Analysis of thermal-mechanical coupling and structural optimization of continuous casting roller bearing

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Abstract

The continuous casting roller bearing was one of the important parts of continuous caster [1], its working temperature was relativity high, the working load was also very large and the working condition was complex. Since the external heat of casting roller bearings was much higher than internal, the continuous casting roller bearing was different from the general high-speed rolling bearing with heavy load. If the external heat that the bearing suffered could not dissipate in time, the extreme high working temperature might accelerate the failure of the bearing and severely reduce the productivity of the caster. To optimize the thermal structure of the continuous casting roller bearing, the thermal coupling analysis of the bearing should be conducted. Firstly, the stress field of the working continuous casting roller bearing should be analysed by ANSYS and the three-dimensional geometric CAD model and the CAE model of it should be established. Then find out the location where the bearing suffered the largest force by stress analysis, in the case of bearing block with cooling water, load the working temperatures to the bearing, after analysing, the result showed that the external temperature was the main contributor of internal stress, and the rolling element was the part inside of the bearing which suffered the largest stress. To optimize the structure of the continuous casting roller bearing, the rolling element was turned into axial hollow structure, which could reduce the extreme stress of the rolling element bearing. By analysing all the maximum thermal stress of rolling element in different feasible hollowness, and finally the most suitable hollowness could be found out. The analysis results above showed that the optimization of the rolling element structure of the bearing could effectively reduce the internal stress and improve reliability of bearings in high working temperature. The conclusion of this study was significant in bearing optimizing or designing.

Keywords: thermal stress, coupling, structural optimization, continuous casting roller

1 Introduction

Casting roller bearing [2] was a kind of rolling bearing, the motion of internal rolling bearing was quite complex, since the bearings could be easily damaged in high temperatures, and the temperature analysis and stress analysis of continuous steel billet and continuous caster itself were quite complex, it was too hard to give a theoretically description or analysis of the bearing. There had been many experts and scholars from China or foreign countries who contributed themselves in finding the cause of failure of the bearing on the basis of researching its temperature. But they almost tend to study the complex internal heat which generated by heavy load and high-speed operation, but there was still few studies under the situation of external heat generation higher then internal. The analysis of rolling bearing temperature field is mainly based heat transfer theory [3]. Analyse and calculate the distribution of bearing temperature field during the heat transfer process by using a combination of theory and simulation methods, the parts which had risk to failure and the steady temperature field without lubricating oil could be predicted during the steady process of bearing. The analysis of the rolling bearing temperature field was mainly based on heat transfer theory; researchers could only study it by actual measuring through the site and testing in the laboratory, which largely relies on the experience accumulated by long-term of work, and these methods still had practical significance on today's studies. However, with the development of iron and steel smelting technology and computer science, traditional experimental methods had shown a lot of drawbacks, which unable to give an accurate result in practical; therefore they could not meet the current needs of the development of steel industry. At present, many research institutions and production enterprises, both here and abroad, applied the finite element techniques to metallurgical equipment design and optimization studies, analysed and calculated the distribution of bearing temperature field during the heat transfer process by using a combination of theory and simulation methods, predict the parts which had risk to failure and the steady temperature field without lubricating oil during the steady process of bearing. They had made a lot of phase achievement. Therefore, conducting mathematical simulation by using the finite element analysis software had become an important means of future research work.

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2 The construction of finite element model of the continuous casting Roller

2.1 THREE-DIMENSIONAL MODEL OF THE CONTINUOUS CASTING ROLLER

The relationship feature of casting rolling bearing model was very complex which was not easy to use the self-modelling, so the mesh division should be use finished in professsional software. The methods that most researchers used are: Firstly, use certain CAD drawing software (such as SOLIDWORKS, PROE, UG, etc.)to transform two-dimensional engineering drawing into the overall structure three-dimensional drawings, and then export to the file (such as iges, step, etc.) that CAE pre-processing software could recognize, finally introduce the model into CAE pre-processing software and make necessary topologies corrections and mesh division [4], the whole CAE model structure could be eventually finished. Since exporting in STEP format might always lost key feature of the model, in this paper, IGS format was used to export the model after finished it with three-dimensional graphics software, for better topology correction and mesh division in CAE pre-processing software. According to the bearing models and drawings provided by a steel mill, use the popular 3D CAD software to build a three-dimensional CAD assembly model of the whole casting rolling bearing (as shown in Figures 1 and 2).

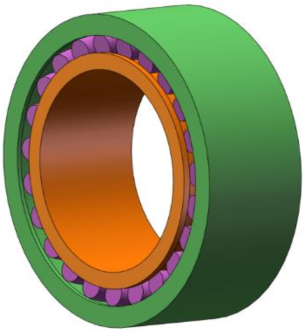

FIGURE 1 Three-dimensional CAD model of the continuous casting roller

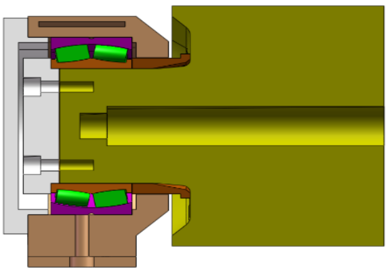

FIGURE 2 Three-dimensional CAD assembly model of the continuous casting roller (section view)

All parts were sat by the way of parametric feature modelling. Firstly, draw sketches of every part, and then generate solid parts according to the shape of each part by stretching, rotating, excision, etc. In sketching and feature modelling, the dimension of three-dimensional geometric model of the part should be set strictly in accordance with the engineering drawings and technical requirements. Every position of parts in the assembly should be located follow the coaxial, overlapping surfaces, parallel with the distance and other different assembly principals. In the assembly process, all the connections in the assembly should be joined in full accordance with requirements of the drawings and specifications of the mechanical coupling.

2.2 BUILD THE FINITE ELEMENT MODEL OF THE CONTINUOUS CASTING ROLLER

In this paper, the mesh model was built by using CAE pre-processing simulation software, in strict accordance with the dimensions and structural characteristics of the three-dimensional CAD geometry model.

This paper mainly considered the impact of load on the bearing, so the commonly used SOLID45 unit should be chosen in the stress analysis. According to the characteristics of the bearing structure, solid elements were used in the meshing process. The model should be reasonable divided to ensure the accuracy of simulation results with the number of grid as less as possible. The model should be divided into mesh after carefully considering, with a large amount of grids, although the computing result could be more accurate, it might also take higher computer resources and a lot more time to finish this simulation. In meshing for bearing stress analysis, the number of grids could be reduced reasonably. As for the density of grid, using the uniform grid, could not only ensure the reasonable amount of meshes, but also avoid the unexpected error caused by the mutations of grids.

Figure 3 was a three-dimensional mesh model of the casting roller, which was used for thermal analysis of the bearing; Figure 4 is a partial mesh structure of bearing caster roller. In order to better simulate the actual working conditions, the assembly mesh model of casting roller bearing was shown in Figure 5. Meshing assembly model was the most difficult task, because of the water cooling pipe inside of it [5], the internal meshing should be divided as well, the tetrahedral and pentahedral mesh were also been used where the shape was extremely irregular. Mesh quality of this site is not as high as hexahedral mesh but the number of tetrahedral mesh or pentahedral mesh grid were little, the impact of the entire model was negligible.

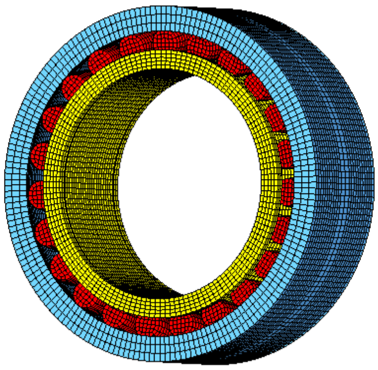

FIGURE 3 The three-dimensional mesh model of the continuous casting roller bearing

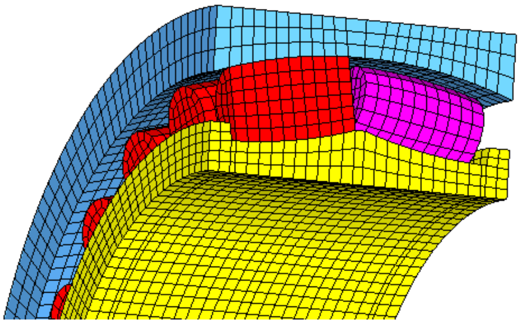

FIGURE 4 The part of three-dimensional mesh model of the continuous casting roller bearing

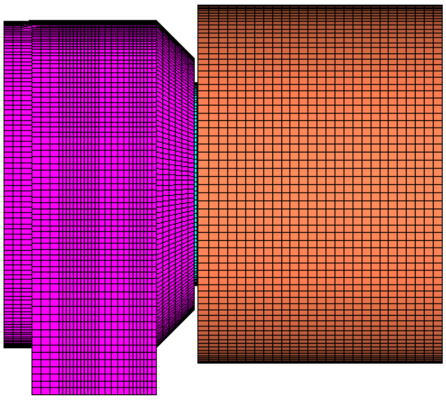

FIGURE 5 The three-dimensional mesh model of the continuous casting roller bearing assembly

3 The continuous casting roller bearing stress field analysis

3.1 MECHANICAL ANALYSIS OF THE CONTINUOUS CASTING ROLLER

3.1.1 The mechanical analysis of the continuous casting roller

In calculating the force [6], the bulging force of steel billet should be considered, the bulging force caused by static pressure of molten steel should be calculated by the mechanical model which based on a certain pair of static pressure between molten and continuous casting roller. As for the force on the nip rolls, it should be calculated follow the theory of material mechanics, such as the equal cross-section beam with both ends fixed and a uniform distributed load (static pressure of molten steel). The calculation of the force on *i*-th roller:

$$F_i = \rho g h_i l_i \left(w - 2k\sqrt{\frac{L}{V_c}} \right), \tag{1}$$

where ρ is the density of liquid steel, the units are kg·m^{-3}. h_i is the relative height of *i*-th pair of rollers to the steel surface, the units are m. l_i is the spacing between *i*-th pairs of roller, the units are mm. w is the width of the billet, the units are mm. L is the arc length of the billet from the mold level, the units are mm. V_c is casting speed, the units are m·min^{-1}. K is the integrated coagulation factor, the units are mm·min$^{-1/2}$.

In the sector segments, when a light dynamic pressure is given to the billet, these segments would get a reacting force caused by the deformation of billet. Therefore, the force could be calculated by flat rolling theory, when the soft-reduction process was conducted on the rollers. As shown in the Equations (2) and (3):

$$P = \sigma 2\delta\sqrt{2R\Delta h - \Delta h^2}\ , \tag{2}$$

$$\Delta h = Ql\ , \tag{3}$$

where σ is the average pressure on unit rolling, the units are t·mm^{-2}. δ is the thickness of casting billet, the units are mm. R is the radius of the pressured rollers on continuous casting roller, the units are mm. Δh is the reduction of casting roller, the units are mm. Q is the reduction rate of casting roller, the units are mm·m^{-1}. l was roller distance, the units are m.

If the production model of steel billet was Q235, the width of billet was 1550mm and the casting speed was 1.2 m/min^{-1}. After calculating, the pressure of No.20 free roller in sector segments (lower roller) was 273KN. All the stress analysis in this paper was based on the 20th free roller (lower roller) casting roller.

3.1.2 The mechanical analysis of the continuous casting roller bearing

Took stress analysis of the No. 20 free roller bearing in sector segment continuous casting roller. Where there were two rollers with total two pairs of bearings, the mechanical analysis of the continuous casting roller was shown in Figure 6.

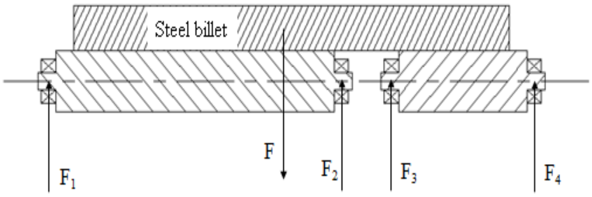

FIGURE 6 The schematic diagram of force on the continuous casting roller

F is the force between roller and casting billets. $\mathbf{F_1}$, $\mathbf{F_2}$, $\mathbf{F_3}$, $\mathbf{F_4}$ are the reaction force given by the bearing.

As shown in the graph, the equation could be drawn according to the mechanical balance [7]: $F-F_1-F_2-F_3-F_4=0$.

By further calculations the following result could be drawn, F_1=0.27F, F_2=0.31F, F_3=0.23F, F=0.19F.

Then it could be drawn the maximum stress of second bearing, F_2=0.31×273KN=84.63KN.

The load carrying capacity of the bearing according to the data provided by the manufacturer was shown as follow, F_{load}=Cr×e=394KN×0.32=126.08KN.

By comparison, it could be known that the supporting bearings in ideal conditions would not be overloaded.

3.2 THE BOUNDARY CONDITIONS OF THE CONTINUOUS CASTING ROLLER THERMAL STRESS ANALYSIS

The coefficient of thermal expansion between different structures that interacted or different parts of the same structure were mismatched. When temperature rose or lowed degree of expansion and contraction was inconsistent with each other, which led to the generation of thermal stress.

3.2.1 The boundary conditions of the continuous casting roller thermal stress analysis

The constraints of continuous casting roller bearing only existed in one place, it was the constraint at the bottom seat of the bearing. That was at the bottom bearing node constraint on its outer surface in radial and tangential and axial displacement of three directions.

3.2.2 The working load of the continuous casting roller thermal stress analysis

Bearing load under steady state was the force from continuous casting roller of bearing. Owing to the model involved only a part of the continuous casting roller, when the applied load needed to bending load, temperature load on the model, using APDL [8] language to read the temperature field calculation results file, the finite element software would automatically obtain the temperature value of each node.

When there was only stress simulation for stress field, the boundary conditions were the same, but it did not need to add the temperature load.

3.3 THE THERMAL STRESS ANALYSIS OF THE BEARING IN THE BEARING SEAT WITH COOLING WATER

The simulation results of maximum stress and thermal stress in each part of the continuous caster roller bearing were recorded, as shown in Table 1.The Table 1 showed that under the temperature load, the continuous casting roller bearing stress almost increased twice and the influence of the temperature on the load bearing was very obvious, and the stress was only 20.4 MPa less than the allowable stress, working under such a high stress the casting roller bearing was easy to failure and it showed that the failure of continuous casting roller was significantly related to the temperature. At the same time, it could be seen that although the temperature of the inner ring was highest, it was still smaller than rolling elements and the maximum stress and the rolling element was the part, which suffered the largest stress in the continuous casting roller bearing.

TABLE 1 The result of each part of the continuous casting roller bearing maximum stress compared with the thermal stress

	Maximum stress (MPa)	The maximum thermal stress (MPa)	The allowable stress of bearing material (MPa)
Continuous casting roller bearings roller	249.3	411.3	
Outer ring	120.2	245.1	431.7
Inter ring	176.0	321.8	
Rolling element	249.3	411.3	

4 The optimization analysis of the continuous casting roller bearing

Take the inner ring as a benchmark, the temperature of rolling elements was different in different positions of the bearing and the stress was changeable. Because of rotating of the bearing, it could be understood that the temperature changed with the rotating of rolling elements and the thermal stress was also continuously variable. And this change will lead to the fatigue damage of bearing rolling elements. The structure of the bearing rolling body should be changed to reduce the stress, so as to improve the life of the bearing.

The middle part of rolling bearing was changed into a hollow to improve the stress distribution. And the rolling body was changed into a hollow [9], the heat transfer in the heat convection and heat radiation under the same condition was relatively small. Because of the hollow, the rolling body could produce self-deformation due to offset the stress produced by thermal and quality, so, the stress of the overall rolling body decreased. And it prolong the working life of bearing.

Hollowness was used to represent the size of roller hollow. Hollowness refers to the ratio of the radius of hollow roller and actual radius of the hollow, it was an important parameter of hollow roller bearing and it must be moderate. The hollowness was too small to reflect the superiority of hollow roller or too large to reduce the bearing ability. It was not appropriate. According to the convention, the thermal stress was analysed of rolling bodies with hollow degree of 20%, 30%, 40%, 50%, 60%, 70%. The result of simulation analysis was shown in Figures 7-12.

From Figures 7-12,it could be seen that with the increase of rolling body hollow ratio, the stress of the rolling body was constantly decreasing, which once again showed that the finite element analysis was consistent with the actual situation. However, the hollow ratio of rolling body could not increase indefinitely, to ensure the bearing strength and service conditions, there should be an upper limit.

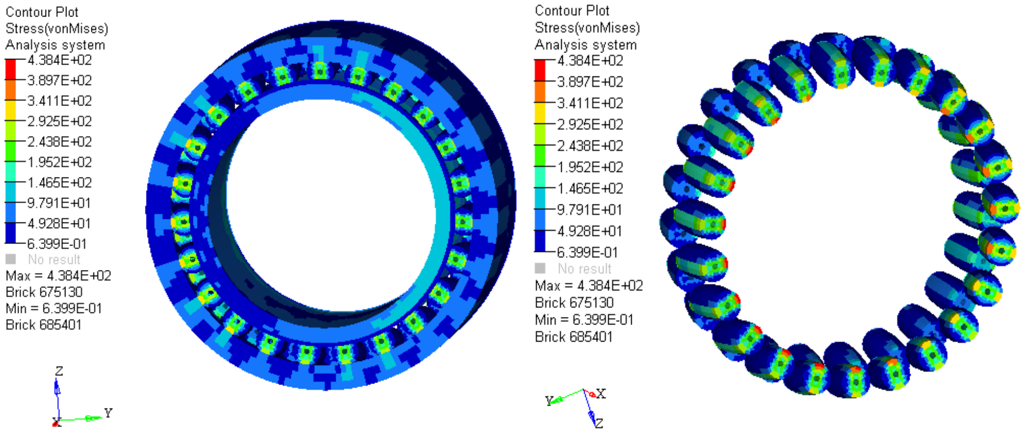

FIGURE 7 The thermal stress field of bearing when the roller hollowness was 20%

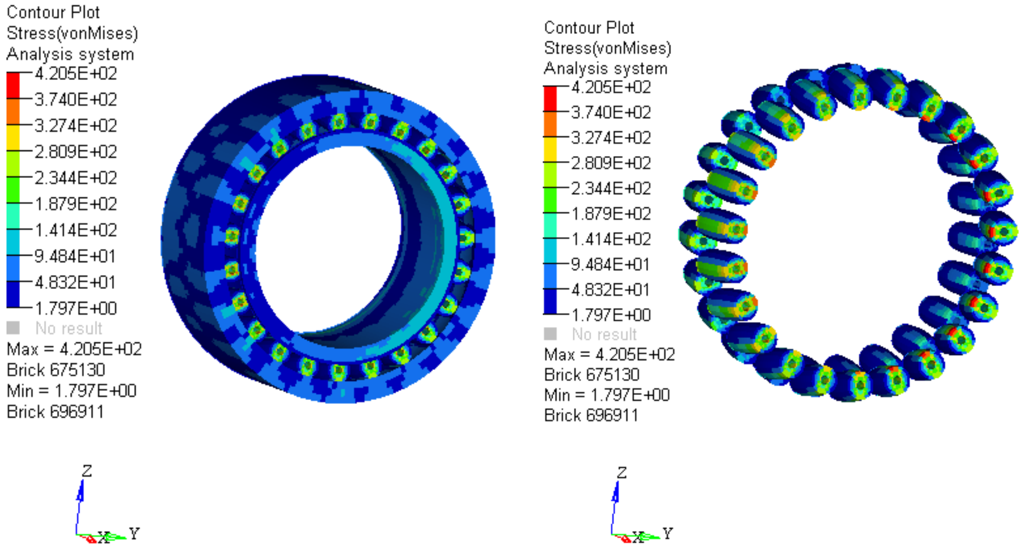

FIGURE 8 The thermal stress field of bearing when the roller hollowness was 30%

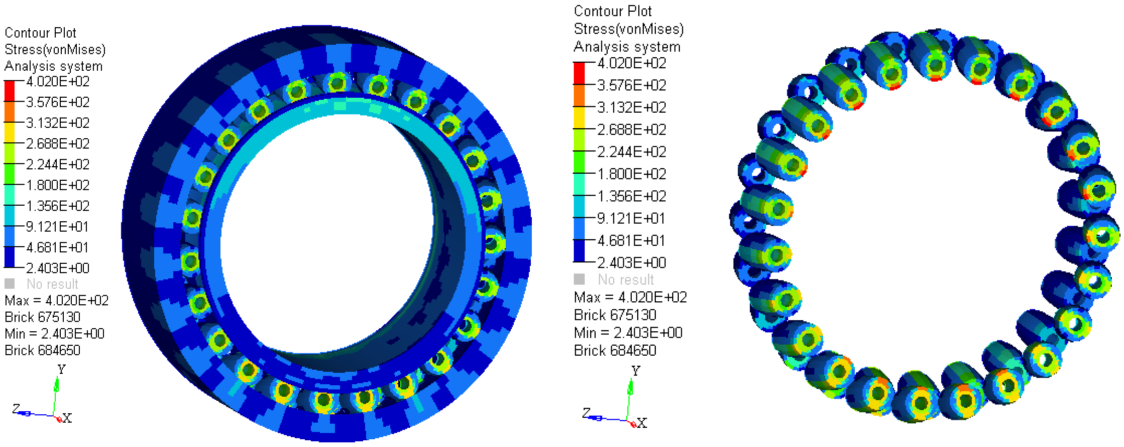

FIGURE 9 The thermal stress field of bearing when the roller hollowness was 40%

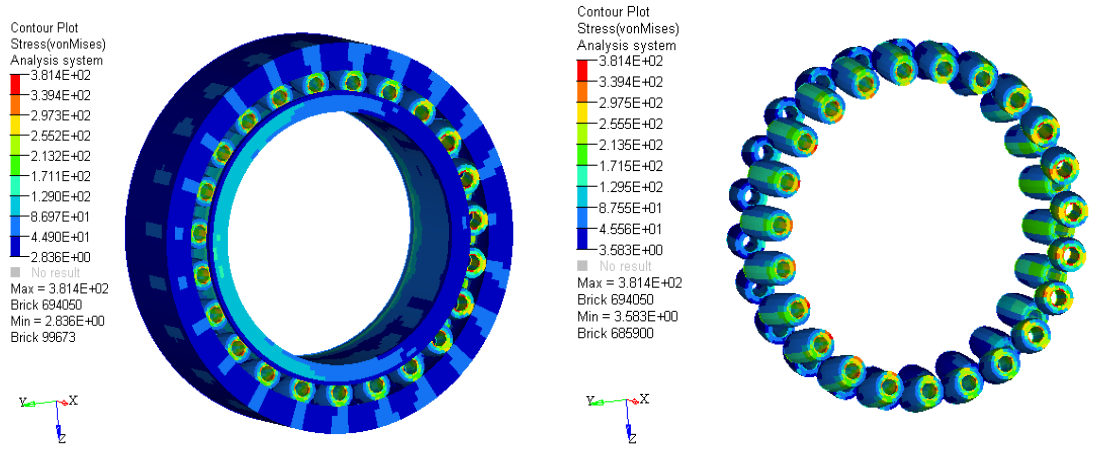

FIGURE 10 The thermal stress field of bearing when the roller hollowness was 50%

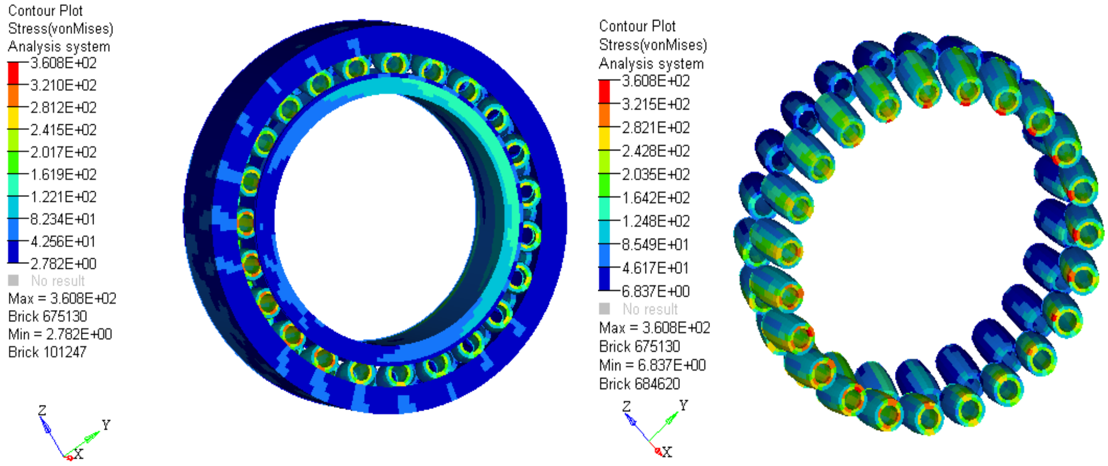

FIGURE 11 The thermal stress field of bearing when the roller hollowness was 60%

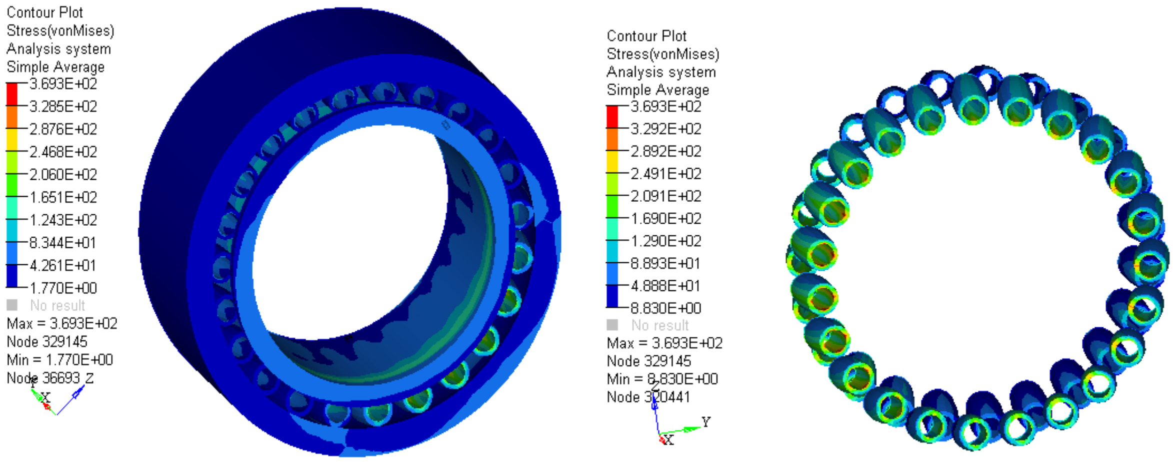

FIGURE 12 The thermal stress field of bearing when the roller hollowness was 70%

By analysing, the maximum thermal stress curve of bearing could be obtained in different roller hollowness. As shown in Figure 13.

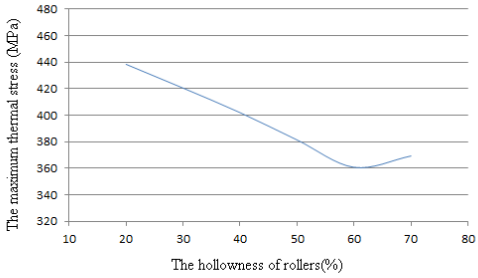

FIGURE 13 The maximum thermal stress curve of bearing roller in different roller hollowness

By observation, it could be seen that the part which the bearing subjected to the maximum stress on the roller. And with the increase of roller hollowness[10], when the roller hollowness was 60%, the bearing subjected to the minimum stress, was 360.8MPa, smaller 50.5MPa than the roller without hollowness. It compared with the allowable stress, in this case the bearing was not easy to failure. Also it could be found that the rolling body stress distribution become uniform, to a certain extent, it also optimized the thermal stress distribution of casting roller bearing and play a role of reference for bearing design.

5 Conclusion

By analysing the stress field of continuous casting roller bearing, it could be found that the maximum stress of bearing was 249.3MPa when the bearing seat was applied cooling water and not applied thermal load, and the coupling stress was 411.3MPa, while the thermal stress caused by temperature was large, the result had been very close to allowable stress of bearing material. At the same time the bearing operating temperature was very high, and the temperature distribution was not uniform, the deformation of bearing different parts caused by different temperature rise of bearing different parts was also inconsistent, affected the bearing accuracy and the rotary bearing capacity of bearing, thus the temperature was the main cause of the failure of continuous casting roller bearing. By altering the hollowness of rolling body from the structure to reduce the stress, and simulated the optimization scheme then the result showed that bearing subjected a minimum stress when the rolling body hollowness was 60%, and the stress distribution was relatively uniform. Thus, it improved the bearing internal heat dissipation and extended the service life of bearing, also played a role of reference for bearing design.

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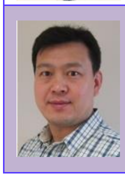	**Honghai Liu, born in 1973, P.R. China** **Current position, grades:** professor in Intelligent Systems, Head of Intelligent Systems and Biomedical Robotics, University of Portsmouth. **University studies:** PhD in Intelligent Robotics in 2003 from Kings College, University of London, UK. **Scientific interest:** approximate computation, pattern recognition, multi-sensor based information fusion and analytics, human machine systems, advanced control, intelligent robotics and their practical applications. Publications: 320

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