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Effect of surface parameters on anti-loosening performance of bolts for engineering machinery

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ABSTRACT

Engineering machinery is characterized by high load frequency, large amplitude, and long continuous working time, which requires high anti-loosening performance of bolts. In this paper, based on DIN65151, a transverse vibration test is designed. By changing the surface roughness, hardness, and coating thickness of the connected parts, the specimens with different surface process parameters were obtained. Tightening and transverse vibration experiments were carried out to monitor the changes in preload force and to study the surface process parameters of the connected parts to investigate their effect on the anti-loosening performance of threaded fasteners. The research results show that the smaller the surface roughness, the higher the surface hardness, and the smaller the coating thickness, the better the anti-loosening performance of the bolt.

Keywords: Bolted fastener; Surface roughness; Surface hardness; Coating thickness.

1. INTRODUCTION

Due to its simplicity and easy maintenance, bolt coupling has been widely used in machinery, chemical industry, transportation, civil engineering and other industries in various types of equipment and structures. Engineering machinery is subject to large loads and harsh working conditions, and the quality of bolt tightening is directly related to the reliability and safety of the whole equipment or structure. Preload force is an important factor in evaluating the quality of bolt tightening, and some studies have shown that [1–3] within a reasonable range, the greater the preload force, the better the performance of anti-loosening.

In recent years, the loosening mechanism of threaded fasteners under different loading conditions has been widely studied. The types of external excitation load that affect the loosening of bolted connections mainly include transverse loads, axial loads, etc. Early studies in this field focused on loosening caused by axial loads. NASSAR *et al.* [4] concluded that plastic deformation of bolts under the action of axial vibration is the main cause of loosening. LIU *et al.* [5–7] further investigated the axial vibration of bolts and concluded that the first stage of bolt loosening is due to the removal of micro convex bodies on the contact surfaces and plastic deformation and that the second stage of micromotional wear leads to a slow decrease in the preload force.

On the other hand, a considerable number of researchers have focused on the response under transverse loads or displacements. In 1969 JUNKER [8] designed a transverse vibration test rig and proposed that transverse loads are more likely to cause bolt loosening. SASE *et al.* [9] et al. found that the loosening of a fastener under a transverse displacement is mainly caused by two factors: one factor is the relative threads of bolt and nut slip, and the other factor is the relative slip between the surface of the bolt (or nut) and the surface of the connected parts. The results of PAI and HESS's [10, 11] analysis of the loosening of bolted joints subjected to dynamic shear loading showed that the loosening of fasteners was due to complete or localized slippage of the contact surfaces of the threads and the head. Due to the localized slip of the contact surfaces, fasteners can loosen at lower loads than previously expected, as confirmed by DINGER and FRIEDRICH [12]. SHOJI and SAWA [13] found that cyclic relative slip between the threads resulted in bolt loosening. YANG *et al.* [14] further showed that with the increase in the number of loading cycles, the amount of relative slip accumulates and the pretension decreases, which ultimately leads to tightening of the bolt joint failure. JIANG *et al.* [15, 16] showed that the self-loosening process of bolt joints under lateral displacement can be divided into two stages. In the first stage, there is no relative rotation between the nut and the bolt, and the loosening is caused by

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material deformation. While in the second stage, there is a significant retraction of the nut and a rapid decrease in the preload force.

In addition to external loading effects, there are also studies on the bolted joint structure itself. Coatings and lubrication are often used to reduce the coefficient of friction of threaded fasteners [17]. However, the influence of the coefficient of friction on the loosening process has been controversial. On the one hand, increasing the coefficient of friction implies increasing the frictional torque to resist relative rotation or slip of the contact surfaces, which acts as an anti-loosening agent. CHEN *et al.* [18] and HOUSARI and NASSAR [19] concluded that increasing the coefficient of friction of the threaded surfaces and that of the supporting surfaces can improve the anti-loosening performance of bolted connections. GONG *et al.* [20, 21] analyzed from the point of view of the critical transverse force and concluded that increasing friction reduces the loss of the preload under transverse vibration, but the preload under the same torque will be reduced. On the other hand, it has also been shown that when lubrication is combined with higher preload, the effect favors vibration resistance. The torque-tension relationship of threaded fasteners is highly sensitive to changes in the coefficient of friction [22]. For the same initial tightening torque, a decrease in the coefficient of friction increases the preload force and thus improves the anti-loosening performance.

The current research on the loosening mechanism of bolts mainly focuses on external factors and the surface properties of the threads, with less research on the surface properties of the connected parts. When the bolt is tightened, the surface friction coefficient of the bearing surface, hardness, and other factors will also affect the preload force because the contact surface between the bolt and the connected part is not smooth. Therefore, it is necessary to study the influence of surface process parameters of connected parts on bolt preload. Based on DIN65151, this paper will study the influence of surface roughness, surface hardness, and coating thickness of the connected parts on the bolt-locking performance through a transverse vibration experiment.

2. TESTING EQUIPMENT

The principle of the transverse vibration test device is shown in Figure 1, through the relative motion of the fixed plate and mobile plate, applying cyclic transverse vibration to the bolt to accelerate the loosening of the bolt. Under the same test conditions, the preload force after assembly and the preload force attenuation after the test are used as the basis for assessment, and the influence of different influencing factors on the anti-loosening performance of the bolt connection can be analyzed through the comparative test.

The transverse vibration test equipment is shown in Figure 2. The transverse vibration test equipment is made according to the requirements of DIN65151 test equipment and according to the size requirements of the test object. After calibration, the testing accuracy of preload force should be ≤± 2%, transverse force testing accuracy should be ≤± 2% and transverse amplitude testing accuracy should be ≤± 0.01 mm, which can realize the accurate detection of force and displacement. The control result is shown in Figure 3.

The experiments will measure the anti-loosening performance of bolted joints by the residual preload force after vibration. The effects of different surface process parameters on the preload force after tightening and the effects of different surface process parameters on the preload force decay during cyclic loading will be investigated respectively.

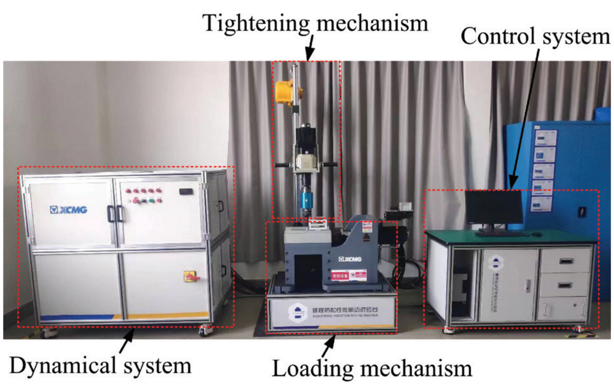

Figure 1: Test equipment.

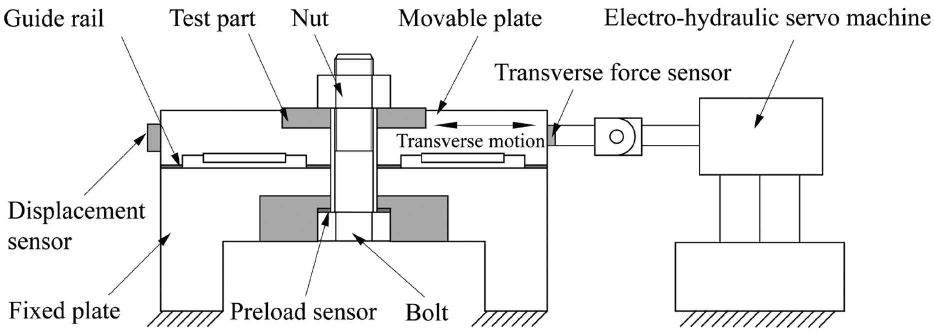

Figure 2: Schematic diagram of test equipment.

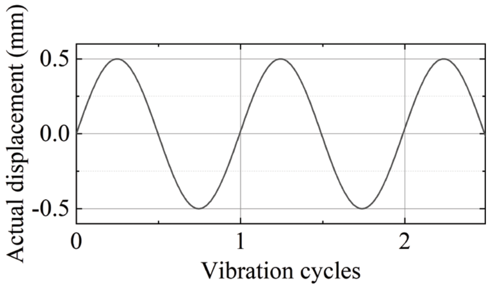

Figure 3: Precise control of lateral displacement.

Figure 4: Test parts with different surface roughness.

3. RESULTS AND DISCUSSION

3.1. The influence of surface roughness on bolt anti-loosening performance

Test parts with different surface roughness were prepared by grinding and turning, and the machined surfaces were inspected by a surface roughness meter. The test parts were categorized according to Ra1.6 ± 0.08, Ra3.2 ± 0.16, Ra6.3 ± 0.32, Ra12.5 ± 0.63, and the test parts are shown in Figure 4. Tightening test and preload decay test, each group of experiments to do 5 times to take the average value, the test results are shown in Figure 5. Design a single factor test, in the coating thickness of 0μm, surface hardness of 300HV, conditions, vibration 2000 cycles, each group of experiments to do 5 times to take the average value, the test results are shown in Figure 6.

As shown in Figure 5, under the same surface roughness, the preload force increases with the increase of tightening torque. And at the same tightening torque, the larger the surface roughness of the test piece, the smaller the preload force. When the tightening torque increases from 160Nm to 265Nm, the preload force increases by 13kN for surface roughness Ra1.6, 15.2kN for Ra3.2, 16.2kN for Ra6.3, and 19.1kN for Ra12.5, which can be seen that the trend of the growth of the preload force becomes higher with the increase of surface roughness.

According to the bolt preload calculation formula:

$$T = kFd \tag{1}$$

Where T is the tightening torque, k is the tightening torque coefficient, and F is the preload force.

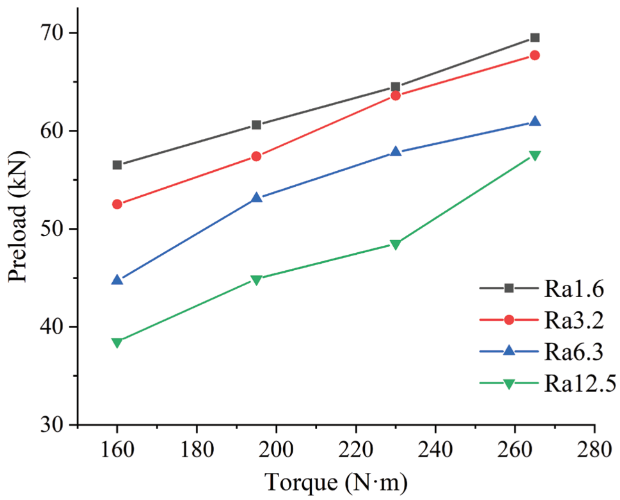

Figure 5: Influence of surface roughness on preload force after tightening.

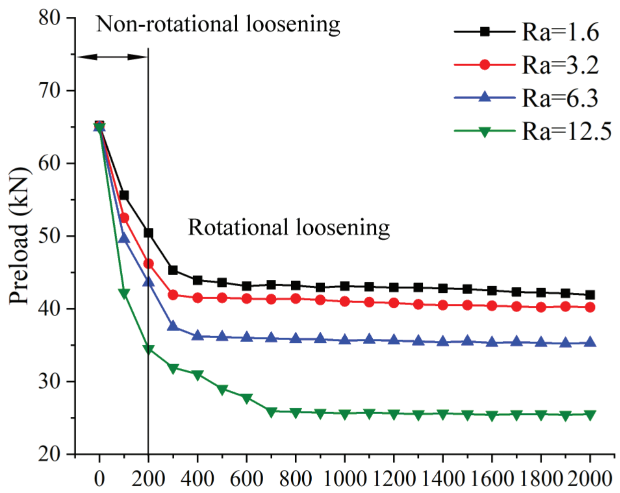

Figure 6: Influence of surface roughness on preload.

The increased surface roughness of the test piece led to an increase in the tightening torque coefficient, resulting in a reduction in the preload force.

According to the Formula (2) for the friction torque of the bearing surface:

$$T_w = \frac{F}{2} d_w \mu_w \tag{2}$$

where T_w is the bearing surface friction torque, d_w is the bearing surface contact outer diameter, and μ_w is the bearing surface friction coefficient.

The value of the bearing surface friction moment is related to the preload force and the bearing surface friction coefficient. As the tightening torque is low, the tightening torque is mainly used to overcome the bearing surface friction moment, the friction coefficient of the bearing surface friction moment plays a dominant role, the surface roughness of the test piece bearing surface friction is greater, and thus the preload force is smaller. However, when the tightening torque increases, the preload force increases, at this time, the preload force on the bearing surface friction torque plays a dominant role, in the roughness of the test piece due to its smaller preload force instead of making the bearing surface friction torque grows slowly, so in the case of increasing the same torque, the preload force growth tendency is gradually becoming higher.

Figure 6 shows the bolt preload decay curve when the initial preload force is 65kN. With the increase of the number of transverse vibration cycles, the preload of the bolt preload rapidly decays in the early stage, and then tends to stabilize; initial preload is the same case, the larger the surface roughness of the connected parts, the faster the preload decay, the smaller the residual preload in the stabilization stage. The wear morphology of the vibration test pieces is shown in Figure 7, and the surface wear of the connected part with roughness Ra12.5 is more obvious than that of the connected part with Ra1.6. Rougher surfaces are subjected to more severe wear under transverse vibration, and the preload during the initial non-rotational loosening phase of vibration is significantly reduced.

3.2. The influence of material hardness on bolt anti-loosening performance

Test pieces with different surface hardness were prepared by heat treatment. Test the hardness of the test pieces with a hardness tester, according to HV150 ± 7.5, HV240 ± 12, HV300 ± 15, and HV375 ± 19 to categorize the test pieces as shown in Figure 8. Design full factorial tightening test, the test results are shown in Figure 9. Design transverse vibration test, under the condition of the coating thickness of 0μm and surface roughness of Ra3.2, vibrates for 2000 cycles, and the test results are shown in Figure 9.

Figure 9 shows the graph of the effect of tightening bolts at the same torque on the preload of test pieces with different surface hardness. Under the same tightening torque, when the hardness is less than HV300 the surface hardness is positively correlated with the preload of the bolt after tightening. When the hardness reaches HV300 and above, the preload force almost no longer changes. In the tightening process, due to surface

Figure 7: Comparison of wear of test pieces with different roughness.

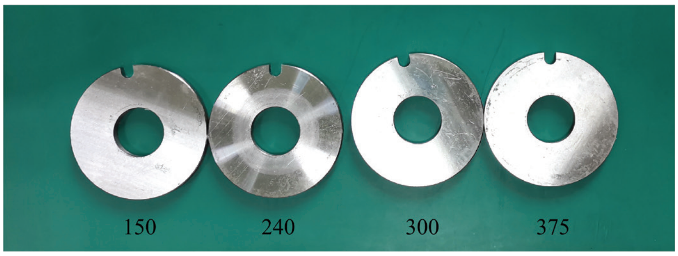

Figure 8: Different hardness test parts.

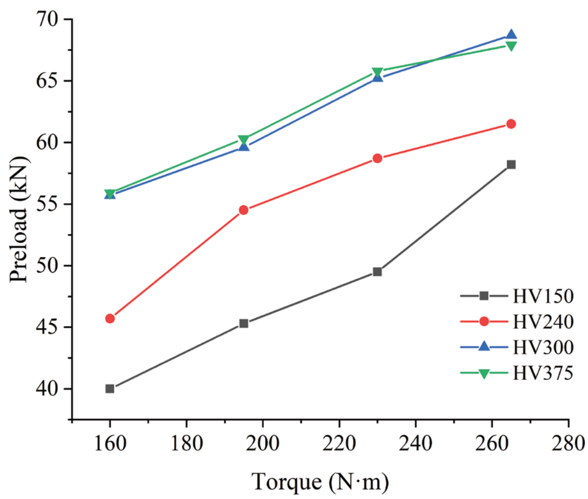

Figure 9: Influence of surface hardness on pretightening force after tightening.

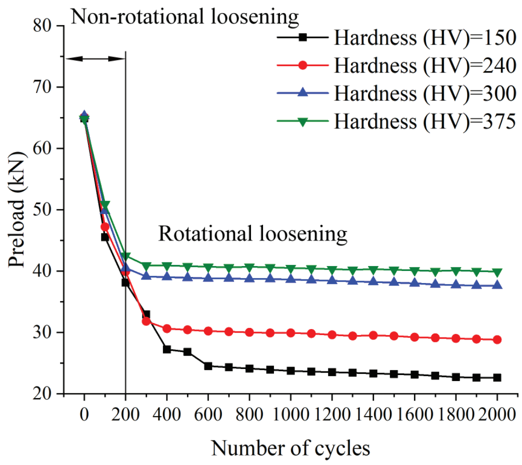

Figure 10: Influence of surface hardness on preload.

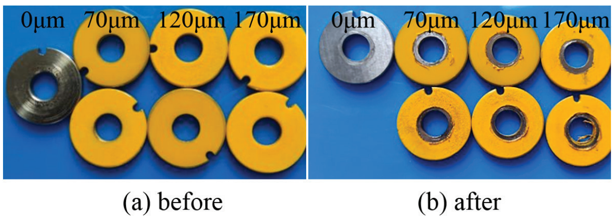

Figure 11: Test parts with different coating thickness.

embedding and micro-wear and other reasons will make the preload force after tightening is small. This effect is more pronounced when the surface hardness of the test piece is small. When the surface hardness of the test piece increases to a certain degree, the surface embedded phenomenon is weakened, and the preload under the same torque tends to stabilize.

Figure 10 shows the initial preload force of 65kN, the bolt preload decay curve, with the increase in the number of cycles, the bolt preload rapidly decays in the early stage and then tends to stabilize. Initial preload is the same, the smaller the surface hardness of the connected parts, the greater the degree of surface embedding. The preload force in the first stage decays faster, and the preload force in the stabilization stage is further reduced. When the surface hardness reaches HV300 or more, its surface is embedded, the surface micro-wear phenomenon is weakened, and the preload decay rate and the residual preload in the stabilization phase no longer obviously changes.

3.3. The influence of coating thickness on bolt anti-loosening performance

Test pieces with different surface coating thicknesses were prepared by spraying robot, and the coating film was solvent-based epoxy primer. The test coating thickness was detected with a coating thickness gauge and categorized according to 0 μm, 70 ± 10 μm, 120 ± 10 μm, and 170 ± 10 μm, and the test pieces are shown in Figure 9. Tightening and preload decay tests were performed separately. The full factorial tightening test was designed and the test results are shown in Figure 10. Design single factor preload decay test, under the condition of surface hardness of 300HV and surface roughness of Ra3.2, vibration 2000 cycles, the test results are shown in Figure 11.

Figure 12 shows the graph of the influence of the surface film thickness of the specimen on the preload force of the bolt after tightening. Under the same tightening torque, there is almost no change in the initial preload of connecting parts with different coating thicknesses. As the paint film is soft, it will be crushed and discharged during the tightening process, which has less influence on the initial preload.

Figure 13 shows the initial preload of 65kN, the bolt preload decay curve. With the increase in the number of cycles, the bolt preload pre-decay rapidly, and then tends to stabilize. In the case of the same initial preload, the thicker the coating thickness of the connected surface, the faster the preload decay, and the smaller the residual preload in the stabilization stage. When the coating thickness is ≤70um, the effect of coating thickness on the preload decay is very small and can be ignored. Comprehensive Figure 11(b) observation shows that the thicker the thickness of the coating on the surface of the test piece, the more residual coating between the bolt

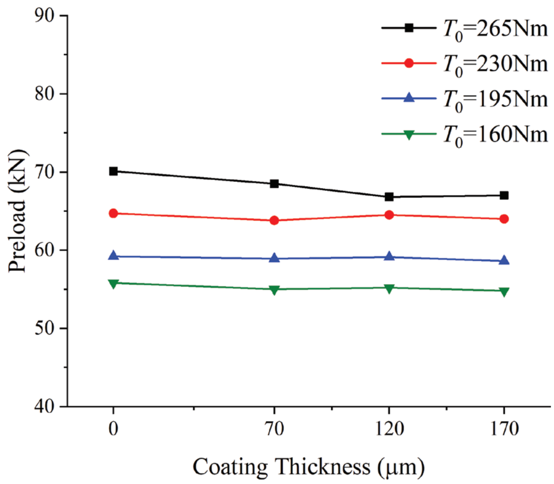

Figure 12: Influence of surface coating thickness on the preload force after tightening.

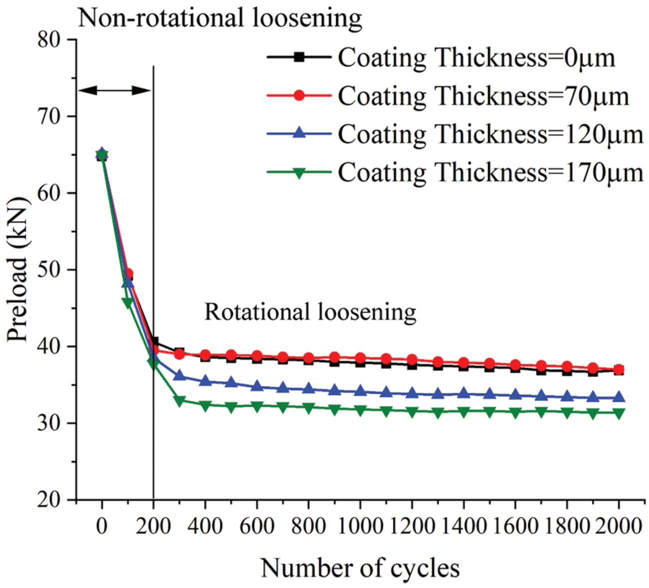

Figure 13: Influence of surface coating thickness on preload.

and the test piece after tightening. Continuously shedding after vibration, the debris can play a certain lubrication role in the bearing surface, resulting in the attenuation of the residual preload.

4. CONCLUSION

In this paper, the relationship between the bolt anti-loosening performance and the surface roughness, surface hardness, and coating thickness of the connected parts was investigated through transverse vibration experiments. The research results show that:

(1) When the same torque is used to tighten the bolt, the preload force decreases with the increase of the surface roughness of the connected parts. However, with the increase of surface roughness, the preload force tends to increase gradually faster. When the initial estimated force of the bolt is the same, the residual preload decreases with increasing surface roughness, and the preload decays due to non-rotational loosening being too large, thus further affecting rotational loosening. The connected parts with less surface roughness have better anti-loosening ability.

(2) Tightening stage, the same torque under the preload increases with the increase of the hardness of the surface of the connected parts, when the surface hardness is greater than HV300, due to the influence of the surface embedded in the small preload tends to stabilize. Vibration stage, the same preload, the residual preload increases with the increase in surface hardness of the connected parts. When the hardness increases

to HV300, with the weakening of the loss of surface embedding, the residual preload changes less. An appropriate increase in the surface hardness of the connected parts can improve the anti-loosening performance of the bolt connection.

(3) The thickness of the surface coating thickness has little effect on the residual preload of the tightening pair. When the initial predicted bolt force is the same, under the action of transverse vibration, the thicker the surface coating thickness thickness of the connected material, the faster the decline rate of the preload, the remaining preload in the stable stage decreases with the increase of the surface coating thickness degree of the connected parts. Moreover, when the thickness of the film is not more than 70um, the influence of the thickness on the preload decline is very small and can be ignored.

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