease of 40% is greater than the decrease in magnetic field caused by shielding when the 1450mm billets are preheated, because the air-gap is much smaller when preheating the 1450mm billets than when preheating the 650mm billet.

Figure 9. Magnetic flux density at the axis of the heating area and percentage decline.

4.3. Comparison of different magnetic shielding

Fig.10 shows comparison of the magnetic flux density distribution in the rollers with different shielding. The semi-shielding has a thickness of 70mm, the full-shielding has a thickness of 30mm, and the compound-shielding consist of two rings with a thickness of 70mm and 30mm respectively. As can be seen, the compound-shielding has a greatest effect on the magnetic field in the rollers, that is, the compound shielding leads to a greatest decrease in the magnetic field of the rollers. The magnetic field distribution at the middle and end lines of the rollers with compound-shielding is similar as the results with the semi-shielding or full-shielding. Compared to without shielding, the magnetic field has an average reduction of 37% at the middle line of the left roller surface, and 31% at the end line of the left roller surface; the magnetic field has an average reduction of 12% at the middle line of the right roller surface, and 23% at the end line of the right roller surface.
Figure 10. Comparison of the magnetic flux density distribution in the rollers with different shielding.

Fig.11 shows the magnetic flux density distribution on the air-gap axis with a compound-shielding, and compares it with the results with a 70 mm thick semi-shielding and a 30mm thick full-shielding. It can be seen from Fig.11 that the weakening effect of semi-shielding, full-shielding, and compound-shielding on the air-gap magnetic field is enhanced sequentially. The magnetic field in the center line of the air gap for a 650mm aluminum billet decreases within 13% with compound-shielding compared to without shielding. And the magnetic field for a 1450mm aluminum billet has a greater decline at the end of the air-gap than in the middle, and the closer it is to the end, the more it decreases, and with a decrease of 47% at the end of air-gap with compound-shielding compared to without shielding. The decrease of 47% is greater than the decrease in magnetic field caused by shielding when the 1450mm billets are preheated, because the air-gap is much smaller when preheating the1450mm billets than when preheating the 650mm billet. And the width of the air gap ends is larger than the middle of the air gap when heating long aluminum billet in order to avoid overheating at the billet ends, therefore the large decrease in magnetic field at the end of the air-gap caused by the magnetic shielding when heating long billet can be compensated by adjusting the air-gap of the iron core.

Figure 11. Magnetic flux density at the axis of the heating area and percentage decline.

4.4. Heating power and electromagnetic force

Fig.12 shows the heating power of the rollers with different magnetic shielding. As can be seen, the presence of the magnetic shielding does can reduce the heating power of the rollers, and the heating power of the left rollers is greater than that of the right rollers at the same magnetic shielding. And the weakening effect of semi-shielding, full-shielding, and compound-shielding on the heating power of the rollers is enhanced sequentially. The heating power of the left roller decreases by 52% with the compound-shielding than without, and the heating power of the right roller decreases by 70%. But the effect of magnetic shielding needs to be further verified through experiments. While the magnetic shielding reduces the heating power by lowering the magnetic field in the roller, it also causes a drop in the magnetic field in the heating area, which in turn causes a drop in the heating power of the aluminum billet, a factor that needs to be considered when designing magnetic shielding.
Figure 12. Heating power of the rollers under different magnetic shielding

Fig. 13 shows the electromagnetic forces on different magnetic shields. As can be seen, the electromagnetic forces of the full-shielding and compound-shielding are greater than that of the semi-shielding except for the z component, because there is a portion of the full-shielding and compound-shielding in the ai-gap. And the electromagnetic forces of the left and right magnetic shielding is different due to the different air-gap width. Therefore, the design of the magnetic shielding needs to take into account the possible electromagnetic forces of the magnetic shielding while considering the reduction of the roller heating power.

Figure 13. Electromagnetic force of the different magnetic shielding.

By comparing the magnetic field results of semi-shielding and full-shielding, it can be seen that the compound-shielding is more effective in reducing the heating power of the roller, but the electromagnetic force is larger than other magnetic shielding. Considering the existing HTS DC induction heater structure, the semi-shielding solution is more feasible than other magnetic shielding though the weakening effect of the semi-shielding on the heating power of the roller is less than the full-shielding and compound-shielding. But the full-shielding and the compound-shielding can be applied to the HTS DC heater to solve the heating of the roller in the future.

5. Conclusion

A magnetic shielding method to alleviate or solve the problem of roller and gripper heat has been proposed. The magnetic shielding is a ring ferromagnetic block around the roller, and has three cases including semi-shielding, full-shielding, and compound-shielding. The weakening effect of the different magnetic shielding on the magnetic field and the heating power in the roller has been compared and analyzed. The weakening effect of semi-shielding, full-shielding, and compound-shielding on the magnetic field and the heating power of the rollers is enhanced sequentially. The electromagnetic force of the different magnetic shielding has also been compared. The semi-shielding is subjected to less electromagnetic force than other magnetic shielding because the semi-shielding does not enter the air-gap.

The influence of the different shielding on the magnetic field in the heating area is also analyzed. The decrease of the magnetic field in the aluminum billet of 650mm is within 5% for the semi-
shielding, within 13% for compound-shielding, which needs to be considered in the process of designing the magnetic shielding. And the decrease of the magnetic field in the end of the air-gap is very large, but which can be compensated by adjusting the air-gap of the iron core because the width of the air gap ends is larger than the middle of the air gap when heating long aluminum billet in order to avoid overheating at the billet ends. Therefore, the magnetic shielding method to alleviate or solve the problem of roller and gripper heat is feasible, which will be used in the 500kW HTS DC induction heater.

6. Acknowledgments
This project was supported by the Science and Technology Department of Jiangxi Province (No. 20203ABC28W003).

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