Effect of bolt relaxation on surface micro dynamic fatigue and wear

Xueyan Jiao*, Ligang Cai, Zhifeng Liu, Congbin Yang, Yongsheng Zhao, Qiang Cheng

School of mechanical and electrical engineering, Beijing University of technology, Beijing, China

*Corresponding author e-mail: 460391671@qq.com, lgcai321@aliyun.com, lzfi@bjut.edu.cn, yangcongbin@bjut.edu.cn, yszhao@bjut.edu.cn, chengqiang@bjut.edu.cn

Abstract. Because of the friction and damping effect between the interfaces, when the bolted structure bears the axial load, there will be no interface dislocation and only axial reciprocating tension and pressure, so it is difficult to have fretting fatigue and wear. Only under the tangential load, the interface will be staggered and the peaks and valleys between the micro-convex bodies will be alternately rubbed. After repeated cycles, the interface will generate sliding and adhesion areas of micro-fatigue and wear. Therefore, this paper conducts an in-depth study on the influence of bolt relaxation on surface fretting fatigue and wear. The relationship between tightening torque and clamping force, design and implementation of tangential relaxation experiment and acquisition and analysis of 3d surface topography are studied.

1. Introduction

The study of fretting fatigue and wear of bolted surfaces has been paid close attention to and plays an important role in the life estimation and reliability of materials. Most of them are used in multi-cycle fatigue and cyclic fatigue scenarios. At present, researches on the application of fretting theory in the field of bolts mostly focus on the study of crack initiation and fretting between contact surfaces of materials with tangential bolt connectors as the carrier, but do not involve the prediction of bolt looseness service life.

Based on the research of Hess [1], Izumi and Sakai [2] [3] pointed out that the contact state should be divided into three types: complete sliding without adhesive region, tiny sliding without stable adhesive region, and local sliding with stable adhesive region. The bolt tension will remain stable after many cycles. Mindlin [4] proposed the concept of existence slip zone and adhesion zone concerning contact zone. Under certain conditions, theoretical calculation and stress distribution analysis of contact surface were carried out, and concerns in the research field of contact mechanics were introduced, laying a foundation for analysis. Hurricane [5] summarizes the previous research results and believes that fretting wear can be divided into three stages: initial stage and abrasive debris stage.

The production phase and the steady-state phase. In recent years, the research on micro-dynamic friction has made great progress in many aspects. For example, bertier and Vincent et al. [6] [7] proposed the motion regulation mechanism of contact interface in the process of micro-dynamic
friction. The theory is not only applicable to dry friction, but also can be extended to lubrication state, and can clearly explain the relative motion process and microscopic friction characteristics between contact interfaces. Alha [8] proposed the influence of contact force and displacement on the fretting fatigue and wear of bolt assembly, and proposed that the greater the contact force, the more obvious the wear. Contact test and finite element simulation were carried out. Chakherlou in Iran and a. b. Aghdam [9] in the United States have proved that the increase of torque leads to the increase of fatigue life, but in a certain range of torque, due to surface wear, the life does not increase with the increase of torque.

Based on the above analysis, the research on bolt relaxation and its influence on the surface characteristics of bolted structure focuses on two aspects. One is to explore the influence of bolted structure such as thread, structural parts, tightening process and external load on bolt clamping force, without introducing the time effect of bolt relaxation. On the other hand, the interface friction, energy dissipation, fretting and contact characteristics are studied with bolt structure as the carrier, but the multi-contact surface and multi-complex factors of the whole bolted structure are not considered. Therefore, it is necessary to introduce the time domain of the bolt relaxation process and further analyze it in order to obtain the changing law of the interface contact characteristics in the bolt relaxation process. The study of the law of energy dissipation in the bolt relaxation process can explain the change process of clamping force in the bolt relaxation process. By further studying the change of contact interface characteristics in the relaxation process, the main influencing factors of bolt relaxation can be analyzed and obtained, which can provide a basis for the optimization and design of the structure.

2. Experimental study on surface micro dynamic fatigue and wear

When subjected to the tangential load, the screw bears the shear action, which causes the plastic unrecoverable deformation in part of the region, and thus causes the clamping force provided by the screw to decrease. On the other hand, there are damping and friction effects between bolted joint surfaces. Under the cyclic load, energy dissipation and accumulation occur between interfaces, and the surface friction coefficient and surface topography change, affecting the connection state and leading to the decrease of bolt clamping force. The change of interface is the fretting fatigue and wear of the surface. Based on the collection and analysis of the relaxation law of bolts in tangential parts, the relationship between the relaxation law and the load size and frequency is obtained.

The cyclic loads with different loading frequency and amplitude are provided by the tensile testing machine. The changes of bolt clamping force are monitored and statistically analyzed. The surface topography of test pieces before and after the experiment is scanned. Figure. 1 shows the experimental scheme.

Experiments were carried out according to the scheme proposed in figure 1. In order to obtain more accurate experimental data and realize real-time monitoring of the change of clamping force, it is necessary to assemble more high-resolution detection equipment. It mainly includes tensile testing machine and its acquisition system, real-time monitoring system of bolt clamping force, high-precision three-dimensional surface topography measuring instrument, and tangential bolt connector.

The tensile testing machine was Instron8801 fatigue tensile testing machine provided by Shanghai instron, and the three-dimensional surface topography measuring instrument was a high-precision three-dimensional surface topography measuring instrument of American Nanovea brand ST400. Equipment assembly and its experimental diagram are shown in Fig 2 and Fig 3.
Clamping force attenuation diagram with time

Appearance of nut bearing surface and connector contact surface

The surface morphology of the two contact surfaces after the experiment

Surface features

Figure 1. Tangential test scheme

Figure 2. Schematic diagram of experimental equipment assembly

Figure 3. Three-dimensional surface topography measuring instrument
A total of 6 sets of test pieces were processed in this experiment, and the material used was 45 steel. The processing requirements of the contact surface are as follows: surface roughness \(Ra=1.6\), Bolts shall be M16\(\times2\times8\) bolts of A2-70 material. Use sandpaper to remove burrs from the edges and remove any iron chips and small oxides from the surface. After checking the defects, label the bolts and connecting parts, so as to prepare for the scanning of three-dimensional surface morphology of connecting parts before subsequent experiments.

![Image](image_url)

**Figure 4.** Marking of tangential connecting parts

The surface topography of tangential components was obtained by using a three-dimensional surface topography measuring instrument, and the surface parameters were analyzed according to the surface topography. The surface topography and its parameters of the contact surface of the same connector are the same, so only the surface topography and its parameters of the two surfaces of the connector need to be scanned. The contact area between nut and connector 1 is smaller than that of nut and connector 1. No scanning is needed here. After the scanning is completed, post processing is carried out in the 3D topography processing software Professional 3D, and accurate surface topography data is obtained through leveling, filling, threshold setting, extraction region and parameter value export, etc.. The three-dimensional morphology of the three treated surfaces is shown below.
Table 1. Contact surfaces of connectors

| The serial number | Connector 1 contact surface | Connector 2 contact surface |
|-------------------|-----------------------------|-----------------------------|
| 1                 | ![Contact Surface 1](image1) | ![Contact Surface 2](image2) |
| 2                 | ![Contact Surface 3](image3) | ![Contact Surface 4](image4) |
| 3                 | ![Contact Surface 5](image5) | ![Contact Surface 6](image6) |
| 4                 | ![Contact Surface 7](image7) | ![Contact Surface 8](image8) |
| 5                 | ![Contact Surface 9](image9) | ![Contact Surface 10](image10) |
| 6                 | ![Contact Surface 11](image11) | ![Contact Surface 12](image12) |
**Table 2.** Connector 1 and nut contact surface three-dimensional appearance

| The serial number | Nut bearing surface 3d surface | The serial number | Nut bearing surface 3d surface |
|-------------------|-------------------------------|-------------------|-------------------------------|
| 1                 | ![Image]                      | 4                 | ![Image]                      |
| 2                 | ![Image]                      | 5                 | ![Image]                      |
| 3                 | ![Image]                      | 6                 | ![Image]                      |

The extracted 3d data and 2d data are shown in table 3, table 4 and table 5.

**Table 3.** Connector 1 Upper Contact surface

| The serial number | Sa μm | Sq μm | Ra μm | Ra μm | Rq μm |
|-------------------|-------|-------|-------|-------|-------|
| 1                 | 3.05945 | 3.85468 | 1.72763 | 1.72424 | 2.12647 |
| 2                 | 3.00470 | 3.78794 | 1.70701 | 1.70469 | 2.10821 |
| 3                 | 2.99455 | 3.76531 | 1.78004 | 1.78031 | 2.21709 |
| 4                 | 3.36699 | 4.34468 | 2.01579 | 2.01508 | 2.54279 |
| 5                 | 4.48486 | 5.74979 | 2.54230 | 2.53913 | 3.24285 |
| 6                 | 2.50087 | 3.12975 | 1.69922 | 1.70496 | 2.08416 |

**Table 4.** Connector 2 Contact surface

| The serial number | Sa μm | Sq μm | Ra μm | Ra μm | Rq μm |
|-------------------|-------|-------|-------|-------|-------|
| 1                 | 1.69191 | 2.17909 | 0.912356 | 0.911257 | 1.13451 |
| 2                 | 1.82555 | 2.34327 | 1.04499 | 1.04582 | 1.32418 |
| 3                 | 3.08921 | 3.86403 | 1.76336 | 1.76282 | 2.16024 |
| 4                 | 2.29996 | 2.95567 | 1.21653 | 1.21770 | 1.53757 |
| 5                 | 1.62816 | 2.11593 | 1.02626 | 1.02374 | 1.28088 |
| 6                 | 1.68699 | 2.15271 | 0.930583 | 0.931422 | 1.16254 |
Table 5. Nut Connection surface

| The serial number | Sa μm   | Sq μm   | Ra μm   | Ra μm   | Rq μm   |
|-------------------|---------|---------|---------|---------|---------|
| 1                 | 2.12534 | 2.68609 | 1.41828 | 1.42894 | 1.74253 |
| 2                 | 2.01265 | 2.54223 | 1.32569 | 1.32659 | 1.65213 |
| 3                 | 1.35502 | 1.72123 | 0.596792| 0.604278| 0.732414|
| 4                 | 2.31102 | 2.97898 | 1.27825 | 1.26477 | 1.61671 |
| 5                 | 2.30662 | 2.97206 | 1.42839 | 1.42862 | 1.85322 |
| 6                 | 1.81390 | 2.31590 | 1.12303 | 1.11430 | 1.38677 |

As shown in the above table, the surface parameters obtained under the same surface roughness processing condition are also different. Different parameters will also have an impact on the results of subsequent experiments. Therefore, under the same processing condition, the preload produced by the bolt joint is different from that under the preload, and the relaxation change under the same load is also different.

3. Conclusion

According to the above methods and theories, the 3d surface topography of the two experiments was obtained, and the influence of bolt relaxation on the surface micro-fatigue and wear of the structure was obtained by comparing the graphics and the extracted parameters.

The change of the surface topography of the tangential parts which produce the fatigue and wear of undersurface micro-movement was studied. The experimental method of high-precision equipment and control variable method, as well as the high-precision three-dimensional surface topography measuring instrument capable of analyzing the surface topography, were adopted to obtain the influence law of bolt relaxation on the surface micro-dynamic fatigue and wear. The main conclusions are as follows:

(1) The measured clamping force of bolt connector presents Gaussian distribution. The tangential connection fitting is designed and machined. Under the same tightening process, the distribution of bolt clamping force presents a Gaussian distribution. The recommended clamping forces generated by the three tightening torques of 30N-m, 60 N-m, 80 N-m are respectively 9~10kN, 17~19kN and 21~23kN. The tightening coefficient increases with the increase of tightening torque, but stays between 0.18 and 0.24. The error range decreases with the increase of the clamping force, but it remains around ±30%.

(2) The experiments of surface fretting fatigue and wear and the pretreatment in the early stage of the experiment were designed. A high-precision cyclic load test of tangential components a real-time monitoring system of bolt clamping force and a surface topography measuring device are designed and assembled. The real-time monitoring system of bolt clamping force is a customized product, including exclusive sensor, data acquisition card and upper computer software. Its accuracy is 0.1%, ensuring the minimum accurate value of bolt clamping force is 1N. The 3D morphologies of 6 sets of experimental pieces and 4 extracted parameters were scanned and obtained as the basic comparison data before and after the experiment.

(3) The bolt relaxation experiments under different pre-tightening forces and loading frequencies were carried out and the results were analyzed. Under the same load, the higher the clamping force is, the higher the attenuation percentage is, and the less the cycle times are needed to reach the stability. Under the same preloading force, the higher the load frequency is, the lower the attenuation percentage will be when it reaches a stable state. In other words, the larger the attenuation difference of the clamping force is, the more obvious the attenuation will be. However, both of them are above
80%. Under both loading methods, the attenuation percentage under the cyclic test of 104 is less than 92%, but both are greater than 80%.

References

[1] Pai N G, and Hess D P. Three-dimensional finite element analysis of threaded fastener loosening due to dynamic shear load [J]. Engineering failure analysis, 2002, 9: 383 - 402.

[2] Izumi S, Sakai S. Analytical modeling of the transverse load-displacement relation of a bolted joint with consideration of the mechanical behavior on contact surfaces [C]. ASME, PVP 2009 - 77612.

[3] Izumi S, Yokoyama T, Iwasaki A. Three-dimensional finite element analysis of tightening and loosening mechanism of threaded fastener [J]. Engineering failure analysis, 2005, 12: 604-615.

[4] Mindlin R D, Deresiewica H. Elastic spheres in contact under varying oblique forces [J]. Journal of applied mechanics, 2013, 20.

[5] Hurricks P L. The Mechanism of Fretting - A review [J]. Wear, 1970 (15): 389 - 409.

[6] Zhou Z R, Vincent L. Effect of external loading on wear maps of aluminium alloys [J]. Wear, 1993, 162:619 - 623.

[7] Zhou Z R, Vincent L. Mixed fretting regime, Wear Vols.181 - 183, 1995, 531 - 536.

[8] A. Benhamena, A. Talhab. Effect of clamping force on fretting fatigue behaviour of bolted assemblies: Case of couple steel–aluminium [J]. ScienceDirect Materials Science and Engineering, (2010) 6413 – 6421.

[9] T. N. Chakherlou, M.J. Razavi. An experimental investigation of the bolt clamping force and friction effect on the fatigue behavior of aluminum alloy 2024-T3 double shear lap joint [J]. ScienceDirect Materials and Design. (2011) 4641 – 4649.