Bolt Preload Variations During Repeated Tightenings

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Abstract: Bolt preload prediction, through torque value, is challenged by friction variations within the bolted joint. Accurately estimating the initially achieved preload, is a persistent problem. This study aims to examine the repeatability of the bolt tightening process, under constant torque values, using experimental data. The experiments were conducted on bolts and nuts with a black finish surface, and the preload and nut factor variations were examined under four lubrication scenarios.

Keywords: Bolt preload variation; Torque-preload relationship; Lubrication; Nut factor

1 Introduction

Fixtures are necessary to join two or more elements together and a wide variety of fixtures are available in the industry. Choosing the right fixture and providing a reliable design requires a thorough system analysis [1] [2]. Among these fixtures, bolted joints assumes an easy-to-release link between parts. Bolted joints have a wide range of applications, such as those seen in [3-5]. In bolted joints, the power is transmitted from one part to another through friction. The task of the bolted link is to assume the normal force allowing this friction. The normal force called preload is a result of the bolt tightening process. The highest allowed bolt preload is usually estimated as a percentage of the bolt material yield strength [6]. Both insufficient or excessive bolt preload can lead to joint failure. Therefore, several methods are used to control the bolt preload, such as torque and angle control, bolt elongation control, and torquing control [7]. During bolt tightening, approximately 10%-20% of the applied torque generates preload, in the bolt. The remaining part is used to overcome friction in the bolted joint [8] [9]. Figure 1 illustrates the estimated torque distribution. It can be seen that friction plays an essential role in preload formation, and its variation in any region significantly impacts the bolt preload. In the literature, J. Drumheller [9] indicated that a 5% friction coefficient increase, under the head or on the thread, could reduce the preload to half. Morgan and Henshall [10] investigated the effect of joint friction on the bolt preload of wheel bolts and nuts. They reported that repeated tightening processes caused up to a 50% reduction in bolt preload, while a constant state was reached when re-lubricated with engine oil.

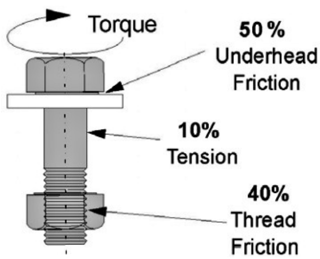

Figure 1
Tightening torque distribution [9]

Nassar et al. [11] examined the effects of the tightening speed and the repeated tightening on the wear pattern and torque-preload relationship for an M12x1.75 bolt of 8.8 grade. They found that for the non-lubricated case, the washer's surface roughness almost doubled after the fifth tightening. Also, they found no significant change in the friction coefficient when increasing the tightening speed after the fifth tightening cycle. However, when lubrication was used on the zinc coating material, the friction coefficient slightly decreased at increasing tightening speed. Eccles et al. [6] investigated the effect of repeated tightening on electro-zinc plated (EZP) nuts, bolts, and washers. They found significant wear on the bolt/nut thread contact surfaces and nut top face. In addition, they observed an increase of 100% in the friction coefficient while the preload decreased to 50% by the tenth tightening. They suggested a nonlinear empirical model for the tightening torque-preload relationship based on the number of tightening cycles. Z. Liu et al. [12] studied the frictional behavior of high-strength bolts during repeated tightening. Their observations are based on the so-called nut factor, discussed later in this paper. W. A. Grabon et al. [13] conducted a systematic tribological study on the threaded fastener. They linked the friction coefficient increase to the plastic deformation at the threads, which was affected by the presence of coating material and lubrication. B. Güler and K. T. Gürsel [14] used the torque-angle control tightening method to investigate a vehicle chassis zinc-coated joint. They concluded that the repetitive tightening process caused an increase in the friction coefficient and linked it to the large worn-out coating material. They summarized the main factors affecting the tightening process in a fishbone diagram.

Actually, manufacturers estimate a tightening torque appropriate for the first tightening in industrial applications. They frequently recommend installing a brand-new bolt-nut pair and washer after disassembly for safety reasons. In various applications, the everyday practice is that the disassembled fasteners are reused due to poor maintenance, cost saving, or lack of spare parts.

Most of the previous experimentally conducted research was conducted on bolts with known standardized material specifications. In everyday practice, there are cases when commercial bolts with unknown material specifications are used during the maintenance operation. The present work targeted such cases during the investigation of the bolts preload behavior. The bolts are taken from fastener shops, as the cheapest types. The bolts and nuts are from the same fastener box, but the manufacturer, material specifications, and the batch numbers are unknown.

Based on the literature background and everyday experience, this research aims to investigate the behavior of the bolt preload and the friction coefficient under repeated tightening-releasing cycles made on the same bolt, using the recommended tightening torque during the entire process. Moreover, we investigated the influence of the bolt/nut surface finish and the presence of lubrication on the generated preload. We conducted experiments to simulate typical tightening-releasing cycles. A perfect application of this idea is the vehicle wheel bolt. During the service time, the wheel bolts are periodically released and then tightened in case of seasonal tire changes or brake pad repairs. If only seasonal tire changes are considered, the bolt bears ten releasing/tightening cycles over five years of service. Due to its special shape, the wheel bolt or nut is not changed during the vehicle's lifetime.

NOMENCLATURE			
D	Bolt nominal diameter (mm)	P	Pitch of the thread (mm)
d_2	Bolt pitch diameter (mm)	r_n	The effective bearing radius (mm)
d_h	Clearance hole diameter (mm)	r_t	The effective thread radius (mm)
D_o	Bearing surface outer diameter (mm)	T_{Pitch}	Torque to generate bolt tension (N.m)
F_i	Preload at the ith tightening cycle	Vi	Percentage change of preload value relative to the initial tightening
F_P, F,	Clamping force, preload (kN)	X	Geometrical and frictional parameters of the joint
K	Nut factor	α	Thread lead angle (°)
T_{in}, T_{Input}, T	Input tightening torque (N.m)	β	Metric thread profile angle (°)
M_H, T_{Head}	Bearing surface friction torque (N.m)	μ_n, μ_b	Under the head friction coefficient
MoS_2	molybdenum disulfide powder	μ_t, μ_{th},	Thread friction coefficient
M_T, T_{Thread}	Thread friction torque (N.m)	ρ'	Computed angle of friction cone on thread surface (°)

2 Theoretical Background

Generally, in machine element theory, the bolt tightening torque equations are composed of three members, where two are linked to friction, and only one is linked to the preload:

$$T_{Input} = T_{Pitch} + T_{Threads} + T_{Head} \tag{1}$$

Motosh [15] introduced the following form in 1976:

$$T_{in} = F_P \left(\frac{P}{2\pi} + \frac{\mu_t r_t}{\cos(\beta/2)} + \mu_n r_n \right) \tag{2}$$

The standard DIN EN ISO 16047 also shows a similar variant:

$$T = F \left(\frac{1}{2} \cdot \frac{P + 1{,}154 \cdot \pi \cdot \mu_{th} \cdot d_2}{\pi - 1{,}154 \cdot \mu_{th} \cdot \frac{P}{d_2}} + \mu_b \cdot \frac{D_o + d_h}{4} \right) \tag{3}$$

As each member contains the preload force F as a parameter, a generalized form can be written as:

$$T = F \cdot X \tag{4}$$

Here T is the input torque, F is the bolt preload, and the constant X reflects the geometrical and frictional parameters of the joint. The problem with this structure is that it is based on a two-dimensional model (axial section cut) of the threaded fasteners. This model uses the assumptions of uniformly distributed contact pressure along the engaged thread surfaces [16] and a constant friction coefficient at every surface pair, as it is difficult to measure the friction under the head bolt/nut and on the thread during rotation. It is known that the real friction coefficients are different during each tightening, and it is not easy to have a constant guess value. From a practical point of view, another short expression can be used for the torque-tension relationship [11, 13, 17, 18], where the input tightening torque T is related to the bolt preload F in the function of the bolt diameter D. Here the constant containing all friction parameters is called the nut factor K (Torque coefficient ISO 16047). This gives the following simple equation:

$$T = K \cdot F \cdot D \tag{5}$$

The ASME Standard PCC-1 [19] states that "*K* is an experimentally determined, dimensionless constant related to the coefficient of friction." Equation (6) has a simple form and is easy to use, as it contains standard measurable data. Unfortunately, many experiments are required to get statistically firm data for each bolt diameter with an acceptably narrow confidence level. These statistically sound results are more accurate for industrial applications [7].

3 Methodology and Experimental Procedure

All experiments were performed according to ISO16047 in a closed room where the air conditioning kept the temperature and humidity at constant levels (25°C, 55%), to have a consistence clamping force results. since the clamping force can be affected by temperature and humidity variations [7].

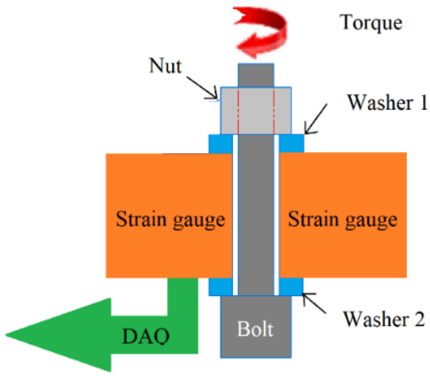

Figure 2
Representation of the tested bolted link

3.1 Preload Variation Measurement

In these experiments, M8x40 full-threaded bolts were used. The bolt head was clamped into a vise; then, a bolt force sensor was mounted between two special washers. The tightening element was an M8 nut (Figure 2). The torque was applied through a ½-inch mechanical torque wrench (Brüder Mannesmann Werkzeuge) of a type II class A with a range of (10-210 N.m, ± 4%). The input torque was set to a constant value of 20 N.m. Referring to ISO 898-1 and ISO 898-7 standards, for bolt of grade 10.9 the breaking torque is specified to be 40 N.m, and according to [20] the recommended tightening torque falls within the range of 50%-60% of the breaking torque, to generate tension in the bolt approximately 60% to 70% of elastic limit (yield strength) of the bolt material. After tightening, the preload force was noted, and then the nut was released till it became loose, and the preload became zero. This tightening cycle was repeated twenty times on the same bolt. For having a statistical base, twenty new bolts and nuts were used, with twenty tightening cycles each.

The effect of the tightening speed was not taken into consideration, as it has little effect on the nut factor [21-23]. Note that all the tightening cycles were conducted by the same operator (the author), using the same tool, in the same experimental environment. Figure 3 shows a sample of the conducted tightening-releasing cycle as a function of time. Here the colored area indicates the time duration needed to generate the preload. The calculated average time is of 1.06 seconds, per one tightening execution.

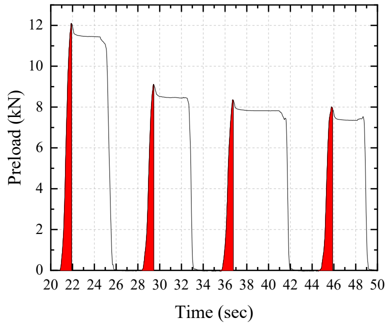

Figure 3
Bolt tightening-releasing cycle vs. time

Four cases of lubrication were studied to consider the effect of an eventual lubrication. In the first case "out of the box", we used the surfaces as they were obtained from the manufacturer, which named as "As-is" case in this article. In the second case, we applied drops of mineral-based 15W-40 motor oil (MOL MSE) on the bolt thread and under the bolt head surface before the first tightening. This is the "oiled" case. In the third case, all surfaces were cleaned with a degreaser (Loctite SF 7061) before the first tightening. This is the "dry" case. In the fourth case, solid powder lubricant (molybdenum disulfide, MoS_2) was applied on the threads and under the bolt head before the first tightening. For each lubrication case, brand-new bolts and nuts were used. Overall, 80 bolts and nuts were used in the study, and 1600 individual measurements were executed (Figure 4).

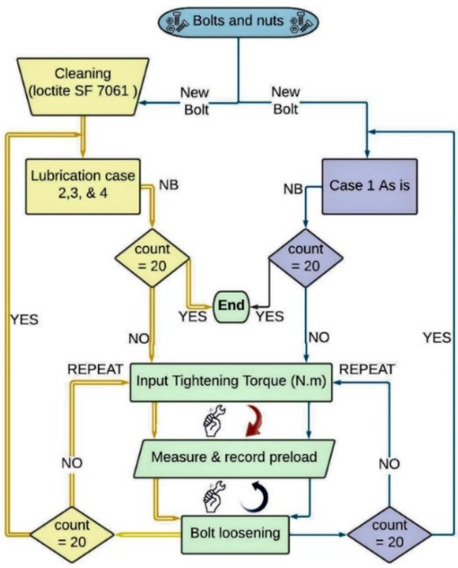

Figure 4
Experimental process flowchart

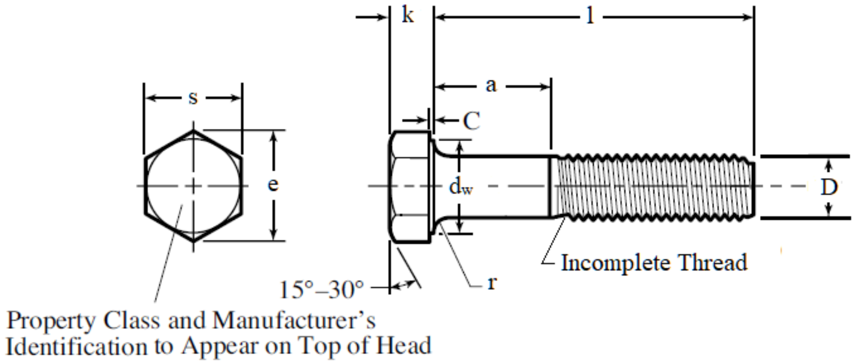

Figure 5

Tested bolt schematic[24]

The data acquisition system consisted of an HBM Quantum X data collector device, a computer, and an HBM KMR+/ 40kN bolt force sensor calibrated as per VDI/VDE 2638, with an accuracy class of 1.5 (±1%). The technical information and geometrical data of the tested bolt (Figure 5) are summarized in Table 1. Furthermore, Figure 6 shows the experimental setup layout.

Table 1

Bolt specifications

Surface finish		Black finish	
Grade	Bolt	10.9	
	Nut	8	
Size, d [mm]	8	Thread lead angle, α [°]	3.168
Thread pitch [mm]	1.25	Distance across flat, s [mm]	13
Metric thread profile angle, β [°]	60	Distance across corner, e [mm]	15
Tightening torque (N.m)	20	Head thickness, k [mm]	5.25
d_1[mm]	7.188	Unthreaded length, a [mm]	2.25
d_2[mm]	10.75	Washer face depth, c [mm]	0.4
Assumed μ_{th} and μ_n from	[25]	Washer face diameter, dw [mm]	12
Computed angle, ρ' [°]	6.587	Head junction radius, r [mm]	0.3

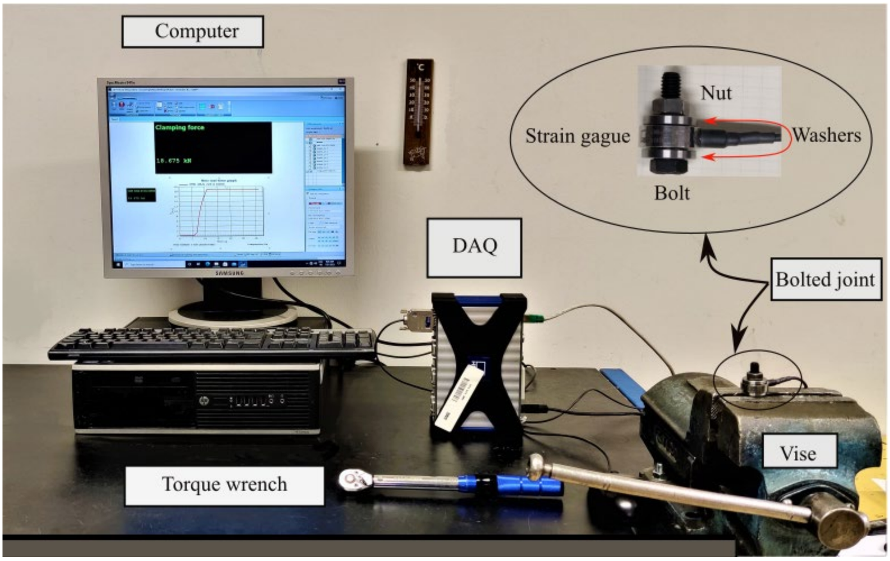

Figure 6
Experimental setup

4 Results and Discussion

The results of the experiments are discussed in two parts. The first part describes the bolt preload variations, and the second the nut factor variation.

4.1 Bolt Preload

In this section, the collected experimental preload data are presented. The effects of the presence of lubrication during the repeated tightening-releasing are shown. To validate the results, a statistical study was performed to show the significance of the achieved data.

The theoretical preload values were calculated using the information provided in Table 1. The values obtained from equation (1) and equation (3) were 17.369 kN and 17.365 kN, respectively. The assumed friction coefficient was used consistently for both equations, resulting in no significant difference between the values. Table 2 presents the mean of the measured preload achieved in the first tightening, sorted in descending order. It can be observed that the theoretical equation is validated for the oiled case. However, when the surfaces are dry, the preload values are lower than the theoretical predictions. Conversely, for the As-is and MoS_2 lubricant cases, the preload during the initial tightening exceeds the theoretical values.

Table 2

Mean of the measured preload for the first tightening cycle

Case	Measured Preload (kN)	Assumed μ_{th} and μ_n	Theoretical Preload (kN)
MoS_2	23.71	0.08 [25]	20.813
As-is	22.83	0.12 [25]	14.904
Oiled	17.71	0.1 [25]	17.369
Dry	12.95	0.13 [25]	13.916

A detailed representation of the distribution of the experimental data for each repetition is presented in the form of boxplots. The medians of the data are depicted by the centers of the boxes, while the interquartile range, represented by the height between the ends of the boxes, provides insight into the spread of the data within the middle 50% of the observations. The height of the whiskers further illustrates the dispersion of the data. All cases have the same vertical axis scale for ease of comparison.

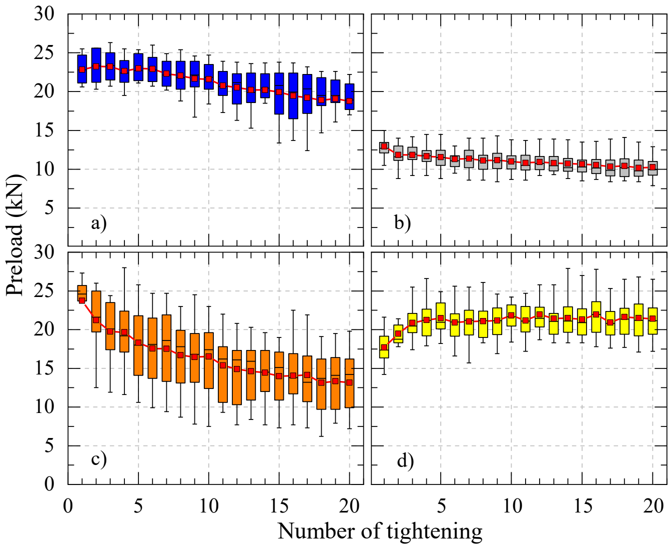

Figure 7

Preload box plot of the black bolt under lubrication conditions: a) As-is, b) dry, c) MoS_2, d) oiled

Let us consider the preload variation (Figure 7). Here, in the As-is case, the median of the preload decreases slightly when the number of tightening cycles increases. The range of the lower quartile increases at the last few tightening runs indicates that the distribution is negatively skewed, and there is a higher tendency to get a lower preload value as the number of tightening increases, see Figure 7. In the dry case, the median of the preload decreases almost linearly with the number of tightening cycles. The short box plots show a small median variation in the observed data, with a platykurtic distribution (Figure 8). In the MoS_2 lubricated case, the result shows a significant scatter with a symmetrical distribution: this could be related to the presence of the rolling powder on the friction surfaces. The preload median gradually decreases as the number of tightening repetitions increases. Finally, in the oiled case, the median gradually increases during the first five tightening cycles and then stabilizes at a value around 20% higher than the initial preload.

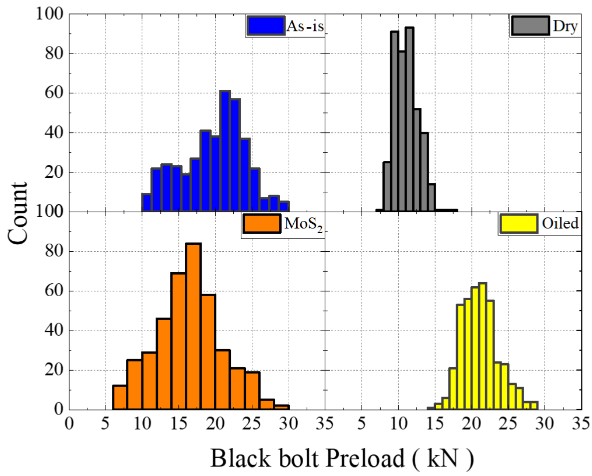

Figure 8
Histogram of black bolt preload for different lubrication conditions

Figure 9 shows the effect of repeated tightening on the mean of the measured preload for different lubrication conditions. The following remark can be made:

1) The preload values exhibited alterations in their relative order as the number of cycles increased. During the second cycle, the order of preload values from highest to lowest was As-is, MoS_2, oiled finally dry. This order changed the subsequent cycles. By the third cycle, the oiled condition had a higher preload value than the MoS_2, which persisted until the tenth cycle. The final order became Oiled As-is, MoS2, and finally Dry, which remained unchanged until the twentieth cycle.
2) For the As-is condition, the preload values decrease gradually from 22.8 kN with a few fluctuations until reaching its minimum value of 15.7 kN at cycle 20.
3) For the MoS_2 condition, the preload values decrease continuously with a few fluctuations until cycle 20, where it reaches its minimum value of 13.1 kN.
4) For the Oiled condition, the preload values show a slight increase from the first cycle to the fifth cycle and then stabilize for the remaining cycles.
5) For the dry condition the preload is the lowest among the tightening

repetitions, and the decreasing range is the smallest (from 12.95 kN to 10.26 kN).

6) Generally, the preload mean values change upon a bilinear curve as a function of the number of tightening cycles. The slope change happens around the fifth tightening for the As-is and the oiled lubrication condition. The first and the second slope depend on the type of lubrication. The trends are summarized in Table 3.

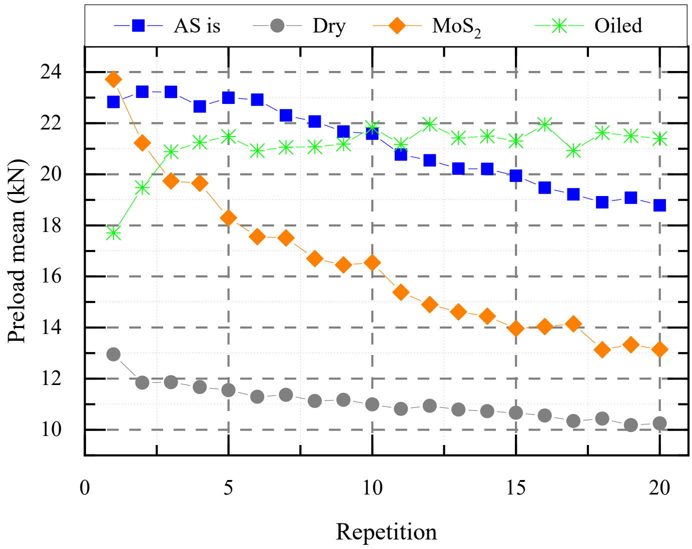

Figure 9

Effect of repeated tightening on the preload for the black bolt under different lubrication conditions

Table 3

Preload variations in the case of black bolts

Lubrication	Range (kN)	First slope	Second slope
As-is	22.8 to 15.7	0	decrease
Dry	13 to 10.3	Slightly decrease	Slightly decrease
MoS_2	23.7 to 13.1	Strong decrease	Strong decrease
Oiled	17.7 to 21.4	increase	0

The collected data is related to a randomly selected 80 bolts with mating nuts, visually inspected for any seen damage, and randomly assigned to each lubrication group. We have the same sample size n=20, over all cycles. For having statistical evidence about the suppositions made previously, a two-way mixed ANOVA design as described in [26] was performed after testing the ANOVA assumption's applicability (e.g., normality, homogeneity, the assumption of sphericity). The target was to compare the means of groups cross-classified by two different types of factor variables, including:

A. Between-subjects factors, which have independent categories:
    1. Lubrication condition (As-is, dry, MoS_2, and oiled)

B. Within-subjects factors, which have related categories, also known as repeated measures:
    1. Cycle (1,…, 20)

The two-way mixed ANOVA tested three null hypotheses (at a significant level α= 0.05) are:

1) The means of preload force are equal for the four lubrication conditions (As-is, dry, MoS_2, and oiled).

   $\mu_{As\text{-}is} = \mu_{Dry} = \mu_{MoS2} = \mu_{Oiled}$

2) The means of preload force are equal over the 20 cycles.

   $\mu_1 = \mu_2 = ... = \mu_{20}$

3) There is no significant effect of the interaction between the lubrication conditions and the cycle.

The two-way mixed ANOVA test was performed using the R software environment, and the results are summarized in Table 4.

Based on the ANOVA result in Table 4, all the main effects of the two factors significantly affected the preload value at $\alpha = 0.05$ since (p-value$< 2e^{-16}$). which leads us to reject the three null hypotheses and accept the alternative hypotheses as follows:

1) The mean of the preload is different for different lubrication conditions.
2) The mean of the preload over the 20 cycles is different for the same lubrication condition.
3) There is a significant interaction effect between the cycle and lubrication conditions.

Table 4

Result table for the Two-way mixed ANOVA

Only between subject factor					
Source of variation	DF	Sum Sq	Mean Sq	F value	Pr(>F) = p-value
Condition	3	27229	9076	83.74	$< 2e^{-16}$
Residuals	76	8237	108		
Between subject factor over the within the factor					
Source of variation	DF	Sum Sq	Mean Sq	F value	Pr(>F) = p-value
Cycle	1	1841.2	1841.2	183.41	$< 2e^{-16}$

Condition : Cycle	3	2263.3	754.4	75.45	$< 2e^{-16}$
Residuals	76	762.9	10.0		

In what follows, we study the overall bolting performance with two more tools: lubrication control and cycle control.

As lubrication control, a Dunnett's test was used to examine the two factors' interactions. This test is used to compare a one-factor level's effect on the response when one of the levels is assumed to be controlled under the null hypothesis:

$$H_0: \mu_{group(i)} - \mu_{control} = 0$$

where $\mu_{group(i)}$ - the mean of the treatment group i, $\mu_{control}$ - the mean of the control group.

In this research, the level "As-is" is assumed to be the control level in the factor lubrication condition. Table 5. Present the outcomes of the Dunnett`s test. From the result, we can conclude the following. For the first cycle, the As-is lubrication was significantly better than the dry and the oiled lubrication, with no significant difference from the MoS_2 lubrication. After five cycles, the As-is lubrication was significantly better than the dry and the MoS_2 lubrications, with no significant difference from the oiled lubrication. After 10 and 15 cycles, the As-is lubrication is still significantly better than the dry and the MoS_2 lubrications, with no significant difference from the oiled lubrication. Finally, after 20 cycles, the oiled lubrication significantly becomes the best lubrication condition.

Table 5
Result of Dunnett's test of the lubrication conditions factor with control level "As-is" over five levels of the cycle factor (1, 5, 10, 15, and 20)

Cycle	Comparison	Difference	p-value
1	Dry – As-is	-9.880	$<2e^{-16}$
	MoS_2 – As-is	0.883	0.473
	Oiled – As-is	-5.125	$5.4e^{-10}$
5	Dry – As-is	-11.440	$<2e^{-16}$
	MoS_2 – As-is	-4.696	$1.5e^{-7}$
	Oiled – As-is	-1.510	0.149
10	Dry – As-is	-10.545	$<2e^{-16}$
	MoS_2 – As-is	-5.050	$7.4e^{-8}$
	Oiled – As-is	0.245	0.982
15	Dry – As-is	-9.275	$<2e^{-16}$
	MoS_2 – As-is	-5.973	$1.5e^{-9}$
	Oiled – As-is	1.360	0.279
20	Dry – As-is	-8.525	$4.9e^{-15}$
	MoS_2 – As-is	-5.633	$5.3e^{-8}$
	Oiled – As-is	2.620	0.0143

For the cycle control, to illustrate the effect of the cycle, let us consider the following expression for the percentage change of the preload force:

$$\mathrm{V}_i = \left|\frac{F_1 - F_i}{F_1}\right| \times 100\% \tag{6}$$

Here *i=1..20* indicates the number of tightening cycles. The preload coming from the first tightening (F_1) is considered as a reference since the manufacturers often prescribe using a new bolt and washer after disassembly. The summary of the variations is plotted in Figure 10. The observations are the following:

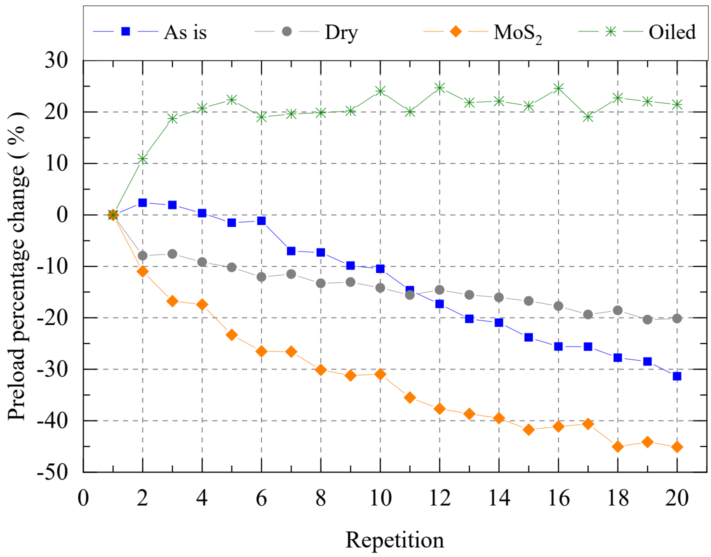

Figure 10
Preload percentage decrease relative to the first tightening

1) In the case of As-is lubrication, the bolt preload loss fluctuates around zero till the fifth tightening. As the number of cycles increases, the preload value loss at the 20th cycle is approximately 31% of the first cycle.

3) For the "MoS2" condition, the preload values decrease more steeply throughout the 20 cycles. The preload value at the 20th cycle was approximately 44.7% lower than that of the first cycle.

4) The presence of oil stabilizes the preload variation and has the best performance among the other lubrications. The preload values show a slight increase till the fifth cycle by 20% higher than the first value and then fluctuate around that percentage.

5) Preload percentage change in the function of tightening cycles for different lubrications is not the same. The oil lubrication gave the best performance; and the rank ordering is: oiled, As-is, MoS_2, and dry until the 11^{th} cycle; then the dry became better than the As-is lubrication.

4.2 Nut Factor Variation

In this section, an analysis of the variation in the nut factor is presented. The nut factor (K) was calculated utilizing the collected experimental preload data and equation (5). The calculation of the nut factor was performed for each tightening instance, and subsequently, the mean value was computed.

For the first cycle, Table 6 shows the nut factor for each lubrication case, where the calculated nut factor value is calculated using the measured preload values, and the theoretical nut factor value is calculated using the theoretical preload values. The difference between these two values can indicate the accuracy in predicting the friction coefficient for the theoretical equation for each lubrication condition. The theory was valid only for the oiled lubrication condition.

Table 6
Theoretical and calculated nut factor for each lubrication condition at the first cycle

Lubrication	Calculated Nut factor K	Theoretical Nut factor K
MoS_2	0.105	0.12
As-is	0.110	0.171
Oiled	0.141	0.144
Dry	0.193	0.18

The mean values of the nut factor (K) are depicted in Figure 11. The nut factor is known to include the effect of all unknown factors that influence the relationship between the input torque and the output preload. Therefore, by using it, we can compare the behavior of each type of bolt preload under different lubrication conditions and have the following remarks:

1) A higher nut factor indicates higher losses in the input torque. It is very significant in the dry case.
2) The lowest initial nut factor means the highest preload value was reached. This happened when MoS_2 was applied.
3) Lubrication improves both the tightening process efficiency and its repeatability. The K value was less than 0.15 in the As-is and oiled cases. Note that the received black bolts might have a thin oil layer to avoid rusting during storage.
4) The lubrication type and the cycle number combinations have an important effect on the preload.

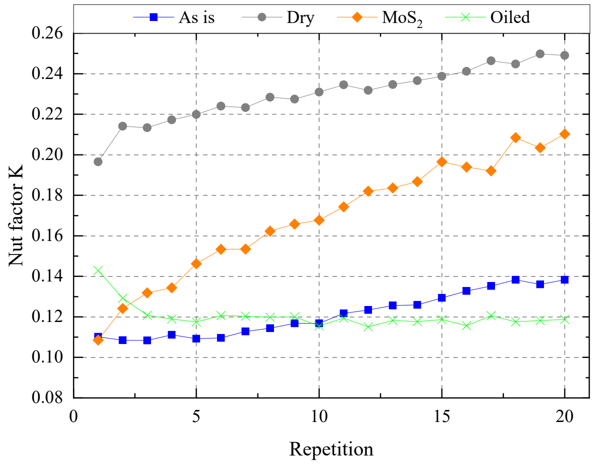

Figure 11
Calculated nut factor and its variation during repeated tightening

In the boxplot of Figure 12, the dispersion of the calculated nut factor is presented for all lubrication conditions throughout the twenty tightening cycles. It can be seen that oiling is good for keeping the nut factor dispersion small. Minimal nut factor values are present in the case of the oiled, followed by the As-is case due to the protection oil film. The wide K range for the MoS_2, despite the high initial achieved preload, can also be seen.

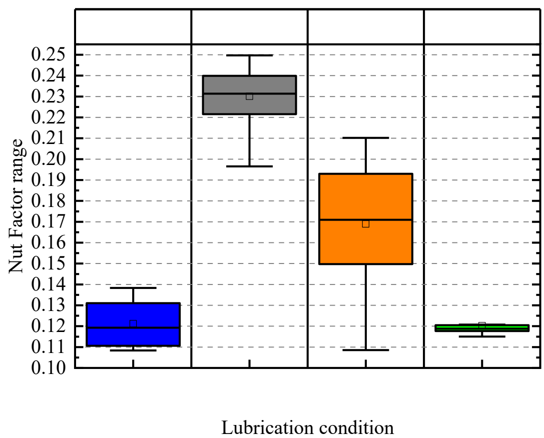

Figure 12
Nut factors range throughout the tightening repetitions

Conclusions

This study examined the variation of preload force, in a bolted joint, under repetitive tightening cycles. Initially, the preload force variation was investigated under different lubrication conditions. The nut factor is a measure of the influence of various unknown factors on the relationship between the input torque and the output preload. This factor was utilized to compare the behavior of the bolt preload under different lubrication conditions. Subsequently, the nut factor variations were computed based on the measurements obtained. The results indicate that the preload force exhibits variations during successive tightening cycles, with a notable decrease.

The study's results validate the engineering practice of not reusing dismantled bolts, washers, and nuts, as the initial preload of new bolts and nuts was the highest in most lubrication cases.

The influence of lubrication on preload variation was observed, with a small amount (few drops) of oil lubricant leading to a stable repeated preload value. Application of a powder lubricant (MoS_2) resulted in higher preload force but also a wider distribution under repeated tightening. Similar preload behavior was observed between the as-is and oiled conditions, which can be attributed to using an oil film during manufacturing to prevent surface rust during storage.

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