Detection methods for springback of assembled camshaft under hydraulic expansion

Zhiwei Gao1*, Lianfa Yang1, Jianping Ma1, Chenchen Don1, Xu Liu1, Lin Song1

1School of Mechanical & Electrical Engineering, Guilin University of Electronic Technology, Guilin, Guangxi, 541004, China

*Corresponding author’s e-mail: 20012201008@mails.guet.edu.cn

Abstract. The assembled camshaft under hydraulic expansion has the advantages of low cost, lightweight and high performance, which is an advanced technology with great development potential. By applying the tube hydroforming to the fabrication of assembled camshaft, the expansion principle is due to the different degrees of resilience of the cam and the shaft. Therefore, the effective detection method of elastic recovery of camshaft is of great significance to research how to improve the connection strength of the assembled camshaft. This paper introduces several springback detection methods for assembled camshaft under hydraulic expansion, namely resistance strain detection method, gap dynamic detection method and finite element simulation.

1. Introduction

The camshaft plays an importance role in engine performance and conversion efficiency [1]. Tube hydroforming is used for assembled camshaft under hydraulic expansion, making the camshaft into the hollow shaft can effectively reduce the overall weight of the camshaft to achieve lightweight. Some domestic colleges and universities first studied the assembled camshaft under hydraulic expansion [2,[3]. It is found that different parts and materials, different hydraulic expansion process parameters, the assembled camshaft in the expansion process (unloading stage), the inner wall of the cam hole and the outer wall of the shaft was connected due to different degrees of elastic recovery. The springback amount will directly affect the expansion effect between the cam and the shaft, that is, the connection strength of camshaft [4,5,6]. The value of the detection for springback of assembled camshaft is looking for the optimal expansion parameters and the product quality, to provide theoretical basis for the assembled parameter quantitative control to improve the assembled strength, and the project has broad engineering application prospects.

Therefore, the study of springback detection method is necessary to evaluate the quality of assembled camshaft expansion. However, the springback amount during the camshaft expansion process is very small, about hundreds of micron or even dozens of micron. Current experimental studies on assembled camshaft springback are mostly indirect measures that amplify the radial springback volume in some special way. The article is based on the expansion principle of assembled camshaft under hydraulic expansion, three detection methods of the assembled camshaft are introduced. Among them, the resistance strain detection method and gap dynamic detection method mainly measure indirectly the springback change of camshaft expansion through experimental equipment, while the finite element simulation method mainly is to use numerical simulation to detect the change of springback amount with finite element software.
2. Expanding principle of assembled camshaft under hydraulic expansion

The expansion principle of hydraulic assembled camshaft is shown in Fig 1. Before expansion, as shown in the Fig 1 (a), the outer diameter of shaft is less than the inner aperture of the cam [7]. Firstly, place the parts such as the cam in the preset position of the shaft, fix it through the mold, and seal the shaft end. Then the high pressure liquid is introduced into the inside from one end of the shaft. When the liquid pressure gradually increases, and the shaft begins to undergo elastic deformation. When the liquid pressure increases to the yield limit of the shaft material, the shaft begins to shape deformation until the initial gap between the shaft and the cam is filled, as shown in the Fig 1 (b). The fluid pressure continues to increase, The inner wall of the cam begins to be affected by the force caused by the shaft due to the liquid pressure and begins to produce a certain elastic deformation. Before the cam is deformed, after the unloading fluid pressure, because the elastic response of the cam is larger in response than the shaft, the tight radial adhesion force between the camshaft and the camshaft (residual contact pressure), as shown in the Fig 1 (c), so as to realize the expansion of the camshaft.

3. Springback detection method

3.1. Resistance strain detection method

The detection principle of resistance strain detection method is mainly by sticking the strain sheet to the surface of the cam. In the process of hydraulic expansion, because the fluid pressure inside the shaft gradually increases, and the elastic plastic deformation of the shaft touches the inner surface of cam, it will apply pressure on the inner surface of the cam, and the whole cam begins to undergo elastic deformation. The fluid pressure is unloaded before the cam has no shaping deformation, and the shaping deformation of the shaft hinders the elastic recovery of the cam, so the elastic strain cannot be fully recovered. Zhang Ge [8] studied the hydraulic expansion of double metal composite tube. By sticking the strain sensor to the outer surface of the substrate and the axial and peripheral strain on the outer wall surface of the substrate were obtained, and the springback amount of the substrate was indirectly obtained by the strain difference before and after unloading the pressure of the hydraulic expansion. The assembled camshaft under hydraulic expansion test where the cam bore was ellipse was performed by Liu G et al [9]. By pasting the resistance strain sensor at different positions on the cam surface, The amount of strain change on the surface at different positions of the cam hole is obtained and the springback amount of the cam after hydraulic unloading.

The measurement circuit diagram shows the Wheatstone bridge as shown in Fig 2 (b). The change in resistance value is converted into electrical signal. By machining the cam into the square shape as shown in Fig. 2 (a), the strain sensor was affixed to the central axis of the outer surface of the cam surface was collected using a static resistors strain gauge. Before expansion, there is no deformation on the cam surface and the initial strain value is zero. When the strain pressure reaches the maximum, the elastic response is $\varepsilon_m$; after unloading, the cam has an elastic recovery, the measured stable strain value of the cam surface is $\varepsilon_r$; the elastic recovery expression of the cam is $\eta_a = (\varepsilon_m - \varepsilon_r)/\varepsilon_m$. 

![Fig.1. Schematic diagram of assembled camshaft under hydraulic expansion](image)
3.2. Gap dynamic detection method

The gap dynamic detection method [10] needs to use the XTDIC digital image correlation measurement system shown in Fig.3. The principle of the system is to use binocular stereo vision technology and digital image processing technology, through the high-speed camera real-time acquisition and recognition of the speckles on the surface of the measured parts for visual recognition and reprocessing. During measurement, speckle should be sprayed on surface of the tested part in advance, install two high-speed cameras on the opposite surface of the tested surface, obtain the speckle image of the surface during the deformation in real time, and match the acquired speckle image with the relevant algorithm. The measurement of the displacement, coordinates and stress strain of the measured surface deformation process is completed by comparing the displacement of the speckle spots and their spacing changes. The measurements results are generally displayed by graphical method to better understand and analyze the properties of the material under test [11].

As shown in Fig. 4, a gap is first cut in the symmetrical central axis of the tested cam and the initial gap is measured, then spraying speckle on the cam surface as shown in Fig.4(a), the cam and the core shaft are mounted on clip mold, and two high-speed cameras are placed opposite the tested cam surface. During the camshaft hydraulic expansion, the internal fluid pressure into the shaft is applied according to the set hydraulic loading curve. In principle, the greater the contact pressure of the shaft to cam, the greater the change in the gap. Assuming that the change of gap during camshaft expansion is shown in Fig 4 (b). At the initial moment, the gap width of the measured cam is $S_0$, with the expansion joint pressure gradually increasing, the outer wall of the shaft begins to contact the inner hole wall of the cam and apply the pressure, and the gap width gradually increases. When the internal fluid pressure of the shaft is maximum, the width of the cam gap is maximum $S_m$. After the fluid pressure unloading, the cam and the shaft begin to produce a radial recovery, but due to the different elastic recovery, the contact pressure of the two is reduced, and the gap width on the measured cam reaches a stable width value $S_r$. The dynamic variation of gap width of the measured cam during the whole camshaft can be detected by
the XTDIC digital image correlation measurement system, The expression of the elastic recovery of the cam during the expansion and connection is: 

\[ \eta_b = \frac{\Delta_2}{(S_m/2)} \]

3.3. Finite element simulation

Finite element simulation method simulates the elastic-plastic deformation of the metal material through the choice of cell types of the core shaft and cam and the setting of the material properties. Many scholars use finite element numerical simulation to study the change of elastic recovery of the assembled camshaft under hydraulic expansion.

Han Lili [12] simulated the expansion process of the assembled camshaft by using the finite element software ANSYS. Due to the symmetry characteristics of the cam inner hole being circular, the author simulated the 1/2 model cam and chose the appropriate friction coefficient. Finally, the minimum liquid pressure eliminating the gap between the cam and the shaft was obtained, and in order to get a better expansion effect, the maximum expansion fluid pressure of the cam without plastic deformation and only elastic deformation was simulated.

The assembled camshafts where the inner holes are elliptic were studied by Liu G et al [9]. The author used the finite element simulation method to build the model and choose the cross section model of 1/4 camshaft to simulate the effect of different offset in the inner hole of the camshaft on the hydraulic expansion effect of the camshaft, and obtains the radial and axial displacement and elastic recovery of the camshaft in the process of expansion.

Ma Jianping et al [10] studied the assembled camshaft with three-bladed equidistant profiles. Numerical simulations were performed using ABAQUS finite element software where the symmetry of the camshaft model selected a cross section model of 1/6, containing 21 characteristic points of the outer wall of the shaft. Radial displacement and elastic recovery amount of the characteristic points of the shaft 1/6 were obtained by simulating different expansion fluid pressure and axial feed. It was found that the elastic recovery of the shaft decreased with the highest expansion fluid pressure.

4. Conclusion

The problem for springback of assembled camshaft has always been the difficulty and focus of experimental research. Due to the difficulty of dynamic elastic recovery detection, it has high requirements for the detection mode and detection precision of the equipment. In conclusion, the following is a summary of the three detection methods for springback of assembled camshaft:

1) The resistance strain detection is performed by exporting the strain on the cam surface to a dynamic electrical signal, which indirectly reflects the change of the springback amount, but because the resistance strain sensor to the external environment is large sensitivity, the error is relatively large. And the radial recovery amount of the cam and the shaft cannot be intuitively measured, which belongs to an indirect detection method.

2) The gap dynamic detection method transforms the springback amount change of the cam into the gap width change of the cam side, and the data is collected using XTDIC digital image correlation...
measurement system. This method destroys the cam and also cannot measure the radial recovery actual value of the cam.

(3) The finite element simulation method has a special advantage over the first two methods, which can comprehensively obtain the radial recovery amount of each position of the cam and the shaft. The calculation accuracy and efficiency can be effectively improved by setting the appropriate grid size and parameters of the model. Therefore, the finite element simulation has always been the first choice for researchers.

Acknowledgments
This work was financially supported by the National Natural Science Foundation of China (52065014), Natural Science Foundation of Guangxi Province (2017GXNSFAA198133), and Innovation Project of Guangxi Graduate Education (JGY2019074).

Reference
[1] Peng Zhang, Shu Qing Kou, Huan Zhu, Wen Chao Liang. Analysis for Transverse Knurling Process of the Assembled Camshaft[J]. Applied Mechanics and Materials, 2014, 3558 {5}.
[2] Koc M, Altan T. An overall review of the tube hydroforming (THF) technology [J]. Journal of Materials Processing Technology, 2001, 108: 384–393.
[3] M. Marré, A. Brosius, A. E. Tekkaya. New Aspects of joining by Compression and Expanding of Tubular Workpieces [J]. International Journal of Materials Forming, 2008, (suppl 1): 1295-1298.
[4] Abson.D. Competitive technologies for camshaft manufacture. Powder Metallurgy, 1997(1), 40: 6-8.
[5] Peng Zhang, Shuqing Kou, Baojun Lin, Yumei Wang. Optimization for radial knurling connection process of assembled camshaft using response surface method[J]. The International Journal of Advanced Manufacturing Technology, 2015, 77(1-4).
[6] Zhai Z F, Yang L F, Ma J P. An Evaluation of the Assemblability of Two Novel Assembled Camshaft Configurations by Tube Hydroforming [J]. AIP Conference Proceedings, 2017, Vol. 1896(1):1-6.
[7] Jia Ting Chen, Lian Fa Yang. State-of-the-Art of Joining Technologies for Assembled Camshaft[J]. Advanced Materials Research, 2013, 2108 {5}.
[8] Zhang Ge. Mechanical analysis and finite element simulation study on hydro-bulging process of bimetallic clad pipe[D]. Xi’an Shiyou University, 2019.
[9] Liu G, Lin J F, Yuan S J, et al. Mechanism of Hydrojoining and Approach to Increase Torsion Strength of Assembled Camshafts[J]. Journal of Manufacturing Science and Engineering, 2015, 137(5): 051015-1-051015-8.
[10] Ma Jianping, Yang Lianfa, Huang Jinjie, Chen Zhanbin, He Yulin, Jiang Jingyu. Residual contact pressure and elastic recovery of an assembled camshaft using tube hydroforming[J]. CIRP Journal of Manufacturing Science and Technology, 2021, 32 {5}.
[11] J Heikkinen, Schajer GS. Engineering - Optical Engineering; New Optical Engineering Findings from University of British Columbia Reported (Remote Surface Motion Measurements Using Defocused Speckle Imaging)[J]. Journal of Engineering, 2020.
[12] Han Lili. The internal high-pressure expanding technology and numerical emulate research of assembled camshaft[D]. Jilin University, 2005.