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Investigation of the Effect of the Surface Treatment and Lubrication During Repeated Tightening on the Nut Coefficient of a Bolted Joint Using the Taguchi Method

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Abstract

Bolted joints are used extensively in mechanical engineering due to their reusability, appearance, and strength advantages. In different industrial applications, the separated mechanical components are clamped together during the assembly using a tightening process. Estimating precisely the initially achieved clamping force is a persistent problem for providing a secure and reliable connection for a particular design. However, the nut coefficient is one of the exploratory methods used for this purpose. This paper aims to investigate how the nut coefficient of a bolted joint is influenced by factors such as bolt/nut surface treatment and the presence of lubrication at joint contact surfaces throughout the cyclic joint assembly/disassembly process, serving as a simulation for real-life maintenance operations where the same bolt/nut are reused. Torquing cycles were introduced to bolted joints with two surface finishes and four lubrication conditions. The experiments were conducted on bolts at room temperature according to ISO16047. The nut coefficient was calculated for bolt sizes M6*1, M8*1.5, and M10*1.5. The results were analyzed using the analysis of variance and Taguchi method L32 for estimating the contribution of the different factors on the nut coefficient. It was found that the lubrication was the most significant parameter affecting the nut factor regardless of the bolt size. Also, a case study was conducted to investigate the underlying reasons behind the significance of lubrication in influencing the nut coefficient across different bolt sizes.

Keywords: Nut coefficient, Bolted joint, Lubrication, Cyclic tightening, Preload control, Taguchi L32 method, ANOVA.

NOMENCLATURE

Symbol	Quantity
a	Unthreaded length(mm)
D	Bolt nominal diameter (mm)
d_2	Bolt mean or pitch diameter (mm)
D_h	Clearance hole diameter (mm)
D_o	Outer diameter of bearing surface (mm)
e	Distance across corner (mm)
F_i	Preload at the i^{th} tightening cycle
F_P	Clamping force (kN)
k	Head thickness(mm)
K	Nut coefficient or nut factor or Torque coefficient
l	Bolt length(mm)
$T_{in,}$	Input tightening torque (N.m)
T_{Head}	Bearing surface friction torque (N.m)
MoS_2	molybdenum disulfide powder
T_{Thread}	Thread friction torque (N.m)
P	Thread pitch (mm)
r_n	The effective bearing radius (mm)
r_t	The effective thread radius (mm)
s	Distance across flat (mm)
T_{Pitch}	Torque to generate bolt tension (N.m)
β	Metric thread profile angle (°)
σ_p	Proof load (kN)
μ_n, μ_b	Friction coefficient at the bearing surface under the turning head
μ_t, $\mu_{th,}$	Friction coefficient at the thread surface

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1. Introduction

In Mechanical engineering, bolted connections are widely used to join various structure components due to their reusability, appearance, and strength advantages [1]. During the assembly process, mechanical components are clamped together through a tightening process. In this process, the turning head of the joint, let us say that the nut is turned relative to the bolt in the tightening direction (against the resistance of gripped material) [2]. The tightening process generates a clamping force that prevents the components from separating. Estimating the clamping force is usually based on the bolt material's yield strength [3]. The torque wrench is widely used for applying torque to the joint through tightening due to its ease of operation

[2]. However, approximately (10%-20%) of the input torque to the joint is converted to clamping force, while the remaining (80%-90%) of the input torque is mainly consumed to overcome frictions at the joint contact surfaces (between the face of the turning head and the surface of the joint and between the mating threads of the bolt and the nut) [4]. So, since the frictional losses are high, at the design stage, inaccurate estimation of the bolted joint frictional parameters can lead to excessive or insufficient clamping force, resulting in joint instability and failure [5], [6]. Several factors influence the torque/clamping force relationship in bolted joints [1], [2]. These involve the material properties of the bolt and nut, the material being clamped, and various geometrical aspects including the class of fit, hole diameter, joint grip length, and thread profile. Moreover, the manufacturing process of the joint material plays a crucial role, involving heat treatment techniques like quenching and tempering that impact hardness, strength, and toughness [7]–[9]. Surface finish considerations, such as oxidizing and coating, further contribute to appearance, corrosion resistance, frictional characteristics, and protection against environmental factors [10]–[13]. Tightening methods employed in the assembly process also play a significant role in the bolting performance. Various tightening control methods and strategies are utilized to generate bolt clamping force, such as torque and angle control, bolt elongation control, and torquing control [2]. However, they have some pros and cons regarding the consistency of the clamping force, and the characteristics and the differences in the clamping force of these methods were evaluated in [14]–[16]. Lee et al. [17] developed a testing device for investigating the torque/clamping force relationship for M14x1.5 steel bolts, and their results showed excellent correlation with the actual measurements. According to ISO 16047, the nut coefficient is one of the approaches used to evaluate the fasteners' torque/clamping force relationship. Several research have been done to investigate the torque/clamping relationship. For instance, B. Güler and K. T. Gürsel [18] used the torque-angle controlled tightening method to investigate vehicle chassis zinc-coated joint. They concluded that repetitive tightening increased the coefficient of friction and linked this to the large worn-out coating material. Nassar [19] proposed a new analytical torque/clamping force relationship using the torque angle method and validated it experimentally for M12×1.75 bolts. His approach increases the consistency of the clamping force from one tightening to another by reducing the friction variation on the error.

S. A. Nassar et al. [20] experimentally investigated the effects of the turning speed, repeated tightening, lubrication, and fastener coating on friction and nut coefficients for M12x1.75 grade 8.8 bolted links. The results revealed that at turning speed under 30 rpm, the friction and nut coefficients were significantly increased during the repeated tightening of the zinc-coated bolts and washers. While for turning speed above 30 rpm, the impact of turning speed was insignificant for the nut coefficient. W. Eccles et al. [3] studied the friction variation during repetitive tightening, using an experimental approach of repeated tightening process of zinc-coated threaded fasteners. They inspected the surface of contact at the threads during repetitive tightening and found surface damage on the pressure flanks of the threads. Coating material was transferred from the nut onto the bolt at the thread contact surface. This phenomenon was stabilized after the tenth tightening repetition. At the same time, they observed severe thread surface damage and distortion in the first engaging thread. They suggested a nonlinear empirical model based on the number of tightening cycles. Nassar and Zaki [21] studied the influence of two joint coating material thickness (thin and thick) using zinc/aluminum coating on the underhead and between the mating threads friction coefficient and evaluated the torque tension relationship using the nut coefficient assessment for M12×1.25 and M12×1.75 steel bolts with zinc/aluminum coating material (Magni 565), and they found that the friction coefficients and the nut coefficient were decreased by increasing the thickness of coating material. Jiang et al. [22] investigated the nut coefficient for M12x1.75x65 Aluminum bolts with two clamping configurations, aluminum, and steel. The results showed a higher K value for the aluminum clamping material. In another study conducted by Rosas et al. [23], the nut coefficient variation was studied using an alloy-steel standardized bolted joint (B7M bolt and 2HM nut) of a size 1 1/8". Four coating conditions under three lubricant cases were investigated after the first and the fifth tightening cycles. The results revealed that the Nickel-Cobalt electroplating was the best coating for having a higher consistent nut coefficient regardless of tightening cycles, and the authors recommended the use of molybdenum disulfide powder (MoS_2) with this type of coating.

Yu et al. [24] studied the nut coefficient under four working conditions using two types of nickel-based alloys (GH4169 and GH159) bolted joints of three geometrical dimensions (size and pitch). They found that lubrication is the most significant factor among the others, while surface roughness had a slight effect. Zou Q et al. [25] conducted an extensive study to investigate the impact of three parameters with different levels, namely, tightening speed (7 levels), lubricants (3 types), and repeated tightening (5 cycles) on the friction and the nut coefficients of a steel bolted joint using class 8.8 M12 bolts. They used two types of pitches, fine and coarse, and three levels of each lubrication type. The conducted research found that the friction and the nut coefficient were significantly affected by the lubrication. Moreover, the solid film lubricant had the lowest value, while the grease and oil lubricants behaved similarly. Insufficient research has been done using the Design of experiment (DoE) approach to investigate the impact of different parameters on the torque/clamping force relationship. Croccolo et al. [26] conducted an experimental and statistical approach. In their DoE, they applied the FFD method using four factors at two levels with their interactions for evaluating the joint overall frictional parameter along with the nut coefficient and how they affect the torque/clamping force relationship for an M8x1.25 zinc-plated screws that clamp aluminum part. At a 90% confidence level, they found that the surface finish was the highest factor impacting the bolting performance, followed by the lubrication factor, and their interaction was the third one. Tightening cycles was the least factor, while the effect of the bolt-forming process was insignificant. In another study by Croccolo et al. [27], they performed a full factorial design (FFD) of two factors (tightening cycle and lubrication) with three levels each to evaluate the impact of these factors on the friction coefficient of a joint made of M8x1.25x60 titanium screw with mating steel threads for clamping an aluminum plate. The conducted research concluded that lubrication was the most significant factor affecting the friction coefficient. In response to this gap in the literature and the insufficient research and studies of different bolt sizes [23], this study employed Taguchi L32 DoE methodology to investigate the significance of three different parameters (surface treatment, lubricant type, and number of tightening cycles) with different levels on the nut coefficient's value to evaluate the bolting performance of three different sizes.

Surface treatment has a crucial effect on corrosion, friction, and wear [28], [29].The investigation into surface treatments revealed that the choice of treatment significantly alters the frictional behavior of bolted joints. For instance, black oxide introduces specific surface characteristics that impact the wear and corrosion resistance, while galvanized zinc provides an alternative set of attributes. The nuanced effects of these treatments on the nut coefficient are discussed in the following sections, emphasizing their direct correlation with the observed outcomes.

Lubrication stands as a critical factor in the optimal functioning of bolted joints. Its significance extends beyond mere facilitation of smooth operation; rather, it plays a multifaceted role. Lubrication ensures a consistent and uniform friction coefficient, thereby intricately influencing the delicate balance in torque and clamping force relationships within the joint. Moreover, it serves as a formidable preventive measure against detrimental phenomena such as seizing (locking) and galling (cold welding), safeguarding the integrity of the joint under various operational conditions [30], [31]. Additionally, the pivotal role of lubrication extends to enhancing corrosion resistance, fortifying the joint against the effects of environmental factors. In essence, lubrication emerges not only as a facilitator of operational ease but as a protector ensuring the longevity, reliability, and performance of bolted joints. The frequency of tightening cycles wields a profound influence on both the stability of the joint and the overall reliability of the underlying structure [32]. This critical aspect introduces a dynamic element to the joint's performance, with variations in tightening cycles directly correlating with its long-term stability and structural robustness. Furthermore, in certain applications, the necessity for periodic assembling and disassembling of bolted joints arises due to the operational demands of maintenance [33]. This practice, integral in specific industrial scenarios, underscores the adaptability and endurance of bolted joints under varied operational conditions. The intermittent nature of assembling and disassembling not only accentuates the joint's resilience but also aligns with the practical needs of maintenance protocols, attesting to the versatility and reliability of bolted joints in real-world applications.

By investigating the influence of the abovementioned parameters on the nut coefficient, this study provides valuable insight into a better understanding of the torque/clamping force relationship. Furthermore, this study emphasizes the importance of each parameter and how much it impacts the overall bolting performance. The conducted experimental approach on the steel bolted joints was performed according to ISO 16047 . The remainder of the paper is organized in the following manner. A brief theoretical and empirical background for the study is in section 2. Section 3 focuses on the experimental methodology and procedures using the Taguchi L32 orthogonal array. Furthermore, a statistical analysis was done using ANOVA, and then the experimental results are presented in section 4. Following in the subsequent section, a case study is provided for further investigation of the roughness and the wear pattern using optical profilometry. Section 6 highlights the conclusion, which summarizes the main findings of the study.

2. Theoretical Framework

Generally, in machine element theory, when the prevailing torque is absent, the torque/clamping force relationship equation is composed of three torque components, as illustrated in **Figure 1**, where two are related to the joint friction, and only one is responsible for generating the clamping force in the bolt, as in

$$T_{In} = T_{Pitch} + T_{Threads} + T_{Head} \quad (1)$$

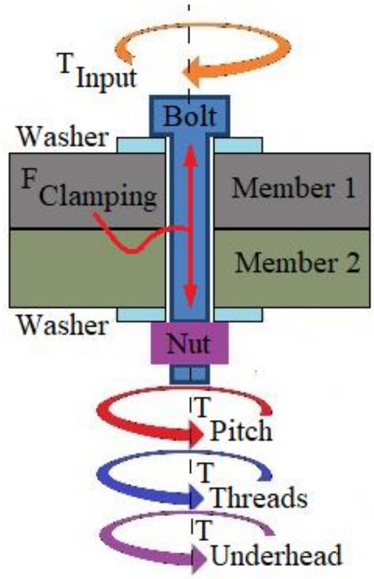

Figure 1. Tightening torque distribution [34]

In 1976, Motosh [35]introduced an accurate form of the torque/clamping force relationship in terms of the joint geometrical and frictional parameters, as in

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

The decomposition of this equation is as follows:

The pitch torque component

$$T_{pitch} = F_P\frac{P}{2\pi} \quad (3)$$

And for the torque component to overcome thread friction

$$T_{threads} = F_P\frac{\mu_t r_t}{cos(\beta/2)} \quad (4)$$

Finally, the underhead component to overcome bearing friction

$$T_{underhead} = F_P\mu_n r_n \quad (5)$$

In a similar way, according to the Fasteners — Torque/clamp force testing standard (ISO 16047) , the torque/clamping force relationship can be expressed as in

$$T_{in} = F_P \left(\frac{1}{2} \cdot \frac{P + 1{,}154 \cdot \pi \cdot \mu_{th} \cdot d_2}{\pi - 1{,}154 \cdot \mu_{th} \cdot \frac{P}{d_2}} + \mu_b \cdot \frac{D_o + d_h}{4} \right) \quad (6)$$

Since the actual friction coefficients at the joint contact surfaces (between the mating threads and under the turning head) are variant during each tightening run, it is difficult to have a constant value. As a result, experimentally, investigations employed a shorter expression for the torque-tension relationship [36]–[38], which contains all friction factors in one parameter called nut coefficient (K), or torque coefficient.

$$K = \frac{T_{in}}{F_P \cdot D} \quad (7)$$

In accordance with the ASME PCC-1 standard, the nut coefficient is a dimensionless constant calculated experimentally. Therefore, the standard measurable parameters in (7) facilitate the calculation of the nut factor. In this matter, the nut factor can be used as an indicator for the bolting performance and comparing different tightening scenarios. However, it requires many experiments to get statistically strict data for each bolt diameter with an acceptable narrow confidence level, which can be more accurate and reliable for industrial applications [2].

3. Experimental methodology and procedures

3.1. Bolts selection and selected samples

The experiments were conducted using 30MnB4 steel bolts and nuts of three sizes: M6x1, M8x1.25, and M10x1.5 hexagonal head and metric threads profile. Figure 2 illustrates the schematic with the assigned dimension. **Table 1** summarizes the technical and geometrical specifications of the bolts and nuts. The tested fasteners were made from two surface finish zinc-coated grade 8.8 and black oxidize grade 10.9, while the nut for both surface finish has grade 8. A total of 480 new bolts were selected randomly. The bolts and nuts were visually inspected for any damage seen in the threads and randomly assigned into groups of 20.

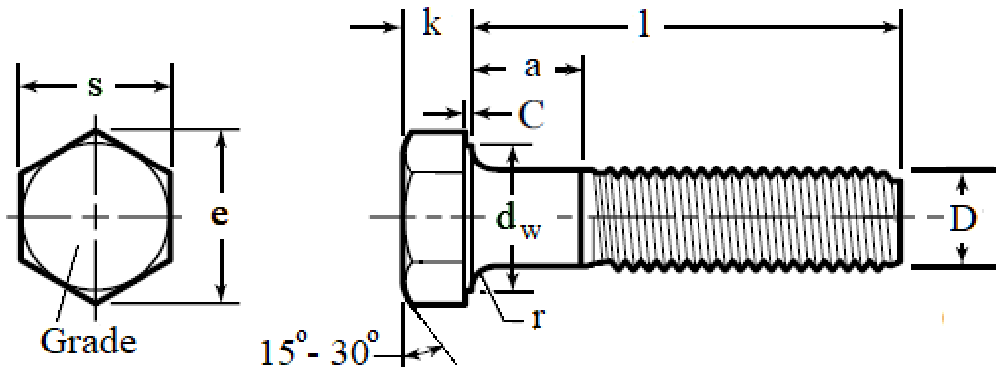

Figure 2. Tested bolt schematic [39]

Table 1. Detailed bolts and nuts, geometrical dimensions, and mechanical properties

Specifications	Surface treatment					
	Zinc coating			Black oxide		
T (N.m)	10	20	40	10	20	40
D (mm)	6	8	10	6	8	10
P (mm)	1	1.25	1.5	1	1.25	1.5
D_h (mm)	8	8	11	8	8	11
S (mm)	10	13	17	10	13	17
e (mm)	11.3	14.5	19	11.3	14.5	18
k (mm)	3.7	4.8	5.8	3.7	4.8	5.8
l (mm)	30	30	60	30	30	60
a (mm)	2	2.25	2.5	2	2.25	2.5
Bolt grade		8.8			10.9	
Nut grade			8			
Proof load stress (MPa) [a]		600			830	

[a]According to the J1199 standard

3.2. Selected parameters and their levels

The selected parameters in this investigation are surface treatment, lubrication, and number of cycles. The reason behind selecting these levels is illustrated as follows:

- Surface treatment: Two surface treatments were employed in this study: zinc-coating and black oxidation. Despite the importance of black and zinc surface treatment from the tribological aspect, their effects on the bolted joints are still not investigated sufficiently [40]. Previous studies highlighted the positive impact of zinc coating on both friction and wear, even without a lubricant state [41], [42]. Regarding black oxidation, developed at the beginning of the last century, this surface treatment enhances the appearance along with the lubricity and the resistance to corrosion and adhesive wear [29], [43].
- Lubricant type: To take into consideration the effect of eventual lubrication on the bolt preload, four cases of lubricants were investigated. The first type was "Out-of-the-box (OB)", indicating that the bolts were tested as they were received directly from the manufacturer, without any surface treatments or additional modifications. The "Clean and dry (CD)" is the second case, where all surfaces were cleaned with a degreaser (Loctite SF 7061) before the first tightening. In the third lubricant type, the "Oiled lubricant (OL)", drops of mineral-based MOL MSE 15W-40 multigrade motor oil were applied. Finally, In the fourth case, "Solid molybdenum powder (SMP)", a solid powder lubricant (MoS_2) was applied. In the scenarios involving OL and SMP lubricants, oil was uniformly applied to both the underhead and mating threads to guarantee thorough coverage across all contact surfaces. Conversely, in the case of solid powder lubrication, the bolt and nut underwent immersion in a bath containing the powder. Subsequently, gentle shaking was employed to remove excess powder from the surfaces. It is essential to note that these procedures were exclusively executed prior to the first tightening, and consistently performed by the same operator. Additive liquid mineral oil and solid-based lubrication has several applications in different industrial field [44] for liquid lubrication, in some applications (in the gear unit), the bolt and the nut can be completely soaked in the lubricant [40], [45], while for the solid based lubrication, standards suggest using lubrication during the assembly [27]. Moreover, if the bolted joint is designed to be used without lubrication, then joint failure can be the result [2] if lucricant is applied. So, the selected lubrication levels for the study can assess the joint frictional behavior for several surface state scenarios.
- Number of cycles: Four consecutive tightening loosening cycles were chosen as a simulation of the maintenance operations, where assembly/ disassembly of the bolted joint is needed, which can change the friction and generate wear to the joint [45], [46].

3.3. Design of experiment and optimization method

To study the impact of different parameters on the nut coefficient of the bolted joints, using the design of experiment (DoE) techniques, such as Central Composite Design (CCD) [47], [48], Taguchi orthogonal array [49]–[52], Box Behnken Design (BBD) [53], [54], and Response Surface Methodology (RSM) [55], [56], are important. The above mentioned methods can give a systematic and structural approach to evaluating the impact of different input parameters on a single response variable, enabling a better understanding of the response surface and the ability to identify the best parameter configurations with increased precision. Taguchi technique is a statistical method that utilizes an orthogonal array to design experimental procedures and analyze the output response. It is specifically useful for enhancing the robustness of a process by identifying the key parameters that influence the performance and finding out the optimal levels of these parameters. One of Taguchi's approaches is the orthogonal arrays utilized in determining the optimal number of experimental trials required to give a comprehensive detail of all parameters affecting the performance parameters [57]. Employing Mean Effect Plot (MEP) graphs and Signal to Noise (S/N) ratio helps as effective tools for decreasing process variability and optimizing output responses [58]. To evaluate the three investigated parameters, the mixed-level L32 array was chosen from the available orthogonal design options. The reason behind using the mixed-level design was due to that there are different parameters that have different levels. **Table 2** presents the corresponding parameter levels within the L32 array.

The S/N ratio is selected according to the studied variables. In this investigation, the output variable is the nut coefficient, and the target is to minimize it. So, the S/N ratio "the smaller the better" is calculated based on the following equation [59]:

$$S/N = (-10) \times log_{10}\left(\frac{1}{n}\right)\sum_{i=1}^{n} y_i^2 \quad (8)$$

Where, n depicts the number of runs and Yi represents the responses of the replicated experiments for each test run.

Table 2. Investigated parameters and their levels

Parameter	levels			
	1	**2**	**3**	**4**
Surface treatment (S)	Black oxide	Galvanized zinc	-	-
Lubrication type(L)	Clean and Dry (CD)	Out-of-the-box (OB)	Oiled lubricant (OL)	Solid molybdenum powder (SMP)
Number of cycles(C)	1	2	3	4

3.4. Experimental process

The experiments were conducted in accordance with ISO 16047 at room temperature. The experiment setup involves using a torque wrench to introduce the input torque to the joint since it is widely used in many industries [60]. A washer strain gauge is used as a clamped component and simultaneously measures the response (the generated preload), taking into consideration its acceptable accuracy, and according toE. Oberg et al. [61], the accuracy of these preload application methods is $\mp$ 25 % and$\mp$1%, respectively.

The bolt head was fixed using a vise. Then, the strain gauge was mounted between two hardened washers. These washers are a special hardened load application disks provided by strain gauge manufacturer with a specifications of flat surface, 47±2 HRC hardness, and 0.8 µm roughness. The turning head was the nut; see **Figure 3**. The torque was applied using a torque wrench set to a constant value according to the bolt size mentioned in **Table 1**. After the tightening process, the clamping force was recorded using the Data Acquisition System (HBM Quantum X MX840A Universal amplifier), then the nut was released till it became loose, and the clamping force became zero. This tightening/loosening cycle was repeated four times on the same bolt, with twenty replicas for each case. The impact of tightening speed was omitted from consideration due to its minimal influence on the nut factor [28]. It is important to highlight that all tightening cycles were consistently performed by the same operator (the author), utilizing the same tool, within a uniform experimental environment. **Figure 4** provides a visual representation of a typical tightening-releasing cycle over time, with the colored region denoting the duration required for preload generation. The average time calculated for tightening execution stands at 1.6 seconds.

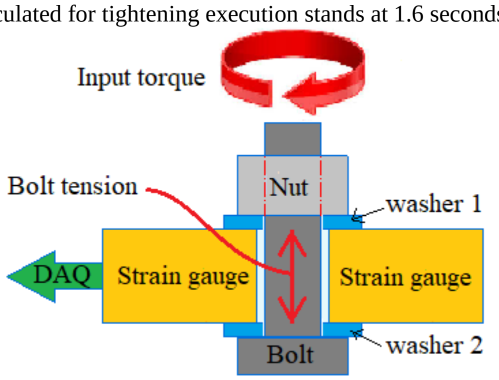

Figure 3. Representation of the tested bolted joint

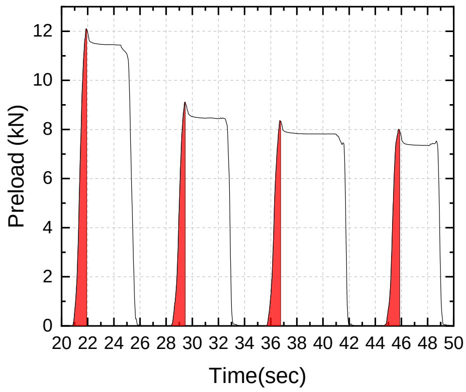

Figure 4. sample of bolt tightening-releasing cycle vs. time

Table 3 summarizes the technical specification of the used torque wrench and strain gauge, and the experimental procedure is illustrated in **Figure 5.**

4. Experimental results and statistical analysis

Table 4 represents the L32 array and the nut factor results for the M6, M8, and M10 bolt sizes, which were calculated using the empirical equation No. 7.

4.1. Probability plot

A probability plot is an effective tool for evaluating the data to a specific probability distribution. This plot provides economics, researchers, and engineers with a visual representation of the correlation between observed variables and expected responses according to a theoretical distribution. This graphical illustration facilitates the identification of the statistical tests. In this investigation, the Anderson-Darling (AD) statistical test was employed to confirm the normality distribution. A larger p-value and smaller AD value denote a better fit of the results to be normally distributed [62]. The experimental results for the response of the nut coefficient closely align with the fitted line, and the AD tests exhibit relatively small values while the p-values surpass the commonly undertaken significant level of 5%. **Figure 6** illustrates these results, verifying the assumption that the experimental results follow the normal distribution. Therefore, further analysis can proceed.

Table 3. Torque wrench and Strain gauge technical specification

	Type	Range	Calibration	Accuracy
Washer strain gauge	HBM KMR+ Donut force sensor	(0-40) kN	As per VDI/VDE 2638	Class 1.5 (±1%)
Torque wrench (Mechanical Push-through Reversible ratchet handle)	Magnus Type II Class A	(0-25) N.m (5-125) N.m	ISO 06789. BG/T15729. ASME B107.14M	±3%

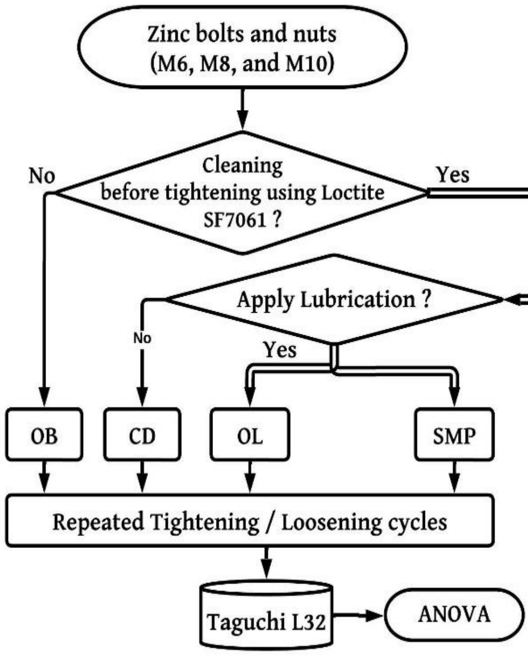

Figure 5. Experimental flowchart

Table 4. Experimental design and nut coefficient results using L32

Run	Surface treatment	Lubrication	Number of cycles	K6	K8	K10
1	Black-oxide	CD	1	0.20134	0.18654	0.18564
2	Black-oxide	CD	2	0.21511	0.19750	0.19176
3	Black-oxide	CD	3	0.23850	0.20334	0.19895
4	Black-oxide	CD	4	0.25395	0.20719	0.20554
5	Black-oxide	OB	1	0.17188	0.11013	0.18054
6	Black-oxide	OB	2	0.15749	0.10230	0.16675
7	Black-oxide	OB	3	0.15316	0.09836	0.16327
8	Black-oxide	OB	4	0.15036	0.06600	0.15385
9	Black-oxide	OL	1	0.14334	0.13600	0.15142
10	Black-oxide	OL	2	0.13203	0.12921	0.14092
11	Black-oxide	OL	3	0.12749	0.12076	0.13626
12	Black-oxide	OL	4	0.12657	0.11892	0.13124
13	Black-oxide	SMP	1	0.10451	0.10855	0.15930
14	Black-oxide	SMP	2	0.10404	0.12413	0.16155
15	Black-oxide	SMP	3	0.10666	0.13184	0.16105
16	Black-oxide	SMP	4	0.10791	0.14000	0.15955
17	Galvanized-zinc	CD	1	0.22616	0.16746	0.16594
18	Galvanized-zinc	CD	2	0.26981	0.22747	0.19479
19	Galvanized-zinc	CD	3	0.28020	0.24690	0.21476
20	Galvanized-zinc	CD	4	0.28487	0.26952	0.21900
21	Galvanized-zinc	OB	1	0.17532	0.16245	0.16601
22	Galvanized-zinc	OB	2	0.19188	0.17097	0.19782
23	Galvanized-zinc	OB	3	0.21147	0.21256	0.21544
24	Galvanized-zinc	OB	4	0.24059	0.22502	0.23931
25	Galvanized-zinc	OL	1	0.09103	0.15605	0.13416
26	Galvanized-zinc	OL	2	0.08515	0.15590	0.11877
27	Galvanized-zinc	OL	3	0.06830	0.15554	0.10740
28	Galvanized-zinc	OL	4	0.10168	0.15294	0.10350
29	Galvanized-zinc	SMP	1	0.13287	0.07920	0.15023
30	Galvanized-zinc	SMP	2	0.14455	0.10047	0.16074
31	Galvanized-zinc	SMP	3	0.16749	0.11057	0.17117
32	Galvanized-zinc	SMP	4	0.16862	0.12516	0.17285

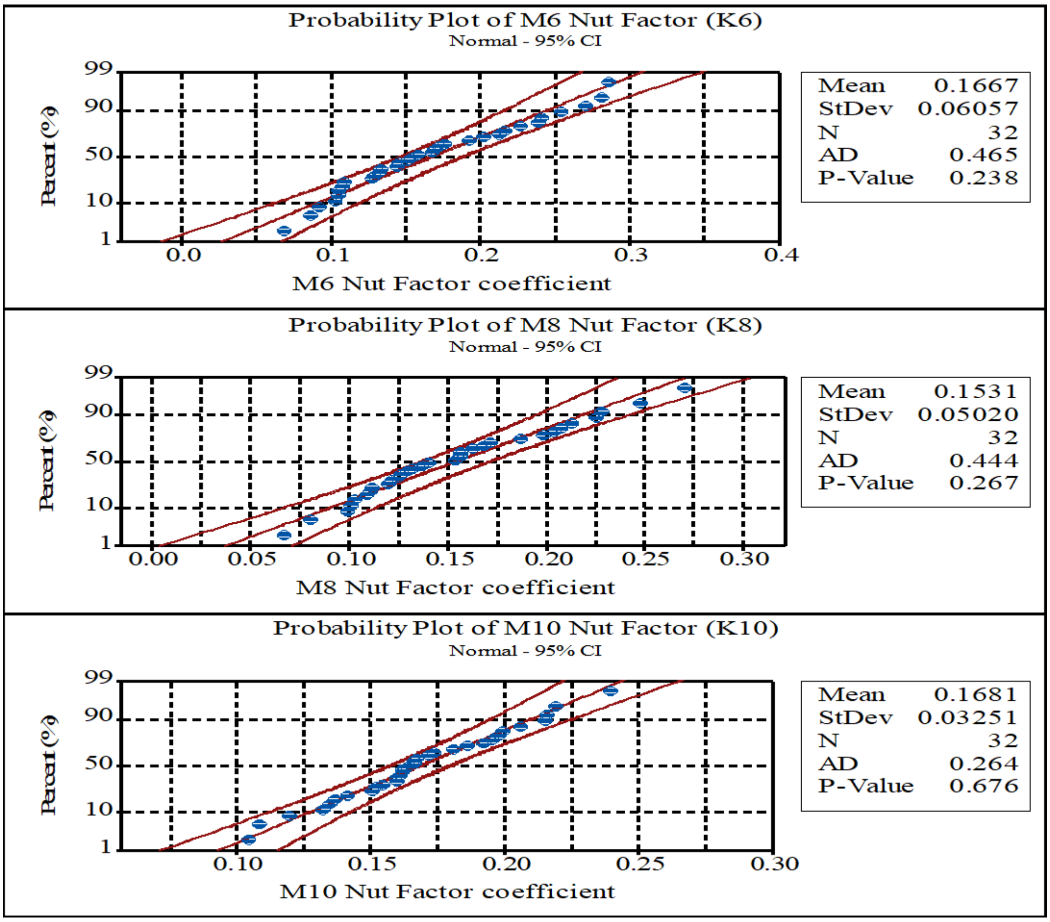

Figure 6. Probability plot of the nut coefficient for M6, M8, and M10 bolt sizes

4.2. ANOVA and MEP for nut coefficient

The ANOVA statistical method is widely employed in many scientific sectors to determine the significance of the input parameters on output response [63], [64]. Employing ANOVA with a confidence level of 95%, the experimental results of this investigation can be considered accurate and reliable. The P-value is the key to the significance of the input parameters and denotes the probability of obtaining the observed results by chance. In this investigation, a p-value less than 0.05 was employed to determine the significance of the input parameters. The results of the ANOVA for the nut coefficient were obtained for three different bolt sizes (M6, M8, and M10), and the contribution percentage of each parameter is illustrated in **Table 5**. **Figure 7-Figure 9)** show the S/N ratios for the nut coefficient response.

For M6 bolt size, the results revealed that lubrication was the most significant parameter affecting the nut coefficient results, with a 78.79% contribution. The surface treatment and the number of cycle parameters had a low effect on the nut coefficient value, with less than 4% for each of them. In contrast, the interaction between the surface treatment and the lubrication contributed to the nut coefficient value of 10.75%. Again, the lubrication was the highest effective parameter for the M8 bolt size, with a 54.44% contribution. When it comes to the interaction between the surface treatment and the lubrication, there contribution to the nut coefficient value was 18.9%. In contrast, the results were a bit different for the influence of the surface treatment parameter. Even though it is not the highest significant parameter, it had a good contribution percentage to the nut coefficient value, with about 11.5%. Regarding the M10 bolt size, the ANOVA results showed that the lubrication parameter is the most significant parameter influencing the nut coefficient value, with a contribution of 67.97% of the total variation. The surface treatment and number of cycles had no significant effect on the nut coefficient value. On the other hand, the contribution percentage of the interaction between the surface treatment and the lubrication was the second parameter, with a 12.04% contribution. In this study, it becomes evident that the interaction effect between surface treatment and lubrication significantly outweighs the impact of cycles across all three bolt sizes (M6, M8, and M10). These results are in concurrence with the research findings previously documented in the Croccolo et al. [26] study.

The impact of the interaction between surface treatment and lubrication on the calculation of the nut coefficient across the three bolt sizes can be justified from a tribological standpoint. Surface treatments impact the microstructure and roughness of bolt surfaces, influencing friction and wear characteristics. Simultaneously, lubrication serves as a protective layer, reducing direct metal-to-metal contact, minimizing abrasive wear, galling, and mitigating the risk of corrosion. The combined effect enhances lubricity, facilitates smooth motion, and reduce torque losses during the tightening process, and enhance the bolting performance.

Table 5. ANOVA for nut coefficient response and the contribution percentage

Bolt size	Source	DF	Seq SS	Adj SS	Adj MS	F	P	% of contribution
M6	S	1	0.003734	0.003734	0.003734	22.36	0.00	3.28
	L	3	0.089617	0.089617	0.029872	178.93	0.00	78.79
	C	3	0.002412	0.002412	0.000804	4.82	0.03	2.12
	S*L	3	0.012232	0.012232	0.004077	24.42	0.00	10.75
	S*C	3	0.001496	0.001496	0.000499	2.99	0.09	1.32
	L*C	9	0.002743	0.002743	0.000305	1.83	0.19	2.41
	Error	9	0.001503	0.001503	0.000167			1.32
	Total	31	0.113736					100.00
M8	S	1	0.009025	0.009025	0.009025	37.39	0.00	11.55
	L	3	0.042532	0.042532	0.014177	58.73	0.00	54.44
	C	3	0.002966	0.002966	0.000989	4.1	0.04	3.80
	S*L	3	0.014766	0.014766	0.004922	20.39	0.00	18.90
	S*C	3	0.003237	0.003237	0.001079	4.47	0.04	4.14
	L*C	9	0.003422	0.003422	0.00038	1.57	0.26	4.38
	Error	9	0.002173	0.002173	0.000241			2.78
	Total	31	0.078121					100.00
M10	S	1	0.000222	0.000222	0.000222	1.12	0.32	0.68
	L	3	0.022274	0.022274	0.007425	37.57	0.00	67.97
	C	3	0.000619	0.000619	0.000206	1.04	0.42	1.89
	S*L	3	0.003944	0.003944	0.001315	6.65	0.01	12.04
	S*C	3	0.001447	0.001447	0.000482	2.44	0.13	4.42
	L*C	9	0.002486	0.002486	0.000276	1.4	0.31	7.59
	Error	9	0.001778	0.001778	0.000198			5.43
	Total	31	0.03277					100.00

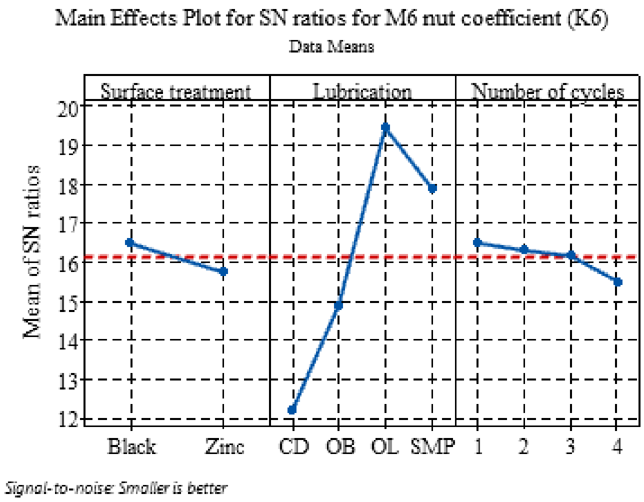

Figure 7. MEP for S/N ratios of the nut coefficient for the M6 bolt size

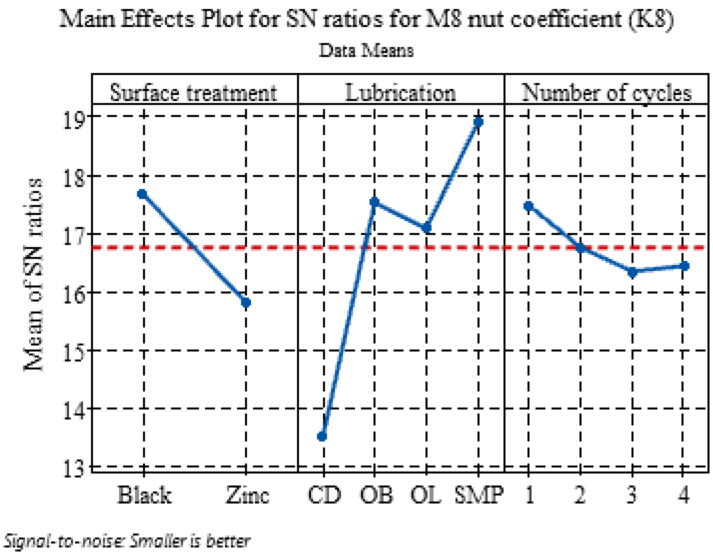

Figure 8. MEP for S/N ratios of the nut coefficient for the M8 bolt size

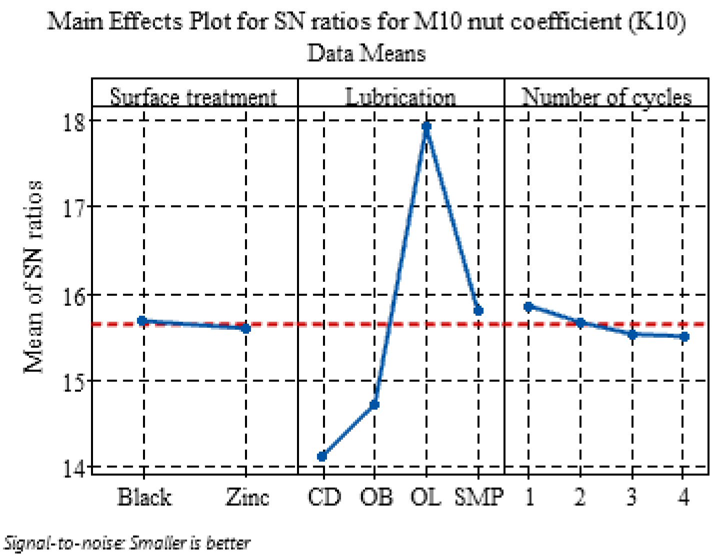

Figure 9. MEP for S/N ratios of the nut coefficient for the M10 bolt size

5. Optical profilometry case study

In general, quantifying the surface texture and roughness is covered in ISO 21920-2:2021. Optical profilometry is one of the methods commonly used to quantify and analyze surface characteristics, and it can fulfill the requirements of ISO 21920-2:2021 [65]. During this, the surface roughness and the wear pattern were monitored on the tightened elment (the turning head) of the nut-bearing contact surface using optical profilometry Keyence (Keyence Corp., Osaka, Japan) instruments.

In this part of the investigation, the Keyence VR-5000 confocal profilometry was employed to measure a three-dimensional profile for the nut-bearing area before and after the tightening experiment, see **Figure 10**.

The reason behind taking this area is that the state of this contact area can have an influence of up to 50% on the generated preload [2]. For more insight into evaluating the contribution of the lubrication on the clamping force, the clean, dry, and oiled lubrication surface roughnesses, and wear patterns were examined for the black coating surface treatment.

5.1. Roughness measurements

The measurements of the surface roughness were recorded for the fresh bearing surface and after the fourth tightening process. **Table 6** shows the Surface Roughness Average (Sa) and Maximum Peak-to-Valley Height (Sz) for the M6 joint size, and **Figure 11** shows the surface texture profile for the three surfaces.

Table 6. Bearing surface roughness measurement

Parameter	Surface roughness (µm)		
	Fresh surface before tightening	After 4th tightening	
		Clean and Dry Lubricant	Oil Lubricant
S_a	41	54	29.5
S_Z	183	477	198.5

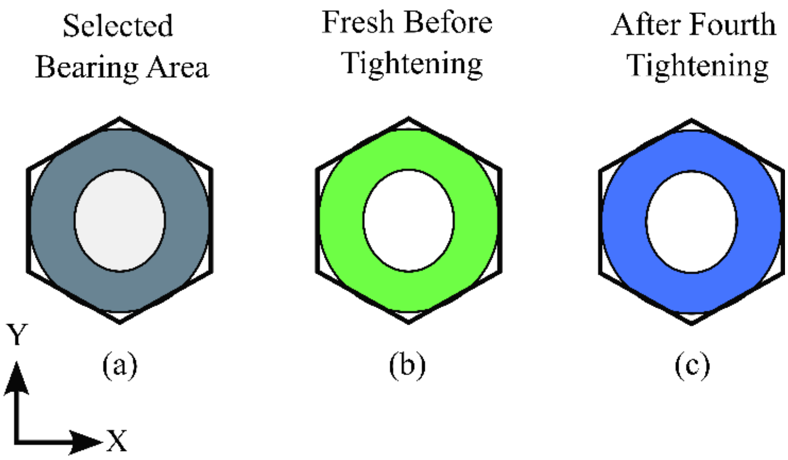

Figure 10. Evaluated nut-bearing area using profilometry measurement: (a) selected bearing surface area, (b) fresh surface before the tightening process, and (c) surface after the fourth tightening

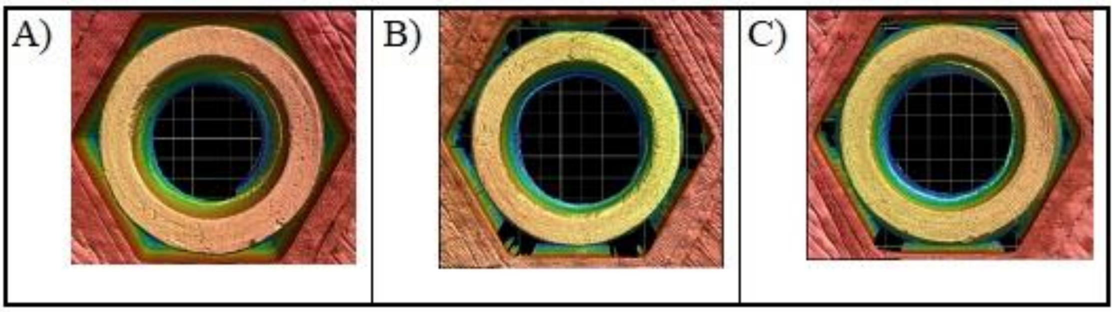

Figure 11. Surface texture profile: A) fresh surface before tightening. B) clean and dry lubricant surface after the 4th tightening, and C) oil lubricant surface after the 4th tightening

Noteworthy distinctions were observed among the lubricant types, which may have implications for product performance and quality.

Firstly, concerning Sa values, it was found that the oiled lubricant condition resulted in the smoothest surfaces, with an average roughness of 29.5 µm. This outcome suggests that the application of oil lubricant contributes to the attainment of a smoother surface finish, which can be advantageous in cases where reduced friction and wear are considered critical [66]. In contrast, the clean and dry lubricant conditions displayed the roughest surfaces among the tested lubricants, with a Sa value of 54 µm. This higher Sa value indicates a rougher surface texture, potentially leading to increased friction and wear in applications where surface smoothness is deemed crucial. These findings not only shed light on the surface quality but also provided compelling evidence for why certain lubricants are more effective than others in influencing the nut coefficient.

The utilization of an oiled lubricant led to a remarkable reduction in the nut coefficient, with surface roughness measurements offering vital insights into this phenomenon.

One significant factor contributing to this decrease is the "smoothing effect." Sa measurements revealed that the oiled lubricant condition produced the smoothest surfaces, boasting an average roughness of 29.5 µm. This substantial reduction in surface roughness highlights the oiled lubricant's capability to smooth out surface irregularities, thereby establishing an environment conducive to reduced friction. The smoother surface facilitates more effortless motion, necessitating lower torque and, consequently, yielding a decreased nut coefficient. Another key contributor to the decreased nut coefficient is the "surface protection" offered by the oiled lubricant. The reduction in surface roughness, as indicated by Sa, underscores the protective nature of the oiled lubricant. It forms a protective barrier that shields both the nut and mating surfaces from wear and abrasion. By minimizing the potential for surface damage, the oiled lubricant upholds the structural integrity of the components, averting increases in the nut coefficient resulting from surface roughness-induced wear over time.

Conversely, employing a dry lubricant led to an elevation in the nut coefficient, and our surface roughness measurements help elucidate the reasons behind this trend. The "surface roughness impact" plays a pivotal role in this increase. Sa measurements illustrated that the clean and dry lubricant condition exhibited the highest average roughness, measuring 54 µm. This heightened roughness suggests the presence of surface irregularities, culminating in a rougher texture. The absence of a lubricating film in dry lubricants allows for metal-to-metal contact, amplifying friction and, consequently, elevating the nut coefficient. Additionally, the "abrasive characteristics" of certain dry lubricants deserve attention. Some dry lubricants incorporate solid particles that can function as abrasives, leading to increased surface wear. This abrasive action, consistent with the higher Sa values observed, contributes to surface irregularities and roughness, further intensifying the nut coefficient. Furthermore, the "temperature-related effects" associated with dry lubricants should not be overlooked. Clean and dry lubricants tend to generate heat during frictional contact due to the absence of effective temperature control mechanisms. This heat generation can exacerbate friction, culminating in higher coefficients of friction, as corroborated by our surface roughness measurements.

Highlights

- The lubrication parameter was the most significant parameter in the three bolt sizes.
- The variation of the nut coefficient is predominantly impacted by the different lubrication levels considered in the analysis.
- The interaction between the surface treatment and the lubrication plays a significant role in calculating the nut coefficient in the three bolt sizes.
- Lubricant type dictates surface roughness: oiled lubricants yield smoother surfaces, reducing friction, while dry lubricants induce rougher surfaces and increased friction.

Conclusion

Our study, anchored in robust statistical methodologies employing ANOVA, delved into the intricate determinants of the nut coefficient across M6, M8, and M10 bolt sizes. The meticulous imposition of a 95% confidence level and a p-value threshold of less than 0.05 underscored the methodological precision of our investigation, and the key findings can be as follows:

- M6 Bolt Size:
  - Lubrication emerged as the predominant determinant (78.79% contribution).
  - Subdued impacts from surface treatment and cycles.
  - Noteworthy interaction between surface treatment and lubrication (10.75%).
- M8 Bolt Size:
  - Lubrication showcased paramount importance (54.44% contribution).
  - Commendable contribution from surface treatment (nearing 11.5%).
- M10 Bolt Size:
  - Lubrication was conclusively established as the dominant influence (67.97% contribution).
  - Minimal effects from surface treatment and cycles.
  - Notable interaction between surface treatment and lubrication (12.04%).
- Surface Roughness Measurements:
  - Sa and Sz measurements provided mechanistic insights.
  - Oiled lubricants consistently yielded smoother surfaces, indicating reduced friction and wear.
  - Dry lubricants resulted in rougher surfaces, signifying heightened friction and wear.

In summation, our comprehensive investigation furnishes pivotal insights into the determinants of the nut coefficient across a spectrum of bolt sizes. The indisputable primacy of lubrication, the nuanced role of surface treatment, and the subtle yet significant interplay between these factors have been meticulously elucidated. The incorporation of surface roughness measurements buttresses our findings with tangible empirical support.

These findings are poised to yield profound implications in engineering contexts where precise control over the nut coefficient is of paramount significance, thereby facilitating more informed decision-making in the realms of bolted joint design and assembly.[1].

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