Detection methods for residual stress of assembled camshaft

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Abstract. Compared with the traditional integrated camshaft, the assembled camshaft has the advantages of lowering production cost, reducing engine weight and improving engine performance, with a broad development prospect. The assembled camshaft is connected by different processes will cause residual stress which will seriously affect the mechanical properties of camshaft. Therefore, the measurement of residual stress is of great importance to the safety and reliability of assembled camshaft. This paper mainly introduces three detection methods currently applied to the residual stress of the assembled camshaft, namely X-ray diffraction method, Hole-Drilling method and Finite element simulation.

1. Introduction
Including a shaft, several cams and other components, a assembled camshaft is connected by various processes, which can be manufactured according to different performance requirements to better exert the performance of the material. After this camshaft is assembled, the residual stress is generated on its surface and inside. The working cam can be easily induced cracks by this stress, which is a great threat to the safety and reliability of camshaft operation. Therefore, studying on the detection of residual stress of assembled camshaft is necessary. Due to the geometries of the camshafts of different manufacturing processes of the same type are relatively close, the residual stress measurement methods of the conventional camshaft are also applicable to the assembled camshaft.

The paper mainly describes three methods currently applied to the detection of residual stress in camshafts, namely X-ray diffraction method, Hole-Drilling method and Finite element simulation. The first two detection methods mainly use specific experimental equipments to measure residual stress, while the last method mainly operates ANSYS, ABAQUS and other software to achieve detection.

2. X-ray diffraction method
In 1929, Russian scholars proposed the basic principle of X-ray stress measurement. Due to the effects of residual stress, the lattice spacing inside the camshaft is changed. Meanwhile, the macroscopic strain is generated. X-ray diffraction technique can be used to calculate the lattice strain by measuring the diffraction on angle of its internal lattice (Figure. 1). The macroscopic strain of the camshaft can be obtained by using the elastic mechanics. According to the consistency of the lattice strain and the macroscopic strain, the macroscopic stress can be calculated. With this technique, since ordinary
X-rays have limited penetration into the metal layer, it is necessary to perform surface depth removal using electrolytic polishing to perform deeper residual stress measurement, but the deviation caused by the removal layer must be corrected.

In 1956, Moore M G et al. [1] took the elastic theory formula to derive modified formulas for the residual stress of the removed layer based on some simple geometric assumptions. However, these formulas did not apply to complex geometries, such as cam lobes and gears, etc. In 2007, Ricardo CLA et al. [2] presented a new stress correction algorithm based on research of literature [1], which considered the effects of X-ray absorption and mechanical equilibrium conditions. This algorithm utilized the stress profile model of the fifth order polynomial to solve the problem of oscillation of the polynomial at a greater depth, and improved the reliability of residual stress measurement.

In 1996, Lambda R. [3] proposed a FEA matrix relaxation correction technique by some ideal assumptions and the idea of layer removal, which was used to correct layer removal in X-ray residual stress measurement. This technique can be taken to create 2-D or 3-D models based on different samples and polished pockets to make stress calculations simple, and is applicable to relatively complex geometries. However, this technique is ineffective for the assumption of simple geometric and symmetric stress fields. In 2012, Savaria V et al. [4] improved Lambda R’s technique by using the average of the residual stress values measured at the top of the upper and lower removal layers (Figure 2) as the calculated value of the correction formula. This improved technique can be used to keep accuracy in high stress gradient zones and it is suitable for more geometric models.

In 2018, LEVIEIL B. et al. [5] utilized X-ray diffraction to measure the residual stress of bars, compared and analyzed the correction methods in the literatures [1,3,4]. The study found that the correction results of the above correction methods proved that the measurement accuracy of the X-ray method is improved. The authors showed the importance of the material retention elasticity after layer removal on the measurement accuracy of the three methods, and found that the elasticity had no effect on the above two finite element correction methods [3,4] below 4 mm on the surface.

3. Hole-Drilling method
The Hole-Drilling method (Blind hole method) was proposed by German scholars in 1934. The specific principle of the method is as follows. Three strain gauges are attached to the surface of the workpiece where residual stress is to be tested and a hole is drilled at the intersection of their neutral lines. Since the stress is redistributed in the vicinity of the hole after drilling, the strain gauge is
strained by the stress release, finally according to the stress-strain relationship, residual stress of this point can be calculated, including the assumed two principal stresses $\sigma_1$, $\sigma_2$ and a main direction angle $\theta$, as shown in Figure. 3.

In 1978, Sandifer J P [6] performed force analysis around the blind hole and calculated the final residual stress by loop iteration. The author through the results of the measurement found that the eccentricity of the borehole will affect the measurement accuracy of the blind hole method, as shown in Figure. 4. But the force analysis process of this method is more complicated, the loop iteration is not easy to converge. In 1994, Liu B et al. [7] through calibration experiments found that plastic deformation occurs at the edge of the hole when using the drilling method to measure residual stress, and proposed a correction formula for the amount of plastic deformation.

In 2012, Liu L L et al. [8] put forward a method of directly correcting the release coefficient by using the finite element method, ignored the influence of plastic deformation on the edge of the hole, which can correct the error caused by the eccentricity of the borehole. Through analysis, it is found that when $D/d \geq 16$ ($D$ — outer diameter of material), the Hole-Drilling method can be applied to determine the residual stress of the tube parts.

In 2014, Von Mirbach D [9] recognized that the plastic strain at the hole edge, which has a great influence on the measurement accuracy of the residual stress of the borehole method. The author used the loop iterative algorithm to derive the calculation and presented the method of adaptive calibration functions. The load type of the material and the performance of the elastoplastic material were taken into account in the method which reduced the calibration procedure and shortened the correction time of the residual stress to some extent.

4. Finite element simulation
Many scholars have employed finite element numerical simulation to observe and study the residual stress distribution of the entire assembled camshaft. The Finite element method is a discretized numerical solution commonly used to analyze and solve complex practical engineering problems.

In 2006, Bayrakceken H et al. [10] utilized the finite element method to determine the residual stress concentration of the camshaft fracture region, including the dangerous zone with high stress concentration, maximum stress and minimum stress. Firstly, the camshaft model is established, then according to the actual force condition, the boundary condition of the camshaft position and the load
such as torsion and pressurization are set, and the angular velocity of the camshaft rotation is considered. Finally, the entire working process of the camshaft is simulated.

In 2011, Qiao J et al. [11] employed finite element software to simulate the expansion process of the steel ball of the assembled camshaft, and obtained the residual contact stress distribution of the camshaft. Firstly, the author simplified the cam in the model into a thick-walled cylinder, treated the expansion process as an axisymmetric problem, and then fine-divided the mesh of the shaft and cam joints, and finally the assembly process was simulated. In 2015, Yang S et al. [12] also utilized ANSYS software to analyze the stress deformation of this connection process, and got the distribution of residual stress on the inner wall of the shaft tube.

In 2015, Liu G et al. [13] simulated the hydraulic connection process of the assembled camshaft by finite element method, and achieved the residual stress distribution of the axial and circumferential directions of the camshaft. The author designed the inner hole of the cam to be elliptical, and selected a 1/4 cam section shape to establish a model base on the symmetrical shape. The simulation process assumed that the shaft is in a thin-walled mode, hydraulic pressure conditions were set.

In 2017, Scherzer R et al. [14] performed a finite element simulation on the Presta joining process of the assembled camshaft, which gained the residual stress distribution after joining. The simulation process was divided into two steps. Firstly, the rolling manufacturing process of the shaft was to simulate, secondly, the interference assembly of shaft and cam was to carry out. The scholar set the mesh of the assembly part to be fine, and regarded the cam as a cylinder treatment. The smallest model section was selected for simulation based on the cyclic symmetry of the cylinder contour.

5. Conclusion

The following are the summaries of three detection methods for residual stress of camshaft.

(1) Through the continuous improvement of the correction method, the accuracy of measuring the residual stress of the camshaft by X-ray diffraction method has been greatly improved. M. Moore's correction method is only suitable for some simple symmetrical geometry, and Ricardo CLA improved the reliability of this method. Although FEA matrix relaxation method has some limitations, it is more versatile and accurate than M. Moore's method.

(2) When measuring the residual stress of the camshaft by the blind hole method, it is necessary to satisfy the axial diameter ratio (D/d). The measurement accuracy of this method is mainly affected by two factors, namely the plastic deformation of the hole edge and the eccentricity of the hole. Many scholars have done a lot of research on these two factors, and the measurement accuracy is getting higher and higher. However, the accuracy of the method required for drilling is relatively high, and it will cause certain damage to the sample.

(3) Finite element simulation has a distinct advantage of a comprehensive observation and analysis of the distribution of residual stress in assembled camshaft. Properly setting the grid size of the camshaft model and selecting the model section can greatly improve the efficiency of calculation.

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