STRUCTURAL CHARACTERISTICS ANALYSIS AND OPTIMIZATION OF MODEL 350 ROLLING MILL

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ABSTRACT: Static analysis and dynamic analysis are carried out for the structural characteristics of the rolling mill. Through the equivalent stress and its deformation distribution of the rolling mill and the housing under the static load, it is tested whether it meets the strength and stiffness requirements. Then, the modal analysis of the whole housing of the rolling mill is carried out, and six order modal parameters are extracted to analyze the dynamic characteristics of the rolling mill. Under the requirements of the rigidity and strength of the rolling mill rolls, the optimization and improvement of the rolling mills provide a theoretical basis for the production enterprises to reduce costs and increase the productivity of the rolling mill.

KEYWORDS: rolling mill; modeling; structural characteristics; optimization

1 INTRODUCTION
Since the beginning of the 21st century, the steel industry has still played a leading role in the world economic system, and steel materials are the main basic materials for global applications. In the development of metallurgical industry, advanced rolling technology and rolling mill are important ways to roll steel in rolling steel production (Zhou and Yang, 2016; Xu and Han, 2006).

The Model 350 rolling mill was modeled in three dimensions by SolidWorks software, and the ANSYS Workbench software was used to analyze the structural statics of the roll and housing of the rolling mill. The analysis shows the equivalent stress distribution and the respective displacement deformation distribution of the roll and housing of the 350 type rolling mill under certain working conditions, so as to check whether the stiffness and strength requirements are met (Tang, 2006). Dynamic analysis of the rolling mill is carried out to obtain the relevant parameters of six order natural frequency and the natural vibration mode of the rolling mill. The effects of various vibration modes on the stiffness and strength of the relevant parts of the rolling mill are analyzed in detail.

Based on the above analysis results, the optimization design is carried out by ANSYS Workbench. According to the analysis of the model, the position and stress distribution of the maximum stress when the roller is subjected to the maximum rolling force is obtained. The optimized design is carried out by opening a hole in the middle of the roll. Taking the diameter of the hole as the independent variable and the mass as the objective function, the best design scheme for obtaining the maximum diameter under the requirement of strength and stiffness is analyzed, which provides a reliable basis for the optimization of the rolling mill.

2 ESTABLISHMENT OF FINITE ELEMENT ANALYSIS MODEL FOR 350 TYPE ROLLING MILL

2.1 Working principle and technical parameters of rolling mill
The object of this paper is to the 350 type rolling mill with a roll diameter of 350mm, which is a two-roll reversing rolling mill. The technical parameters are shown in Table 1. The working principle (Yang et al., 2010) is shown in Figure 1.

Table 1, Technical parameters of 350 type rolling mill

<table>
<thead>
<tr>
<th>Project</th>
<th>Parameter</th>
<th>Project</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll diameter (mm)</td>
<td>350</td>
<td>Roll arrangement</td>
<td>Two-roll mill</td>
</tr>
<tr>
<td>Roller length (mm)</td>
<td>700</td>
<td>Rack arrangement</td>
<td>Single housing</td>
</tr>
<tr>
<td>Rolling speed (m/s)</td>
<td>2.25</td>
<td>Configuratio n power (KW)</td>
<td>680</td>
</tr>
<tr>
<td>Rolling pressure (T)</td>
<td>80</td>
<td>Rolling temperature (°C)</td>
<td>1000</td>
</tr>
</tbody>
</table>
2.2 Three-dimensional solid model of 350 type rolling mill

The solid parts of the rolling mill’s housing, roll, left and right adjustment device and other key components were built with SolidWorks software, and the 3D solid model of the rolling mill was imported into the ANSYS Workbench software for structural static analysis of the roll and housing of the rolling mill.

### Table 2, material properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>Poisson’s ratio</th>
<th>Elastic Modulus (GPa)</th>
<th>Yield Strength (MPa)</th>
<th>Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZG340-640</td>
<td>7850</td>
<td>0.3</td>
<td>202</td>
<td>340</td>
<td>640</td>
</tr>
<tr>
<td>ZG270-500</td>
<td>7850</td>
<td>0.3</td>
<td>180</td>
<td>270</td>
<td>500</td>
</tr>
<tr>
<td>40Cr</td>
<td>7870</td>
<td>0.277</td>
<td>211</td>
<td>980</td>
<td>785</td>
</tr>
</tbody>
</table>

(2) Meshing type

There are several types of meshing including: Hex Dominant, tetrahedrons, and automatic (Wang, 2011). Select reasonable correlation and reasonable division method and size to make a reasonable grid division. Some places can be roughly divided. When some precision requirements are relatively high, they should be carefully divided. The structure of the 350 type rolling mill is very complicated and has a lot of force. According to the actual working requirements, the method of automatically dividing the grid is adopted, the grid size is set to 20 mm, and the contrast is selected to be 100. Such a division method is reasonable for analysis and calculation.

2.3 Definition for mesh properties

Define some basic properties of the research object before meshing, it usually includes: the material properties of each component of the research object, and the type of the divided mesh. By defining the mesh properties to pave the way for the next step of the mesh, it is to send a signal to the software, which kind of mesh to use to divide the selected research object.

(1) Definition of the properties of the materials used in each part of the rolling mill

The properties of the material usually include the following attributes: density of the material, elastic modulus of the material, Poisson's ratio of the material, elastic modulus of the material, yield strength of the material, and tensile strength. The research object of this paper is the 350 type rolling mill. The whole housing adopts ZG270-500, the roller adopts ZG340-640, and the connecting rod and nut adopt 40Cr. The performance properties of these three materials are shown in Table 2.

2.4 Definition of boundary conditions

When the meshing is completed, the research object should be constrained and the boundary conditions should be defined according to the actual working conditions of the research object and the structural characteristics of the research object. According to the structural characteristics of the object to be studied and the actual working conditions, the load to be received and the constraints to be fixed are selected. The position between the upper and lower rolls is adjusted by the hand wheel, and the rolling is performed by the screw. Therefore, in order to simplify the analysis, the rolling force is directly applied to the rolls, the base is fixed, and the total rolling pressure at both ends is performed. Both are 21975N. The boundary condition of the

Rolling mill and the boundary condition model of the rolling mill after the load setting are shown in Figure 3:
3 STATIC CHARACTERISTICS ANALYSIS

3.1 Static analysis of the overall structural strength of the rolling mill

By setting the cell properties of the finite element model of the rolling mill, selecting the material properties, rationally dividing the cells, defining the boundary conditions and other pre-treatments, the equivalent stress and deformation of the overall structure are solved, and the rolling mill is obtained. The equivalent stress contour map is shown in Figure 4.

Through the above analysis, the following conclusions can be drawn:

When the rolling mill is in working condition, the rolling mill is mainly affected by rolling force and gravity. As shown in Fig. 4, the maximum stress on the rolling mill mainly occurs between the roll and the bearing housing, and the maximum equivalent stress value is 94.634Mpa. By examining the actual working conditions of the rolling mill, it can be seen that the maximum equivalent stress of the rolling mill under this working condition does not exceed the allowable stress. Therefore, the strength of the rolling mill meets the design requirements. It can be seen from the above equivalent stress contour map that the strength of the rolling mill is high, but to improve the manufacturing precision of the rolling mill, it is necessary to select a suitable optimization method. It is possible to reduce the importance of the rolling mill by appropriate, and at the same time to check whether it meets the strength requirement, whether the maximum equivalent stress value is less than the allowable stress value, and through multiple analyses and experiments, select the best solution to achieve the purpose of optimization design.

3.2 Finite Element Analysis of Rolling Mill Stiffness

Through the static analysis of the overall rolling mill, it can be seen that the maximum deformation of the overall housing of the rolling mill is at the axial end of the roll, and the maximum deformation value is 0.097446 mm. The maximum deformation position of the overall housing of the rolling mill in the X direction is at the bottom of the housing, and the maximum deformation value is 0.003878 mm. The maximum deformation position of the overall housing of the rolling mill in the Z direction is at the lower bearing seat and the base of the housing, and the maximum deformation value is 0.0097619 mm. The maximum deformation position of the overall housing of the rolling mill in the Y direction is at the axial end of the upper roll, and the maximum deformation value is 0.095398 mm.

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3.3 Finite element analysis of rolling mill housing

The rolling mill housing is an important part of the rolling mill. It is a permanent part among the key components of the rolling mill, and the structure and stress conditions of the rolling mill housing are complicated. Moreover, the rigidity and strength of the rolling mill affect the working safety of the rolling mill and the accuracy and quality of the rolled product directly. Therefore, the analysis of the rolling mill housing is very important (Fan and Liu, 1995; Zhang et al., 2014). Therefore, this paper conducted a finite element analysis of the housing of the rolling mill.
Through the above analysis, the following conclusions can be drawn:

It can be seen from the equivalent stress contour map that the maximum deformation of the rolling mill housing occurs at the position of the lower beam of the housing, and the maximum equivalent stress is 27.246 MPa. With the same calibration method as above, it is known that the maximum stress of the rolling mill housing does not exceed the allowable stress and meets the strength requirements of the material. Moreover, it can be seen from the equivalent stress contour map that the housing of the rolling mill has a large optimization space, and the rigidity can be reduced to meet the strength requirements to optimize the quality. From the obtained displacement deformation contour map, it can be seen that the maximum displacement deformation of the rolling mill housing occurs in the middle of the bottom beam of the rolling mill housing, and its value is 0.022547 mm, which meets the strength requirements.

3.4 Finite element analysis of rolling mill rolls

In order to choose the optimum roll diameter, it is necessary to consider such factors as the minimum gauge in rolling, consumption of energy, shape control faculty, allowable roll contact pressure (Hajime, 1983). Therefore, the finite element analysis of the rolling stock rolls is crucial for the accuracy and quality of the rolling mill steel. The strength, stiffness and deformation of the rolls have a great influence on the rolled products, and have a great influence on the rolling speed of the rolling mill and the production efficiency of the rolled products. Therefore, a finite element analysis was performed on the rolls of the rolling mill.

It can be seen intuitively from the contour map, under the working condition, the maximum equivalent stress distribution of the rolling mill rolls is at the joint of the rolling mill rolls and the bearing seat. The maximum stress value is 176.94 MPa, which meets the strength requirements. The maximum displacement deformation of the rolling mill rolls occurs in the middle of the roll, and the maximum displacement shape becomes 0.085663 mm. According to the design criteria, it meets the stiffness requirements. The roll has a large optimization space, which can reduce the roll quality under the requirement of the roll strength and rigidity, so as to optimize the roll.

4 DYNAMIC CHARACTERISTICS ANALYSIS

4.1 Principles of model analysis

Model analysis is a method of analyzing the natural frequency and modal shape of a structure. In fact, it is to solve the structural vibration equation of the research object. The structural vibration equation (Yu et al., 2004; Wang and Liu, 2009) is:

\[
[M][\ddot{\xi}] + [C][\dot{\xi}] + [K][\xi] = \{P\}
\]  

(1)

where

\[ [M]: \text{The quality matrix of the research object; } \]
\[ [K]: \text{The stiffness matrix of the research object; } \]
\[ [C]: \text{The damping matrix of the research object; } \]
\[ \{\ddot{\xi}\}: \text{Research object node acceleration vector; } \]
\[ \{\dot{\xi}\}: \text{The node velocity vector of the research object; } \]
\[ \{\xi\}: \text{Research object node displacement array; } \]
\[ \{P\}: \text{The load array of the study object.} \]

Since the damping of the research object is very small in the modal analysis, let \{P\} be a zero matrix, so that the free vibration equation of the member in the undamped state is obtained:

\[
[M][\ddot{\xi}] + [K][\xi] = 0
\]  

(2)

The form of the solution to this equation is:

\[
\{\xi\} = \{\xi_0\} \sin(\omega t + \psi)
\]  

(3)

Where

\[ \{\xi_0\}: \text{The amplitude of the node; } \]
\[ \omega: \text{The natural frequency of the vibration; } \]
\[ \psi: \text{The initial phase of the vibration; } \]
\[ t: \text{Time} \]

The linear equation is:

\[
[K] - \omega^2[M][\xi] = 0
\]  

(4)
When the determinant of the (3) coefficient is equal to zero, there will be a non-zero solution as shown in (5).

\[
[K] - \omega^2[M] = 0 \tag{5}
\]

4.2 Results of modal analysis

When the modal analysis of the rolling mill is carried out, its pre-processing steps are basically the same as the static analysis. The modal analysis of the whole housing of the rolling mill was carried out (Meng, 2015; Zheng et al., 2013), and six order modal parameters were extracted to analyze the dynamic characteristics of the rolling mill.

![Fig.16 First-order mode shape result](image1)

![Fig.17 Second-order mode shape result](image2)

![Fig.18 Third-order mode shape result](image3)

![Fig.19 Fourth-order mode shape result](image4)

![Fig.20 Fifth-order mode shape result](image5)

![Fig.21 Sixth-order mode shape result](image6)
Through the above analysis, the following conclusions can be drawn:

After analyzing the influence of the first six-order modal characteristic parameters of the rolling mill on the working performance of the rolling mill, the maximum deformation of the rolling mill can be obtained under various frequency frequencies of the rolling mill. It is found that the frequency of each step has little effect on the normal operation of the rolling mill. The six order modes obtained by modal analysis are shown in Figure 16 to Figure 21.

The first-order mode has little effect on the rolling mill housing. The maximum deformation of the rolling mill is 0.74443 mm, and it mainly occurs at the upper beam of the rolling mill housing and at the connecting rod of the housing. This is because the connecting rod itself is relatively thin. Under the working condition of the rolling mill, the two side housings are connected, and the load is large, so the rigidity is small, and the deformation is large. It can be improved by increasing the diameter of the connecting rod and the material, but from the viewpoint of the normal working performance of the rolling mill, the first-order vibration mode has little effect on the rolling process of the rolling mill.

The vibration amplitude of the second-order mode is relatively large compared with the first-order mode. The maximum deformation of the rolling mill occurs in the middle of the connecting rod of the upper beam of the housing, and the maximum deformation is 4.1902 mm. The maximum deformation of the third-order formation also occurs in the middle of the upper beam of the housing, with a maximum deformation of 0.886 mm.

The fourth, fifth and sixth-order modes are mainly realized as the connecting rods of the lower beam of the rolling housing, and the maximum deformation amounts are 9.4216 mm, 9.5066 mm and 10.681 mm respectively. It can be seen that the deformation amount of the connecting rod is large and the rigidity is small, which has a great influence on the work of the rolling mill, hinders the normal rolling process of the rolling mill and reduces the rolling precision of the rolling mill. Therefore, it is necessary to optimize the rolling mill connecting rod.

From the above analysis of contour map, it can be intuitively found that the first, second, third, fourth, fifth, and sixth-order modes have a great influence on the connecting rod of the rolling mill housing. Under the working conditions of the rolling mill housing, deformation of the front and rear, left and right, up and down may occur, which will reduce the rigidity and strength of the rolling mill housing, and will accelerate the wear of the rolls and reduce the rolling speed.

5 STRUCTURAL OPTIMIZATION DESIGN

In scientific research and engineering practice, there are a large number of target optimization problems, such as structural optimization, shop scheduling, and program optimization etc (Kang and Zou, 1981; Wang et al., 2015).

5.1 Optimization analysis steps

The basic theory of optimization is to obtain the optimal optimization design by establishing an optimization model and using various mathematical optimization algorithms to obtain the maximum or minimum value of the objective function through multiple iterations. Recently the mathematical model of the widely used optimization design is as follows:

\[ f(x) = f(x_1 + x_2 + \ldots + x_n) \]

\[ g_i(x) = g_i(x_1 + x_2 + \ldots + x_n) \quad (i = 1, 2, \ldots, n) \]

\[ h_i(x) = h_i(x_1 + x_2 + \ldots + x_n) \quad (i = 1, 2, \ldots, n) \]

The objective function: \( f(x) \), the constraint function: \( g_i(x) \), \( h_i(x) \) are the structural response obtained from the analysis of ANSYS Workbench, and the design variable \( x \) is mainly determined by the model parameters.

From the previous analysis, we found that the strength and rigidity of the rolling mill rolls are better. Therefore, according to the structural characteristics and force characteristics of the rolling mill roll, a small hole can be opened in the center of the roll, and the diameter of the hole is selected as a design variable. The maximum equivalent strength of the roll and the maximum displacement deformation are taken as the state quantity, and the target mass is minimized as the objective function. A small hole is opened in the middle of the roll shaft, and the optimal solution is obtained by multiple iterations (A.F.M 2004).

In the optimization process, the diameter: \( d \) of the small hole opened in the center of the roll is a design variable, and \( 10 \text{mm} \leq d \leq 160 \text{mm} \), state variable extracts the maximum equivalent stress value and the maximum displacement deformation value in the static analysis solution result. The constraint is the maximum equivalent stress value \( \text{SIG}11 \leq 235 \text{MPa} \), Maximum equivalent displacement \( \text{SIG}22 \leq 0.5 \text{mm} \), The total weight of the roll \( W_t \) is the optimized objective function. After setting the input parameters and output
parameters, change the input parameter range to 10-160mm. After the parameter setting is completed, the value of the output parameter will be automatically produced, as shown in Figure 22.

After the parameter setting is completed, the value of the output parameter will be automatically produced, as shown in Figure 22.

Fig. 22 Design points for roll optimization

5.2 Optimizing the analysis plan

This article has designed the following two optimization scenarios:

Option 1: The input parameter of the diameter of the hole in the rolling mill is regarded as the non-target type, and the two output parameters of the maximum equivalent stress and the maximum displacement shape variable are selected as the maximum value, and the quality of the rolling mill roll is set to the minimum value. The optimized results obtained through analysis and calculation is shown in Fig. 23.

Fig. 23 Rolling mill roll optimization plan result one

From the analysis of the results in Figure 23, it can be obtained that in the optimization scheme 1, the first candidate design point is the optimal solution, and the latter two candidate design points are unreasonable. The quality of the rolling mill rolls obtained by this scheme is 578.59 kg, and the diameter of the small holes opened in the rolling mill rolls is 160 mm.

Option 2: The diameter of the small hole opened in the rolling mill roll, the maximum equivalent stress of the rolling mill roll and the maximum shape variable are taken as the non-target type, and the roll quality of the rolling mill roll is set to the minimum value. The optimization results obtained by analysis are shown in Figure 24:

Fig. 24 Rolling mill roll optimization plan result two

It can be seen from the analysis of Fig. 24 that the candidate design point 1 is the best design scheme, and it is verified that the maximum equivalent stress and the maximum shape variable of the rolling mill roll are satisfied. The diameter of the small hole opened in the rolling mill roll is 160 mm, and the roll quality is 578.59Kg.

Table 3. Optimization of the optimal solution of rolling mill

<table>
<thead>
<tr>
<th>Diameter of the Opened hole (mm)</th>
<th>Maximum equivalent stress of rolling mill rolls (MPa)</th>
<th>Rolling mill roll maximum displacement deformation (mm)</th>
<th>Minimum quality of rolling mill (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td>216.02</td>
<td>0.20044</td>
<td>578.59</td>
</tr>
</tbody>
</table>

When studying the influence of the diameter change of the small hole in the rolling mill roll on the quality of the rolling mill roll, the correlation curve between them is analyzed by ANSYS Workbench, as shown in Fig. 25. At the same time, the equivalent stress contour map of the rolling mill roll after optimization is shown in Fig. 26. The displacement deformation contour map of the rolling mill roll after optimization design is shown in Fig. 27.
CONCLUSION

(1) By studying the equivalent stress contour map and the displacement deformation contour map of the overall housing of the rolling mill under the working condition of the rolling mill, the maximum equivalent stress and the maximum deformation of the overall housing of the rolling mill are obtained, so that the strength and rigidity of the overall housing of the rolling mill are checked.

(2) The model analysis of the overall structure of the rolling mill is carried out. Extract the model parameters of the first six orders of the rolling mill housing, including the corresponding mode contour map and the natural frequencies of each order. According to the various modes of vibration pattern, the influence of each mode shape on the structural characteristics of the housing is analyzed reasonably.

(3) Optimize the roll of the rolling mill, select the diameter of the opened hole as the independent variable, take the maximum equivalent stress and the maximum displacement deformation of the roll as the boundary conditions, and minimize the mass of the overall housing of the rolling mill as the objective function. The best solution to meet the stiffness and strength requirements of the rolling mill rolls was chosen.

ACKNOWLEDGMENT

The project was supported by a key research project of Higher Education of Henan Province (17A460019), Postgraduate Education Reform Project of Henan Province. North China University of Water Resources and Electric Power Mechanical engineering Excellence in teaching team project

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