Finite Element Analysis of Misalignment and Contact State on the Interface of Bearing Bore Under Preload Condition

Meng Zhaohang\textsuperscript{2, a}, Ma Wei\textsuperscript{1, b*}, Zhou Ping\textsuperscript{2}, Zhang Zhenyu\textsuperscript{2}, Ding Ze\textsuperscript{1}

\textsuperscript{1}Weichai Power Company Limited, Weifang, Shandong, China
\textsuperscript{2}School of Mechanical Engineering, Dalian University of Technology, Dalian, Liaoning, China
\textsuperscript{a}e-mail: mengzh@mail.dlut.edu.cn
\textsuperscript{*Corresponding author: \textsuperscript{b}e-mail: maw@weichai.com

Abstract:} The split bearing bores of diesel engine are generally bored after tightening bolts to install crankcase and cylinder block. Machining accuracy significantly affects the contact state during sliding bearing operation, thereby reducing the service life of bearing. For effectively suppressing misalignment of interface caused by deformation of bearing bore, this paper presents finite element model and experimental measurement. The theoretical analysis and numerical calculation of interface are carried out in this paper. The finite element models of bearing bore and interface between crankcase and cylinder block are established to quantitatively analyze the deformation characteristic and contact state. The results indicate that the contact pressure of interface increases gradually with increase of the pre-tightening torque. The sliding distance of interface is positively correlated with the contact pressure of interface. Furthermore, the direction and value of the principal stress are calculated by measuring the strain of nodes around the bearing bore. Differential forces on both sides of bearing bore lead to joint surface sliding. Finite element simulation results are compared with experimental results to verify the finite element model.

1. Introduction
Manufacturing is the leading industry of the national economy. The internal combustion engine is regarded as the primary resource for automotive and automobiles\textsuperscript{[1-2]}. The engine is the core of various mechanical equipment, and the engine manufacturing capacity is one of the symbols of national industry. Due to the features of high efficiency, durability, reliability and good economic performance, diesel engines are widely used in the transportation, automotive, agricultural application and industrial sector\textsuperscript{[3]}. Diesel engine production industry has formed a series of supporting enterprises. With the continuous improvement of engine performance, the requirements of the crankcase in the manufacturing process are increasing, especially in the processing of crankshaft bores, it has put forward higher requirements.

The bearing bore of diesel engine is one of the locating datums during assembly\textsuperscript{[4]}, it maintains the crankshaft and bearing in accurate relative position during engine operation\textsuperscript{[5-6]}. The deformation of bearing bore greatly affects diesel engine performance. The manufacturing process of the main bearing bore generally adopts the combined processing method under preload condition. After bolts are tightened, problem such as bearing bore deformation occurs. Bearing bore deformation not only affects the circular degree of bearing bore but also results in the misalignment of interface between crankcase and cylinder block.
In the past few years, scholars published several systematic academic papers to analyse the deformation of bearing bore during manufacturing and assembly process. Stenin\cite{7} proposed a mathematical model for the crank mechanism of a diesel engine. Stancekova et al.\cite{8-9} analysed the causes of bearing ring deformation during heat treatment and manufacturing process. Linjamaa et al.\cite{10} established a parametric calculation model for sliding bearing considering the elastic deformation of the bearing surface. Cho et al.\cite{11} introduced finite element-based assessment of the gasket and bolt to characterize the degree of fretting of the interface between crankcase and bearing cover. Zhang et al.\cite{12-13} developed a multiscale numerical model to analyse the microscopic interfacial property of bolted composite structure.

Previous studies have mainly analyzed the deformation of bearing bore in working process instead of pre-tightening process. But these papers lack the research on the misalignment of the interface between crankcase and cylinder block. In this paper, the finite element model of diesel engine is established in Hypermesh after calculating values of penalty stiffness and material parameters. The finite element analysis of different pre-tightening torque is carried out in Ansys to illuminate the mechanism of bearing bore deformation and interfacial misalignment under preload condition. The principal stress is calculated after measuring the strain around bearing bore, and the finite element simulation results are compared with experimental results to verify the validity of finite element model.

2. Finite element analysis

2.1. Problem statement
Crankshaft is one of the most critical components in diesel engine, which is installed in bearing bore. The reliability and lifetime of diesel engine depends heavily on the machining accuracy of bearing bore. In the manufacturing process of bearing bore, bolts should be pre-tightened to assemble crankcase and cylinder block before boring process. In this process, misalignment of the interface between crankcase and cylinder block occurs.

![Fig. 1 Misalignment of interface between crankcase and cylinder block.](image)

2.2. Finite Element model
Finite element analysis is an effective method to analyze contact state. A finite element model is established in Hyper Mesh. In order to calculate the deformation of bearing bore accurately, elements near bearing bore are divided precisely.
Three contact pairs are presented in Fig. 2 which represents three interfaces between different rough surfaces.

Contact pair ①: interface between crankcase and cylinder block.
Contact pair ②: interface between crankcase and 14 bolts.
Contact pair ③: interface between crankcase and 3 locating pins.

In order to perform contact analysis in Ansys, the penalty stiffness $K$ needs to be set in finite element model.

$$K = \frac{E(1-\nu)}{2\xi_0(1+\nu)(1-2\nu)}$$  \hspace{1cm} (1)

where $\nu$ is the poison’s ratio of the whole interface, $\xi_0$ is the thickness of interface used in FEM model. Pre-tightening force can be calculated by:

$$F = \frac{T}{d\left[\frac{d_2}{d_2} \tan(\phi + \rho_v) + \frac{\mu}{3d}\left(D_7 - d_0\right)\right]}$$  \hspace{1cm} (2)

where $T$ is pre-tightening torque, $\mu$ is equivalent coefficient of friction. Follows are geometric parameters of bolts: $d$ is the nominal diameter of bolt, $\phi$ is lead angle, $\rho_v$ is equivalent frictional angle, $d_2$ is pitch diameter, $D_w$ is the torus diameter of nut, and $d_0$ is the diameter of bolt hole. M18 bolt fasteners were selected.

2.3. Finite element analysis

Mechanical device is composed of various components according to certain requirements. The surface in contact between different components is called “mechanical bonding surface” or “interface” for short. The core of interfacial analysis is the contact research of two rough surfaces. The analysis of the contact state of rough surface has important application value, and it has significant influence on the static and dynamic characteristics of the whole machine[14-15].
Due to manufacturing tolerances of contact surfaces, the contact stress is not theoretically distributed on a rigid plane. Furthermore, the initial forces will be redistributed non-uniformly in the presence of lateral loads\cite{16}. Contact pressure is concentrated near the bearing hole. As the pre-tightening torque increases, the contact stress is concentrated on the area close to the bolt.

When the pre-tightening torque increases, the area of stick region increases while the area of sliding region decreases. The maximum of contact pressure is located at the area between two bolts. The maximum of contact pressure is 151.03 MPa. Macro-slip occurs at the edge of bolt hole along the circumference. Contact pressure gradually decreases away from the bolt hole.
Fig. 4 Sliding distance of different pre-tightening torques.

The sliding distance of interface increases with increase of pre-tightening torque. Compare Fig. 4 with Fig. 3, the contact pressure is inversely proportional to the sliding distance. In areas with low contact pressure, the sliding distance is large. The maximum of sliding distance is 19.14 μm. The increase of pressure on the contact surface results in the increase of sliding distance.

3. Experiment

3.1. Strain measurement

The strain of main bearing bore is measured by static resistance strain indicator. Strain rosette is composed by three strain gauges, which are used to measure the strain in the direction of 0°, 45° degree and 90° respectively. In this experiment, the strain values of crankcase and cylinder block on both sides of bearing bore (nodes 1, 2, 3, 4) are measured by four strain rosettes. In the experiment, a strain gauge is isolated and connected to the public temperature compensation terminal. Paste it on the same material where there is no strain for temperature compensation.
Twelve channels of resistance strain indicator are used to measure the three-way strain values of four nodes. Numbers of 12 channels are illustrated in Fig. 5. Four nodes in this experiment are conducted to measure the strain values around the bearing bore under pre-tightening torque of 140 N\(\text{m}\). The equipment is controlled by software to measure the strain. The public temperature compensation method is adopted to prevent the influence of temperature in the process of strain measurement.

3.2. Principal stress
The stress values in X direction, Y direction and shear stress of the nodes at measuring points are obtained by strain measurement. The principal stress of the measured point is obtained by calculation. Compared with experimental results, the stress diagram is presented in Fig. 6.

During the process of pre-tightening bolts, the direction of principle stress of adjacent nodes is opposite. The opposite principal stress causes the crankcase and cylinder block to move in opposite direction, which leads to the misalignment of interface. Due to the influence of the single locating pin, the tangential forces at nodes 1 and 2 are less than tangential forces at nodes 3 and 4. The angle between the
principal stress and the vertical direction is the largest at node 4, leading to more amount of misalignment than another side.

4. Conclusion
The installation of diesel engine adopts combined processing method under preload condition. In the assembly process of diesel engine, crankcase bolts are tightened. Bearing bore deforms under the effect of stress, and the misalignment of the interface between crankcase and cylinder block occurs. In order to effectively suppress the misalignment of the main bearing bore caused by assembling process, the finite element analytical model of bearing bore is established. The finite element model is used to quantitatively analyse the frictional characteristics of the interface between crankcase and cylinder block.

(1) During the bolt preloading process, the contact pressure of interface is positively correlated with the pre-tightening torque. With the increase of contact pressure, the area of stick region increases and the area of sliding region decreases. The tangential force of interface increases with increase of pre-tightening torque. When tangential force is high, micro-slip between asperities occurs, the entire interface begins to slide, resulting in macro-slip.

(2) During the process of tightening bolts, the directions of principle stress of adjacent nodes are opposite. The opposite principal stress causes the crankcase and cylinder block to move in opposite direction, which leads to the misalignment of interface. The sliding distance on the side constrained by unilateral locating pin is less than another side.

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