Yan *et al.*
Chinese Journal of Mechanical Engineering (2024) 37:97
https://doi.org/10.1186/s10033-024-01082-w

Chinese Journal of Mechanical Engineering

REVIEW

Open Access

Preload Control Method of Threaded Fasteners: A Review

Xing Yan[1,2], Zhifeng Liu[1,3*], Mingpo Zheng[1,2], Ying Li[1,2*], Yuezhen Wang[1,2] and Wentao Chen[1,2]

Abstract

Threaded fasteners are one of the most commonly used connection methods for mechanical structures. Its primary function is to generate appropriate clamping forces and fasten the connected parts. An inappropriate preload can cause loosening, fatigue fracture, and other problems. This will affect the safety and reliability of mechanical equipment. The precise control of the preload has become a critical issue in mechanical assembly processes. Over the past few decades, various tightening measures and methods have been proposed to address this issue. However, many problems continue to exist with practical applications that have not been reviewed comprehensively and systematically. First, various control methods were summarized systematically, and their advantages and disadvantages in engineering applications were analyzed. Torque control is the most widely used tightening method owing to its simple operation and low cost. Therefore, the research on the torque control method was summarized systematically from three aspects: the torque–preload correlation formula, effective friction radius, and friction characteristics during tightening. In addition, the special circumstances that may increase preload uncertainty were discussed. Finally, based on a summary of the current research status, the prospects for future research were discussed. This study would aid researchers in extensively understanding the problems in preload control.

Keywords Threaded fasteners, Preload, Tightening method, Torque control method, Friction characteristics

1 Introduction

Threaded fasteners are used for joining two or more mechanical parts. This is one of the most widely used connection methods in engineering applications. The most significant advantages of threaded fasteners are the convenience of assembly, disassembly, interchangeability, and maintenance. These are widely used in various mechanical structures such as aerospace, rail transit, automobiles, machine tools, and pressure pipeline vessels [1–5]. According to statistics, the number of bolt assemblies in a car can exceed 3000. This accounts for over 30% of the total work volume in automobile manufacturing and assembly [6]. The purpose of a bolted joint is to achieve the expected preload to prevent movement and separation of the mechanical parts. The preload is also known as the initial clamping force. The amount and stability of the bolt preload directly affect the normal operation of the entire machine and safety of humans in critical applications.

Bickford [7] reported that the most common problems with bolted joints are caused by incorrect preload. Incorrect preloading may cause various problems such as the static failure of fasteners and connectors, vibration loosening, fatigue failure, relative sliding, or separation of connected parts. The failure of a bolted joint may cause

*Correspondence:
Zhifeng Liu
lzf@bjut.edu.cn
Ying Li
li_ying@bjut.edu.cn
[1] College of Mechanical & Energy Engineering, Beijing University of Technology, Beijing 100124, China
[2] Beijing Key Laboratory of Advanced Manufacturing Technology, Beijing University of Technology, Beijing 100124, China
[3] Key Laboratory of CNC Equipment Reliability, Ministry of Education, School of Mechanical and Aerospace Engineering, Jilin University, Changchun 130012, China

© The Author(s) 2024. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

severe accidents and economic losses. For example, an accident attributed to bolt failure occurred in 1979 when Flight 191 from Chicago's O'Hare Airport crashed 30 s after take-off, killing 273 passengers. On November 12, 2001, Flight 587 crashed shortly after it took off from JFK International Airport, killing 265 individuals. This was attributed to the loosening of the bolts that fixed the vertical stabilizer to the airplane tail [8].

However, monitoring the preload during tightening is difficult. Hence, achieving the expected preload is challenging. In addition, many variables and uncertainty factors affect the generation of the expected preloads. These include the factors related to the joint (materials, configuration, surface finishes, and gaskets) and threaded fasteners (materials, shape, coating, and lubrication), types of tools and their accuracy, assembly strategies, and environmental factors. To obtain the expected preload, researchers have extensively studied preload control methods in the past few decades. Several tightening methods are currently used. These include torque, torque angle, strength, yield, ultrasonic, and strain controls.

However, a comprehensive review of the tightening methods for threaded fasteners, which is the motivation for this study, is unavailable. In this paper, the extensive literature on preload control is summarized systematically, and a review article on preload control methods is presented. This review would help researchers understand the technological developments and research status of tightening methods.

The framework of this review is illustrated in Figure 1. First, it introduces several tightening methods. Subsequently, a detailed and systematic discussion of the torque control method is presented from three aspects: the torque–preload correlation formula, effective friction radius, and friction characteristics during tightening. In addition, the special circumstances that can cause uncertainty in the preload are summarized. Finally, the perspectives and future research directions for preload control methods are discussed based on a comprehensive review and summary.

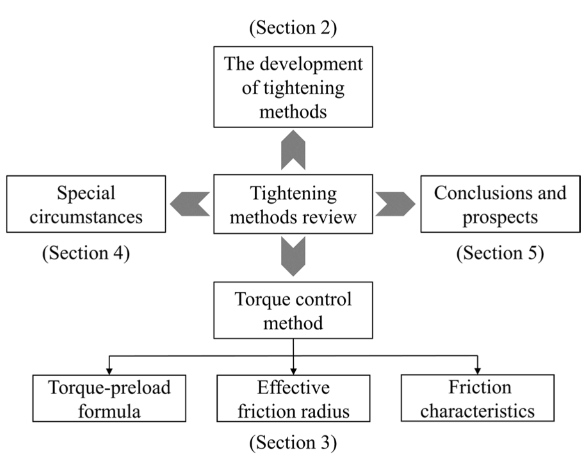

Figure 1 Framework of the review

2 Development of Tightening Methods

The primary reason for bolted joint failures is the incorrect bolt preloading at the initial assembly and the decrease in clamping force during the subsequent service. Achieving the expected bolt preload is the objective of the initial assembly of bolted joints. Researchers and engineers have developed various methods for measuring and controlling bolt preload. This section describes the development of these methods.

2.1 Torque Control Method

Torque control is a method for indirectly controlling the preload by rotating the bolt head or nut to a specified torque. This is the most widely used method because of its convenience of operation. The following is a brief description of the two most commonly used models.

2.1.1 Short-Term Torque–Preload Correlation

Researchers have attempted to include all the factors that influence the torque–preload correlation by using the nut factors. The simplest equation, generally called the short-term equation, can be expressed as follows:

$$T = KDF, \tag{1}$$

where T denotes the tightening torque, K denotes the dimensionless nut factor, D denotes the nominal diameter of the fastener, and F denotes the bolt preload.

When the short-form equation is used, the nut factors are estimated, obtained from a table, or determined through testing. Bickford [7] provided the mean values of the nut factors for various combinations of joint materials and surface conditions. However, the scatter in the tabulated values of the nut factors is too high to provide a reliable prediction of the torque–preload correlation according to Eq. (1). As stated in VDI 2230, the nut coefficient is associated with the tightening method, and different tightening methods correspond to different ranges of nut coefficients. In addition, a method to determine the nut coefficient has been provided to ensure accurate control of the preload [9]. The preload is considered a percentage of the proof strength or yield strength. This percentage is generally assumed to be constant (e.g., 75% of yield). Therefore, the short-term equation does not address the role that torsion plays in achieving the maximum preload. To optimize the bolt preload using this approach, the percentage of yield strength should vary with the changes in the nut factors.

2.1.2 Long-Term Torque–Preload Correlation

Many additional equations are available in the engineering literature that relate the input torque to the preload, thread geometry, and friction coefficients. Motosh [10] first defined this relationship. In the absence of a prevailing torque and omitting the three-dimensional effect of the helix angle of the thread profile, we obtain

$$T = T_p + T_t + T_b, \tag{2}$$

$$T_p = \frac{P}{2\pi}F, \tag{3}$$

$$T_t = \frac{\mu_t r_t}{\cos\beta}F, \tag{4}$$

$$T_b = \mu_b r_b F, \tag{5}$$

where T_p is the pitch torque component, T_t is the thread friction torque component, T_b is the bearing friction torque component, P is the thread pitch, μ_t is the thread friction coefficient between the thread of the bolt and nut, r_t is the effective contact radius between threads, β is half of the thread profile angle (30° for standard UN and ISO threads), r_b is the effective bearing radius, and μ_b is the bearing friction coefficient between the bolt head or nut and joint surface.

In general, 90% of the tightening torque is used to overcome friction. Here, the friction on the bearing surface and thread pair account for approximately 50% and 40%, respectively. Only approximately 10% of the tightening torque is used to stretch the bolt and generate a preload. This is the "5-4-1" criterion. Many variables affect the friction in threaded fasteners. Therefore, the friction coefficient is difficult to control and essentially infeasible to predict. With a large amount of friction scatter, the amount of preload achieved by the torque control method may not be close to the calculated or expected value.

2.2 Torque-Angle Control Method

Considering the shortcomings of the torque control method, it is determined that the rotation angle of the bolt head is proportional to the bolt elongation. Therefore, the torque-angle method can be adopted to achieve a predetermined preload by rotating the bolt head or nut to a specified angle. It was first introduced and implemented by the Association of American Railroads approximately 70 years ago. It was subsequently modified by the Bethlehem Pacific Coast Steel Corporation [11]. The original torque-angle method, also known as the turn-of-the-nut method, stretched the bolt beyond its yield point. The torque-angle method currently used in the industry is a modified version of the original turn-of-the-nut method. The bolts are tightened within the elastic range.

Figure 2 shows the preload–angle curve. The torque–angle tightening process can be divided into two stages. First, a threshold torque is selected to bring the bolt head or nut close to the connected part, which reaches the linear stage (as shown in Figure 2). During the rundown of the signature, negligible to no preload is produced until the joint parts are aligned and snugged together to a threshold level. The bolt head or nut is then turned to a specified angle. However, if the bolt head or nut continues to rotate, the bolts can exceed the yield point and eventually break after the linear region ends.

Bickford [7] provided a linear relationship between the preload and the rotation angle of the bolt head/nut in the linear phase as follows:

$$F = \left(\frac{K_b K_c}{K_b + K_c}\right) P \frac{\Delta\theta}{360^\circ}, \tag{6}$$

where K_b and K_c are the tensile elastic moduli of the bolt and compression elastic moduli of the connected parts, respectively.

Bray and Levi [12] concluded that the torque-angle control method afforded significantly better control of the induced bolt load than the torque control method. The scatter in the bolt preload induced by a given tightening torque may be over four times larger than that for angle-rotation control under comparable conditions. In addition, researchers [13–15] have contended that the preload generated by torque-angle control is proportional to the angle of turn regardless of the frictional variables. Although the torque-angle control method has remarkable advantages compared with the torque control method, it has the following problems. First, the stiffness

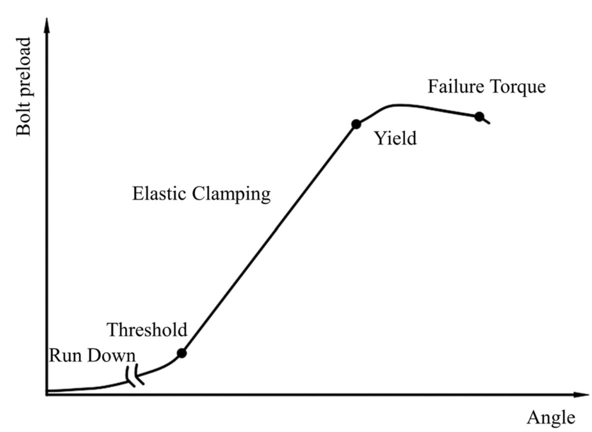

Figure 2 Preload–angle signature

values of the threaded fastener and connected parts are relatively difficult to calculate, particularly when the bolt is short. In addition, the starting point of the linear phase of the preload–angle curve varies with the bolts, which increases the uncertainty of the elastic constant.

Subsequently, Fukuoka et al. [16] considered the effects of the surface roughness and the inclination angle of the bearing surface when calculating the stiffness. They concluded that the surface roughness causes a highly nonlinear tension–angle relationship. Additionally, they recommended the torque-angle control method in the elastic range as more appropriate for bolted joints with large grip lengths and high bolt tensions. In 2008, Nassar and Yang [17] proposed a modified torque-angle (M-T-A) method that considered the effects of the evolution of friction coefficients, rotational clearances in the socket and/or tool drive, twist angle of the bolt, and elastic angle of twist of the drive of the machine. The M-T-A control method can significantly reduce the effect of the friction coefficient variation from one tightening cycle to another on the error.

2.3 Stretch Control Method

Stretch control is a method in which the variations in the length of a threaded fastener are monitored. The relationship between the bolt length variation and bolt preload during the tightening process of the elastic bolts is given by Corbeet [14] as follows:

$$\Delta L = \frac{F}{K_b} = F\left(\frac{0.4D}{EA_D} + \frac{L_1}{EA_1} + \frac{L_2}{EA_2} + \frac{0.4D}{EA_D}\right), \quad (7)$$

where K_b is the bolt stiffness; D is the nominal bolt diameter; E is the Young's modulus of the bolt material, L_1 and A_1 are the length and cross-sectional area of the bolt shank, respectively; L_2 and A_2 are the length and area of the grip thread, respectively; A_D is the area at the nominal diameter; and $0.4D$ is the effective length of the bolt head and the effective length of the threads engaging a nut or tapped hole.

Similar to the torque-angle control method, the key to the stretch control method is the accurate calculation of the threaded fastener stiffness. Several formulas have been proposed to accurately estimate the stiffness. In general, a preferable result can be obtained using the stiffness estimation formula. However, it is necessary to determine the stiffness of threaded fasteners through tensile tests for certain special connections.

In addition, it is important to measure the length of the threaded fastener accurately using the stretch control method. The most commonly used methods for measuring threaded fastener elongation include the C-micrometer, gauge screw, gauge rod bolts, and ultrasonic methods. These methods are time-consuming, have certain limitations, and may not be suitable for mass bolt assembly applications. High-accuracy ultrasonic measurement is a potential technology for measuring the residual clamping force of long-term service bolts.

2.4 Yield Control Method

Tightening a bolt to yield was first presented by the Association of American Railroads approximately 70 years ago [11]. Its advantage is that the tightening process is controlled by material properties regardless of the torque. The scatter of the final preload is relatively small because the material properties vary negligibly [14]. In addition, a higher preload is obtained. Hence, these are generally applied to crucial connections that require high clamping forces. Tightening to yield requires the simultaneous measurement of the tightening torque and rotation angle during the tightening process. The torque–angle curve and torque gradient curve are shown in Figure 3. The slope of the curve varies (Point B), which signifies the beginning of material yield.

There are two methods to achieve tightening-to-yield-point. The first method ensures that the fastener safely exceeds its yield point at a fixed rotation angle. However, it has a significant disadvantage in that most fasteners run the risk of thread distortion or necking if used more than two–three times. Therefore, reuse of the bolts is not recommended. The second method uses a torque gradient. This method was first presented by Boys and Wallace [18] with an emphasis on mass-production applications such as automotive assembly plants. It employs a torque gradient–angle curve (Figure 4) to detect the yield point and stops tightening when the gradient drops at the yield point (Point B). This is the most effective yield tightening method: It achieves a high and accurate preload and minimum bolt-elongation past yield without the need for special calibration. Moreover, it permits bolt reuse.

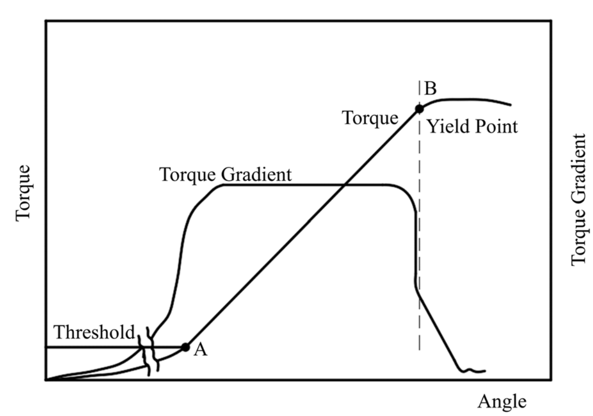

Figure 3 Torque–angle signatures

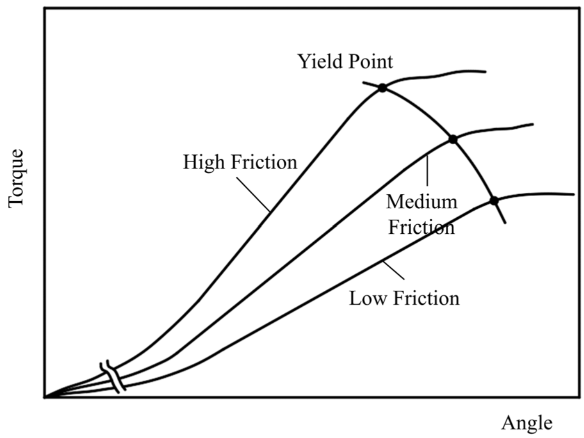

Figure 4 Effect of friction on fastener yield point

The yield of threaded fasteners is caused by the combined action of axial and shear stresses. Therefore, it is different from the torque-angle control method in that friction has a significant influence on the final preload obtained using the yield point control method. Bray and Levi [12] were the first to experimentally verify that the rotation angle of the nut required to tighten the bolt to the yield point is significantly affected by lubrication. Monaghan [19] obtained similar results in a series of experiments. Bickfold et al. [14] determined the effect of friction on the yield point, as shown in Figure 4: When the friction coefficient is larger, the friction torque on the bolt is also larger, and a higher torsional stress was generated. A higher shear stress implies a lower bolt tension.

A few researchers [13, 20] employed the finite element method to investigate the behavior of bolted joints tightened beyond the yield point. They indicated that the threshold of the nonlinear behavior and maximum bolt tension at yield decreases with an increase in the friction coefficient. Toth [21, 22] presented a complete theoretical model for tightening a screw over its yield point and simulated tightening using Monte Carlo and Taylor series expansions, respectively. Additionally, the effect of tightening to the yield point on the joint performance was investigated systematically [23–25].

Tightening to yield creates a significantly higher preload during the joint assembly. The preload scatter is reduced significantly compared with the torque control method. However, this method cannot be applied to brittle bolts. In addition, the effects of tightening plastic zones on the joint dynamic performance, fatigue performance, and repeated tightening performance of the bolts should be studied further.

2.5 New Tightening Technology

In addition to conventional methods, researchers have proposed improved tightening methods based on these methods. Hagiwara and Ohashi [26] proposed a new technique based on the torque difference and relative rotation angle during the tightening and loosening processes of threaded fasteners. The experimental results demonstrate that this technique can estimate the preload with high accuracy. Mori et al. [27–29] proposed a new tightening method based on the torque method to reduce the scatter of bolt preloads. However, the tightening process is complex. Moreover, the effect of the friction variation caused by repeated tightening need to be considered. Zhang et al. [30] introduced the torque gradient, tightening speed, and stiffness of the connecting structure into a torque–preload relationship formula using an integrated yield control and torque control method. The friction effect was compensated for by the torque gradient. However, a calculation error was introduced in the bolt stiffness. Hareyama et al. [31, 32] considered the tightening torque and equivalent stress coefficient as independent random variables. They established a method to increase the target tightening torque using the elliptical confidence limit. This method can obtain a higher preload to maintain the tightening reliability. Hwang et al. [33] used finite element analysis with a detailed three-dimensional model and dynamic simulation to simulate the fastener installation process and obtain the torque–angle signature curves for different static and kinetic friction coefficients. Finally, the installation torque was determined based on the torque–angle curves. Schüthe et al. [34] proposed a method for measuring the preload based on bolt torsion to overcome the friction uncertainty in conventional torque measurement methods. Zhang et al. [35] improved the reliability of mechanical products by directly controlling the preload during bolt tightening using an improved intelligent wrench and signal processing system.

2.6 Ultrasonic Control Method

The ultrasonic control method for a bolt preload is essentially a method for measuring its elongation or stress state during tightening. Therefore, there are two methods for tightening bolts using ultrasonic instruments. One directly measures the bolt elongation, whereas the other directly measures the bolt stress. Ultrasonic control that relies on elongation measurement is a convenient method to achieve stretch control. Therefore, it cannot eliminate potential variations in the stretch control method. Meanwhile, it is also affected by the stress distribution on the bolts. In practical applications, the precision of ultrasonic control is ensured by calibration [36].

Ultrasonic elongation measuring devices were first developed by Douglas Aircraft Co. and Erdman Instruments Co. in the early 1970s [11]. In 1988, Bickford [37] summarized certain factors that affect the accuracy of elongation measurements using ultrasonication, such as the non-uniform tensile stress, anisotropy of the bolt material, residual manufacturing stresses, and variations in bolt material properties such as non-uniform thermal coefficients and elastic modulus. In the subsequent decades, to improve the accuracy of elongation measurements using ultrasonic waves, researchers extensively studied the effect of non-uniform tensile stress [38–40] and stress state [41–45] on wave velocity. In 2016, Persson et al. [46] compared the accuracy of preloads obtained by torque control, angle control, gradient control (yield control), elongation control, and ultrasonic control. The results showed that ultrasonic control obtained the smallest preload dispersion, whereas torque control achieved the largest preload dispersion. In addition, the relationship between the axial stress of the bolts and nonlinear coefficient was studied. This provided a new method for detecting stress in bolts in the service state [47].

Ultrasonic measurement is typically used as a nondestructive testing technology to monitor the residual axial force of a bolt in service, as opposed to controlling the bolt preload during tightening. It is considered a potential method for the accurate, rapid, and convenient monitoring of bolt preloads. However, bolts have certain special requirements such as the surface roughness of the bolt head. In addition, the equipment is expensive and complex, and the error percentage is relatively high for exceptionally short bolts. These factors significantly limit the widespread use of ultrasonic technology in practical engineering applications. In addition, the accuracy of ultrasonic measurements is influenced by many factors such as temperature, residual stress, and material properties.

2.7 Strain Control and Direct Preload Control Method

2.7.1 Strain Control Method

Strain control is achieved by continuously monitoring the elastic strain of the bolt shank until it attains a specified value. The relationship between the bolt tension and elastic strain is as follows:

$$F = A_t E \varepsilon, \tag{8}$$

where A_t is the tensile area of the bolt and ε is the axial strain.

In general, strain control is achieved by installing a strain gauge on the bolts or using a piezoelectric-enhanced load washer. With technological developments, researchers and manufacturers have begun to integrate strain gauges and bolts. Although strain control has high precision, it has significant shortcomings such as the high cost, time consumption, inconvenience of implementation, and incapability of being removed. Therefore, these are used only in laboratories for research purposes and are impractical for mass-production applications.

2.7.2 Direct Tension Indicator (DTI) Method

The tension of the bolt is measured using a washer with protruding features or a bolt head (specially designed or otherwise). All DTIs are designed for specific joints and unique purposes. The advantage of this method is that it is simple to install and use. However, its disadvantage is that it requires a special design for each connection. In addition, bolts that indicate tension owing to deformation are generally not reusable. Figure 5 shows common DTI bolts.

Another DTI bolt is shown in Figure 6. A gauge pin at the center of the bolt supports a red indicator disk. When the bolt is tightened, the pin moves away from the window. This enables a certain black liquid to enter the chamber between the disk and window. Simultaneously, the color can be observed to shift from red to black from the window.

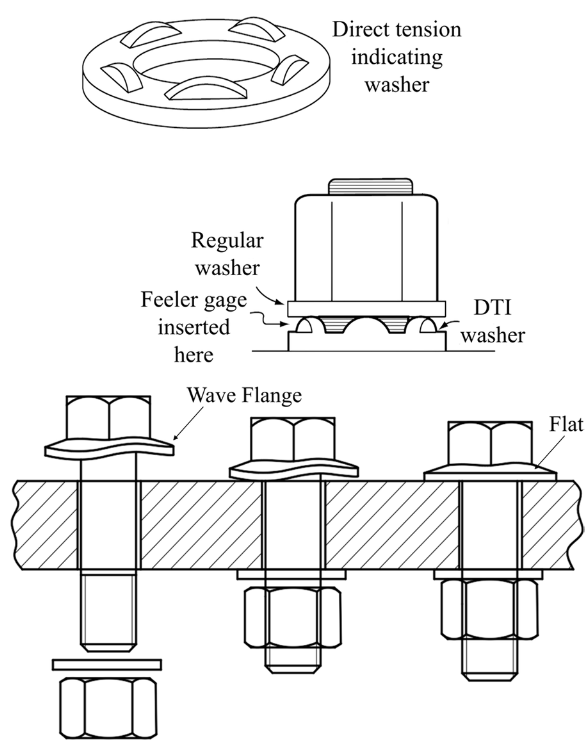

Figure 5 Direct tension indicator bolts [7, 11]

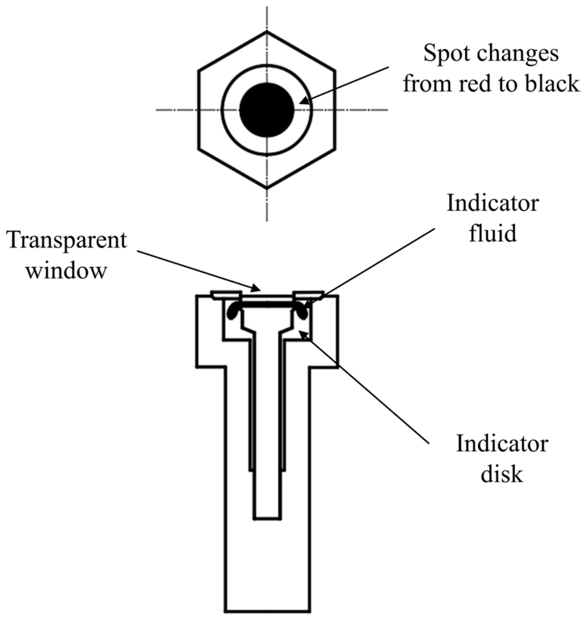

Figure 6 Direct tension indicator bolt [11]

2.7.3 Alternate Design Bolt

Bolts with additional design features to indirectly indicate bolt tension are used occasionally. The common design features include twist-off bolts and lockbolts. The tension of the alternate-design bolt is determined by the snap-off of the spline or pintail of the bolt. Thus, alternate bolt designs are limited to one-time use [7, 11].

2.7.4 Bolt Tensioner

The intent of a family of tools called bolt tensioners is tension control. A significant advantage of the tightening operation with a bolt tensioner is its inherent independence from the friction coefficients that generate uncertainties in the bolt tension [48]. Therefore, this method is used to tighten critical structures in which the clamping force should be controlled with a high accuracy.

The ratio of the expected clamping force to the initially applied tension (termed "effective tensile coefficient") is the most important factor to be predicted in advance for given joint configurations. Researchers have systematically calculated the effective tension coefficient using theoretical derivations [48, 49] and numerical analyses [48, 50]. In 2008, Hashimura et al. [51] analyzed in detail the variation in the fitting state of the engagement thread during the process of tensile tightening. They concluded that the higher the target preload, the smaller is the error after tightening.

2.7.5 Bolt Heater

Although the equipment and procedures used differ significantly, the task accomplished by a bolt heater is similar to that achieved by a bolt tensioner. A major advantage of the bolt heater is that it is inexpensive. The cost advantage of the bolt heater increases with an increase in the diameter of the threaded fasteners. Therefore, bolt heaters are widely used for tightening bolted joints with large nominal diameters, where high tension is required. However, it is a relatively slow process. Moreover, the actual tightening operation requires a significant amount of operator skill. In addition, decarbonization may occur on the threaded surfaces when the bolts are heated [7].

Fukuoka et al. [52–54] systematically investigated the effects of grip length, rundown torque, and thermal contact resistance on the heating operation using the finite element method. They proposed a practical method to predict the heating period necessary for the target bolt preload under certain conditions. Because of their unique advantages, hydraulic bolt tensioners and bolt heaters are used in critical structures with large-diameter bolts. However, guidelines for the practical application of these two methods are unavailable. In most cases, this relies on the experience and skills of workers.

2.8 Summary of Various Tightening Methods

As mentioned above, extensive research has been conducted on the control of bolt preloads. Various tightening methods have been proposed. These can be divided into direct and indirect control according to their working principle. These are suitable for different situations owing to their unique characteristics. The characteristics are summarized in Table 1.

Certain tightening methods achieve higher precision than the torque control method. However, these are not widely used in practical engineering because of their high cost, complex operation, and other constraints. Many of these methods are used only for critical structures that require high precision or tension. Conversely, although the scatter of the preload obtained using the torque control method is larger, it is the most widely used method in practical engineering because of its convenient implementation. Thus, many studies have been conducted over the past few decades to improve the accuracy of torque control methods. The next section systematically summarizes these studies.

3 Research on Torque Control Method

The scatter of the clamping forces obtained by the torque control method can be attributed to three factors: the inaccurate torque-preload correlation formula,

Table 1 Summary of characteristics of various tightening methods

Type of method	Tightening method	Characteristics
Direct	Strain control	Advantages: high accuracy, not affected by friction coefficient and lubrication conditions Disadvantages: high cost, time-consuming, inconvenient to implement, and not removable
	Direct tension indicator	Advantages: convenient implementation, simple theory, low cost Disadvantages: low accuracy, requires specific designs for each structure
	Alternate design bolt	Advantages: independent of friction Disadvantages: cannot be reused, low versatility
	Bolt tensioner	Advantages: no torsional stresses, suitable bolts with large diameters Disadvantages: high cost, elastic recovery, complex operation
	Bolt heater	Advantages: low cost, no torsional stresses, suitable bolts with large diameters Disadvantages: complex operation, decarbonization, affected by temperature and material properties
Indirect	Torque control	Advantages: convenient implementation, simple theory, low cost Disadvantages: low accuracy, affected by friction and lubrication conditions
	Torque-angle control	Advantages: independent of friction, relatively high accuracy Disadvantages: complex operation, determination of close torque and part stiffness
	Stretch control	Advantages: relatively high accuracy Disadvantages: complex operation, high cost
	Yield control	Advantages: high preload, relatively high accuracy Disadvantages: complex operation, affected by friction and material properties, determination of yield point
	Ultrasonic control	Advantages: high accuracy, real-time monitoring Disadvantages: high cost, high error percentage for short bolts, affected by environmental factors and material properties

replacement of the effective friction radius with the average radius, and complex friction characteristics during tightening. Many studies have been conducted on these three aspects to improve the accuracy of torque control methods. This section summarizes the development history and research status of the torque control method based on these three aspects.

3.1 Torque–Preload Correlation Formula

It is critical to establish an accurate torque–preload correlation model for torque control. As shown in Eq. (1), the relationship between the torque and preload was established using nut factors and the nominal diameter of the bolt. However, the scatter in the preload obtained by turning the bolt head or nut to a preset torque (calculated using the nut factors) is significantly large. Hence, researchers have attempted to establish a more accurate torque–preload correlation formula. The formula is mainly based on the balance relationship between the force and moment during the tightening process. Because the geometric structure of threaded fasteners is highly complex, researchers generally simplify it to a certain extent during mechanical analyses.

Motosh [10] appears to have been the first to propose a precise torque–preload correlation formula. It is shown in Eqs. (2)–(5). As discussed previously, it is pertinent to cases without prevailing torque and omits the three-dimensional effect of the helix angle of the thread profile. Based on the work of Motosh, Yamamoto [55] developed the torque–preload correlation further by considering the effect of the thread helix angle. They replaced the half thread profile angle α in Eq. (4) with α'. It is the half thread angle in a plane perpendicular to the thread helix angle:

$$\alpha' = \arctan\left[\tan\alpha\cos\left(\arctan\left(P/\pi d_p\right)\right)\right], \tag{9}$$

where d_p is the pitch diameter of the bolt.

Subsequently, researchers considered the effect of the three-dimensional helix angle on the torque–preload correlation and provided another calculation formula [56]. Eccles [57] provided another torque–preload correlation formula based on the principle of energy conservation. It can be applied to both tight and loose processes. Juvinall and Marshek [58] improved the torque–preload correlation formula.

Nassar and Yang [59] systematically studied the torque–preload correlation. They provided a three-dimensional torque–preload correlation for both tightening and loosening stages considering the lead helix and thread profile angles. The equations for the breakaway loosening and audit tightening stages account for the static and kinetic components of friction. The percentage difference between the new formula and previous formulas [10, 56, 58] was analyzed. Moreover, the effects of the thread pitch, thread profile angle, friction coefficient, and fastener geometry were discussed.

In 2011, Huang and Guo [60] provided a torque–preload correlation that accounts for the non-axial forces and bending moments generated during the tightening process. This relationship was verified using three-dimensional finite element models. Subsequently, Oberg et al. [61] provided another torque–preload correlation that included the bolt preload, tightening torque, bearing friction coefficient, and thread friction coefficient. In 2017, Jeong et al. [62] provided a new formula related to the preload and the tightening–loosening torque difference to predict the preload of a joint screw assembly between an implant and abutment based on a mechanical analysis. In addition, researchers have established a theoretical formula for torsion-tension in the tightening process of a non-standard thread. It provides theoretical guidance for the installation of nonstandard threaded fasteners [63]. All these torque–preload correlation models are based on the equilibrium of forces and moments during bolt tightening. This is owing to the complex geometry of the thread and the forces acting on several planes during tightening. Researchers generally simplify it to varying degrees. Thus, various torque–preload correlation formulas have been obtained. A preliminary examination may indicate these formulas to be different. However, the differences are marginal. Although the formula provided by Motosh is the result of certain simplifications, it can still accurately describe the relationship between the tightening torque and preload. This is the simplest form. Hence, it remains the most widely used torque–preload correlation formula. The effective friction radius and friction characteristics during tightening have also been studied based on Motosh's formula in most of the published literature.

3.2 Effective Friction Radius

It is well known that the torque–preload correlation in threaded fasteners and the resulting joint clamping force are highly sensitive to the friction torque components. It can be observed from Eqs. (3)–(5) that the torque–preload correlation is determined by geometric factors (α, β, and P), friction coefficients (μ_b and μ_t), and effective friction radii (r_b and r_t). Because the geometric factors are fixed for a specific type of threaded fastener, the torque–preload correlation depends primarily on the friction coefficients and effective friction radii on the contact surfaces.

Over the past few decades, approximate values have been used rather than the actual effective friction radius of the contact surface. This is because an accurate contact pressure distribution is difficult to obtain for a bolted joint. For convenience of calculation, this approximate value is generally the mean contact surface radius. This generates errors in the calculation of the friction torque component and affects the accuracy of the final preload. In recent years, the development of numerical and contact mechanics calculation methods has enabled the attainment of accurate contact pressure distributions. Therefore, researchers have conducted successive investigations on the effective friction radius.

Nassar et al. first proposed that errors are introduced in the calculation of friction torque when the actual effective friction radius is replaced with the mean radius of the contact area. They assumed a pressure distribution on the bearing and thread surfaces and provided the corresponding effective friction radius calculation formula [64, 65]. They concluded that more attention should be paid to the effective friction radius of the bearing surface than to that of the threaded surface. This is mainly because the radius ratio of the thread is significantly small, which implies that the range of the actual effective friction radius is limited. In addition, the calculation formula considers the effect of the varying sliding speed. They observed that this effect on the bearing friction torque component increased with an increase in the bearing radius ratio [64]. The formulae for calculating the proposed effective friction radius are based on the assumed pressure distribution, which may not be consistent with the actual contact pressure distribution.

Hence, Zou et al. [66] performed contact mechanics analysis to determine the actual contact pressure distribution between the bolt head/nut and joint surface for various contact surface roughness. Based on the pressure distribution, the effective friction radius was calculated precisely. They observed that surface roughness plays an important role in determining the effective bearing radius. However, they did not establish experimental procedures for measuring the frictional torque components in this study. In another study, they provided an experimental procedure to determine the effective friction radius and friction coefficients [67]. These experimental results are consistent with those of previous studies.

The calculation efficiency and reliability of FEM have improved gradually with the development of numerical methods and computing capabilities. Researchers [68, 69] began to use the FEM to obtain the contact pressure distribution on the bearing surface and then, calculate the effective friction radius. The effects of geometrical, material, and frictional factors on the effective friction radius were also discussed.

In addition, Zhu et al. [70] considered contact problems on bearings and threaded surfaces as punch problems to obtain the actual contact pressure distribution. They proposed new formulas to predict the preload and loosening torque and conducted an experimental verification. The results showed that the proposed approach is more effective for precisely controlling the preload and estimating the anti-loosening performance of threaded fasteners. This is a good example of the simplification of the contact problem in a bolted joint to a special contact model.

The key to calculating the effective friction radius is the solution of the actual contact pressure distribution on the bearing and thread surfaces. This is a complex contact mechanics problem with many factors. For a specified bolted joint structure, the FEM appears to be capable of obtaining effective results. However, it is unrealistic to obtain the contact pressure distribution of each structure using precise finite element analysis in a mass-product assembly. Hence, efforts should be undertaken to establish an accurate and simple contact-pressure distribution solution model that includes the primary influencing factors.

3.3 The Friction Characteristics During Tightening

Another main factor in the torque–preload correlation formula is the friction coefficient. In practice, the friction coefficient is affected by various factors, highly difficult to control, and essentially infeasible to predict. Bickford [7] stated that 30 or 40 variables affect the friction in a threaded fastener. The Ishikawa diagram in Figure 7 illustrates the complexity involved in determining the preload magnitude in a bolted joint. This diagram illustrates the important factors that should be addressed while designing and assembling a threaded joint to obtain the expected preload.

3.3.1 Measuring Method and Device

The friction characteristics of threaded fasteners are generally reflected in the friction coefficients of the bearing and threaded surfaces. These can be determined in two ways. The first method is based on the relationship between the tightening torque and preload under the premise that the thread friction coefficient is equal to the bearing friction coefficient. According to Eqs. (2)–(5) and assuming $\mu_t = \mu_b = \mu_m$, the total friction coefficient μ_m can be obtained as follows:

$$\mu_m = \frac{T/F - P/2\pi}{r_t/\cos\beta + r_b}. \tag{10}$$

This method is relatively convenient to implement and requires only the simultaneous measurement of the tightening torque T and axial preload F.

The second method measures the thread friction torque T_t, bearing friction torque T_b, and preload F, and calculates the thread friction coefficient μ_t and bearing friction coefficient μ_b using Eqs. (2) and (5). In this method, T_t and T_b should be measured separately. Therefore, a specially designed testing machine is required to separate the torque components. Researchers have proposed several different measurement machines for achieving separate measurements. In 1966, Bray and Levi [12] developed the testing machine illustrated in Figure 8. It can measure the input torque, combination of the thread friction torque and pitch torque, bolt preload, and nut rotation.

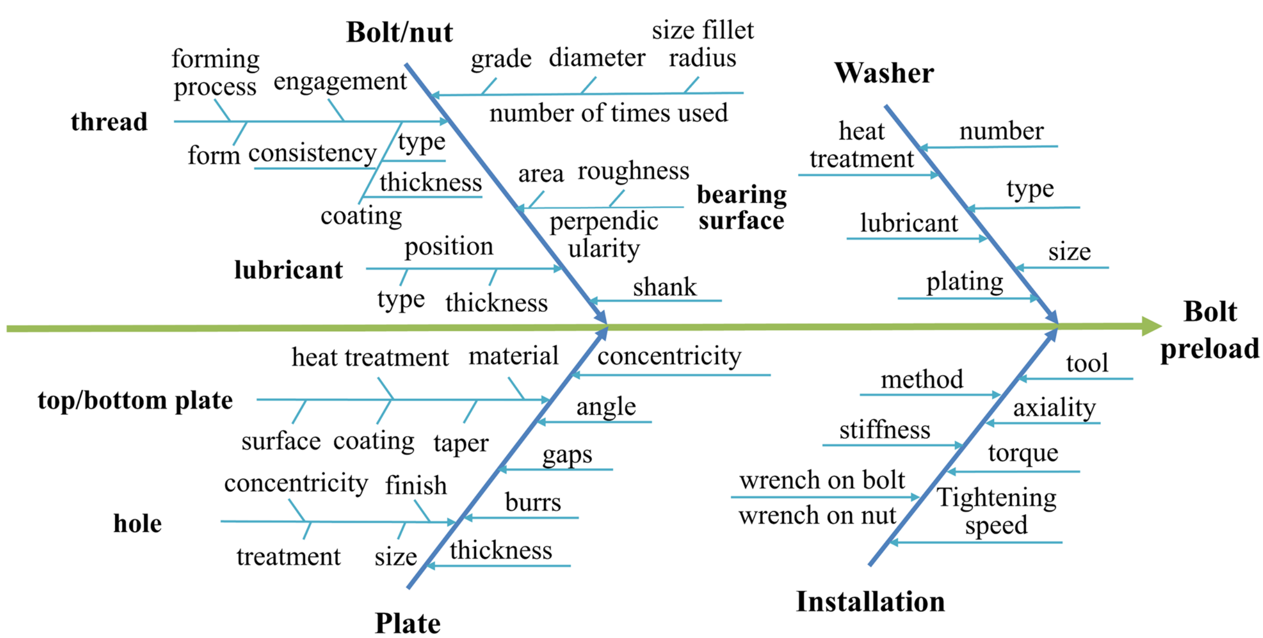

Figure 7 Ishikawa diagram showing the factors that contribute to the bolt preload

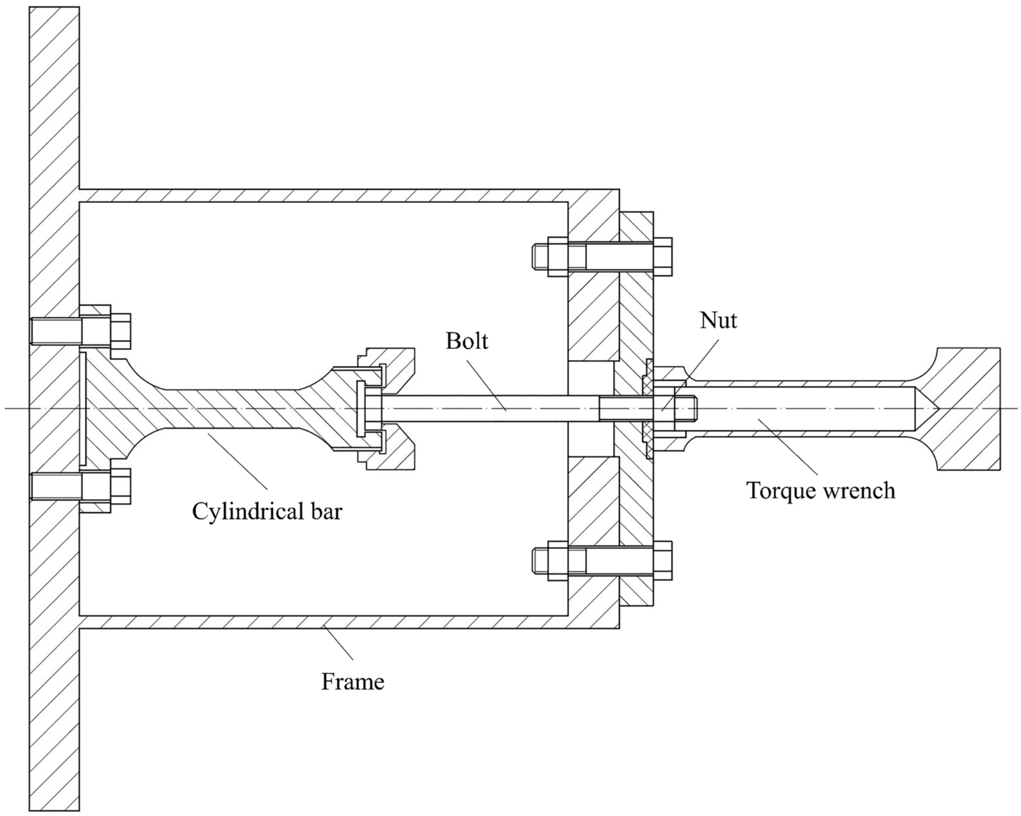

Figure 8 Fastener testing machine [12]

The structure of the testing machine developed by Bray and Levi is simple. However, if there is an eccentric load or the bearing surface is inclined, the sensor for measuring the thread friction torque and preload is likely to bend. Sakai [71] presented an improved measurement setup as shown in Figure 9. However, the friction of the thrust bearing affects the accuracy of separating T_t and T_b. Both the devices require the calibration of output values or data correction.

In 2001, Jiang et al. [72] presented a new approach for investigating the friction in a bolted joint. Thread friction and bearing friction can be measured separately using a tension-torsion servo-hydraulic material testing system. Compared with previous fastener testing machines, it has unique advantages and provides a new method to study the friction characteristics of threaded fasteners.

These machines and their improved versions have been used by several researchers for tightening purposes. Threaded fastener friction coefficient testing machines have matured and have been commercialized successfully.

3.3.2 Factors Affecting Friction Coefficient of Threaded Fasteners

To improve the torque control technique, considerable efforts have been undertaken in the past few decades to investigate the factors that may affect the torque–preload correlation. We have classified the factors involved in the published literature into seven categories according to their characteristics and summarized the literature that studied each type of influencing factor. This is shown in Table 2.

Lubrication: Lubrication is one of the most significant factors affecting the friction performance. Effective lubrication has a significant effect on reducing the friction coefficient and is convenient to achieve. Therefore, lubrication is a primary concern for researchers.

In 1966, Bray and Levi [12] experimentally demonstrated that the effect of lubrication on the friction performance of fasteners is highly significant. They concluded that lubrication can reduce the friction coefficient and the scatter of the preload. Subsequently, researchers conducted relevant research using other experimental methods and obtained similar conclusions [71, 73–75]. In addition, the lubricant type [76–78], lubrication position

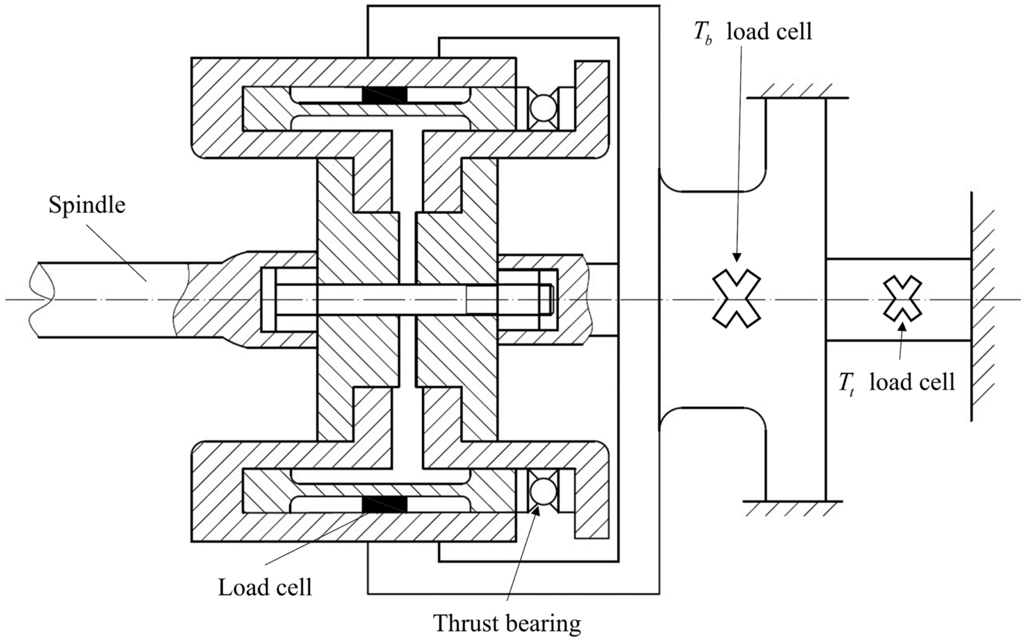

Figure 9 Fastener testing machine [71]

Table 2 Summary of the research on the factors influencing friction

Large categories	Specific influencing factors	References
Lubrication	Type of lubricant, lubrication position	[12, 71, 73–88]
Material	Materials of fastener and/or washer and/or joint	[12, 56, 67, 71, 75, 78, 85, 88–92]
Coating	Coating thickness and types	[71, 77, 79, 93–100]
Manufacturing	Surface treatment, forming process, surface roughness	[71, 74, 75, 82, 90, 101]
Geometry	Fastener diameter, thread pitch, grip length, size of the hole, thread clearance, contact area and position, use of a slot …	[12, 67, 72, 76, 78, 88, 91, 95, 96, 102–104]
Operation	Tightening speed, turning side	[71, 73, 75, 76, 84, 86, 87, 91, 95, 97, 102, 105–111]
Re-tightening	Number of tightenings and loosenings	[71, 72, 74–76, 80–85, 88, 90, 91, 95, 97, 112–114]

[79, 80], and effect of lubrication on the friction performance of fasteners during repeated tightening [75, 80, 81] were investigated. The results showed that bearing surface lubrication is more important than threaded surface lubrication. Lubricants can protect the contact surface. Moreover, the friction coefficient becomes more stable during repeated tightening. In 2011, Croccolo et al. [82, 83] indicated that the friction performance of titanium screws was inferior to that of steel screws. They indicated that titanium screws require lubrication. They also concluded that thread friction generally decreases with an increase in the time interval before tightening when the lubricant is a thread-locking agent [84]. Kopfer et al. [85] concluded that titanium screws cannot function without lubrication. Yu et al. [74, 77] investigated the effects of lubrication on the tribological properties of Ni-based superalloy fasteners. Rosas et al. [77] recommended the use of MoS2 for installing Ni-Co fasteners. Yue et al. [86, 87] investigated the influence of lubrication on the friction characteristics of composite structures with bolts.

The friction coefficient can vary significantly among lubricant–material combinations [88]. The lubrication mechanisms and wear resistances of the different lubricants also differ. In general, a good lubricant should exhibit accurate and repeatable frictional properties during tightening. Moreover, it should enable fasteners to resist loosening and fretting wear during service.

Material: With the sustainable development of engineering, lightweight materials have become important indicators of mechanical equipment. Materials with high strength and weight ratios, such as titanium alloys, are being used increasingly in engineering applications

[88]. The type and chemical composition of materials are important factors affecting the friction coefficient.

In 1966, Bray and Levi [12] investigated the effects of bolt material grade and washer hardness on friction coefficient. Subsequently, Sakai [71] investigated the effect of the material combination of bolts and nuts on the friction coefficients of fasteners during repeated tightening. In 2001, Jiang et al. [51] studied the effect of the washer material on the torque–preload relationship during repeated tightening. They concluded that the effect of repeated tightening on friction is associated with the washer material. In 2005, through a series of experiments, Nassar et al. [67] indicated that the fastener material class exerts the most significant effect on the thread friction coefficient. Shao et al. [75], Aycock et al. [78], and Brown et al. [89] conducted similar studies. In another study, Nassar indicated that the nut factors are marginally higher for aluminum joints than for steel joints at all levels of surface roughness [90]. Shao et al. [75] also concluded that compared with the bolt and washer material classes, the joining material is a significant factor affecting nut factors. Cooper et al. [91] studied the effect of three bolt materials (alloy steel, carbon steel, and stainless steel) commonly used in the industry on the nut factors. Kopfer et al. [85] investigated the friction characteristics of bolted joints in lightweight designs. The results indicated that the friction performance of titanium screws is inferior to that of steel screws. Unlike the above studies, Yu et al. [92] investigated the effect of the elastic modulus and strain-hardening exponent on the torque–preload relationship using finite element analysis. They concluded that the elastic modulus and strain-hardening exponent have negligible influence on the torque–preload relationship.

Coating: Coatings are an effective means of protecting metal parts. It can slow the interface damage and improve the material wear or antifriction performance [93]. With the development of surface engineering technologies, coatings have been widely applied to threaded fasteners. However, because the preparation of thread coatings is difficult, compared with other factors, negligible research has been conducted on the effect of coatings on the friction properties of threaded fasteners.

In 1978, Sakai [71] introduced the two types of coating materials named "μ-stabilizers" that could substantially reduce the effect of the lubricant, washer and screw material, and bolt surface treatment on the scatter of friction coefficients. In 2002, Jiang et al. [94] investigated the effect of coating on frictional properties using ten different nuts and nine washers. They concluded that the coating had a significant effect on the friction characteristics during repeated tightening. Nassar et al. [95] studied the effect of three coatings with different friction rates on the torque–preload relationships. They further studied the effect of coating thickness on the nut factors [96] and the effect of coating on wear patterns [97]. Rosas et al. [77] compared the performances of different coatings with respect to thread engagement and the nut factors. In 2017, the effects of screw coating were investigated in detail by Croccolo et al. [79]. They concluded that in addition to lubrication, the effect of the coating was significant. Morozov [98] studied the influence of temperature on the antifriction properties of coatings. Recently, researchers analyzed the effects of process parameters [99] and storage conditions [100] on the frictional properties of threaded fastener coatings. Thereby, they expanded the relevant research fields.

Manufacturing: For the same material, the variations in hardness and surface properties owing to different manufacturing processes also affect the fastener friction. Compared with the other factors, the research on the effect of the manufacturing process on the friction performance is relatively insufficient. At present, the factors studied mainly include the surface treatment [71, 82], forming process [82], and surface roughness [74, 75, 82, 90, 101].

Sakai [71] conducted a series of experiments to investigate the influence of the surface treatment on the friction coefficients of fasteners. They concluded that the effect of repeated tightening on the friction coefficients depends on the surface treatment. Nassar et al. [90] considered the effects of surface roughness on the nut factors. The results showed that the effect of surface roughness on the nut factors varied with the joining material. In 2013, Fukuoka et al. [101] reached similar conclusions using new and simple test equipment. Shao [75] and Yu et al. [74] indicated that the higher the surface roughness, the larger is the nut factor. Croccolo et al. [82] investigated the effect of the roughness, forming process (cast or forged), and surface finishing (spray-painted or anodized) on the friction coefficients in the torque–preload relationship. The analytical results showed that the forming process had an insignificant influence on the friction conditions. In addition, they concluded that for an equal applied torque, the preload can vary by up to 320%.

Geometry: Geometric parameters are among the main design parameters of bolted joint structures. These include the fastener diameter, fastener length (clamping length), hole diameter, thread pitch, thread clearance, and contact area and position. In engineering, other geometric parameters are generally determined after those of the fastener are determined. Thus, researchers have focused mainly on the effects of the fastener diameter, thread pitch, and thread fit class on the friction performance of fasteners.

In 1966, Bray and Levi [12] concluded that the fit class of mating threads had an insignificant effect on the tightening characteristics. Nassar et al. [67, 76, 95, 96, 102] conducted a series of experiments to investigate the effects of thread pitch and fastener size on the friction performance. They indicated that fine (versus coarse) threads marginally reduced the preload obtained by a specific tightening torque. In addition, Liu et al. [103] analyzed the effect of the pitch error of a variable-pitch nut on the torque–preload relationship through experiments and finite element models. Yu et al. [104] reached a similar conclusion by finite element analysis. In addition, they concluded that the assembly clearance has a negligible influence on the torque–preload relationship. Brown et al. [89] and Aycock et al. [78] investigated the effect of bolt diameter on the nut factors. They concluded that the smaller the diameter, the higher is the nut factor. Brown et al. [89] indicated that the effect of the bolt diameter on the nut factors differs significantly for different materials. In 2011, Cooper and Heartwell [91] investigated the effect of the bolt length on the friction performance. The results indicated the bolt length to be an insignificant contributor. Jiang et al. [72] investigated in detail the effect of the size and shape of the hole, use of a slot, contact area, and position on the frictional properties of bolted joints. They indicated that these geometric parameters have an insignificant influence on the friction in a bolted joint.

Operation: In addition to the above objective factors, factors in the operation process (such as the tightening speed and turning elements) affect the friction performance of fasteners. In addition, with the development of intelligent manufacturing production lines, electric tightening tools are being used more widely, and the tightening speed is increasing. Therefore, researchers and engineers are focusing on the variations in the frictional properties of fasteners at different speeds.

In 1978, Sakai [71] conducted a series of experiments to investigate the effect of tightening velocities from 0.8 to 12 r/min on the friction coefficients of fasteners. The results showed that the effect of the tightening speed was significant below 2 r/min. In addition, they concluded that the lower the speed, the larger are the friction coefficients. Since then, other researchers have attained similar conclusions [73, 84, 95, 105]. They also indicated that with an increase in the tightening speed, the wear of the bearing surface may increase [73, 97]. Zou et al. [76] considered the effect of tightening speeds from 1 to 100 r/min. They concluded that the tightening speed affects the lubrication effect of the lubricant. In 2007, Ganeshmurthy et al. [106] proposed a two-stage process for tightening threaded fasteners and investigated the effect of tightening speed combinations (for stages 1 and 2) on the torque–preload relationship. The results showed that a high tightening speed in the final stage may cause a torque overshoot beyond the target torque. Unlike the above conclusions, experimental results have shown that the friction coefficient decreases with an increase in the tightening speed and tends to be stable [107–109]. Wettstein et al. [110, 111] studied the friction difference in the fastening process of an impact wrench at different speeds. They indicated that the speed has a significant influence on friction during the impact tightening process. Shao et al. [75] indicated that the tightening speed is insignificant compared with the other factors. These differences may have been caused by the different tightening speed ranges selected by the researchers during the experiment. Yue et al. [86, 87] studied the influence mechanism of different process factors on the torque–preload curve during the fastening process of the bolted joints of composite structures. They determined the optimal tightening speed under different working conditions.

Researchers have also investigated the effect of turning elements on the torque–preload relationship [91, 102]. Nassar et al. [102] indicated that the preload achieved in a fastener when tightening from the nut end is marginally lower than that achieved when tightening from the bolt head side. However, Cooper et al. [91] concluded that turning elements are insignificant contributors. Yue et al. [87] indicated that the friction coefficient increases with an increase in tightening speed when the bolt head is tightened in a composite structure. Thus, the effect of the turning element on the tightening characteristics should be studied further. In addition, the tightening tool affects the tightening characteristics of the fasteners. However, there are few reports on this aspect.

Re-tightening: One of the main reasons why threaded fastener is widely used is that it is detachable and convenient to maintain. Fasteners cannot be reused in most critical precision systems. However, fastener reuse can save costs and time, and increases the sustainability of the system. In engineering, the large majority of fasteners are disassembled repeatedly. Therefore, to ensure the safety and reliability of bolted-joint structures, it is necessary to investigate the effect of repeated tightening on the friction characteristics of threaded fasteners.

Over the past few decades, extensive research has been conducted in this field. In 1978, Sakai [71] experimentally investigated the effect of repeated tightening on the friction coefficients of fasteners. They concluded that the effect of repeated tightening on friction coefficients depends on the surface treatment, plating, and materials. Jiang et al. [72] further indicated that the effect of repeated tightening on friction is associated with the washer material. In addition, they concluded that with an increase in the tightening time, the thread friction coefficient first increases and then stabilizes. Eccles et al. [112] also obtained a similar conclusion. They indicated that the magnitude of the thread friction coefficient became dependent on the clamping force as the number of tightenings increased. Cooper et al. [91] concluded that repeated tightening resulted in a significant increase in the nut factors in the absence of washers. Jiang et al. [94] reported that lubrication could reduce the scatter of the friction coefficient during repeated tightening. Other researchers have arrived at similar conclusions [76, 80, 81]. Croccolo et al. [83] further indicated that ceramic paste shows the best results in terms of friction coefficient constancy throughout re-tightening operations, as well as the best protection of the thread and bearing surfaces against wear. Nassar et al. investigated the effect of coating [95] and tightening speed [97] on the torque–preload relationship during repeated tightening.

Nassar et al. [90] and Shao et al. [75] investigated the effect of the number of tightening cycles on surface roughness. Shao et al. [75] observed that the surface roughness and nut factor decreased with an increase in the number of tightenings. However, Nassar et al. [90] indicated that this is related to the initial surface roughness. Considering the effect of repeated tightening on the friction coefficient, Croccolo et al. [82, 113] recommended that maintenance operations adjust the tightening torque each time. Fukuoka et al. [101] determined that the removal of the metal powder generated by galling between mating surfaces is effective in reducing the scatter of friction coefficients during repeated tightening. In 2018, Yu et al. [74] discussed the effect of repeated tightening on the nut self-locking torque. The results showed that the torque decreased with an increase in the number of repeated tightening cycles within a certain range. Moreover, the effect decreased after two to three tightening cycles.

In general, the friction coefficients of well-lubricated fasteners are lower during repeated tightening, whereas those of ineffectively lubricated fasteners increase gradually. Because well-lubricated fastener surfaces “run in” during assembly, repeated tightening processes increase the risk of overtightening. Therefore, in the case of the repeated use of fasteners, the variations in friction coefficient should be considered [88, 114].

To summarize, 90% of the input torque is dissipated in the form of friction during tightening. Therefore, a variation in the friction has a disproportionate effect on the preload: a marginal variation in friction can result in a significant alteration in the preload. However, the friction characteristics represent a complex systemic behavior influenced by numerous factors. For threaded fasteners, the significant factors affecting friction include the fastener material, lubrication, geometric dimensions, and repeated tightening. The interplay between these factors should also be considered. In addition, the nonlinearity of the friction coefficient during tightening has been discussed [115, 116]. In the tightening process, with an increase in the tightening torque, the surface topography of the contact surface varies. This results in a variation in the friction characteristics and a nonlinear torque–preload relationship. Sufficient attention should be paid to this in threaded connections, where the material of the connected part is worn straightforwardly and the tightening torque is large.

4 Special Circumstances During Tightening

Researchers have also observed certain special circumstances that may cause uncertainty in the preload. For example, the preload is reduced after the tightening torque is released. This is called the initial loss of clamping force. In addition, geometric errors such as nonparallel contact of the bearing surface may also cause uncertainty in the preload.

4.1 Initial Loss of Preload

During the fastener tightening process, even if the corresponding relationship between torque and preload is determined, an initial loss of preload after bolt tightening is observed [7]. This phenomenon is referred to as initial preload loss.

Fisher and Struik [117] reported that the preload decreased by 2%–11% immediately after bolt fastening in structural steel. Mayer [118] indicated that most of the preload loss occurs within 15–20 s after tightening and that this reduction persists gradually for a certain period. Through experiments and numerical methods, Fukuoka et al. [119] studied the phenomena of reductions in the thread friction torque and axial tension, which occur immediately after the tightening torque is released. The results showed that the initial loss of clamping force was affected mainly by the bearing friction coefficient. Moreover, the rates of variation in the clamping force increased with a decrease in the grip length. However, they did not consider the effects of other factors. Zhu et al. [120] systematically studied the effects of six factors (joint materials, fastener class, gasket grade, lubrication, surface roughness, tightening speed, and number of repeated tightening cycles) and their interactions on the initial loss of clamping force. They determined that the amount of initial loss of clamping force decreased significantly with an increase in the number of repeated tightening cycles. Therefore, they considered that eliminating plastic deformation during tightening could minimize the initial loss of clamping force. Through experiments and finite element analysis, Liu et al. [121, 122] recently concluded that the initial loss of clamping force is caused by the elastic rotation of the bolt shank and plastic deformation of the bolted joint structure.

Few studies have been conducted on the initial loss of clamping force. This may be because the percentage of the initial loss of clamping force is small. However, the percentage of the initial loss of clamping force can be 13% under certain conditions [120]. This indicates the need to focus on the initial loss of the clamping force. It severely affects the safety and reliability of bolted joints, particularly in critical applications.

4.2 Non-parallel Bearing Surface

The geometric deviations of the bolted joint structures also increase the uncertainty of the tightening process. Bolted joints are complex combinations of bolts, nuts, and several connected parts. Therefore, the cumulative total deviations need to be considered during tightening. It has been reported that the preload scatter caused by the introduction of geometric deviations significantly exceeds that caused by friction alone.

The non-parallel contact of the bearing surface is a typical geometric deviation. It can cause the bolts to bend and deform during tightening and thereby, generate uncertainty in the preload. Ganeshmurthy et al. [123] investigated the effect of nonparallel contact surfaces on the tightening process using finite element analysis. The results showed that a significant nonlinear process occurs during the tightening process with a non-parallel contact. However, they did not explain the mechanical reason for the nonlinear interval or its influence on the tightening accuracy. Hashimura et al. [124] experimentally studied the linearity slope of the torque–preload correlation during the tightening process with an inclined bearing surface. However, they attributed the preload deviation to the variation in the equivalent friction radius caused by the non-uniform contact pressure without considering the influence of the nonlinearity of the tightening process. In 2019, Sun et al. [125, 126] obtained a similar conclusion through a theoretical derivation and finite element analysis. In addition, they concluded that the additional thread friction torque caused a preload deviation.

The bolted joint is a complex combination. Therefore, the accumulation of geometric deviations would be considerable. Thus, the deviations in clamping force caused by geometric deviations need to be considered. The effects of geometric deviations on the effective friction radius, friction torque, and preload deviation and the transfer and accumulation of geometric deviations in bolted joints should be studied further.

5 Conclusions and Prospects

An inappropriate preload can cause a wide range of problems. Precise control of the preload has become a critical issue in mechanical assembly processes. Therefore, researchers and engineers have studied preload control methods. By classifying, analyzing, and summarizing relevant literature, the research progress of preload control methods for threaded fasteners has been summarized systematically. The conclusions are as follows:

(1) The torque control method is most widely used in engineering because of its simple operation and convenient implementation in mass-production applications. Other tightening methods such as yield control, ultrasonic control, bolt heaters, and hydraulic bolt tensioners have unique advantages. These are typically used in critical joint applications. However, relatively few studies have used these methods. Their engineering application has significant limitations.

(2) The scatter of the preload obtained by the torque control method is larger. This can be attributed to three aspects: the inaccurate torque–preload relationship, assumed effective friction radius, and complex friction characteristics. Friction is the most important factor affecting the torque–preload relationship. It is highly difficult to control and essentially infeasible to predict.

(3) The friction characteristics of the tightening process do not depend on an individual factor (such as the material or lubrication conditions). These constitute the response of the entire system. Different combinations of conditions can yield varying results. These should be analyzed for a specific system. Future research should be directed toward identifying the correct combination of materials and lubricants to achieve repeatable friction during tightening and repeated tightening, prevent loosening and fretting during service, and prevent galling during repeated disassembly processes.

(4) In critical applications, threaded fasteners should not be tightened repeatedly. In cases where threaded fasteners are used repeatedly, the variations in friction during repeated tightening should be considered. In general, the friction coefficients of well-lubricated fasteners are lower during repeated tightening, whereas those of ineffectively lubricated fasteners increase gradually. Because well-lubricated fastener surfaces “run in” during assembly, repeated tightening processes increase the risk of overtightening.

(5) Researchers should pay attention to the special circumstances that may cause higher scatter of the preload in bolted joints, i.e., the initial loss of clamping force and the preload deviations caused by geometric deviations. These factors should be considered to realize precise control of the bolt preload.

In addition, the mechanical behavior, dynamic characteristics, and fatigue performance of bolted joint structures under different tightening methods remain unclear. Furthermore, there are no guidelines for the practical application of certain methods. In most cases, this relies on the experience and skills of workers. In the future, it would be important to study these problems extensively to improve the quality and efficiency of the assembly of bolted joints.

Acknowledgements
Not applicable.

Author Contributions
XY: methodology, data curation, writing—original draft, and writing—review and editing. ZL: funding acquisition, supervision, writing—review and editing. MZ: formal analysis, investigation, writing—review and editing; YL: validation, investigation, writing—review and editing. YW: validation, writing—review and editing. WC: visualization. All authors read and approved the final manuscript.

Funding
Supported by National Natural Science Foundation of China (Grant Nos. U23B20104, 52075012 and 52205510).

Data availability
Not applicable to this article as no new data were created or analyzed in this study.

Declarations

Competing Interests
The authors declare no competing financial interests.

Received: 6 October 2022 Revised: 23 July 2024 Accepted: 29 July 2024
Published online: 26 August 2024

References

[1] Z Y Li, X Q Li, Y J Han, et al. A review of aeroengines' bolt preload formation mechanism and control technology. *Aerospace*, 2023, 10(3): 307. https://doi.org/10.3390/aerospace10030307.
[2] P Niu, Q Cheng, C H Chen, et al. An approach for crucial geometric error analysis and accuracy enhancement of gantry milling machines based on generalized correlation sensitivity. *Journal of Manufacturing Processes*, 2024, 119: 401-413. https://doi.org/10.1016/j.jmapro.2024.03.091.
[3] F Zhou, X L Dong, W C Jiang, et al. Contact mechanical behavior and leakage prediction of metal lenticular gaskets in bolt flange joints of ultrahigh pressure pipelines. *International Journal of Pressure Vessels and Piping*, 2023, 206: 105038. https://doi.org/10.1016/j.ijpvp.2023.105038.
[4] B Sun, X Z Chen, H Q Wang. A triboelectric vibration sensor for detecting loose bolts in automobile. *Materials Technology*, 2023, 38(1): 2214775. https://doi.org/10.1080/10667857.2023.2214775.
[5] Y Q Feng, F S Li, K Shu, et al. Multiaxial fatigue analysis of connecting bolt at high-speed train axle box under structural subharmonic resonance. *Sensors*, 2023, 23(18): 7962. https://doi.org/10.3390/s23187962.
[6] J H Liu, Q C Sun, H Cheng, et al. The state-of-the-art, connotation and developing trends of the products assembly technology. *Journal of Mechanical Engineering*, 2018, 54(11): 2-27. (in Chinese)
[7] J H Bickford. *Introduction to the design and behavior of bolted joints: Non-gasketed joints (4th Edition)*. Oxfordshire: Taylor & Francis, 2008.
[8] H Gong, X Y Ding, J H Liu, et al. Review of research on loosening of threaded fasteners. *Friction,* 2022, 10(3): 335–359. https://doi.org/10.1007/s40544-021-0497-1.
[9] Verein Deutscher Ingenieure. VDI 2230 Systematic calculation of high duty bolted joints with one cylindrical bolt. Germany, 2003.
[10] N Motosh. Development of design charts for bolts preloaded up to the plastic range. *Journal of Engineering for Industry - Transactions of the ASME*, 1976, 98: 849-851. https://doi.org/10.1115/1.3439041.
[11] A D Meng, S A Nassar, D Templeton. A novel optical method for real-time control of bolt tightening. *Journal of Pressure Vessel Technology - Transactions of the ASME*, 2011, 133(6): 1–5. https://doi.org/10.1115/1.4004797.
[12] A Bray, R Levi. Factors affecting the tightening characteristics of bolts. *Experimental Mechanics*, 1966, 6(8): 409-419. https://doi.org/10.1007/bf02326286.
[13] T Fukuoka, T Takaki. Elastic plastic finite element analysis of bolted joint during tightening process. *Journal of Mechanical Design - Transactions of the ASME*, 2003, 125(4):823-830. https://doi.org/10.1115/1.1631579.
[14] J Bickford, S Nassar. *Handbook of bolts and bolted joints*. Florida: CRC Press, 1998.
[15] B. Güler, K T Gürsel. Experimental analysis of the friction coefficient effect of the zinc-lamella coated fasteners on bolt preload and tightening moment. *Materialwissenschaft und Werkstofftechnik*. 2019, 50: 696-705. https://doi.org/10.1002/mawe.201800057.
[16] T Fukuoka, T Takaki. Evaluations of the tightening process of bolted joint with elastic angle control method, *ASME/JSME 2004 Pressure Vessels and Piping Conference*, 2004, 478: 11-18. https://doi.org/10.1115/PVP2004-2617.
[17] S A Nassar, X J Yang. Torque-angle formulation of threaded fastener tightening. *Journal of Mechanical Design - Transactions of the ASME*, 2008, 130(2): 1073-1080. https://doi.org/10.1115/1.2821388.
[18] J T Boys, P W Wallace. Design and performance of an automatic control system for fastener tightening. *Proceedings of the Institution of Mechanical Engineers*, 1977, 191: 371-380. https://doi.org/10.1243/pime_proc_1977_191_045_02.
[19] J M Monaghan. The influence of lubrication on the design of yield tightened joints. *The Journal of Strain Analysis for Engineering Design*, 1991, 26: 123-132. https://doi.org/10.1243/03093247V262123.
[20] M Tanaka, N Henmi, H Ishibashi. On the behaviour of bolted joints tightened in plastic region (elasto-plastic analysis by the finite element method). *Proceedings of the Japanese Mechanical Society. C plait*, 2000, 66(650): 1059-3488. (in Japanese)
[21] G R Toth. Controlled tightening over the yield point of a screw: based on taylor's series expansions. *Journal of Pressure Vessel Technology - Transactions of the ASME*, 2003, 125(4): 460-466. https://doi.org/10.1115/1.1613299.
[22] G R Toth. Torque and angle controlled tightening over the yield point of a screw-based on Monte-Carlo simulations. *Journal of Mechanical Design - Transactions of the ASME*, 2004, 126(4): 729-736. https://doi.org/10.1115/1.1701877.
[23] I Chapman, J Newnham, P Wallace. The tightening of bolts to yield and their performance under load. *Journal of Vibration Acoustics Stress and Reliability in Design - Transactions of the ASME*, 1986, 108(2): 213-221. https://doi.org/10.1115/1.3269326.
[24] J Newnham, L Curley. Bolted joints under tensile service loads: The effect of torsion in the bolt on in-service clamping loads. *Journal of Mechanical Design - Transactions of the ASME*, 1993, 115(1) 36-40. https://doi.org/10.1115/1.2919321.
[25] S A Nassar, P H Matin. Fastener tightening beyond yield. *ASME/JSME 2004 Pressure Vessels and Piping Conference*, 2004, 478: 29-40. https://doi.org/10.1115/PVP2004-2619.

[26] M Hagiwara, N Ohashi. A new tightening technique for threaded fasteners. *Journal of Offshore Mechanics and Arctic Engineering*, 1994, 116(2): 64-69. https://doi.org/10.1115/1.2920134.

[27] K Mori K, Y Murakami, S Hashimura, et al. A new measurement method of bolt tightening forces based on simultaneous loading of torque and compressive force. *Transactions of the Japan Society of Mechanical Engineers*, 1988, 64(622): 2212-2217. (in Japanese) http://www.mendeley.com/research/geology-volcanic-history-eruptive-style-yakedake-volcano-group-central-japan/.

[28] K Mori, S Hashimura, Y Murakami, et al. A new tightening method for bolted joints by the simultaneous application of torque and compressive force. *SAE Technical Papers*, 2001. https://doi.org/10.4271/2001-01-0978.

[29] S Hashimura, K Mori, Y Murakami, et al. Application of the compressive force method to the angle control method of bolt tightening. *Transactions of the Japan Society of Mechanical Engineers*, 1999 65 (635): 2898-2904. (in Japanese)

[30] X W Zhang, X D Wang, Y Luo. An improved torque method for preload control in precision assembly of miniature bolt joints. *Strojniski Vestnik/Journal of Mechanical Engineering*, 2012, 58(10): 578-586. https://doi.org/10.5545/sv-jme.2012.538.

[31] S Hareyama, K I Manabe. Advantage of elliptical confidence limit method for bolted joint tightening reliability. *ASME 2015 International Mechanical Engineering Congress and Exposition*, 2015.

[32] S Hareyama, K I Manabe, M Nakashima. Improving tightening reliability on bolted joints for calibrated wrench method (an analysis on optimum tightening torque by confidence limit ellipse). *ASME 2013 International Mechanical Engineering Congress and Exposition*, 2013. https://doi.org/10.1115/IMECE2013-63387.

[33] H Y Hwang. Bolted joint torque setting using numerical simulation and experiments. *Journal of Mechanical Science and Technology*, 2013, 27(5): 1361-1371. https://doi.org/10.1007/s12206-013-0317-2.

[34] T Schüthe, K R Riemschneider, A Meyer-Eschenbach. Magnetic sensor array for determining the assembly torsion and preload of a bolted joint. *2022 IEEE Sensors Applications Symposium*, 2022: 3-8.

[35] Z Zhang, J Liu, H Gong, et al. Invention of smart tightening tool for directly controlling the preload of bolted joints. *Smart Materials and Structures*, 2023, 32(2): 027001. https://doi.org/10.1088/1361-665X/acb02a

[36] Q Pan, R Pan, C Shao, et al. Research review of principles and methods for ultrasonic measurement of axial stress in bolts. *Chinese Journal of Mechanical Engineering*, 2020, 33(1): 11. https://doi.org/10.1186/s10033-020-0431-x.

[37] J H Bickford. Using ultrasonics to measure the residual tension in bolts. *SEM Spring Conference on Experimental Mechanics*, 1988.

[38] Q X Pan, R P Pan, M L Chang, et al. A shape factor based ultrasonic measurement method for determination of bolt preload. *NDT & E International*, 2020, 111: 102210. https://doi.org/10.1016/j.ndteint.2019.102210.

[39] N Takeshi. Ultrasonic measurement of axial stress in short bolts with consideration of nonlinear deformation. *Chemical Pharmaceutical Bulletin*, 1977, 57(534): 364-370. (in Japanese) http://www.mendeley.com/research/geology-volcanic-history-eruptive-style-yakedake-volcano-group-central-japan/.

[40] X X Zhao, Y M Li, X G Liu, et al. Ultrasonic measurement on axial force of high-strength bolt in service. *Journal of Low Frequency Noise Vibration and Active Control*, 2020, 39(3): 596-603. https://doi.org/10.1177/1461348418815405.

[41] S M Kelardeh, S V Hosseini, M Heidari, et al. An investigation of the effect of bolt tightening stress on ultrasonic velocity in cylinder head and main bearing cap bolts of diesel engine. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 2021, 43(8): 1-12. https://doi.org/10.1007/s40430-021-03095-1.

[42] S Chaki, G Corneloup, I Lillamand, et al. Combination of longitudinal and transverse ultrasonic waves for in situ control of the tightening of bolts. *Journal of Pressure Vessel Technology - Transactions of the ASME*, 2007, 129(3): 383-390. https://doi.org/10.1115/1.2748821.

[43] M Hirao, H Ogi, H Yasui. Contactless measurement of bolt axial stress using a shear-wave electromagnetic acoustic transducer. *NDT & E International*, 2001, 34(3): 179-183. https://doi.org/10.1016/S0963-8695(00)00055-4.

[44] K Y Jhang, H H Quan, J Ha, et al. Estimation of clamping force in high-tension bolts through ultrasonic velocity measurement. *Ultrasonics*, 2006, 44: 1339-1342. https://doi.org/10.1016/j.ultras.2006.05.190.

[45] S A Nassar, A B Veeram. Ultrasonic control of fastener tightening using varying wave speed. *Journal of Pressure Vessel Technology - Transactions of the ASME*, 2006, 128(3): 427-432. https://doi.org/10.1115/1.2218347.

[46] E Persson, A Roloff. Ultrasonic tightening control of a screw joint: A comparison of the clamp force accuracy from different tightening methods. *Proceedings of the Institution of Mechanical Engineers Part C-Journal of Mechanical Engineering Science*, 2016, 230(15): 2595-2602. https://doi.org/10.1177/0954406215619648.

[47] Q X Pan, M L Chang, R P Pan, et al. Research on nonlinear ultrasonic testing technology of bolt axial stress. *Journal of Mechanical Engineering*, 2021, 57(22): 88-95. https://doi.org/10.3901/JME.2021.22.088. (in Chinese)

[48] T Fukuoka. Analysis of the tightening process of bolted joint with a tensioner using spring elements. *Journal of Pressure Vessel Technology - Transactions of the ASME*, 1994 116(4): 443-448. https://doi.org/10.1115/1.2929614.

[49] T N Guo, G Li, L G Cai, et al. The study of high strength bolt preload with hydraulic tensioner installation. *Advanced Materials Research*, 2011, 314-316: 988-994. https://doi.org/10.4028/www.scientific.net/amr.314-316.988.

[50] T Fukuoka, Q Xu. Finite element simulation of the tightening process of bolted joint with a bolt heater. *Journal of Pressure Vessel Technology - Transactions of the ASME*, 2002, 124(4): 457-464. https://doi.org/10.1115/1.1493205.

[51] S Hashimura, K Komatsu, C Inoue, et al. A new tightening method of bolt/nut assembly to control the clamping force. *Journal of Advanced Mechanical Design, Systems, and Manufacturing*, 2008, 2(5):896-902. https://doi.org/10.1299/jamdsm.2.896.

[52] T Fukuoka, T Takaki. Simplified analysis of the tightening process of bolted joint with a bolt heater. *ASME Pressure Vessels and Piping Division Conference*, 2005, 2: 37-43. https://doi.org/10.1115/PVP2005-71168.

[53] T Fukuoka. Finite element simulation of tightening process of bolted joint with a tensioner. *Journal of Pressure Vessel Technology - Transactions of the ASME*, 1992, 114(4): 433-438. https://doi.org/10.1115/1.2929251.

[54] Fukuoka, Q Xu. Analysis of the tightening process of bolted joint with bolt heater. *Transactions of the Japan Society of Mechanical Engineers. A*, 1997. (in Japanese)

[55] A Yamamoto. *The theory and computation of thread connection*. Shanghai: Shanghai Scientific and Technological Literature Publishing House, 1984. (in Chinese)

[56] A C Ugural, Y Chung, E A Ugural. *Mechanical engineering design (3rd Edition)*. Florida: CRC Press, 2020.

[57] W Eccles. Design guidelines for torque controlled tightening of bolted joints. *SAE Technical Paper*, 1993: 930578.

[58] R C Juvinall, K M Marshek. *Fundamentals of machine component design*. New Jersey: John Wiley & Sons, 1983.

[59] S A Nassar, Xianjie Yang. Novel formulation of the tightening and breakaway torque components in threaded fasteners. *Journal of Pressure Vessel Technology - Transactions of the ASME*, 2007, 129(4): 653-663. https://doi.org/10.1115/1.2767354.

[60] J Huang, L S Guo. The research on the torque-tension relationship for bolted joints. *Key Engineering Materials*, 2011, 486: 242-245. https://doi.org/10.4028/www.scientific.net/KEM.486.242.

[61] E Oberg, F D Jones, H H Ryffel, et al. *Machinery's handbook*. New York: Industrial Press, 2012.

[62] C G Jeong, S K Kim, J H Lee, et al. Clinically available preload prediction based on a mechanical analysis. *Archive of Applied Mechanics*, 2017, 87(12): 2003-2009. https://doi.org/10.1007/s00419-017-1307-0.

[63] X J Deng, J H Liu, Z W Zhang, et al. Theoretical analysis on torque-tension relationship and tightening characteristics of wedge threaded connection. *Journal of Mechanical Engineering*, 2021, 57(19): 180-191. https://doi.org/10.3901/JME.2021.19.180. (in Chinese)

[64] S A Nassar, G C Barber, D Zuo. Bearing friction torque in bolted joints. *Tribology Transactions*, 2005, 48(1): 69-75. https://doi.org/10.1080/05698190590899967.

[65] S A Nassar, P H Matin, G C Barber. Thread friction torque in bolted joints. *Journal of Pressure Vessel Technology - Transactions of the ASME*, 2005, 127(4): 287-393. https://doi.org/10.1115/1.2042474.

[66] Q Zou, T S Sun, S A Nassar, et al. Contact mechanics approach to determine effective radius in bolted joints. *Journal of Tribology - Transactions of the ASME*, 2005, 127(1): 30-36. https://doi.org/10.1115/1.1829717.

[67] S A Nassar, H El-Khiamy, G C Barber, et al. An experimental study of bearing and thread friction in fasteners. *Journal of Tribology - Transactions of the ASME*,2005, 127(2): 263-272. https://doi.org/10.1115/1.1843167.

[68] N Wang, B T Li, J Hong, et al. Factors affecting bolt bearing surface effective radius. *Journal of Xi'an Jiaotong University*, 2012, 46(4): 132-136. (in Chinese)

[69] H Gong, J H Liu, X Y Ding. Calculation of the effective bearing contact radius for precision tightening of bolted joints. *Advances in Mechanical Engineering*, 2016, 8(9): 1-8. https://doi.org/10.1177/1687814016668445.

[70] L B Zhu, J Hong, X J Jiang. On controlling preload and estimating anti-loosening performance in threaded fasteners based on accurate contact modeling. *Tribology International*, 2016, 95: 181-191. https://doi.org/10.1016/j.triboint.2015.11.006.

[71] T Sakai. The friction coefficient of fasteners. *Transactions of the Japan Society of Mechanical Engineers*, 1977. (in Japanese)

[72] Y Y Jiang, J J Chang, C H Lee. An experimental study of the torque-tension relationship for bolted joints. *International Journal of Materials and Product Technology*, 2001, 16(4-5): 417-429. https://doi.org/10.1504/IJMPT.2001.001264.

[73] M P Oliver, V K Jain. Effect of tightening speed on thread and underhead coefficient of friction, *ASTM Symposium on Structural Integrity of Fasteners including the Effects of Environment and Stress Corrosion Cracking*, 2007, 1487: 45-52. https://doi.org/10.1520/stp45257s.

[74] Q M Yu, X J Yang, H L Zhou. An experimental study on the relationship between torque and preload of threaded connections. *Advances in Mechanical Engineering*, 2018, 10(6): 1-10. https://doi.org/10.1177/1687814018797033.

[75] G Q Shao, L B Zhu, J Hong, et al. The factors influencing torque-preload relationship of bolted joints in heavy truck. *Journal of Xi'an Jiaotong University*, 2015, 49(10): 14-21. (in Chinese)

[76] Q Zou, T S Sun, S A Nassar, et al. Effect of lubrication on friction and torque-tension relationship in threaded fasteners. *Tribology Transactions*, 2007, 50(1): 127-136. https://doi.org/10.1080/10402000601105490.

[77] O Rosas, A O Garcia, J Hernandez, et al. Nut-factor variation on coated high-strength steel fasteners after cycling torquing. *ASME 2019 Pressure Vessels & Piping Conference*, 2019, 2. https://doi.org/10.1115/PVP2019-93874.

[78] J B Aycock, J Wilson, A Bausman. Variables affecting nut factors in bolted flange connections. *ASME 2019 Pressure Vessels & Piping Conference*, 2019: 2. https://doi.org/10.1115/PVP2019-93721.

[79] D Croccolo, M De Agostinis, S Fini, et al. Tribological properties of bolts depending on different screw coatings and lubrications: An experimental study. *Tribology International*, 2017, 107: 199-205. https://doi.org/10.1016/j.triboint.2016.11.028.

[80] Z F Liu, M P Zheng, X Yan, et al. Changing behavior of friction coefficient for high strength bolts during repeated tightening. *Tribology International*, 2020, 151: 106486. https://doi.org/10.1016/j.triboint.2020.106486.

[81] M D Agostinis, S Fini, G Olmi. The influence of lubrication on the frictional characteristics of threaded joints for planetary gearboxes. *Proceedings of the Institution of Mechanical Engineers Part C-Journal of Mechanical Engineering Science*, 2016, 230(150): 2553-2563. https://doi.org/10.1177/0954406215605863.

[82] D Croccolo, M De Agostinis, N Vincenzi. Failure analysis of bolted joints: Effect of friction coefficients in torque-preloading relationship. *Engineering Failure Analysis*, 2011, 18(1): 364-373. https://doi.org/10.1016/j.engfailanal.2010.09.015.

[83] D Croccolo, M De Agostinis, N Vincenzi. Influence of tightening procedures and lubrication conditions on titanium screw joints for lightweight applications. *Tribology International*, 2012, 55: 68-76. https://doi.org/10.1016/j.triboint.2012.05.010.

[84] D Croccolo, M De Agostinis, S Fini, et al. Threaded fasteners with applied medium or high strength threadlockers: effect of different tightening procedures on the tribological response. *Journal of Adhesion*, 2020, 96(1-4): 64-89. https://doi.org/10.1080/00218464.2019.1679630.

[85] H Kopfer, C Friedrich, M De Agostinis, et al. Friction characteristics in light weight design focusing bolted joints. *ASME 2012 International Mechanical Engineering Congress and Exposition*, 2012: 3.

[86] X D Yue, Y Xie, L Liu, et al. Analysis and determination of bolt tightening process factors for composite structures under multiple working conditions. *Proceedings of the Institution of Mechanical Engineers Part C-Journal of Mechanical Engineering Science*, 2024, 238(4): 1057-1079. https://doi.org/10.1177/09544062231181814.

[87] X D Yue, X G Dang, T Geng, et al. Effect of tightening process parameters on the T-F curve of bolts in composite structures. *Proceedings of the Institution of Mechanical Engineers Part C-Journal of Mechanical Engineering Science*, 2024, 238(80): 3578-3601. https://doi.org/10.1177/09544062231205181.

[88] C J Dyson, W A Hopkins, D A Aljeran, et al. Tribological considerations of threaded fastener friction and the importance of lubrication. *Tribology International*, 2024, 191: 109162. https://doi.org/10.1016/j.triboint.2023.109162.

[89] W Brown, L Marchand, A E´vrard, et al. The effect of bolt size on the assembly nut factor. *ASME 2007 Pressure Vessels and Piping Conference*, 2007: 3.

[90] S A Nassar, T S Sun. Surface roughness effect on the torque-tension relationship in threaded fasteners. *Proceedings of the Institution of Mechanical Engineers, Part J-Journal of Engineering Tribology*, 2007, 221(2): 95-103. https://doi.org/10.1243/13506501JET192.

[91] W G Cooper, T M Heartwell. Variables affecting nut factors for field assembled joints. *ASME 2011 Pressure Vessels & Piping Conference*, 2011, 2: 23-27. https://doi.org/10.1115/PVP2011-57197.

[92] Q M Yu, H L Zhou. Finite element study on pre-tightening process of threaded connection and failure analysis for pressure vessel. *Procedia Engineering*, 2015, 130: 1385-1396. https://doi.org/10.1016/j.proeng.2015.12.307.

[93] J H Liu, H J Ouyang, J F Peng, et al. Experimental and numerical studies of bolted joints subjected to axial excitation. *Wear*, 2016, 346-347: 66-77. https://doi.org/10.1016/j.wear.2015.10.012.

[94] Y Y Jiang, Z Ming, T W Park, et al. An experimental investigation on frictional properties of bolted joints. *ASME 2002 Pressure Vessels and Piping Conference*, 2002.

[95] S A Nassar, T Sun, Q Zou. The effect of coating and tightening speed on the torque-tension relationship in threaded fasteners. *SAE Technical Papers*, 2006: 24. https://doi.org/10.4271/2006-01-1252.

[96] S A Nassar, A M Zaki, Effect of coating thickness on the friction coefficients and torque-tension relationship in threaded fasteners. *Journal of Tribology - Transactions of the ASME*, 2009, 131(2): 1-11. https://doi.org/10.1115/1.3085941.

[97] S A Nassar, S Ganeshmurthy, R M Ranganathan, et al. Effect of tightening speed on the torque-tension and wear pattern in bolted connections. *Journal of Pressure Vessel Technology - Transactions of the ASME*, 2007, 129(3): 426-440. https://doi.org/10.1115/1.2749290.

[98] A V Morozov. Experimental estimate of tribological characteristics of epilam-coated materials that operate in threaded joints under dry friction. *Journal of Friction and Wear*, 2014, 35(3): 170-176. https://doi.org/10.3103/S106836661403009X.

[99] V V Efremov, O S Bondareva, OS Dobychina, et al. Influence of structure, roughness, microhardness, and friction coefficient of zinc coating on the tightening torque of a threaded connection. *Journal of Friction and Wear*, 2023, 44(5): 304-308. https://doi.org/10.3103/S1068366623050021

[100] M Kumar, E Persson, I Sherrington, et al. Changes in friction of zinc flake coated threaded fasteners due to humidity, temperature and storage duration. *Tribology International*, 2022, 170: 107498. https://doi.org/10.1016/j.triboint.2022.107498.

[101] T Fukuoka, M Nomura, H Kawabayashi. A new experimental approach for measuring friction coefficients of threaded fasteners focusing on the repetition of tightening operation and surface roughness. *ASME 2013 Pressure Vessels and Piping Conference*, 2013, 2: 1-9. https://doi.org/10.1115/PVP2013-97606.

[102] S A Nassar, S Ganeshmurthy, X Yang. Kinetic versus static frictional torque components in threaded fastener applications. *ASME 2006 International Mechanical Engineering Congress and Exposition*, 2006: 1-13. https://doi.org/10.1115/IMECE2006-15959.

[103] X Liu, B Wang, N A Noda, et al. Bolt clamping force versus torque relation (F-T relation) during tightening and untightening the nut having slight pitch difference. *Mechanics Based Design of Structures and Machines*, 2023, 51(7): 3632-3649. https://doi.org/10.1080/15397734.2021.1931308.
[104] Q M Yu, H L Zhou, L B Wang. Finite element analysis of relationship between tightening torque and initial load of bolted connections. *Advances in Mechanical Engineering*, 2015, 7(5): 1-8. https://doi.org/10.1177/1687814015588477.
[105] H A Bulaqi, M M Mashhadi, F Geramipanah, et al. Effect of the coefficient of friction and tightening speed on the preload induced at the dental implant complex with the finite element method. *Journal of Prosthetic Dentistry*, 2015, 113(5): 405-411. https://doi.org/10.1016/j.prosdent.2014.09.021.
[106] S Ganeshmurthy, S A Nassar. Study of two-stage tightening of threaded fasteners using. *ASME 2007 Pressure Vessels and Piping Conference*, 2007: 1-14.
[107] H P Zhang, X B Wang, Y M Mo, et al. Analysis on the influence of bolt tightening speed on the bolt torque coefficient. *Journal of Wuhan University of Technology (Transportation Science & Engineering)*, 2014, 38(4): 860-863. (in Chinese)
[108] D Matsubara, T Nakano, M, Shimada, et al. Effect of tightening velocity on the torque coefficient of timber jointing with bolts. *Journal of the Japanese Wood Society*, 2015: 33-39. (in Japanese)
[109] X Q Li, Q K Meng, Y F Du, et al. Influence of tightening strategy on pre-tightening force of aero-engine single-bolt connection. *Journal of Mechanical Engineering*, 2020, 56(13): 231-241. https://doi.org/10.3901/JME.2020.13.231. (in Chinese)
[110] A Wettstein, T Kretschmer, S Matthiesen. Investigation of dynamic friction during impact tightening of bolted joints. *Tribology International*, 2020, 146: 106251. https://doi.org/10.1016/j.triboint.2020.106251.
[111] A Wettstein, S Matthiesen. Investigation of the thread coefficient of friction when impact tightening bolted joints. *Forschung im Ingenieurwesen/Engineering Research*, 2020, 84(1): 55-63. https://doi.org/10.1007/s10010-019-00392-z.
[112] W Eccles, I Sherrington, R D Arnell. Frictional changes during repeated tightening of zinc plated threaded fasteners. *Tribology International*, 2010, 43(4): 700-707. https://doi.org/10.1016/j.triboint.2009.10.010.
[113] D Croccolo, N Vincenzi. Tightening tests and friction coefficients definition in the steering shaft of front motorbike suspension. *Strain*, 2011, 47(4): 337-342. https://doi.org/10.1111/j.1475-1305.2009.00694.x.
[114] T Alsardia. Bolt preload variations during repeated tightenings. *Acta Polytechnica Hungarica*, 2024, 21(2): 133-150. https://doi.org/10.12700/APH.21.2.2024.2.7.
[115] Y Li, Z F Liu, Y Z Wang, et al. Experimental study on behavior of time-related preload relaxation for bolted joints subjected to vibration in different directions. *Tribology International*, 2020, 142: 106005. https://doi.org/10.1016/j.triboint.2019.106005.
[116] H R Yang, L L An, X Chen, et al. Preload loss of CFRP bolted joint without rotation under transverse and axial loading. *Advances in Mechanical Engineering*, 2023, 15(1): 16878132221145342.https://doi.org/10.1177/16878132221145342
[117] G L Kulak, J W Fisher, J H A Struik. *Guide to design criteria for bolted and riveted joints (2nd Edition)*. Chicago: American Insitite of Steel Construction. Inc, 2001.
[118] K H Mayer. Relaxation tests on high-temperature screw fastenings. *Wire*, 1973, 23: 1-5.
[119] T Fukuoka, T Takaki. Mechanical behaviors of bolted joint during tightening using torque control. *JSME International Journal, Series A: Solid Mechanics and Material Engineering*, 1998, 41(2): 185-191. https://doi.org/10.1299/jsmea.41.185.
[120] L B Zhu, J Hong, G Q Yang, et al. Experimental study on initial loss of tension in bolted joints. *Proceedings of the Institution of Mechanical Engineers Part C-Journal of Mechanical Engineering Science*, 2016, 230(10): 1685-1696. https://doi.org/10.1177/0954406215583080.
[121] M P Zheng, Z F Liu, X Yan, et al. Initial losing behavior of pre-tightening force for threaded fastener during repeated tightening. *Engineering Failure Analysis*, 2022, 134: 106021. https://doi.org/10.1016/j.engfailanal.2021.106021.
[122] Z F Liu, B E Wang, Y Li, et al. Analysis of self-loosening behavior of high strength bolts based on accurate thread modeling. *Engineering Failure Analysis*, 2021, 127: 105541. https://doi.org/10.1016/j.engfailanal.2021.105541.
[123] S Ganeshmurthy, S A Nassar. Finite element simulation of process control for bolt tightening in joints with nonparallel contact. *Journal of Manufacturing Science and Engineering - Transactions of the ASME*, 2014, 136(2): 1-9. https://doi.org/10.1115/1.4025830.
[124] S Hashimura, H Ito, K Komatsu, et al. Influences of squareness error at bolt bearing surface on a frictional coefficient between bearing surfaces and on tightening accuracy. *Journal of Japanese Society of Tribologists*, 2016, 61(12): 882-892. (in Japanese)
[125] D A Chen, Y Ma, B W Hou, et al. Tightening behavior of bolted joint with non-parallel bearing surface. *International Journal of Mechanical Sciences*, 2019, 153-154: 240-253. https://doi.org/10.1016/j.ijmecsci.2019.01.038.
[126] B Yang, Q C Sun, Q Y Lin, et al. Influence mechanism of bolted joint with geometric irregularity bearing surface on anti-loosening performance. *International Journal of Pressure Vessels and Piping*, 2021, 191: 104364. https://doi.org/10.1016/j.ijpvp.2021.104364.

Xing Yan born in 1996, is currently a PhD candidate at *College of Mechanical & Energy Engineering, Beijing University of Technology, China*. He received his master degree from *Beijing University of Technology, China*, in 2021. His research interests include high-performance assembly and bolted joint.

Zhifeng Liu born in 1973, is currently a professor at *Beijing University of Technology and Jilin University*, China. He received his PhD degree from *Northeastern University, China*, in 2001. His research interests include digital design and manufacturing technology and high-performance assembly.

Mingpo Zheng born in 1992, is currently an engineer at *Jiangsu XCMG Construction Machinery Research Institute Ltd, China*. He received his PhD degree from *Beijing University of Technology*, China, in 2023. His research interests include high-performance assembly and bolted joint.

Ying Li born in 1988, is currently an assistant research fellow at *College of Mechanical & Energy Engineering, Beijing University of Technology, China*. He received his PhD degree from *Beijing University of Technology*, China, in 2020. His research interests include bolted joint and high-performance assembly.

Yuezhen Wang born in 1989, is currently a lecturer at *North China Institute of Aerospace Engineering, China*. She received her PhD degree from *Beijing University of Technology, China*, in 2023. Her research interests include high-performance assembly and bolted joint.

Wentao Chen born in 1997, is currently a PhD candidate at *College of Mechanical & Energy Engineering, Beijing University of Technology, China*. He received his bachelor degree from *Beijing University of Technology, China*, in 2020. His research interests include high-performance assembly and bolted joint.