Feasibility Study of a Novel Superconducting DC Induction Heater Structure

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Abstract. A novel superconducting DC induction heater which can heat more than two aluminum billets at a time is proposed. The workpiece can rotate on its axis and move around the center cylinder of the iron core. In order to evaluate the effect of the movement speed and the rotation speed on the heating the aluminum billet, a 2D simulation model has been built by the finite element software. And the magnetic flux density distribution and the temperature distribution under different movement speed for different rotation speed has also been evaluated. Results show that the movement can improve the temperature uniformity of the aluminum billet at the cost of increasing the heating time. What is more, the new superconducting DC induction heating structure is feasible.

1. Introduction

In aluminum manufacturing plants, typical aluminum billets having a radius of 100 mm and a height of 1000 mm are required to preheated to a temperature of 723.15 - 773.15 K to soften the billet before pressing it through the die of the extruder [1]. The efficiency of the conventional AC heaters is around 50%, and nearly half energy is carried away by the cooling water, because the physical properties of aluminum billet and copper coil are similar [2]. Therefore, an innovative method of induction heating has been proposed to improve efficiency [3]. In this method, the billet is driven by a motor to rotate in the DC magnetic field produced by a DC superconducting coil with an iron core. Since the losses of the DC superconducting coil can be neglected, the efficiency of the heating system is approximately that of the motor [4].

The induced current generated by aluminum billet rotation in the DC magnetic field is alternating current. Because of the skin effect, the current is mainly concentrated in the surface layer of the aluminum billet in the heating process, which will lead to the uneven temperature distribution. It is known that preheating the billet before pressing it into the die is the most critical part of the manufacturing process of metal profiles [5]. It is crucial to have a uniform temperature distribution in the aluminum billet, which will affect the quality of the products. Although the temperature penetration depth can be increased by reducing the rotation speed, the heating time can also be increased. Therefore, it is necessary to minimize the influence of skin effect.

In this paper, a novel superconducting DC induction heater structure has been proposed for improving the temperature uniformity of aluminum billets. And several aluminum billets can be heated simultaneously in this structure. In order to evaluate the effect of the movement speed and the rotation speed on the heating the aluminum billet, a 2D simulation model has been built by a finite element software. And the effect of the new superconducting DC induction heating structure on heating aluminum billet is discussed.
2. Novel Superconducting DC Induction Heater Structure

Two possible 3D geometries of the new superconducting DC induction heater structure, including iron core and superconducting coils, are shown in figure 1. The left structure shown in figure 1 can heat six aluminum billets at the same time, and the billets can both rotate on its axis in the air gap and move around the annular air gap consisted of the six C-type iron cores. The right structure shown in figure 1 can also heat six aluminum billets or more at a time. The superconducting coils generate a radially distributed DC magnetic field in the annular air gap, in which the billets also can both move around a central cylinder and rotate on its axis to be heated. The billets will be placed vertically, and several rotatable pallets can carry the billets. The pallet with an appropriate mechanical structure can clamp the bottom of the billet automatically by using its weight. And the upper end of the billet is connected to the rotator. Therefore, the impact of aluminum billet weight on the clamping device is much less than when the billet is placed horizontally. And when the size of the billet is small, the mechanical stress can be acceptable. The magnetic flux density distributions in the iron core and in the air gap of the right structure in figure 1 are shown in figure 2. From figure 2, we can see that the magnetic field distribute radially in the annular air gap. In order to confirm the feasibility of the new structure, a 2D simulation model has been built, which will be described in the next section.

![Figure 1. The structure of a novel superconducting DC induction heater.](image)

![Figure 2. The magnetic flux density distribution in the iron core and the annular air gap.](image)

3. 2D Simulation Model

3.1. Simulation method

The induction heating process usually includes two physical fields: the electromagnetic field and the thermal field. And the temperature change is driven by the resistance heating of the induced current, and the induced current depends on the electrical conductivity, which in turn depends on the temperature. In other words, the two physical field models are coupled in both directions. And the coupling problems can be solved by numerical method. The induction heating process will be divided into a sequence of fine time steps in the numerical method. And it is reasonable to ignore the electromagnetic transient process caused by the temperature change in each time step because the temperature of the billet increases smoothly and slowly [1]. Based on the above assumption, the electromagnetic field can be considered to reach a steady-state immediately in each time step, and the materials electromagnetic parameters hold constant. And the induced power generated in the billet during the time step will be
taken as the heat source of the thermal field. Next, a new temperature distribution is calculated in the thermal field analysis, and the electromagnetic and thermal parameters of the billet will be updated in the calculation of the next time step [5]. The above calculation process will be repeated until the end of the calculation, which is shown in figure 3. The relative permeability of the aluminum has very weak temperature dependence, and it is a constant of 1 in the simulation. The heat exchange at the billet boundary is related to the rotation and movement speed of aluminum billet, which is included in thermal analysis. And the data for the properties of aluminum is from the software.

![Figure 3. The calculation process of the simulation method.](image)

### 3.2. Geometry of the 2D simulation model

A 2D simulation model has been built to verify the feasibility of the new superconducting DC induction heater structure, which is shown in figure 4, and the specifications are given in table 1. The permanent magnet (PM) is adopted to generate the static magnetic field shown in figure 5. The aluminum can rotate on its axis and moves horizontally at the same time. In this model, the magnetic field distributed vertically arising from the PM is used to simulate the radially distributed one generated by the new structure. And the horizontal movement of the billet can simulate the movement of the billet around the center cylinder of the new structure. The aluminum billet moves to the right in the simulations. In order to speed up the calculation, the convection and heat radiation is not considered. This does lead to overestimated temperature and efficiency but does not affect the overall trend of the calculated results, which can be used to confirm the feasibility of the new structure.

![Figure 4. The 2D model for verifying the feasibility of heating the aluminum billets has been built.](image)

![Figure 5. The magnetic flux density distribution of the 2D model is shown, and the maximum magnetic field in the iron core is 1.28 T.](image)

| Table 1. Specifications of the 2D simulation model. |
|---------------------------------------------------|
| Items                              | Specifications                  |
|---------------------------------------------------|
| Metal billet type                   | Aluminum Billet                 |
| Average temperature                | 723.15 - 773.15 K               |
| Rotation speed                      | 200 - 3000 rpm                  |
| Billet size                         | Φ200×1000 mm or smaller         |
| Width/height of the PM              | 1000/50 mm                      |
| Remanent flux density of the PM     | 1.4 T                           |
| Magnetic field at the center of the billet | 0.35 T                       |
4. Results and discussion

4.1. Electromagnetic field

The magnetic flux density distributions of the 2D model while the billet does not rotate are shown in figure 6. The maximum magnetic field in the iron core is 1.28 T when the billet is static, which indicates that the iron core is not saturated. The maximum magnetic field in the iron core reaches up to 2.21 T indicating the iron core is saturated when the billet moves to the right with 0.6 m/s, and the magnetic flux density distribution in the iron core varies greatly. The magnetic flux density on the right side of the iron core decreases with the horizontal movement speed and the left side opposite, which is the result of the interaction between the induced current in the billet and the permanent magnet.

Figure 6. The magnetic flux density distributions of the 2D model are shown when the horizontal movement speed of the billet without rotation is 0 (left) and 0.6 (right) m/s.

Figure 7. The magnetic flux density distributions in the billet are shown when the horizontal movement speed of the billet without rotation is 0 (left), 0.2 (middle), 0.6 (right) m/s.

Figure 8. The induced current and power density distributions of the billet are shown when the horizontal movement speed of the billet without rotation is 0.2 (left), 0.6 (right) m/s.
The relationships between magnetic flux density distribution of the billet and the horizontal movement speed when the rotation speed is 0 rpm can be seen in figure 7. It can be seen that the magnetic flux density distribution in the billet varies with the horizontal movement speed. And the magnetic flux density on the side of the movement direction of the billet increases with the horizontal movement speed, the other side opposite. The relationships between induced current density, power density distributions in the billet, and the horizontal movement speed when the rotation speed is 0 rpm can be seen in figure 8. The variations of the induced current and the power density are similar to the magnetic field. It can be seen that both the induced current and the power density concentrate on the side in the direction of movement, which can result in uneven temperature distribution.

The magnetic flux density distributions of the 2D model while the billet both rotates with 240 rpm and moves horizontally with 0 and 0.6 m/s are shown in figure 9. The maximum magnetic field in the iron core is 1.23 T when the billet only rotates with 240 rpm, which indicates that the iron core is not saturated. And the maximum magnetic field in the iron core reaches up to 2.14 T indicating the iron core is saturated when the billet rotates with 240 rpm and moves with 0.6 m/s. And the variation of magnetic flux density distribution in the iron core is similar to the case (figure 6) when the billet moves only horizontally. The relationships between magnetic flux density distribution of the billet and the horizontal movement speed when the rotation speed is 240 rpm can be seen in figure 10. We can see that the magnetic flux density on the side of the movement direction of the billet also increases with the horizontal movement speed and the other side opposite. And the magnetic flux density distribution for different rotation speeds is similar to the one for 240 rpm, but the magnetic field distortion caused by the induced current in the billet becomes worse when the rotation speed is larger. The relationships between induced current density, power density distributions in the billet, and the horizontal movement speed when the rotation speed is 240 rpm can be seen in figure 11. The variations of the induced current and the power density are similar to the magnetic field, that is, the induced current and the power density concentrate on the side in the direction of movement. But the radial temperature distribution of the billet is centrosymmetric due to the rotation of the billet.

**Figure 9.** The magnetic flux density distributions of the 2D model are shown when the horizontal movement speed is 0 (left), 0.6 (right) m/s, and the rotation speed of the billet is 240 rpm.

**Figure 10.** The magnetic flux density distribution in the billet are shown when the horizontal movement speed is 0 (left), 0.2 (middle), 0.6 (right) m/s, and the rotation speed of the billet is 240 rpm.
Figure 11. The induced current and power density distributions of the billet are shown when the horizontal movement speed is 0 (left), 0.2 (middle), 0.6 (right) m/s, and the rotation speed of the billet is 240 rpm.

4.2. Heating effect

The temperature distribution in the aluminum billet at the time 104 s when the horizontal movement speed of the billet is 0.2 m/s, and the rotation speed is 3000 rpm is shown in figure 12. We can see that the temperature at the center is lower than the one on the surface of the billet. The heating power injected in the billet, heating time, and temperature difference of the billet varying with the horizontal movement speed under different rotation speeds are shown in figure 13. The temperature difference is the difference between the maximum and the minimum temperature of the billet, which can reflect the uniformity of temperature distribution in the billet. It can be seen that the heating power and temperature difference increase with the rotation speed, however heating time exactly opposite. And the heating power and temperature difference decrease with the movement speed at a high rotation speed, however, heating time exactly opposite. And the heating power and temperature difference at low rotation speed decrease first and then increase with the horizontal movement speed of the billet, however heating time exactly opposite.

According to the above analysis, we can see that the horizontal movement speed will improve the temperature uniformity, but the heating time is longer. For example, when the rotation speed is 3000 rpm, and the horizontal movement speed is 1 m/s, the time for heating the aluminum to 773.15 K is 142 s, and the temperature difference is 71 K. But if the aluminum does not move horizontally and the temperature difference required is also 71K, then the rotation speed will be 2250 rpm, and the heating time is 133 s. We can see that the decrease of the horizontal movement on the heating time can be achieved by lower rotation speed.

Figure 12. The temperature distribution in the aluminum billet at the time 104 s. The movement speed is 0.2 m/s, and the rotation speed is 3000 rpm.
Figure 13. The total heating power injected in the billet, heating time and temperature difference of the billet vary with the movement speed under different rotation speeds.

5. Conclusion
The new superconducting DC induction heater can heat more than two aluminum billets once time. And the aluminum billet can both rotate on its axis and move around the center cylinder. The movement will cause the magnetic field to concentrate on the side of the motion direction. And the horizontal movement speed will improve the temperature uniformity, but the heating time is longer. The decrease of the horizontal movement on the heating time can be achieved by lower rotation speed. So this new structure does not improve the temperature difference effectively under considering the heating time. But it can enhance the heating power by times via increasing the number of aluminium billets at a time. Therefore, it can also improve the production efficiency more than the other superconducting DC inducting heater structure.

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