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Effect of different underhead shot-peening and lubrication conditions on high-strength screws undergoing multiple tightenings

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ABSTRACT

This study investigates the effect of shot-peening on the bearing friction coefficient of 42CrMoV grade 14.9 screws. An experimental campaign was conducted on a tribological testing rig, investigating the combined effects of shot peening treatments, lubrication conditions, and number of tightenings on the frictional coefficient. A first set of tests was performed, considering the same shot-peening conditions as in a previous study to highlight the role of different material. A second campaign was carried out, adjusting the process parameters to enhance the tribological response. Small shots and high-impact energy are suitable for tightening with lubricant, whereas, in dry conditions, larger shots and lower-impact energy lead to particularly low friction coefficients that are well aligned to those achievable when using lubricants.

1. Introduction

High-strength threaded joints are of a paramount importance in several machines, particularly in the transportation field where a high strength-to-weight ratio is needed [1,2]. A proper preloading force of the fastener is critical to ensure a reliable connection between parts. This is especially relevant in dynamic load and under vibrations, which can lead to joint failure [3,4].

In common engineering practice, the clamping force F is related to the tightening torque T by Eq. (1) [5]:

$$T = F\,K\,D \tag{1}$$

where D is the nominal diameter of the bolt and K is a constant named *nut factor* or *torque coefficient*, a constant provided by the bolt manufacturer, as prescribed by international standards [6,7]. The nut factor accounts for torque dissipations upon the preloading of threaded joints due to friction phenomena. Motosh proposed a more detailed formula, which is provided in Eq. (2) and isolates the different sources of friction. In this formula, the tightening torque T is the sum of three different contributions: T_p, T_t and T_b.

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

T_p is the pitch torque, i.e. the portion of the total torque determining the clamping force, and can be calculated as shown in Eq. (3)

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

where p is the pitch of the bolt.

T_t is the thread friction torque, the torque required to overcome the friction between the threads of the screw and those of the nut. This coefficient can be calculated using Eq. (4):

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

where μ_t is the friction coefficient between threads, β is half of the thread profile angle, and R_t is the effective radius of threads. An accurate definition and estimation of the radius R_t must take the actual distribution of pressure between male and female threads [8] into account.

Finally, T_b is the bearing torque, the torque required to overcome the friction between the head of the bolt (or the nut) and the underlying surface of the assembled parts. The value of T_b can be calculated using Eq. (5)

$$T_b = \mu_b R_b F \tag{5}$$

where μ_b is the friction coefficient between the surfaces in contact, and R_b is the effective bearing radius. The actual value of R_b, as in the case of R_t, depends on the specific pressure distribution at the interface between the screw underhead and the part [9].

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List of acronyms

ANOVA	Analysis Of Variance
DOE	Design Of Experiment
DOF	Degrees Of Freedom
UTS	Ultimate Tensile Strength

According to Zou et al. [9], the bearing torque accounts for almost 50% of the total torque T, while T_p is only 10% of T. This outcome highlights the relevant role of the bearing friction, which is universally regarded as the main influential factor affecting the achievable clamping force obtained during assembly for a given tightening torque [10]. Accordingly, a number of studies focused on the effect of different materials, substrates, and processing conditions on the bearing torque [11–16]. The value of T_b is highly affected by lubrication, which contributes to lower the actual friction coefficient at the bearing interface [17,18]. These studies are typically carried out by experimental tests that measure the input tightening torque, the clamping force, and the thread [19] or the bearing friction torque. The literature in this field highlights that the bearing torque may significantly differ over multiple retightenings [20]. At each tightening cycle, the interaction between the asperities of the two surfaces triggers a modification in the surface roughness, which affects the friction coefficient at the interface [21,22]. As discussed by Croccolo et al. [23], the evolution of T_b over retightenings strongly depends on the involved materials and lubricating conditions. These potential variables result in uncertainties regarding the actual clamping force obtained for the predetermined tightening torque. Insufficient or excessive axial forces may be produced along the axis of the screw, which increases the risk of failure of the threaded joint [4].

The frictional characteristics of the bearing are also profoundly affected by treatments of the surfaces in contact, as previously discussed in studies [24]. Shot-peening, in particular, has been found to be a promising treatment for reducing the friction coefficient of steel surfaces. This is due to the creation of dimples on the surface resulting from the impact of shots, which can reduce the actual contact area and limit wear phenomena, in addition to the residual compressive stress and surface morphology [25–27].

However, research on the effects of shot-peening on multiple tightenings in threaded joints is still limited, with only one study conducted by Croccolo et al. [28] on grade 13.9 36NiCrMo threaded joints. They showed that shot-peening can reduce the influence of multiple tightenings on the bearing friction coefficient when lubricated. However, significant variations in μ_b were still observed in dry conditions.

This study explores the effects of shot-peening on the tightening torque of high resistant threaded joints, specifically 42CrMoV screws. A first experimental campaign replicates the shot-peening treatments proposed by [28] to observe the influence of the material. A second campaign is conducted based on the results of the first tests, using different shot-peening conditions, with particular reference to shot size, material, and Almen intensity, accounting for impact severity. These process parameters are specifically selected to reduce bearing friction coefficient and its variations in dry conditions.

2. Materials and methods

2.1. Screw design and manufacturing

The experimental tests were conducted on M10x1 bolts of grade 14.9, which were made of 42CrMoV alloy. These are high-resistant commercial screws intended for advanced applications in the automotive field. The nominal pitch of the screw was 1 mm. A schematic drawing of the screw used for testing is depicted in Fig. 1.

The dimensions of the screw underhead can be observed in Fig. 1. Specifically, the external diameters measures 13.5 mm. The internal diameter of the underhead, namely the diameter of the hole, is equal to 11 mm. These identical dimensions also apply to the nut.

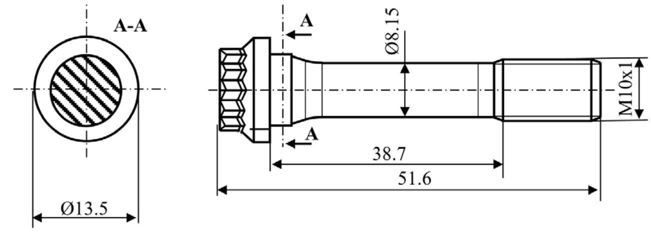

Fig. 1. A sketch of the screw used for testing (dimensions are in mm).

The bolts were manufactured, following a standard working cycle, which involved cold forcing, quenching and tempering, turning, and thread rolling. At the end of these treatments, the screw hardness was measured and proved to be 47 HRC. The material Ultimate Tensile Strength (UTS) ranges from 1400 MPa to 1450 MPa, and its yield strength and minimum elongation at fracture are 1250 MPa and 11%, respectively. The average roughness Ra at the underhead after turning is 0.4 μm.

During shot-peening treatments, the thread was protected to prevent any damage to its profile and, therefore, was not shot-peened.

2.2. Tightening tests

The tightening tests were conducted in accordance with international standard ISO 16047 [29] using a Model 201 tribological testing rig manufactured by TesT GmbH (Erkrath, Nordrhein-Westfalen, Germany) and shown in Fig. 2.

Fig. 3 shows a scheme of the testing rig.

As it can be observed in Fig. 3, the screw is bolted on the bearing-plate by means of a nut. The test-bearing-plate, which is labeled in Fig. 2, is manufactured complying with the recommendations in [6] with reference to type HH. It is made of carbon steel, with 56 to 58 HRC hardness and 0.3 to 0.4 μm Ra roughness. Plate thickness is 2.5 mm and it contains not-chamfered holes with 11 mm diameter. A constraining device avoids the rotation of the nut. The bearing plate is integral with the measuring head, which comprises an axial and a ring torsional load cells. The axial load cell measures the axial force F, while the torsional cell measures the torque T_b transmitted at the bearing. The screw is fastened by means of a spindle equipped with an angular position sensor and another ring torsional load cell that allows for measuring the tightening torque T.

As the measuring head reads the axial load F and the bearing torque T_b, the coefficient of friction μ_b can be calculated, according to Eq. (5), as in Eq. (6).

$$\mu_b = \frac{T_b}{R_b F} \tag{6}$$

Fig. 4a and Fig. 4b provide representative plots depicting the relationship between the applied torque T and, respectively, the bearing coefficient of friction μ_b and the bearing torque T_b.

As illustrated in Fig. 4a, μ_b keeps steady after an initial transient period. In this phase, an almost linear relation between T and T_b can be observed in Fig. 4b. The μ_b value measured at the maximum torque is utilized in the subsequent analyses. This coefficient is particularly significant for this study since it is directly affected by the surface treatment of the bolt underhead

As stated in Section 1, the lubricating conditions of the bearing assembly have a significant impact on its tribological behavior. To quantify this influence, all threaded joints were tested under both dry and lubricated conditions. Prior to testing, all screws and nuts were cleaned in a ultrasonic bath. For lubricated screws, a commercial MoS_2

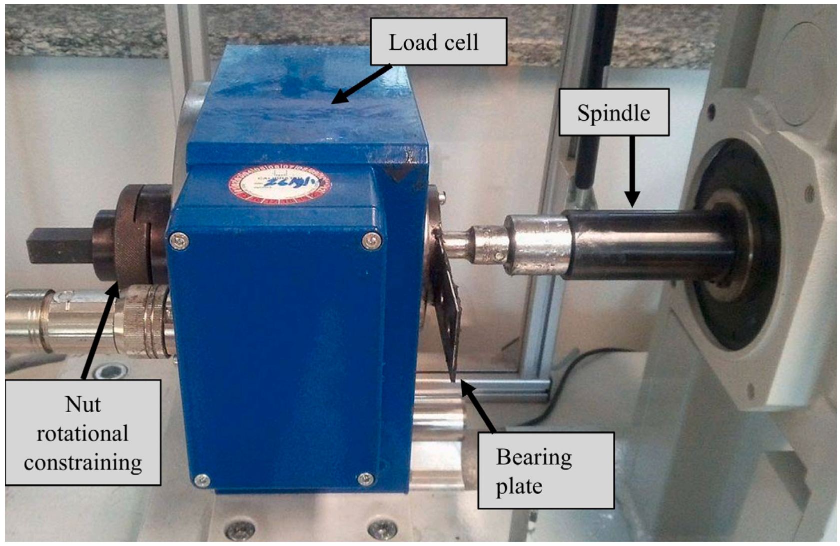

Fig. 2. Tribological testing rig used for testing.

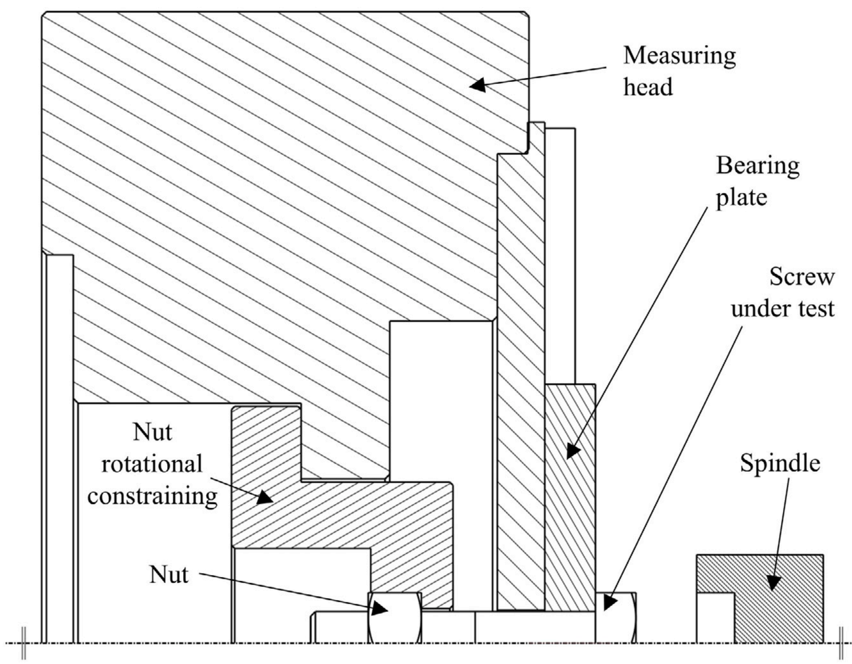

Fig. 3. Working scheme of the testing rig.

lithium grease was applied to the entire screw. Three cycles of tightening and loosening were performed at a rotational speed of 25 rpm for each combination of surface treatment and lubrication to monitor changes of μ_b. In the case of lubricated screws, grease was applied at the beginning of the trial only, i.e, was not replaced upon every tightening–untightening cycle. A full-factorial Design Of Experiment (DOE) was conducted to combine shot-peening treatment, bearing lubrication, and the number of re-tightenings. Each experimental point was replicated five times.

2.3. Preliminary yield tests

Preliminary destructive tests were performed to determine the tightening torque T_y required to yield the screws, under both dry and lubricated conditions. Each test was replicated five times to ensure the validity of the results. The tightening torque used for subsequent tests (T_t) was set at 0.75 T_y, as suggested by Standard [29]. Fastening and unfastening were performed at the same rotational speed of 25 rpm.

Fig. 5 displays representative torque/force curves obtained in the preliminary destructive tests in dry and lubricated conditions. Positive values of T correspond to the tightening phase, whereas negative values correspond to the unscrewing phase.

It is noteworthy that, during the first phase of tightening, the curve exhibits an almost linear correlation between the axial force on the screw and the tightening torque, as it is highlighted in the sketched diagram. This region corresponds to the elastic deformation of the material. Based on the results obtained from these preliminary tests, the recommended tightening torque T_t was set at 85 Nm under dry conditions and 70 Nm when applying lubricant.

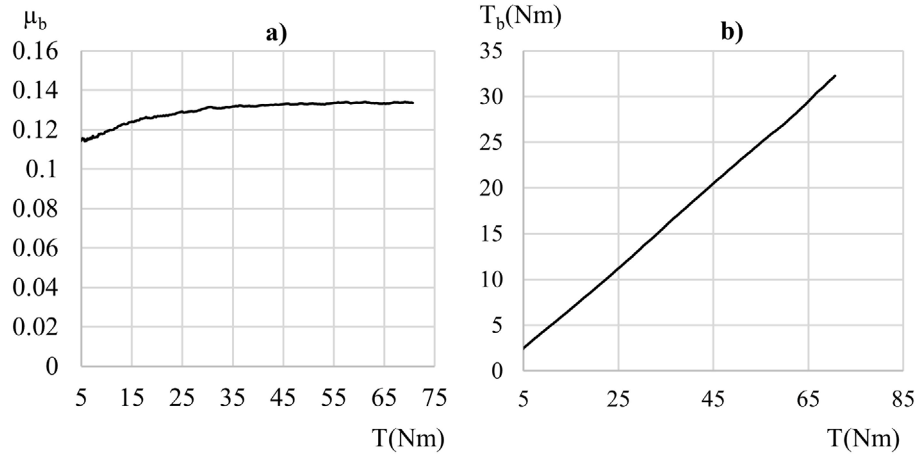

Fig. 4. Representative curves of (a) the bearing coefficient of friction μ_b and (b) the bearing torque T_b during tightening.

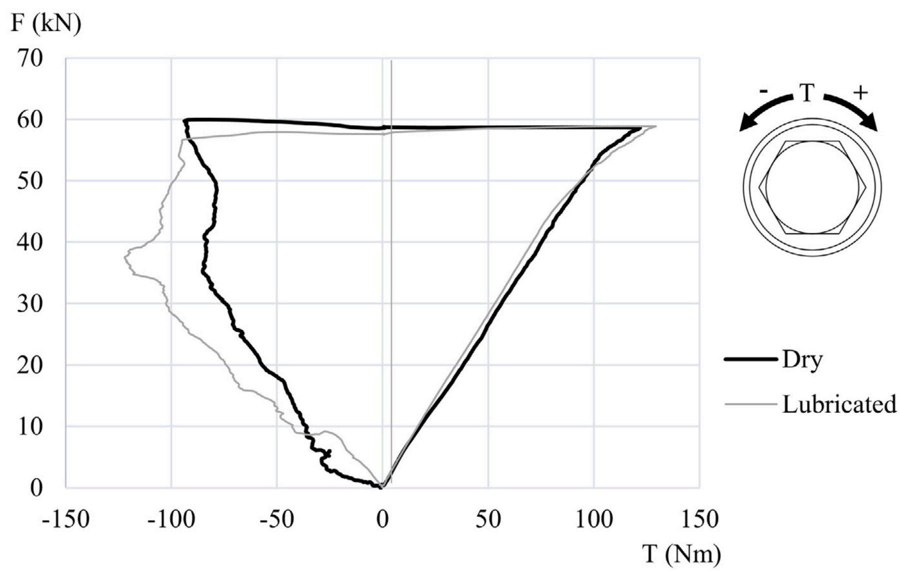

Fig. 5. Typical yield test curve. T is positive for clockwise rotations (tightening) and negative for counterclockwise rotations (untightening).

3. Data analysis

The data collected by experimental data were analyzed through statistical methods. Specifically, one-way and two-way ANOVA were used to investigate the influence of the different experimental factors, namely shot-peening treatments and lubrication, on the bearing friction coefficient μ_b.

One-way ANOVA clusters the experimental data into sets characterized by the same level of the investigated factor. Then, a test is performed on the null hypothesis that the investigated factor does not affect the output and the observed differences for different factor levels are only due to chance. Whether the null hypothesis is rejected, it is possible to conclude that the influence of the investigated factor on the output is statistically significant. Two-way ANOVA allows for the extension of this analysis to investigate the effects of two variables [30].

The most common approach to quantify the significance of a variable is the *p*-value. The *p*-value indicates the probability of failing when asserting the input significantly affects the output. Thus, the lower the *p*-value, the more evidence against the null hypotheses arise from ANOVA. The threshold for this value is usually set equal to 0.05. Therefore, if the *p*-value of an experimental factor is < 0.05, it is possible to conclude that the investigated factor does significantly affect the output variable [31].

Many calculation tools are available to perform ANOVA tests. In this study, the software STATA/SE 18.0 by StataCorp LLC ©was used.

4. Shot-peened threaded joints and experimental tests

4.1. Shot-peening parameters

Before the first experimental campaign the screws underwent two distinct shot-peening treatments, whose process parameters are reported in Table 1. In both treatments, a 200% coverage was applied [28]. Additionally, a set of non-treated bolts were included in the experiment as a reference for comparison purposes.

4.2. Surface morphology

Fig. 6 shows a microscopic picture of the surface of screws of the surfaces after shot-peening. The roughness Ra at the underhead surfaces and the average size of observed dimples are summarized in Table 2.

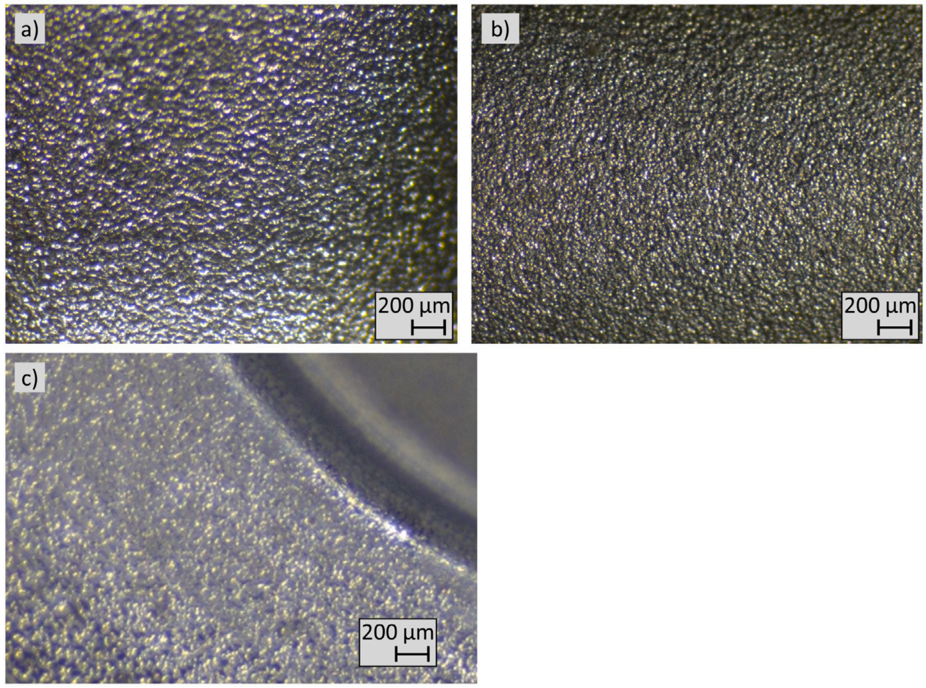

Fig. 6. Morphology of the surface of screws that were shot-peened with (a) Z100 10-12N, (b) UFS70 10-12N parameters and (c) example of underhead (Z100 10-12N).

Table 1
Details of the shot-peening cycles tested in the first experimental set.

Label	Treatment	Shots	Shot diameter (µm)	Coverage (%)	Intensity (Almen N)
A	Z100 10-12N	Ceramic	100	200%	10–12
B	UFS70 10-12N	Steel	40÷70	200%	10–12

Table 2
Surface roughness and dimple size of screws shot-peened with treatments A and B.

Label	Treatment	Ra (µm)	Average dimple size (µm)
A	Z100 10–12N	1.3 ÷ 1.6	83.0 ± 8.9
B	UFS70 10–12N	2.0 ÷ 2.1	60.8 ± 13.3

Table 3
Bearing friction coefficient (μ_b) at multiple tightening (Set 1).

Treatment	Lubrication	Tightening 1	Tightening 2	Tightening 3
Not peened	Dry	0.150 ± 0.019	0.203 ± 0.026	0.289 ± 0.060
	Greased	0.201 ± 0.003	0.185 ± 0.006	0.152 ± 0.007
Z100 10-12N	Dry	0.118 ± 0.009	0.187 ± 0.043	0.242 ± 0.027
	Greased	0.125 ± 0.010	0.127 ± 0.019	0.127 ± 0.016
UFS70 10-12N	Dry	0.111 ± 0.008	0.145 ± 0.038	0.177 ± 0.063
	Greased	0.116 ± 0.002	0.115 ± 0.018	0.099 ± 0.004

Table 4
Average values of μ_b over multiple tightenings (Set 1).

Treatment	Dry	Lubricated
Not peened	0.214	0.179
Z100 10-12N	0.183	0.127
UFS70 10-12N	0.145	0.110

Table 5
p-value of the number of tightening in one-way ANOVA (Set 1).

Treatment	Dry	Lubricated
Not peened	1.05×10^{-3}	5.78×10^{-8}
Z100 10-12N	2.84×10^{-4}	9.79×10^{-1}
UFS70 10-12N	1.35×10^{-1}	8.30×10^{-2}

4.3. Tribological results and discussion

Table 3 presents the average values of the bearing coefficient of friction (μ_b) for dry and greased screws in the first set. These values are also depicted in the bar chart of Fig. 7.

It is evident from the results in Table 3 and Fig. 7 that both shot-peening treatments result in a reduction of the bearing coefficient of friction for all the investigated combinations of tightenings and lubrication conditions. The influence of the shot-peening treatment was also confirmed by a two-way ANOVA. Specifically, the average values of μ_b over all the tightening cycles are summarized in Table 4.

The results in Table 4 demonstrate that the Z100 10-12N treatment entails an average reduction of µb by 14.7% and 29.4% in dry and lubricated conditions, respectively. The benefits are even more evident in the case of the UFS70 1012N peening, which leads to a decrease of μ_b by 32.5% in dry conditions and 38.5% when lubricant is applied.

The tool of ANOVA was utilized to investigate the effect of each factor on the bearing coefficient of friction. The surface treatment and lubrication were considered as external discrete factors, and a single-way ANOVA was carried out for each combination of these parameters to determine the significance of the number of tightenings. The results of ANOVA in terms of p-values are summarized in Table 5. The corresponding main effects plots are presented in Fig. 8 to highlight the trend of the bearing coefficient in each case.

The findings in Table 5 indicate that the number of tightenings has a strong effect on μ_b for non-treated screws under dry conditions (p-value $= 1.05 \times 10^{-3}$). Fig. 8 shows that the initial value of μ_b is relatively low, namely around 0.15. This can be explained considering the low value of roughness on this surface (Ra = 0.4 µm). During the subsequent untightenings and tightenings, spalling particles appear on the surface, and their abrasive action tends to exacerbate wear. Consequently, there is an observed increase in the coefficient of friction μ_b, as highlighted in Fig. 8. This finding is consistent with previous studies [32].

A similar trend is observed in Fig. 8 for screws subjected to Z100 10-12N shot-peening and operating under dry conditions. In this scenario,

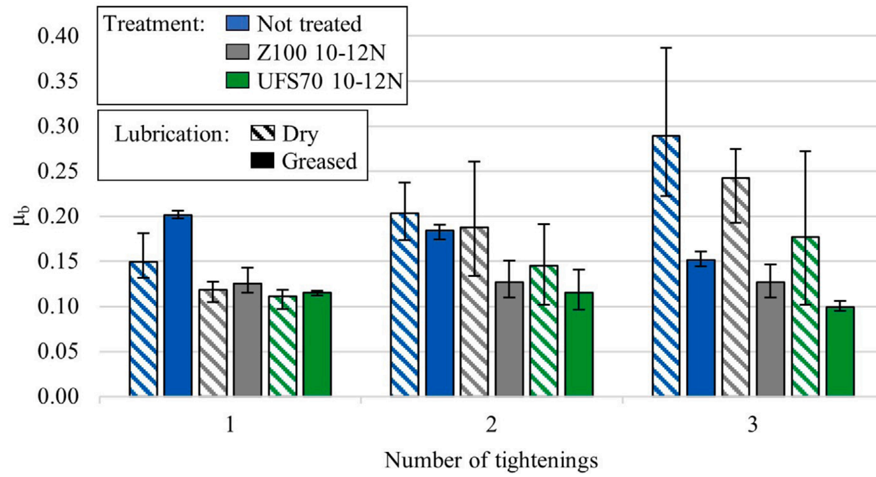

Fig. 7. Bearing friction coefficient (μ_b) at multiple tightening in different lubrication conditions (Set 1). The error bars show the maximum and minimum values obtained within experimental tests.

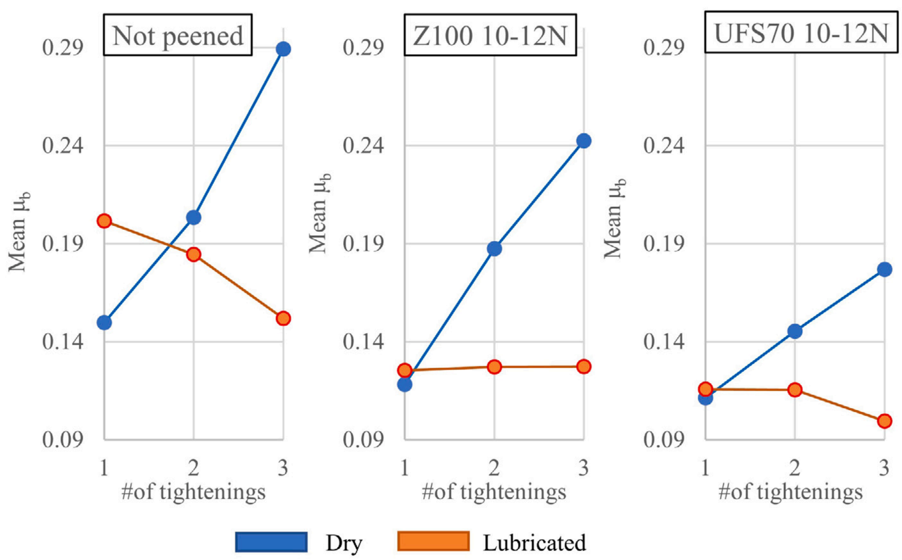

Fig. 8. Main effect plot of number of tightening vs μ_b (Set 1).

the *p*-value of 2.84×10^{-4} reported in Table 5 indicates a significant impact of the number of tightenings on the friction coefficient [30,31].

Surprisingly, the results of the ANOVA suggest that screws treated with UFS70 10-12N are not affected by the number of tightenings, despite the increasing trend plotted in Fig. 8. However, it is worth mentioning the increasing rate is much lower than that obtained for the other treatments. This singularity may be due to the large scattering of data around the mean value, as it is highlighted by the variation intervals in Fig. 7. In addition, the mean values vary within a limited range.

Therefore, even though treatments Z100 10-12N and UFS70 10-12N lead to a beneficial overall reduction of the friction coefficient, there is still variation in the coefficient of friction among multiple tightening cycles. This is consistent with previous findings [28] for grade 13.9 36NiCrMo threaded joints. It can be concluded that material change only does not allow to overcome the limitations identified in that study.

The increase in coefficient of friction can be explained considering surface wear and spoiling induced by the three tightening–untightening cycles, as highlighted in Fig. 9. This phenomenon is promoted by the high roughness of the surface after shot peening, as reported in Table 1, which causes severe wear of the bearing. Thus, high roughness is, in turn, presumably related to the small size of the peening induced dimples reported in the same table.

Regarding lubricated tests, it is evident from Table 5 that the *p*-value resulting from one-way ANOVA is under the threshold value of 0.05. This finding indicates that the number of tightening cycles remains statistically significant for non-peened screws with lubrication.

Interestingly, the coefficient of friction at the first tightening appears to be higher than that observed in dry conditions. A possible reason for this phenomenon is that during the first tightening, the grease, which is manually applied on screws, must be spread to reach a uniform height. Over the next tightening and untightening cycles, the lubricant reaches the optimal height with a consequent decrease in the coefficient of friction.

Conversely, for treated screws, the shot peening treatments result in a nearly flat trend and *p*-values exceeding 0.05. Therefore, it can be concluded that the number of tightening cycles does not affect the bearing friction coefficient for treated screws.

This finding is consistent with previous research [28] and may be due to a hydrostatic effect arising from lubricant being trapped in the dimples left by shot-peening.

It can also be highlighted that the coefficient of friction at the first tightening is approximately the same in dry and lubricated conditions.

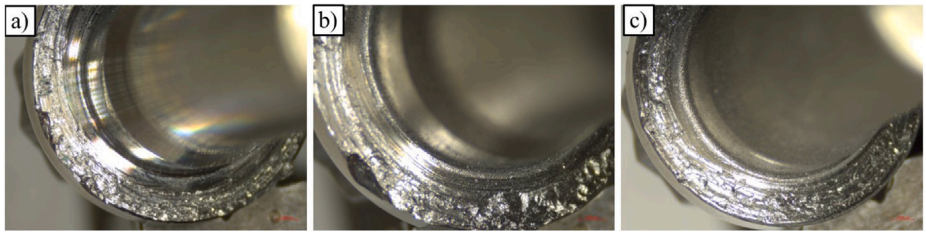

Fig. 9. Pictures of the screw underhead at the end of dry tightening cycles. (a) Non-peened, (b) Z100 10-12N and (c) UFS70 10-12N.

Table 6
Details of the shot-peening cycles tested in the second experimental set.

Label	Treatment	Shots	Shot diameter (μm)	Coverage (%)	Intensity (Almen N)	Ra (μm)
C	Z100 4N	Ceramic	100	200%	4	0.5 ÷ 1.0
D	S110 8.8N	Steel	280	200%	8.8	0.5 ÷ 1.0

Table 7
Surface roughness and dimple size of screws shot-peened with treatments A and B.

Label	Treatment	Ra (μm)	Average dimple size (μm)
C	Z100 4N	0.5 ÷ 1.0	77.3 ± 4.6
D	S110 8.8N	0.5 ÷ 1.0	153.1 ± 15.4

5. Shot-peening parameters revisited and a new experimental campaign

5.1. New shot-peening parameters

The parameters of the shot-peening treatment were redefined based on the results presented in Section 4. Specifically, since the main detrimental effects observed in the first experimental campaign were attributed to a generally small dimensions of dimples, and, especially, to the induced not negligible roughness, larger shots and lower impact energies were used. As a result, the shot-peening treatments reported in Table 6 were used. Treatment Z100 4N was derived from treatment Z100 10-12N (Table 1) by reducing the intensity of peening, leaving shot material and diameter unchanged, whereas treatment S110 8.8N was obtained by simultaneously increasing shot diameter and decreasing intensity with reference to treatment UFS70 10-12N. These parameters were adjusted in order to achieve a target roughness ranging between 0.5 and 1 μm.

The second campaign was also arranged as a full-factorial DOE with five replications, varying lubrication conditions and the number of tightenings as in the first campaign. As a result, additional 60 tightening–untightening tests were carried out.

5.2. Morphology of the treated surface

Micrographic pictures of screws treated with shot peening Z100 4N and S100 8.8N are shown in Fig. 10a and Fig. 10b, respectively. The measured values of surface roughness and the average dimple size are reported in Table 7.

The results in Table 7 shot peening parameters result in a different texture of the treated surface. Specifically, the lower impact energy of treatment C with respect to treatment A leads to a barely unchanged dimple size. Nevertheless, a reduced dimple depth results in a lower surface roughness, thus meeting the target. In the case of treatment D, the higher diameter of shots allows for impact energy redistribution on a larger surface, again reducing the depth of dimples. This is also confirmed by the higher average size of dimples reported in Table 7.

Table 8
Bearing friction coefficient (μ_b) at multiple tightening (Set 2).

Treatment	Lubrication	Tightening 1	Tightening 2	Tightening 3
Not peened	Dry	0.150 ± 0.019	0.203 ± 0.026	0.289 ± 0.060
	Greased	0.201 ± 0.003	0.185 ± 0.006	0.152 ± 0.007
Z100 4N	Dry	0.118 ± 0.005	0.119 ± 0.013	0.113 ± 0.010
	Greased	0.149 ± 0.001	0.135 ± 0.005	0.129 ± 0.001
S110 8.8N	Dry	0.132 ± 0.005	0.127 ± 0.009	0.120 ± 0.007
	Greased	0.165 ± 0.013	0.139 ± 0.011	0.128 ± 0.015

Table 9
Average values of μ_b over multiple tightenings (Set 2).

Treatment	Dry	Lubricated
Not peened	0.214	0.179
Z100 10-12N	0.117	0.138
UFS70 10-12N	0.126	0.144

Table 10
p-value of the number of tightening in one-way ANOVA (Set 2).

Treatment	Dry	Lubricated
Not peened	1.05×10^{-3}	5.78×10^{-8}
Z100 4N	6.47×10^{-1}	2.91×10^{-6}
S110 8.8N	8.85×10^{-2}	6.39×10^{-3}

5.3. Tribological results and discussion with new shot-peening parameters

The average values of μ_b obtained in the framework of the second experimental campaign are summarized in Table 8 and presented in Fig. 11. The effectiveness of the shot peening treatments tagged as C and D was also confirmed by a preliminary two-way ANOVA. The results indicate that these treatments (detailed in Table 6) also reduce the bearing friction coefficient, if compared to that of non-treated screws, as confirmed by the average values in Table 9.

Specifically, the average coefficient of friction was reduced by 45.4% and 23.2% in dry and lubricated conditions, respectively, for Z100 4N. As for S110 8.8N, the reduction was 41.0% and 19.7% under dry and lubricated conditions, respectively. By observing Fig. 11, it can be noticed that such an advantage is especially evident at the third tightening in dry conditions.

To investigate the influence of multiple fastening cycles on the screws belonging to each set, the results have been analyzed via one-way ANOVA, as presented in Section 4.3. The *p*-values obtained through these analyses are summarized in Table 10.

The results in Fig. 11 show that the new treatments lead to a sharp reduction in the coefficient of friction at the first tightening cycle. This result is consistent with the discussion in Section 4, as these treatments were optimized to achieve a proper finishing of the surface (see Fig. 10).

The ANOVA results show that for both treatments C and D, the *p*-value in dry conditions is higher than 0.05, indicating that the number of tightenings no longer affects the bearing friction coefficient of screws, thus taking advantage of the improved parameters. This

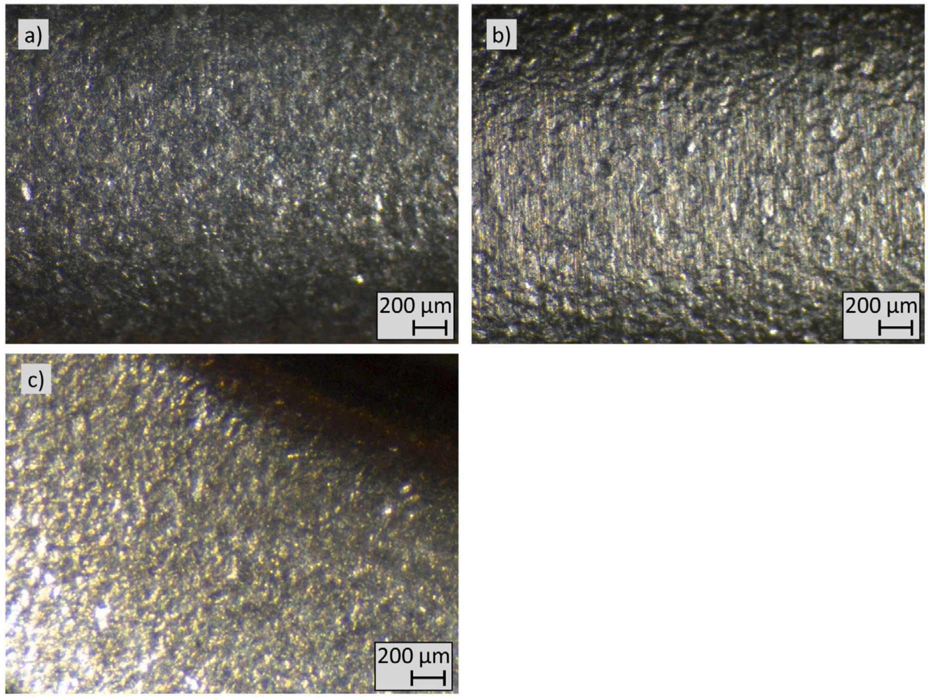

Fig. 10. Morphology of the surface of screws shot-peened with (a) Z100 4N and (b) S110 8.8N and (c) example of underhead (S110 8.8N).

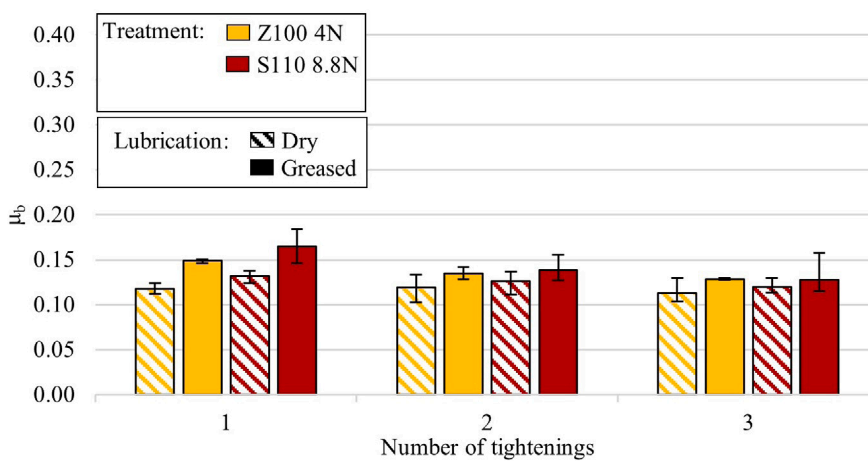

Fig. 11. Bearing friction coefficient (μ_b) at multiple tightening in different lubrication conditions (Set 2). The error bars show the maximum and minimum values obtained within experimental tests.

outcome is also highlighted by the main effect plots of Fig. 12, which show a nearly-constant trend of μ_b over fastening cycles. Therefore, the actual coefficient of friction, and, in turn, the achievable axial preload are made well predictable than for non-treated screws.

This result is of primary relevance, as it demonstrates that shot peening treatments C and D, whose optimized parameters are summarized in Table 6, make it possible to overcome the main limitation of the previously investigated ones (tagged as A and B in Table 1). Such an improvement is surely related the lower roughness of the surfaces, as reported in Table 7, as an effect of the adoption of larger shots and lower impact intensity. This reduced roughness and improved surface texture leads to a reduction of wear phenomena affecting the underhead surface. This outcome is also confirmed by the observation of the underhead surfaces, shown in Fig. 13.

By comparing Figs. 9 and 13, it can be pointed out that the modified shot-peening treatments dramatically reduce damaging of the bearing surface. On the other hand, μ_b significantly depends on the number of tightenings when lubrication is applied, as shown in both Table 10 and Fig. 12.

In this case, the coefficient in lubricated conditions appears to be higher than that in dry conditions. As far as the first tightening is concerned, the same considerations presented in Section 4 can be applied. On the other hand, the differences at the second and third cycles range between 0.01 and 0.02, making them statistically insignificant, especially considering the scattering of data.

Consistently with the outcome of the first campaign, the friction coefficient exhibits a decreasing trend, following lubricant spread over the surface that is also promoted by the peening-induced dimples. The achievable friction values upon the three re-tightenings are all very close to those of the campaign involving treatments A and B. It is worth highlighting that the decreasing trend of μb over tightenings yields a generally beneficial increase of the preload force that can prevent screw self-loosening [33,34].

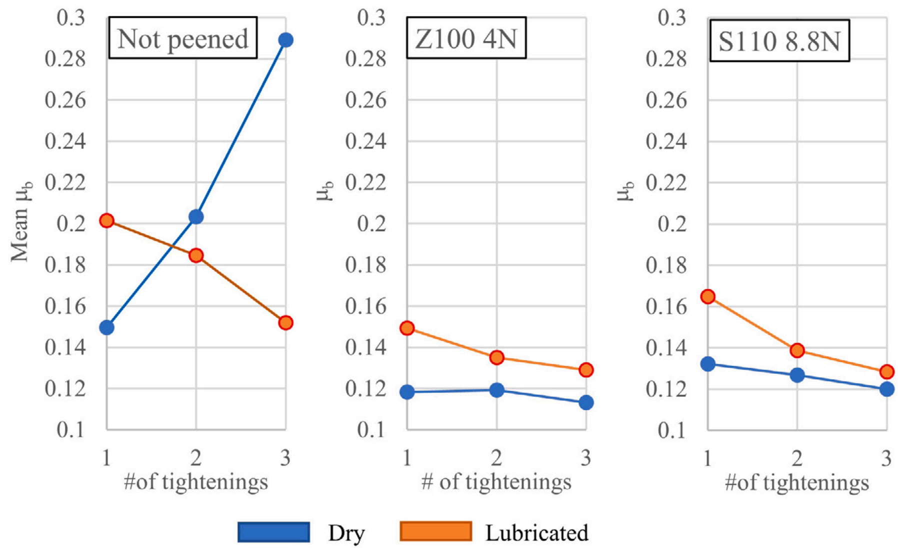

Fig. 12. Main effect plot of number of tightening vs μ_b (Set 2).

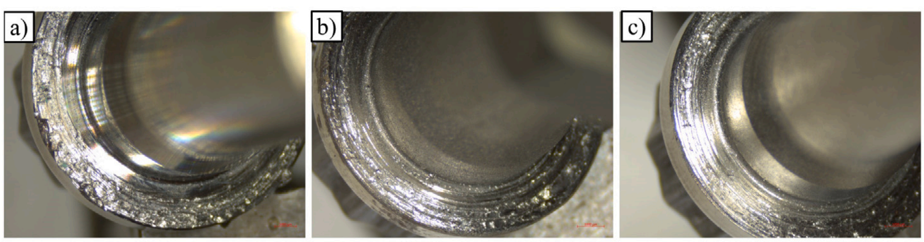

Fig. 13. Pictures of the screw underhead at the end of dry tightening cycles. (a) Non-peened, (b) Z100 4N and (c) S110 8.8N.

6. Conclusions

In this study, the effect of shot peening on the bearing coefficient of high strength threaded joints was investigated. The experimental results confirm that shot peening can significantly reduce the average coefficient of friction over multiple fastening cycles. The results demonstrate that shot peening treatments Z100 10-12N and UFS70 10-12N can be applied to a new material with similar outcomes. Specifically, it has been found that the bearing coefficient of friction becomes stable over multiple tightening cycles in the case of lubrication, whereas it still varies in the case of dry fastening, even if an increase rate reduction can be observed. This is due to the too high roughness of the treated surfaces. The application of treatments Z100 4N and S110 8.8N demonstrated that a decrease of surface roughness and dimple depth can be achieved by reducing the impact energy and increasing the diameter of shots used for shot peening. As a consequence, these treatments make the bearing friction coefficient steady at multiple tightening cycles. A slight decrease of this coefficient is introduced in the case of lubrication, probably due to the spreading of the lubricant over tightenings that is again promoted by the beneficial surface texture. On the whole, it can be asserted that, to have a repeatable preload for a given tightening torque, relatively small shots and high impact energy can be used in case of lubrication. On the other hand, shot-peening treatments with lower energy impact and higher shots size are highly preferable for dry threaded joints. These optimized parameters have the capability of yielding particularly low friction coefficients, in the range between 0.1 and 0.15 upon three tightenings, which are well aligned to those achievable when using lubricants. This outcome suggests that a proper optimization of peening parameters can lead to a new trend involving reduction of lubricant use with positive effects on eco-sustainability.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] Tan F, Xuan D, Zheng Z, Zhang P, Shen H. Experimental study on fatigue performance of high strength bolts of rail vehicles under axial alternating load. IOP Conf Ser Earth Environ Sci 2021;714(3). http://dx.doi.org/10.1088/1755-1315/714/3/032055.

[2] Gerstmayr G, Mori G, Leitner H, Eichlseder W. On the applicability of high strength self-tapping aluminium bolts in magnesium. Mater Corros 2010;61(5):379–87.

[3] Bickford J. An introduction to the design and behavior of bolted joints, revised and expanded. Routledge; 2018.

[4] Croccolo D, De Agostinis M, Fini S, Mele M, Olmi G, Scapecchi C, et al. Failure of threaded connections: A literature review. Machines 2023;11(2). http://dx.doi.org/10.3390/machines11020212.

[5] Juvinall RC, Marshek KM. Fundamentals of machine component design. John Wiley & Sons; 2020.

[6] ISO. EN 1993-1-8. Eurocode 3: design of steel structures – Part 1-8: Design of joints. Tech. rep., 2005.
[7] ISO. EN 1090-2. Execution of steel structures and aluminium structures. Tech. rep., 2019.
[8] Nassar SA, Matin PH, Barber GC. Thread friction torque in bolted joints. Trans ASME, J Press Vessel Technol 2005;127(4):387–93. http://dx.doi.org/10.1115/1.2042474.
[9] Zou Q, Sun TS, Nassar S, Barber GC, El-Khiamy H, Zhu D. Contact mechanics approach to determine effective radius in bolted joints. J Tribol 2005;127(1):30–6. http://dx.doi.org/10.1115/1.1829717.
[10] Grabon WA, Osetek M, Mathia TG. Friction of threaded fasteners. Tribol Int 2018;118(October 2017):408–20. http://dx.doi.org/10.1016/j.triboint.2017.10.014.
[11] Nassar SA, Xianjie Y. Novel formulation of the tightening and breakaway torque components in threaded fasteners. Trans ASME, J Press Vessel Technol 2007;129(4):653–63. http://dx.doi.org/10.1115/1.2767354.
[12] Croccolo D, De Agostinis M, Vincenzi N. Failure analysis of bolted joints: Effect of friction coefficients in torque-preloading relationship. Eng Fail Anal 2011;18(1):364–73. http://dx.doi.org/10.1016/j.engfailanal.2010.09.015.
[13] Croccolo D, Vincenzi N. Tightening tests and friction coefficients definition in the steering shaft of front motorbike suspension. Strain 2011;47(4):337–42. http://dx.doi.org/10.1111/j.1475-1305.2009.00694.x.
[14] Graboń W, Mucha J, Osetek M, Szlachta J. Influence of different thermochemical treatments of bolts on tightening parameters of a bolted joint. Strength Mater 2016;48(4):495–506. http://dx.doi.org/10.1007/s11223-016-9791-y.
[15] Clark KP. The effects of fluoropolymer coated fasteners on nut friction factors. Am Soc Mech Eng, Press Vessels Pip Div (Publ) PVP 2018;2(19 mm):1–8. http://dx.doi.org/10.1115/PVP2018-84027.
[16] Robusto F, Gerini-Romagnoli M, De Agostinis M, Lee JH, Nassar SA. Effect of using 3D printed parts on the torque-tension relationship of threaded joints. In: ASME international mechanical engineering congress and exposition, proceedings (IMECE), vol. 2-A. 2022, p. 1–8. http://dx.doi.org/10.1115/IMECE2022-95614.
[17] De Agostinis M, Fini S, Olmi G. The influence of lubrication on the frictional characteristics of threaded joints for planetary gearboxes. Proc Inst Mech Eng C 2016;230(15):2553–63. http://dx.doi.org/10.1177/0954406215605863.
[18] Croccolo D, De Agostinis M, Fini S, Olmi G, Robusto F, Cavalli O, et al. Experimental measurement of the shank torque as a function of the stiffness and frictional characteristics of the bolted joint. Am Soc Mech Eng, Press Vessels Pip Div (Publ) PVP 2018;2(ii):1–8. http://dx.doi.org/10.1115/PVP2018-84531.
[19] Lee J, Kim D, Seok CS. Methodology for evaluating the tightening torque-clamping force relationship and friction coefficients in bolted joints. J Mech Sci Technol 2022;36(4):1913–9. http://dx.doi.org/10.1007/s12206-022-0328-y.
[20] Croccolo D, De Agostinis M, Vincenzi N. Influence of tightening procedures and lubrication conditions on titanium screw joints for lightweight applications. Tribol Int 2012;55:68–76. http://dx.doi.org/10.1016/j.triboint.2012.05.010.
[21] Fukuoka T, Nomura M, Kawabayashi H. A new experimental approach for measuring friction coefficients of threaded fasteners focusing on the repetition of tightening operation and surface roughness toshimichi. In: ASME 2013 pressure vessels and piping conference. 2013, p. 1–9.
[22] Jiang K, Liu Z, Yang C, Zhang C, Tian Y, Zhang T. Effects of the joint surface considering asperity interaction on the bolted joint performance in the bolt tightening process. Tribol Int 2022;167(December 2021):107408. http://dx.doi.org/10.1016/j.triboint.2021.107408.
[23] Croccolo D, De Agostinis M, Fini S, Olmi G, Robusto F, Vincenzi N. Effect of material and lubrication conditions on the underhead frictional response in high strength socket-head screws. Am Soc Mech Eng, Press Vessels Pip Div (Publ) PVP 2020;2:1–7. http://dx.doi.org/10.1115/PVP2020-21506.
[24] Croccolo D, Fini S, Cavalli O. The influence of material, hardness, roughness and surface treatment on the frictional characteristics of the underhead contact in socket-head screws. In: Proceedings of the ASME 2018 pressure vessels and piping conference. 2018, p. 1–7.
[25] Mitrovic S, Adamovic D, Zivic F, Dzunic D, Pantic M. Friction and wear behavior of shot peened surfaces of 36CrNiMo4 and 36NiCrMo16 alloyed steels under dry and lubricated contact conditions. Appl Surface Sci 2014;290(June 2018):223–32. http://dx.doi.org/10.1016/j.apsusc.2013.11.050.
[26] Vicen M, Bok uvka O, Trško L, Drbul M, Nikolić R, Nový F. Influence of shot peening on the wear behaviour of medium carbon steel. Prod Eng Arch 2022;28(3):241–5. http://dx.doi.org/10.30657/pea.2022.28.29.
[27] Wu Y, Kang Y, Chen Y. Effect of shot peening on the corrosion and wear resistance of 2205 duplex stainless steel. J Mater Eng Perform 2022;32(April):3186–201. http://dx.doi.org/10.1007/s11665-022-07310-5.
[28] Croccolo D, De Agostinis M, Fini S, Olmi G, Paiardini L, Robusto F. Tribological properties of connecting rod high strength screws improved by surface peening treatments. Metals 2020;10(3). http://dx.doi.org/10.3390/met10030344.
[29] ISO EN. 16047: 2005. 2005, Fasteners–torque/clamp force testing.
[30] Montgomery DC. Design and analysis of experiments eighth edition. 2013, p. 757. http://dx.doi.org/10.1198/tech.2006.s372.
[31] Berger PD, Maurer RE, Celli GB. Experimental design. CA (USA): Wadsworth Group Belmont; 2002.
[32] Croccolo D, De Agostinis M, Vincenzi N. Experimental analysis on the tightening torque - preloading force relationship in threaded fasteners. In: IMECE2010-37153 experimental. 2010, p. 1–9. http://dx.doi.org/10.3390/machines11020212.
[33] Dinger G, Friedrich C. Avoiding self-loosening failure of bolted joints with numerical assessment of local contact state. Eng Fail Anal 2011;18(8):2188–200. http://dx.doi.org/10.1016/j.engfailanal.2011.07.012.
[34] Dinger G. Design of multi-bolted joints to prevent self-loosening failure. Proc Inst Mech Eng C 2016;230(15):2564–78. http://dx.doi.org/10.1177/0954406215612813.