Analysis of the thermal-force roll profile control ability under different hole structures and slot structures in the RPECT

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Abstract
Roll profile electromagnetic control technology (RPECT) is a control technology for strip flatness based on the flexible control of roll profiles. As the core component, electromagnetic sticks can bulge with induction heating of induction coils. To ensure the integrity of the coil circuit, the surfaces of the electromagnetic sticks need to be provided with slots. Moreover, the inner hole of the electromagnetic control roll is also needed to install the electromagnetic stick in the roll. The structures of the inner hole and slots affect the local structure of the electromagnetic stick and the electromagnetic control roll and then change the roll profile control ability. To research the radial bulging ability, the roundness of bulging, and the composition between the thermal crown and force crown under different holes or slots, a finite element model of circumferential RPECT is established by using the finite element software Marc. After analysis, the results showed that the radial bulging ability and the roundness under the influence of the roll radius were larger than those under the influences of the slot radius and slot amount, and the composition characteristics of the comprehensive roll profile were different under different conditions. Therefore, to achieve accurate roll profile control, the influences of the structures of holes and slots need to be included in the RPECT index.

Keywords Roll profile electromagnetic control technology · Hole structure · Slot structure · Thermal-force roll profile control ability · Electromagnetic stick

1 Introduction
Roll profile electromagnetic control technology (RPECT) is a new strip flatness control technology based on a flexible control method for the roll profile. Considering the bulging mechanism of the electromagnetic stick (ES) and the internal restraint mechanism of the electromagnetic control roll (ECR), the roll profile of the ECR can be controlled to form a new roll profile with a controllable shape. In the control process, the multi-segment structure of the ES can be powered by coils in different sections, and thus, it can generate the target roll profile in the corresponding section of the coils to adjust the high-order and local strip flatness. Regarding RPECT, researchers have studied this technology and obtained a series of research results. Feng et al. proposed a large sleeved backup roll based on RPECT and analysed the characteristics of this roll [1]. By researching the induction heating efficiency, the energy conversion ability, and the roll profile, Liu et al. designed the structure of an ES with highly controlled performance and built an ECR with five control regions based on a φ560 × 2180 mm roll [2, 3]. Reling on the principle of RPECT and the new roll profile test technology, Du et al. designed and built a roll profile electromagnetic control experimental platform (RPECEP) to test RPECT [4]. Based on the relationship between the hardness and the elastic modulus, Wang et al. established the FE model of a heterogeneous electromagnetic control roll and proposed the influence of a heterogeneous treatment on the characteristics of RPECT [5]. The above studies are the basis of RPECT and promote the development of this technology. However, these studies did not include the
influence of the space occupied by the coil winding on the roll profile control ability. In RPECT, the structure of the ES includes the induction zone and the contact zone, as shown in Fig. 1. The induction zone can be used to wind the coils, and the contact zone can be used for thermal bulging. To build a closed circuit between the coils and the external power supply, slots for laying coil wires must be made in the surface of the contact zone. The number of slots is twice the number of the induction zones to ensure the input and output of the current. The space between the slots can change the local structure of the ES and then affect the electromagnetic control of the roll profile.

The ES is the core control element of RPECT and provides a thermal-force hybrid drive for roll profile control. Due to the influence of the local structure and local load, the structure of the slots and the ECR inner hole can change the roll profile and affect the roll profile control ability. Because the local structure can affect the results expected from the equipment, scholars have studied the problems associated with the control capabilities of different equipment. Lee et al. analysed the combustion characteristics of casting filters with porous media and found that the effective emissivity of porous media was 0.845; therefore, the operational safety of this casting filter was confirmed [6]. Based on thermochromic liquid crystal (TLC) technology, Li et al. analysed the film cooling performance on a rotating twisted turbine blade; the results showed that the film hole diameter on the leading edge had a significant effect on the spanwise average film cooling effectiveness [7]. Enke et al. proposed that the lifetime and performance of axial grooved ammonia heat pipes (HPs) and can be affected by the generation of noncondensable gas (NCG) and revealed how the presence of different amounts of NCGs distorted the temperature profile of the pipe [8]. Dai et al. developed a numerical model of the combustion and cooling performance of an aero-engine combustor and analysed the reduction of the thermal load by thermal barrier coatings with cylindrical, conical, fan-shaped, or console cooling holes [9]. Xu et al. compared and analysed the film cooling characteristics with two slot structures in a perpendicular crossflow channel and found that the film cooling effectiveness of slot-sectional diffusion holes was far superior to that of fan-shaped holes [10].

This type of research focuses on the analysis of specific objects and considers the impact of the local characteristics on the overall performance. This paper mainly studies the problem of the roll profile control ability and thermal-force hybrid driving for different hole structures and slot structures.

In view of the crucial influence of the local structure of RPECT on the control ability of the ECR and the thermal-force hybrid driving ability, this paper compares and studies several aspects of the ECR: roundness, radial bulging ability, and the stress and temperature fields for different roll radii, slot radii, and numbers of slots; this paper also discusses the thermal crown and the force crown in different cases.

2 Model establishment and verification

2.1 Model establishment

According to the literature [2], the FE model of RPECT includes simulations of the electromagnetic field and the thermal field and the nonlinear coupling relationship between them. The FE model also includes the ECR, ES, induction coils, and air. Based on the theory of electromagnetics and thermodynamics, an electromagnetic-thermal-mechanical coupled axisymmetric model has been built using MARC software in the literature [2–5], as shown in Fig. 2. This model has a high degree of consistency and a small deviation, while the results of the experiment and the simulation have been verified by the RPECEP. In the bulging process of the ES, heat was generated in the induction zone of the ES when the induction coils were electrified; then, heat was transmitted to
the contact zone of the ES to control the roll profile. The above model can simulate the temperature field in the contact zone and meet the needs of this study.

To study the influence of different hole structures and slot structures on the roll profile control ability, a FE model of circumferential RPECT is established in this paper. The object of this analysis is the slicing model of the ECR. The model includes the ECR with its inner hole, air units, and the ES with slot structures, as shown in Fig. 3. The contact zone of the ES can be divided into several slicing models. The slicing models have different roll profile control ability caused by the change in core temperature. Therefore, this paper takes the face at the end of the contact zone near the induction zone as the research object, which has a higher core temperature; the analysis results for this zone are representative.

Since the bulging of RPECT is driven by the thermal bulging of the contact zone of the ES, caused by heat from the induction zone of the ES, the core zone of the ES is the connection between the induction zone and the contact zone, as shown in Fig. 4. Therefore, the core zone of the ES can be selected as the thermal boundary used to study the circumferential bulging of RPECT in this model. Since the heat transfer inside the ECR has little effect on the temperature field of the core zone of the ES, the temperature variation in the thermal boundary can be derived from the electromagnetic-thermal-mechanical coupled axisymmetric model with the same size.

For the FE calculation, the frequency was 400 Hz, the current density was 3 A/mm², and the contact heat transfer coefficient \( h_1 \) was 3 kW/(m²·K) between the ES and ECR. The selected range of the roll radius was from 80 to 250 mm, the selected range of the slot radius was from 2.5 to 7.5 mm, and the selected range of the slot amount was from 4 to 8. The basic condition parameters of the hole structure and slot structure were as follows: the roll radius was 135 mm, the radius of the ECR inner hole was 60 mm, the slot radius was 3 mm, and the slot amount was 4. According to research in the literature [11], the optimum heat transfer coefficient \( h_2 \) is 1 kW/(m²·K) between the ECR and air. The radiation heat transfer was small enough to be ignored. The original temperature was 30 °C. The material of the ECR and ES was #45 steel. The thermal properties are shown in Fig. 5. The region within the 25 mm diameter in the core zone of the ES is the thermal boundary of the model, and the temperature variation within the control time can be calculated in the electromagnetic-thermal-mechanical coupled axisymmetric model. The temperature variation can be shown in Fig. 6.

### 2.2 Model verification

In this paper, the RPECEP was modified to measure circumferential bulging at different centre angles, as shown in Fig. 7. According to Formula (1), the radial bulging of the ECR can be calculated from the strain value of the foil gauge and the original length of the foil gauge:

\[
\Delta R = \frac{l + \varepsilon l}{\theta + \Delta \theta} \cdot R
\]  

where \( \Delta R \) is the radial bulging of the ECR, \( R \) is the original radius of the ECR, \( l \) is the original length of the foil gauge, \( \varepsilon \) is the strain value of the foil gauge, \( \theta \) is the angle at the centre of the circle corresponding to the length of the foil gauge, and \( \Delta \theta \) is the angle variation in the centre of the circle. Compared with the value of \( \theta \), the value of \( \Delta \theta \) is small and can be ignored in Formula (1).
The experimental conditions were as follows: the control frequency was 400 Hz, the control current was 90 A, the number of coil turns was 20, the ambient temperature was 17 °C, the maximum temperature of the temperature control point of ES was 130 °C, the structure of ES was the segmented electromagnetic stick, and the cooling intensity of the roll surface was 0 kW/(m²·K). Figure 8 shows the average radial bulging profile in the experiment and simulation. In the first stage of Fig. 8, the difference between the experimental results and the simulation results can be seen. The reason was that the contact between the ECR inner hole and the ES was insufficient in this stage, and magnetic flux leakage occurred, leading to an actual effect that was lower than the simulated effect. With the control of the roll profile, the ES bulged and came into close contacts with the ECR; the magnetic flux leakage phenomenon disappeared; and the regulation effect gradually achieved the expected effect.

Overall, the experimental results and the simulation results showed a high degree of consistency, and the deviation was small. Therefore, the circumferential FE model of RPECT can be used for researching the problem associated with RPECT, and the results are credible.

3 Results and discussion

3.1 The influence of the roll radius

To describe the state of the hole structure, the concept of the hole structure ratio of ECR is proposed, and the calculation formula is as follows:

\[ \delta = \frac{R_o}{R_h} \]  

where \( \delta \) is the hole structure ratio of the ECR, \( R_h \) is the radius of the ECR inner hole, and \( R_o \) is the radius of the ECR outer circle.

To study the influence of the hole structure on the roll profile control ability, the roundness and the radial bulging of the ECR for different \( \delta \) are shown in Fig. 9. In RPECT, when the thermal-force hybrid drive stabilizes, the roll profile of ECR can become a target, and then, it can be used to control the roll gap. Therefore, research on the roll profile control ability needs to be carried out about the stability of RPECT. In this paper, the stable status of every case was approximately

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**Figure 4** The connection diagram of ES zones

**Figure 5** The thermal properties of #45 steel

**Figure 6** Temperature variation in the core zone of the ES and the temperature control point
300 s, and the data were collected for stable states. The result in Fig. 9a shows that the variation in roundness can be considered in two stages. In the first stage, the roundness decreases gradually with increasing $\delta$, and the relationship between the roundness and $\delta$ can be considered an approximately linear correlation. In the second stage, when $\delta$ exceeds 2.8, the roundness does not decrease and gradually stabilizes at 0.04 μm. In contrast to the roundness, the radial bulging value continues to decrease with increasing $\delta$, as shown in Fig. 9b. Notably, there is a plateau in the radial bulging value in the range where $\delta$ is more than 1.6 and less than 2.4, and the radial bulging value does not decrease with the increase in $\delta$ in this plateau.
Considering that the roll profile of the ECR is composed of a force and a thermal contribution, further analysis of the stress and the temperature fields is needed for a causal analysis of this radial bulging plateau. Figure 10 shows the stress status of the ECR with different $\delta$. The result shows that the circumferential distribution of stress is asymmetric when $\delta$ is small. The circumferential uniformity of stress in Fig. 10a is the worst, and its stress field can be described as a quadrilateral distribution corresponding to four slots of the ES. When $\delta$ is increased to 2.25, the maximum stress of the roll surface among the cases appears, and the difference in stress between the roll surface and the ECR inner hole wall is much smaller than in the other cases. Moreover, the circumferential uniformity of stress is obviously improved compared with Fig. 10a. In Fig. 10c, the stress of the roll surface decreases, but the circumferential uniformity of the stress increases. In the control process, the stress field has a quadrilateral distribution near the ECR inner hole and a circular distribution far away from the hole. With increasing $\delta$, the scale of the quadrilateral distribution area decreases, while that of the circular distribution area increases. Furthermore, the variation in the roll radius can lead to the variation in stress between the roll surface and the ECR inner hole wall, resulting in the change in the stress and the temperature fields.

Figure 11 shows the temperature field of the ECR when $\delta$ is from 1.67 to 2.5. The result shows that the increase in $\delta$ has a nonlinear influence on the temperature distribution of the ECR. Compared with Fig. 11a and Fig. 11b, the roll surface temperature of the ECR is 62 °C with a 100 mm roll radius and 38 °C with a 135 mm roll radius. Due to the increase in $\delta$, the distance between the heat source and the roll surface decreases, which results in a decrease in the roll surface temperature. Compared with Fig. 11b and Fig. 11c, when $\delta$ is increased to 2.25, there is little difference among the roll surface temperatures of the ECR in different cases, and the scale of the temperature field is decreased.

To analyze the roll profile control ability, it is necessary to further analyze the variation in the force crown and the thermal crown under the influence of $\delta$. The force crown and the thermal crown for stable RPECT are shown in Fig. 12. When $\delta$ is increased from 1.67 to 2.25, the difference in the thermal crown is small, and the force crown decreases with the increase of $\delta$. When $\delta$ is increased from 2.25 to 2.5, the thermal crown is decreased, and the force crown is increased with the increase of $\delta$. Combined with the results of Fig. 9b, when $\delta$ is increased from 1.67 to 2.5, the change of the thermal crown is basically equal to that of the force crown, leading to mutual compensation between the thermal crown and the force crown. The compensation makes the comprehensive crown undergo little change, and the curve has a plateau.

According to the above results, when $\delta$ is increased from 1.67 to 2.5, the root cause of the compensation is that the effects of the temperature field and the stress field of the ECR on the roll profile are in dynamic equilibrium. The stress variation in the ECR is mainly affected by the thermal expansion mechanism of the ES and the internal restraint mechanism of the ECR; the two mechanisms are affected by the temperature fields of the ES and ECR. The results in Fig. 10a and Fig. 11a show that when the roll radius is small, the distance between the heat source of the ES and the ECR surface is shorter, the heat transfer from the ECR inner hole to the ECR surface is increased, the temperature difference between the ECR surface and the ECR inner hole is smaller, the internal restraint mechanism of RPECT is weakened due to the small roll radius, and the force crown is reduced. The results in Fig. 10b and Fig. 11b show that the temperature difference between the inside and the outside of the ECR is larger than that in the previous cases, but the internal constraint mechanism is still weak. At the same time, affected by the increase in $\delta$, the force bulging ability of the ECR is weakened, and the force crown is smaller than in the previous cases. The results in Fig. 10c and Fig. 11c show that the temperature difference between the internal and the exterior of the ECR is larger than in the first two cases: the high-temperature region is distributed near the ECR inner hole; and the internal restraint mechanism is stronger than in the first two cases. At this point, the force crown is still affected by the increase in $\delta$, but overall, the force crown increases. In addition, because the high-temperature region is smaller than in the first two cases, the thermal crown is also decreased. As in the above series of

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**Fig. 10** Stress field of the ECR with different $\delta$: a the roll radius is 100 mm, and $\delta$ is 1.67; b the roll radius is 135 mm, and $\delta$ is 2.25; and c the roll radius is 150 mm, and $\delta$ is 2.5
3.2 The influence of the slot radius

To analyse the influence of the slot radius on the roll profile control ability, the roundness of the ECR and the radial bulging for different slot radii are shown in Fig. 13. By increasing slot radius, the difference between the maximum bulging value and the minimum bulging value can be increased, and the variation in radial bulging can be decreased. When the slot radius is increased from 2.5 mm to 7.5 mm, the maximum roundness is 0.291 μm, and the corresponding roll bulging value is 46.76 μm. Furthermore, the minimum roundness is 0.076 μm, and the corresponding roll bulging value is 59.29 μm. The roll profile control ability and the circumferential uniformity can be significantly weakened when the slot radius increases. In this process, the slot with the larger radius can provide more installation space for the induction coil, indirectly improve the selection range of the coil cross-sectional area, and expand the adjustable range of the current.

To further analyse the reason for the variation in radial bulging, the internal stress fields of the ECR with different slot radii are extracted, as shown in Fig. 14. With increasing slot radius, the scale of the stress field of the ECR continuously decreases, the maximum stress value decreases, and the stress field near the ECR inner hole begins to show a quadrilateral distribution. This phenomenon is the result of the reduction in the contact area of the ES, while the slot is expanding, and the distribution of contact pressure between the ES and ECR begins to exhibit the cam effect. When the slot radius is larger, the cam effect is more obvious. Even when the slot radius is 7.5 mm, the ECR has a symmetrical internal stress field controlled by four bulging regions, and the asymmetry of the stress field is intensified.

Figure 15 shows the temperature field of the ECR with different slot radii. The temperature field of the ECR also has a nonuniform circumferential distribution. Compared with the stress field, the temperature field is less sensitive to the slot radius. The reason for this phenomenon lies in the difference between the thermal contribution roll profile and the force contribution roll profile in RPECT. The heat can be transferred in the circumferential direction, but the contact pressure can only act on the contact surface between the ES and the ECR. When the slot radius is small, the circumferential transmission of heat is not affected by the slot, and the temperature field cannot be affected by the slot structure of the ES, as shown in Fig. 15a and Fig. 15b. However, when the slot radius is large enough, the space occupied by the slot can block the circumferential heat transfer around the ES, forming four thermally affected fan-shaped zones at right angles, which leads to the difference in the internal constraint mechanism of RPECT, as shown in Fig. 15c and Fig. 15d.
Figure 16 shows the variations in the thermal crown and the force crown with the slot radius. With increasing slot radius, the force crown first increases and then decreases; the thermal crown first decreases, then tends to be stable, and finally decreases. Combined with the previous analysis, when the slot radius is less than 4 mm, increasing the slot radius can increase the proportion of the force crown in the comprehensive roll crown, and the comprehensive roll crown decreases less as a result. When the slot radius exceeds 4 mm, increasing the slot radius does not increase the proportion of the force crown, and this can cause the comprehensive roll crown to decrease.

In addition to the bulging ability, the stress distribution of the ES with different slot radii should be analysed because the slots change the local structure of the ES. The stress status of the ES under different slot radii is extracted, as shown in Fig. 17. The results show that when the slot radius increases, the internal stress of the ES and the risk of crushing the ES increase. The high-stress region appears around the slots and in the centre of the ES. When the slot radius is 2.5 mm, 3 mm, and 5 mm, the size of the stress and the scale of the stress field in the core of the ES are basically the same, and the stress field in the core can be regarded as a circular distribution; when the slot radius is 7 mm, the high-stress area of the ES can connect the core of the ES with the area around the slot and form the maximum stress around the slot. This decreases the roll profile control ability of the ES and increases the roundness, which is not conducive to achieving the goal of roll profile control.

### 3.3 The influence of the slot amount

According to the above study, electromagnetic sticks with 2.5-mm, 3-mm, and 5-mm slots are selected to study the influence of the slot amount on the roll profile control ability. Figure 18 shows the roundness of the ECR and the variation in radial bulging with different numbers of slots. The roundness of the ECR and the variation in radial bulging can decrease with increasing slot amount, and the decreasing trend is more
obvious when the slot radius is larger. This shows the improvement of circumferential uniformity and the decrease of the roll profile control ability after electromagnetic control roll bulging. When there are 4 slots, the regularity of the roundness and the radial bulging variation are the same as in the previous analysis; when the number of slots increases, the roundness value is less for the ECR with a 3-mm slot than the ECR with a 2.5-mm slot, and the reduction of the radial bulging value is less for the ECR with a 3-mm slot than the ECR with a 5-mm slot. Moreover, the results in Fig. 18b show that the radial bulging ability is better for the ECR with a 3-mm slot than the ECR with a 5-mm slot for arbitrary numbers of slots. Therefore, a reasonable configuration strategy can be to use the slot radius and the slot amount to reduce the roundness of the ECR while ensuring that the roll has the control ability required for strip flatness control.

Figure 19 shows the stress status of the ECR for different amounts and radii of slots. With increasing slot amounts, the stress field around the ECR inner hole can be described by a polygonal distribution. The number of sides of this polygon corresponds to the slot amount. In addition, the heterogeneity of the stress distribution can be enhanced with increasing slot radius, which increases the heterogeneity of the force contribution to the roll profile. When the slot amount and slot radius are large, a large stress can form in the contact position between the ECR inner hole and the surface of the ES, and the stress field far from the ECR inner hole also presents a polygonal distribution trend.
**Fig. 19** Stress status of the ECR under different slot amounts: a) $R_s=2.5\text{ mm, } N=4$; b) $R_s=2.5\text{ mm, } N=6$; c) $R_s=2.5\text{ mm, } N=8$; d) $R_s=3\text{ mm, } N=4$; e) $R_s=3\text{ mm, } N=6$; f) $R_s=3\text{ mm, } N=8$; g) $R_s=5\text{ mm, } N=4$; h) $R_s=5\text{ mm, } N=6$; and i) $R_s=5\text{ mm, } N=8$.

**Fig. 20** Temperature field of the ECR under different slot amounts: a) $R_s=2.5\text{ mm, } N=4$; b) $R_s=2.5\text{ mm, } N=6$; c) $R_s=2.5\text{ mm, } N=8$; d) $R_s=3\text{ mm, } N=4$; e) $R_s=3\text{ mm, } N=6$; f) $R_s=3\text{ mm, } N=8$; g) $R_s=5\text{ mm, } N=4$; h) $R_s=5\text{ mm, } N=6$; and i) $R_s=5\text{ mm, } N=8$.
Figure 20 shows the temperature field of the ECR under different slot amounts and slot radii. The temperature field around the ECR inner hole is also affected by the space occupied by the slot, which shows a polygonal distribution, and the side number of the polygon is the same as the slot amount. When the slot radius is 2.5 mm, the slot amount has little influence on the temperature distribution around the ECR inner hole. The reason is that the smaller slot cannot block the circumferential heat transfer between the ES and the ECR, and the temperature field can still be homogenized on the inner hole wall of the ECR. With increasing slot radius, the slot size is large enough to block circumferential heat transfer on the inner hole wall of the ECR, and the temperature field begins to show a nonuniform distribution. When the slot radius is 5 mm, the ECR temperature field for various numbers of slots presents a nonuniform phenomenon, and the temperature near the ECR inner hole is far less than that in the other cases. Therefore, the thermal expansion ability and the internal restraint ability are greatly reduced.

To further analyse the influence of the changes in the stress field and the temperature field on the roll profile control ability, the thermal crown and the force crown are extracted for different cases, as shown in Fig. 21. The result in Fig. 21a shows that the thermal crown can be decreased by increasing the radius and the number of slots. According to the result of Fig. 20, with the increase in the slot radius or slot amount, the temperature field of the ECR is weakened, and the thermal bulging ability of the ECR can be decreased. Notably, when the slot radius is larger, the decrease in the thermal crown is larger with an increasing slot amount. In the case of a large slot radius and many slots, the heat transfer area between the ES and ECR is greatly reduced by the influence of the slots, resulting in the weakening of heat transfer between the ES and the ECR, the decrease of heat storage in the ECR, and the decrease of the thermal expansion ability.

The result in Fig. 21b shows that the entire trend of force crown variation is a slight increase at first and then a decrease with an increase in the slot amount. Therefore, the change in the force crown can be regarded in two stages. In the first stage, when the slot radius or the slot amount increases, the contact area between the ES and the ECR is decreased, and the temperature of the ES can be increased, resulting in an increase in the ES bulging ability and an improvement in the force crown. In the second stage, although the bulging ability of the ES is enhanced, the internal restraint ability of the ECR is weakened due to the influence of the temperature field, which reduces the contact stress between the ES and the ECR, and the force crown is decreased.

Figure 22 shows the stress status of the ES for different slot amounts. The results show that the stress field scale of the ES can be increased with increasing slot amounts, and the increase in slot amount has little influence on the stress field of the core of the ES and has an influence on the stress field in the area between the two slots. The previous analysis shows that the high-stress region appears around the slots and the core of the ES. The slots are the local structure of the ES surface. When the slot amount is increased, the distance between two slots is decreased, and the surface structure of the ES can be changed. Different high-stress regions can be connected, and the stress scale of the area between two slots can be increased. The increase of the slots is symmetrical and cannot change the symmetry of the stress field of the ES. Moreover, the slot can affect the surface structure of the ES, but not the core structure. Therefore, the influence of the slots on the stress field of the core of the ES is less.
4 Conclusion

In this paper, the hole structure and the slot structure, the radial bulging ability, the roundness of bulging, and the contributions of the thermal crown and the force crown for different holes or slots are discussed. The conclusions obtained are as follows:

(1) The radial bulging ability and the roundness are larger under the influence of the roll radius than under the influences of the slot radius and the number of slots; the number of slots is the least influential factor. Due to the difference in heat force hybrid driving under different conditions, the comprehensive crown, which is composed of the thermal crown and the force crown, differs.

(2) In ECR with the same inner hole and different roll radii, an increase in the roll radius can decrease the roll profile control ability, while the roundness can be well maintained. In this process of a roll radius increase, a plateau in radius deformation is obtained by the dynamic equilibrium between the temperature field and the stress field, and the existence of a variation curve of radial bulging must be considered in the process of ECR selection. To ensure the roll profile control ability and the demand of the mill roll system, a smaller roll radius can be selected.

(3) The slot radius and the slot amount can determine the current load of the coil and the number of segments of the ES. Increasing the slot radius and number of slots can decrease the value of the radial bulging for the ECR, and the roundness can be maintained below 0.3 μm. The ES with a 3-mm slot radius, and 8 slots have good comprehensive crown control ability and roundness, and it can be used for different rolling conditions.

Author contributions The analysis of roundness, temperature field, stress field, and roll profile control ability were done by Tingsong Yang; FE model establishment and FE model validation were carried out by Jiayang Liu and Haonan Zhou; experimental platform was built by Jiayang Liu and Zhiqiang Xu with the support of Fengshan Du; Tingsong Yang revised the paper. All authors have read and agreed to the published.

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Declarations

Ethical approval Not applicable.

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