





Article

# Tribological Properties of Connecting Rod High Strength Screws Improved by Surface Peening Treatments

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**Abstract:** Bolted joints are highly loaded components and serious issues may arise from improper fastening and in particular from too high or too low preload. Friction at the underhead plays an important role, as it significantly affects the achievable preload for fixed and controlled tightening torque. In addition, multiple tightening is usually performed on connecting rod screws, which may be a further source of friction increment. This study investigates the effect of two surface treatments, shot-peening and deep-rolling, on the tribological properties upon bolt fastening. This topic was tackled experimentally and the campaign involved MJ9 X 1 4 g grade 13.9 36 NiCrMo connecting rod screws, in both lubricated and dry conditions. The results, processed by statistical tools, indicate that deep-rolling does not affect friction, whereas shot-peening yields significant benefits. As an effect of the generation of dimples and multiple contacts, it is able to lower (up to 25%) the bearing frictional coefficient in lubricated conditions, also making the friction level independent of the number of re-tightenings. For a dry surface, an even higher friction decrease (up to 30%) is achieved. Without lubrication, the friction coefficient keeps increasing for the incremented number of tightenings, but the increase rate is lowered with respect to the untreated surface.

**Keywords:** connecting rod screw; deep-rolling; shot-peening; multiple tightenings; friction

## 1. Introduction

The connecting rod may be regarded as one of the most critical components in an engine. In fact, it has the role of transferring loads from the piston to the crankshaft and often operates under high fatigue as well as inertial loads during service. Some previous studies have been focused on the failures of rods, which in turn caused engine catastrophic failures; regarding this point, a large collection of failures involving connecting rods (con-rods) is, for instance, provided in [1]. A detailed analysis of con-rod states of load and stress is delivered in [2], whereas, again with reference to this component, focus is placed on static and dynamic material properties in [3–5]. The primary reasons for rod breakage were mainly related to fatigue cycling that triggered crack initiation in zones with too high stress concentrations owing to poor design [6]. It is interesting to remark that, in some cases, failure occurrence was associated to rod big hole coupling by bolts; in fact, the design of the threaded joint or the triggering procedure are believed to have led to some serious issues. For instance, in [6], the authors point out that a too high tightening torque induced a too high preload. As an effect of this too high clamping, and of poor design leading to a too high stress concentration, a particularly strong tensile stress was induced on the rod in the neighborhood of the bolt hole. In addition, a local bending

effect was produced as well, which led to premature rod fatigue failure. The study [7] and common literature dealing with bolted joints [8] highlight that it is generally recommended to fasten screws up to a sufficiently high tightening torque, which makes it possible to achieve a sufficiently strong preload. In fact, the higher the preload, the lower the stress amplitude being transferred to the screw under fatigue in service condition. The studies [6,7] highlight that the actually achieved big hole bolt preload does have a significant impact on the screw behavior and on the rod response from different points of view. In fact, on one hand, a too high preload may generate a too high load on the rod surface, thus weakening this component, and exposing it to fatigue and fretting failures. On the other hand, a too low preload leads to an increment of the stress amplitude affecting the screw under fatigue, with a consequent risk of bolt failure.

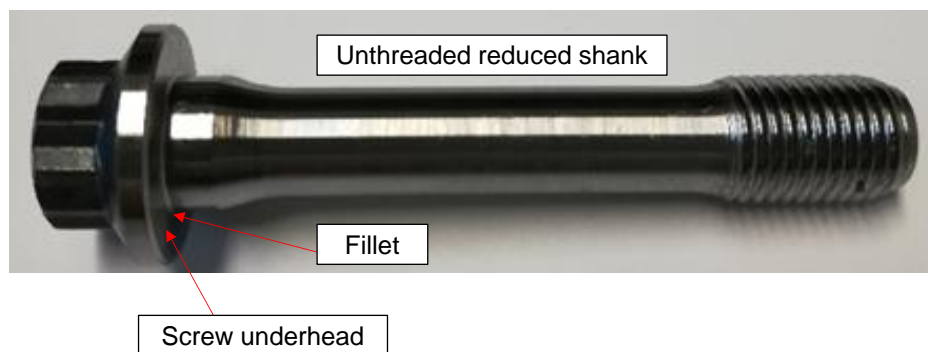
Previous studies from the same group [9–11] have indicated that the bearing and the thread frictional coefficients have a strong impact on the achievable preload for a fixed tightening torque being controlled by a torque wrench upon fastening. In addition, specifically regarding con-rod screws, it must be emphasized that the usually recommended fastening procedure involves a retightening, meaning that they are tightened, untightened, and retightened again. This means that the screw is re-tightened at least once, which implies some wear issues affecting the bearing surface. Moreover, further retightening(s) may occur upon maintenance or refurbishment. Multiple tightenings have an important role, as they are likely to highly affect the tribological behavior. This outcome occurs as an effect of the induced progressive wear that makes the mating surfaces coarser and coarser, which, in turn, increases friction. As a matter of fact, an error on friction estimation leads to an inaccurate estimation of the actual achieved preload; in particular, underestimation or overestimation may lead (for fixed applied torque) to a too low or too high preload.

This research focuses on the possible use of surface treatments to improve the tribological behaviour of high strength con-rod screws. Considering the state-of-the-art in the scientific and technical literature dealing with fasteners, this improvement mainly involves friction coefficient reduction and its steady trend versus repeated tightenings. The study [12] indicates that shot-peening can be highly promising from this point of view. This treatment consists of the impact of different material small shots on the surface of the treated component; compressed air is used to generate a stream of small sized shots. As an effect of these impacts, some modifications affecting material hardness, structure, and roughness are induced. Regarding this last point, dimples are generated on the surface and a compressive residual stress state is consequently induced, which has a further effect on the mechanical response of the treated component. The above-mentioned dimples proved to have an important role from the points of view of friction and wear, affecting the mating treated surfaces. In fact, the porous texture and the incremented number of contact points have a beneficial impact in dropping down friction. Moreover, wear issues may also be made less serious, as wear debris gets trapped in the valleys, thus reducing the impact on friction upon mating surface relative sliding. Finally, when a lubricant is also present, a further beneficial hydrostatic effect is induced at the interface, as an effect of the pressure transmitted by the lubricant that is contained in the peened surface dimples. However, it is worth mentioning the results in [12] were obtained by conventional tests by a tribometer (pin-on-disk tests), whereas applications on real components are missing in the scientific literature. The beneficial effect of shot-peening is also emphasized in [13], where 17-4 stainless steel parts were treated by glass beads. The outcomes of this research also highlighted a surface flattening effect, which, in turn, induced a significant wear volume reduction with respect to untreated parts. However, as above, this experimentation was also carried out by tribometer trials. Further studies [14–16] in the scientific literature have dealt with other novel surface treatments, such as cavitation peening, water jet peening, laser peening and simultaneous shot-peening of hard and soft particles. They are indeed highly promising from the points of view of surface smoothing, friction reduction, and fatigue enhancement. However, on one hand, these technological processes are able to yield some benefits with respect to more conventional shot-peening treatments, but, on the other hand, they are quite difficult to implement on screws and bolts.

Therefore, the present study focuses on the achievable friction reduction through suitable treatments of shot-peening. This treatment was also coupled to deep-rolling, which is usually applied to these kinds of screws, to enhance their fatigue response [17]. The response of combined treatments was, therefore, assessed experimentally, thus considering the usual processing of con-rod screws and trying to replicate their actual service conditions. Moreover, regarding this point, the effect of repeated tightenings, always occurring when considering con-rod screws, was also investigated. Issues of novelty arise from the lack of studies regarding the effect of the investigated treatments, in particular shot-peening, on the tribological response of high strength screws. In fact, the literature studies addressing the effect of shot-peening are generally conducted by tribometer tests, as highlighted above. Moreover, this research addresses this question in both dry and lubricated conditions, thus providing some reference friction values for screw producers and customers.

## 2. Materials and Methods

The study involved con-rod screws made of steel 36 NiCrMo. All of them had the geometry depicted in Figure 1, with 7 mm diameter at reduced shank and MJ9 X 1 4 g grade 13.9 thread features.

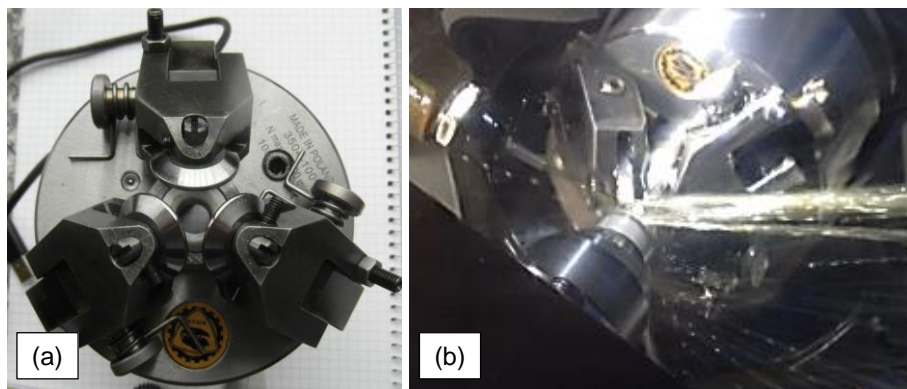


**Figure 1.** Geometry of the screws involved in the experimental campaign for tribological properties.

The screws underwent the following heat and forming treatments that replicate those actually conducted before regular service: cold forging, followed by quenching, tempering, turning, grinding, and thread rolling, aimed at the achievement of a 44 Rockwell C Hardness (HRC) final hardness. The material mechanical properties were initially assessed by static tensile tests, which led to the estimation of a tensile strength ranging between 1300 MPa and 1350 MPa and of an average 1100 MPa yield point, with 9% as minimum percentage elongation at fracture. In addition, screws with the same specifications were involved in a fatigue testing campaign, as described in [17].

The tribological tests involved two technological factors, namely the surface treatments being performed on the screws, as specified below. The first treatment, deep-rolling, was run at the underhead fillet; in particular, the radial load was applied by three 120° equally-spaced tungsten carbide rollers with initial 45° inclination with respect to the screw axis. They were shaped with the same fillet radius at the screw underhead (0.35 mm) and were free to rotate around their axis. Provided that they were mounted on a separate fixture, they were able to bend by a few degrees around a hinge, thus covering the entire fillet. Deep-rolling was run under oil lubrication and under a 1,200 rpm rotational speed around the screw longitudinal axis. A suitable load was gradually increased and then maintained for approximately 5 s at the interface between the rolls and the fillet. This load was subsequently optimized to a target value, in order to achieve the desired flow pattern and residual stress state at the fillet. In particular, four load levels were considered: the usually recommended load by companies treating fasteners, as well as 35% and 70% incremented loads. Moreover, an additional “zero” level, corresponding to not rolled screws, was considered for comparison purposes. Some fatigue limits were then determined by abbreviated staircase methods. Their comparison led to the selection of the 35% incremented load that was able to maximize the fatigue strength. Further details are available

in [17]. Two photos depicting a typical device for deep-rolling with 120° spaced rollers (screw to be applied at the centre) and a stage of the treatment are shown in Figure 2a,b. Deep-rolling factor was regarded as on–off, meaning that two levels were considered, consisting of deep-rolling not being run and deep-rolling being performed at the aforementioned optimized load. As above, deep-rolling is commonly applied to enhance the fatigue properties. The rationale for considering this factor, when addressing the tribological response, is that plastic flow is likely to alter the surface shape and flatness at the underhead, introducing undulations around the fillet, thus affecting friction.



**Figure 2.** (a) A typical device for deep-rolling with equally spaced rollers; (b) a stage of the process.

Shot-peening was performed (by Peen Service, Bologna, Italy) after deep-rolling, involving the screw underhead, the fillet, and the unthreaded reduced shank (Figure 1). Three levels were considered in this case: unpeened screws, Z100 (100  $\mu\text{m}$  diameter ceramic shots) 10–12N, and UFS70 (70  $\mu\text{m}$  diameter steel shots) 10–12N peening treatments (both with 200% coverage). The selected levels accounted for both ceramic and steel shots, in order to address possible material effects. As highlighted above, shot-peening is likely to beneficially affect friction, based on tribometer trials involving the same material [12].

A third factor, being strictly related to con-rod screw service conditions, was the number of (repeated) tightenings. The number of levels was properly selected, based on the actual tightening procedure, consisting of two subsequent tightenings upon assembly (tightening, untightening, and again tightening) and of a further tightening, usually run upon maintenance (meaning that the screw is unfastened and then fastened again under the same controlled tightening torque). Thus, three levels corresponding to one, two, or three subsequent tightenings were considered. A suitable number of replications per treatment combination was run for the sake of statistical evidence, also based on the recommendations of Standard [18].

Finally, in order to address the tribological response for both the dry and for lubricated bearing surface, thus accounting for these different service conditions, the experimental plan was repeated with and without lubrication. From this point of view, lubrication condition can be regarded as an external factor with two levels, whereas the previous three are internal levels, according to the Taguchi theory [19].

The number of replications was set to ten with regard to the trials in dry conditions, which were performed first; therefore, the three-factor plan involved an overall number of 180 tests. In the campaign in lubricated conditions, which, consistently with the outcomes in [9], exhibited a much lower scattering than that without lubrication; the number of replications was reduced to five. This number seemed to be reasonable to properly estimate the experimental uncertainty affecting the results, also based on previously published studies dealing with screw tribological assessments [9,11], in agreement with Standard [18]. Therefore, 90 further trials were run under lubrication, which led to the overall number of tests of 270. The experimental plan is resumed in Table 1 with regard to the internal factors, that is, deep-rolling, shot-peening, and the number of tightenings.

**Table 1.** Experimental design.

Deep-Rolling	Shot-Peening	Multiple Tightenings
Not performed	Not performed	1
		2
		3
	Z100 10-12N	1
		2
		3
	UFS70 10-12N	1
		2
		3
Performed (optimized rolling load)	Not performed	1
		2
		3
	Z100 10-12N	1
		2
		3
	UFS70 10-12N	1
		2
		3

The main output variable was the frictional coefficient at the underhead ( $\mu_b$ ), as the tribological properties in this area are directly affected by the conducted surface treatments. In addition, the total friction coefficient ( $\mu_{tot}$ ) was considered as well, in order to assess the impact of the modified tribological properties at the underhead on the total frictional response.

The tests were run on a tribological testing rig (Model 201, by TesT GmbH, Erkrath, Nordrhein-Westfalen, Germany), having the capability of working out the previously mentioned friction coefficients, processing the online measurements (0.5% accuracy) of (total) tightening and bearing torques and of the induced axial load. Schemes and photos of benches with the aforementioned features, thus meeting the requirements of Standard [18], are available in [10,20]. The frictional coefficient estimation was addressed based on recommendations and related formulas in [18]. In particular, the bearing and the total friction coefficients were determined by Equations (1) and (2) [18], in agreement with Motosh's formula, which is provided in Equation (3).

$$\mu_b[-] = \frac{T_b}{F_V} \cdot \frac{2}{d_b} \quad (1)$$

$$\mu_{tot} = \frac{\frac{T}{F} - \frac{p}{2\pi}}{0.577d_2 + 0.5d_b} \quad (2)$$

$$T[Nm] = F_V \cdot \left( 0.159 \cdot p + 0.577 \cdot \mu_{th} \cdot d_2 + \mu_b \cdot \frac{d_b}{2} \right) \quad (3)$$

$F_V$  indicates the axial load, whereas  $T$  and  $T_b$  are the (total) tightening torque and the torque being dissipated as an effect of friction at the underhead (bearing), respectively.  $\mu_{th}$  in Equation (3) indicates the friction coefficient in the screw threads. The meaning of the other symbols as well as the values of screw dimensional and geometrical features are provided in Table 2.



**Table 2.** Main features of the tested screws.

Symbol	Meaning	Value	Unit
S <sub>u</sub>	Ultimate strength	1300–1350	MPa
S <sub>y</sub>	Yield strength	1100	MPa
d	Nominal diameter	9	mm
d <sub>2</sub>	Pitch diameter	8.35	mm
d <sub>b</sub>	Mean diameter at the underhead	12.6	mm
p	Pitch	1	mm

The values upon the maximum tightening torque were considered for data processing, but it was checked that the friction coefficient trends remained steady at the last stage of tightening.

All the results, in terms of bearing and total friction coefficients, were processed by the tools of three-factor analysis of variance (ANOVA) to investigate the significance of the investigated factors. The tribological response was then assessed, plotting the total and the bearing friction coefficient versus the numbers of repeated tightenings in both dry and lubricated conditions. The analysis was then completed in the light of the observation of the underhead surfaces at the end of the conducted tightenings, thus comparing the level of wear with and without shot-peening and involving dry and lubricated testing conditions. These surfaces were observed with the aid of a stereoscopic microscope (STEMI 305, by ZEISS, Oberkochen, Germany).

### 3. Experimental Procedure

All the tightening tests were run, utilizing a steel test-bearing-plate (type HH) to be placed under the screw head, having 0.5 µm average roughness, 10 mm diameter holes, and with screw features as in Table 2 and consistent with those recommended in [21].

All the tests were run under tightening torque control with controlled 25 rpm speed in steady conditions. During tightening, the nut was fully constrained and prevented from rotating, according to the recommended layout in Standard [18]. The same paper [18] requires performing tightening up to an axial load equalizing 75% of the proof load, as listed in [22]. Some preliminary tests were conducted in order to estimate the tightening torque amount corresponding to this preload in both dry and lubricated conditions. Five replicated tests led to the averaged values of 80 Nm and 70 Nm for unlubricated and lubricated screws, respectively. It was also checked that the determined values were sufficiently far away from yielding conditions, in order to ensure the determination of the tribological properties in the linear elastic field, as recommended in [18].

Before starting every test, all the screws were polished and degreased by ultrasonic bath. Unused nuts were also utilized and degreased according to the same procedure before tightening. The tests in dry conditions were run first, following a randomized order. An unused hole was utilized for every test; after tightening to a maximum torque equalizing 80 Nm, the screw was untightened and then tightened again without changing its hole. Then, it was untightened and re-tightened for the third time. The trial was completed by screw final untightening. The tightening and bearing torque as well as the axial load were measured online by the machine proprietary load cell, whereas the thread (shank) torque was computed by difference. As highlighted above, the bearing plate hole was then changed before running the subsequent test. The nut was also replaced by a new degreased one.

The same procedure was followed for the lubricated tests. A commercial MoS<sub>2</sub> lithium grease was used to conduct lubrication and was applied on the entire screw, both at the underhead and at the threads. The tests were conducted, following the same procedure for dry condition tests, provided that tightening torque was gradually incremented up to 70 Nm and that lubricant was not added before repeated tightenings.

#### 4. Results

The results of the two experimental campaigns in dry conditions are collected in Tables 3 and 4 with regard to bearing and total friction coefficients. The same results retrieved with grease lubrication are reported in Tables 5 and 6.

**Table 3.** Results in terms of bearing friction coefficients ( $\mu_b$ ) in dry conditions.

Deep-Rolling	Shot-Peening	Multiple Tightenings	Replicated Results											
Not performed	Not performed	1	0.175	0.192	0.176	0.168	0.150	0.160	0.169	0.154	0.150	0.129		
		2	0.230	0.257	0.229	0.243	0.342	0.246	0.261	0.241	0.279	0.211		
		3	0.308	0.393	0.428	0.310	0.352	0.271	0.405	0.312	0.328	0.317		
	Z100 10–12N	UFS70 10–12N	1	0.177	0.144	0.136	0.139	0.140	0.144	0.134	0.145	0.117	0.123	
			2	0.217	0.158	0.141	0.156	0.261	0.143	0.198	0.249	0.178	0.140	
			3	0.228	0.298	0.143	0.246	0.292	0.188	0.211	0.297	0.240	0.251	
		Not performed	Z100 10–12N	1	0.186	0.127	0.129	0.116	0.118	0.155	0.118	0.108	0.135	0.110
				2	0.286	0.260	0.132	0.123	0.220	0.230	0.191	0.249	0.220	0.145
				3	0.342	0.303	0.289	0.173	0.200	0.229	0.308	0.276	0.245	0.244
Performed (optimized rolling load)	Not performed	1	0.187	0.196	0.157	0.175	0.181	0.141	0.154	0.143	0.144	0.153		
		2	0.304	0.352	0.189	0.267	0.494	0.175	0.224	0.189	0.247	0.421		
		3	0.341	0.429	0.180	0.266	0.610	0.174	0.283	0.238	0.311	0.412		
	Z100 10–12N	UFS70 10–12N	1	0.170	0.146	0.136	0.154	0.140	0.143	0.143	0.139	0.120	0.135	
			2	0.292	0.250	0.137	0.229	0.235	0.151	0.215	0.286	0.131	0.235	
			3	0.323	0.260	0.156	0.308	0.342	0.242	0.259	0.439	0.219	0.358	
		UFS70 10–12N	1	0.160	0.130	0.114	0.113	0.136	0.111	0.107	0.100	0.110	0.105	
			2	0.272	0.226	0.126	0.112	0.190	0.114	0.198	0.160	0.139	0.160	
			3	0.403	0.190	0.155	0.113	0.262	0.176	0.302	0.336	0.297	0.255	

**Table 4.** Results in terms of total friction coefficients ( $\mu_{tot}$ ) in dry conditions.

Deep-Rolling	Shot-Peening	Multiple Tightenings	Replicated Results											
Not performed	Not performed	1	0.270	0.197	0.180	0.271	0.172	0.216	0.225	0.149	0.159	0.156		
		2	0.314	0.257	0.211	0.299	0.294	0.283	0.273	0.198	0.241	0.211		
		3	0.387	0.345	0.335	0.365	0.283	0.318	0.394	0.242	0.277	0.260		
	Z100 10–12N	UFS70 10–12N	1	0.230	0.215	0.223	0.169	0.199	0.277	0.186	0.223	0.129	0.155	
			2	0.273	0.209	0.244	0.177	0.263	0.207	0.242	0.282	0.161	0.181	
			3	0.287	0.288	0.261	0.233	0.273	0.236	0.262	0.358	0.198	0.318	
		Not performed	Z100 10–12N	1	0.185	0.137	0.154	0.144	0.147	0.139	0.132	0.130	0.139	0.125
				2	0.272	0.210	0.145	0.156	0.213	0.200	0.165	0.229	0.184	0.145
				3	0.337	0.248	0.235	0.203	0.199	0.199	0.243	0.259	0.213	0.200
Performed (optimized rolling load)	Not performed	1	0.248	0.266	0.250	0.260	0.206	0.240	0.191	0.156	0.221	0.168		
		2	0.324	0.365	0.285	0.327	0.420	0.257	0.268	0.185	0.247	0.421		
		3	0.368	0.429	0.289	0.348	0.508	0.279	0.322	0.217	0.383	0.397		
	Z100 10–12N	UFS70 10–12N	1	0.178	0.172	0.165	0.181	0.152	0.175	0.190	0.161	0.206	0.175	
			2	0.278	0.246	0.167	0.228	0.220	0.199	0.245	0.257	0.231	0.237	
			3	0.312	0.254	0.194	0.286	0.305	0.275	0.282	0.367	0.311	0.314	
		UFS70 10–12N	1	0.175	0.202	0.143	0.178	0.166	0.145	0.134	0.142	0.140	0.128	
			2	0.250	0.274	0.147	0.209	0.167	0.141	0.181	0.223	0.153	0.156	
			3	0.303	0.249	0.172	0.256	0.217	0.182	0.239	0.438	0.243	0.209	

**Table 5.** Results in terms of bearing friction coefficients ( $\mu_b$ ) in grease lubricated conditions.

Deep-Rolling	Shot-Peening	Multiple Tightenings	Replicated Results					
Not performed	Not performed	1	0.204	0.208	0.138	0.173	0.251	
		2	0.165	0.166	0.135	0.155	0.185	
		3	0.146	0.158	0.118	0.142	0.215	
	Z100 10–12N	1	0.111	0.132	0.149	0.164	0.132	
		2	0.116	0.239	0.157	0.157	0.195	
		3	0.127	0.203	0.127	0.149	0.167	
	UFS70 10–12N	1	0.114	0.118	0.154	0.105	0.105	
		2	0.115	0.111	0.127	0.102	0.094	
		3	0.109	0.093	0.131	0.104	0.094	
	Performed (optimized rolling load)	Not performed	1	0.202	0.156	0.178	0.217	0.259
			2	0.179	0.153	0.171	0.139	0.163
			3	0.144	0.174	0.154	0.136	0.147
Z100 10–12N		1	0.124	0.123	0.136	0.114	0.124	
		2	0.125	0.132	0.133	0.113	0.123	
		3	0.116	0.119	0.110	0.114	0.120	
UFS70 10–12N		1	0.095	0.109	0.122	0.109	0.095	
		2	0.098	0.139	0.136	0.111	0.116	
		3	0.095	0.126	0.123	0.120	0.152	

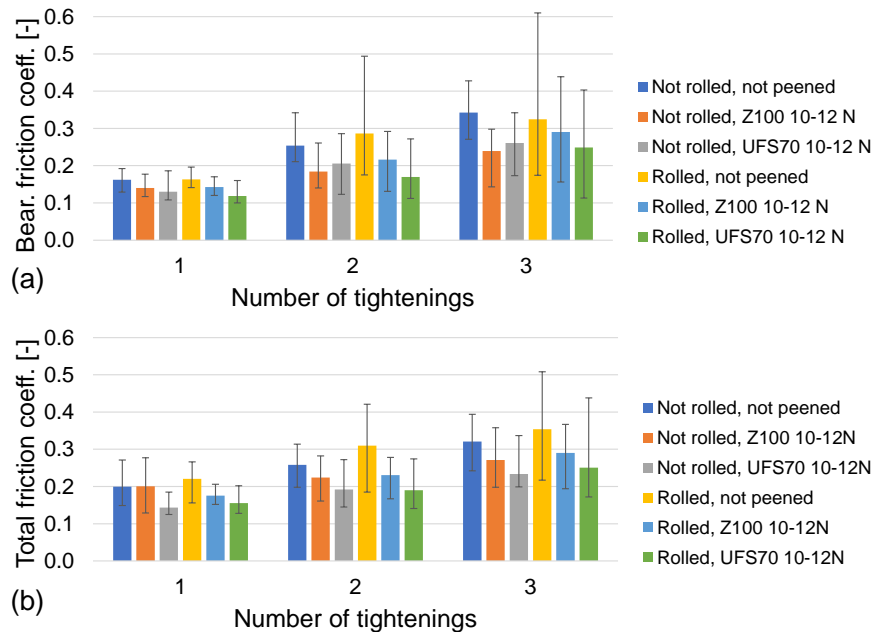
**Table 6.** Results in terms of total friction coefficients ( $\mu_{tot}$ ) in grease lubricated conditions.

Deep-Rolling	Shot-Peening	Multiple Tightenings	Replicated Results					
Not performed	Not performed	1	0.180	0.182	0.136	0.165	0.221	
		2	0.151	0.156	0.133	0.154	0.166	
		3	0.139	0.150	0.124	0.145	0.191	
	Z100 10–12N	1	0.120	0.140	0.143	0.161	0.141	
		2	0.123	0.202	0.147	0.153	0.171	
		3	0.125	0.177	0.130	0.146	0.154	
	UFS70 10–12N	1	0.125	0.127	0.151	0.114	0.121	
		2	0.123	0.123	0.133	0.113	0.111	
		3	0.118	0.108	0.133	0.115	0.109	
	Performed (optimized rolling load)	Not performed	1	0.177	0.163	0.166	0.182	0.213
			2	0.159	0.156	0.156	0.135	0.151
			3	0.139	0.157	0.144	0.132	0.142
Z100 10–12N		1	0.132	0.131	0.140	0.124	0.134	
		2	0.130	0.134	0.135	0.119	0.130	
		3	0.123	0.124	0.120	0.119	0.128	
UFS70 10–12N		1	0.112	0.120	0.132	0.115	0.116	
		2	0.113	0.135	0.138	0.113	0.127	
		3	0.112	0.127	0.126	0.116	0.149	



## 5. Discussion

The results retrieved in dry conditions are collected in the bar graphs in Figure 3a,b with reference to bearing and total friction, respectively. Variation intervals, from minimum to maximum values, were also appended.



**Figure 3.** (a) Bearing and (b) total friction coefficients retrieved during the tests in dry conditions.

The data regarding the friction coefficients at the underhead were processed first. As mentioned above, the tool of three-factor ANOVA was utilized to assess the significance of the three factors and of their interactions. In particular, the overall variance was split into eight terms, corresponding to the three main effects the three two-factor interactions, the three-factor interaction, and finally accounting for the experimental uncertainty. The Fisher test was then applied, to determine if the aforementioned effects and related variances were significant with respect to the scattering affecting the experiment. The outputs of the analysis of variance are provided in Table 7, where the main effects of the three factors are reported first.

**Table 7.** Analysis of variance (ANOVA) table with regard to the bearing friction coefficient ( $\mu_b$ ) in dry conditions.

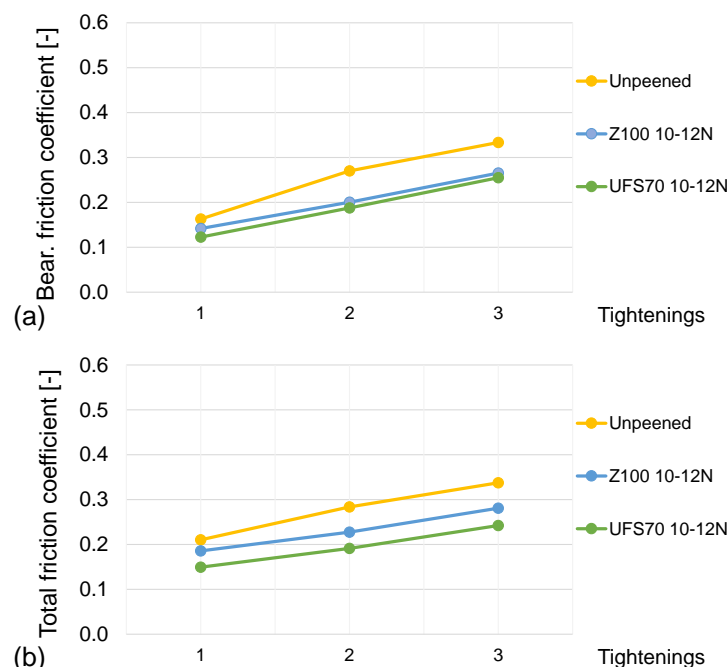
Effects and Interactions, Error, and Total Variance	Sum of Squares	Degrees of Freedom	Mean Squares	Fisher Ratio	<i>p</i> -Value
Deep-rolling	0.00095	1	0.00095	0.26	0.61
Shot-peening	0.14840	2	0.07420	20.29	$1 \cdot 10^{-8}$
Mult. tight.	0.60337	2	0.30168	82.49	$2 \cdot 10^{-25}$
Deep-rolling–Shot-peening interaction	0.01759	2	0.00880	2.41	0.09
Deep-rolling–Mult. tight. interaction	0.00125	2	0.00063	0.17	0.84
Shot-peening–Mult. tight. interaction	0.01821	4	0.00455	1.24	0.29
Three-factor-interaction	0.01313	4	0.00328	0.90	0.47
Error	0.59251	162	0.00366		
Total	1.39542	179	0.00780		

The Fisher test highlights that deep-rolling does not have a significant impact on the tribological response; its  $p$ -value is remarkably high (beyond 60%), whereas the Fisher's ratio is under 1. Conversely, shot-peening proved to be highly significant at dropping down friction, as proved by the very low  $p$ -value, in the order of  $10^{-8}$ , retaining the meaning of the very low error affecting the significance assertion. This outcome is clearly related to the reasons highlighted in the Introduction Section, arising from a more porous texture, multiple contacts, and dimples retaining wear debris. Finally, repeated tightenings, consistent with [9], proved to be highly significant, with a  $p$ -value of barely zero. All the interactions are very low and under the significance threshold, considering a 5% significance level [23,24]. Regarding the poor effect of deep-rolling, this result suggests that plastic flow-induced undulations around the fillet do not significantly affect the flatness of the underhead surface that slides on the bearing upon tightening. It is clear that deep-rolling cannot affect the texture of the underhead surface far away from the fillet.

Multiple tightenings indeed negatively affect friction, as an effect of increasing wear occurring on the two mating surfaces. It is also remarkable that the absence of interaction involving shot-peening ensures that its beneficial effect is maintained regardless of fillet rolling and also independently of the number of re-tightenings.

The same statistical approach was applied to process the results involving the total friction coefficients. The output of the analysis and of the subsequent Fisher test are not shown here for the sake of synthesis. The study has yielded well comparable results, emphasizing the effects of shot-peening and multiple tightenings, whereas deep-rolling was confirmed to keep a very poor effect and all the interactions appeared to be negligible.

In order to better investigate the beneficial effect of shot-peening for increasing number of re-tightenings, the average results for each peening treatment, with and without deep-rolling, were plotted together versus the number of tightenings. The related graphs are shown in Figure 4a,b for bearing and total friction, respectively.

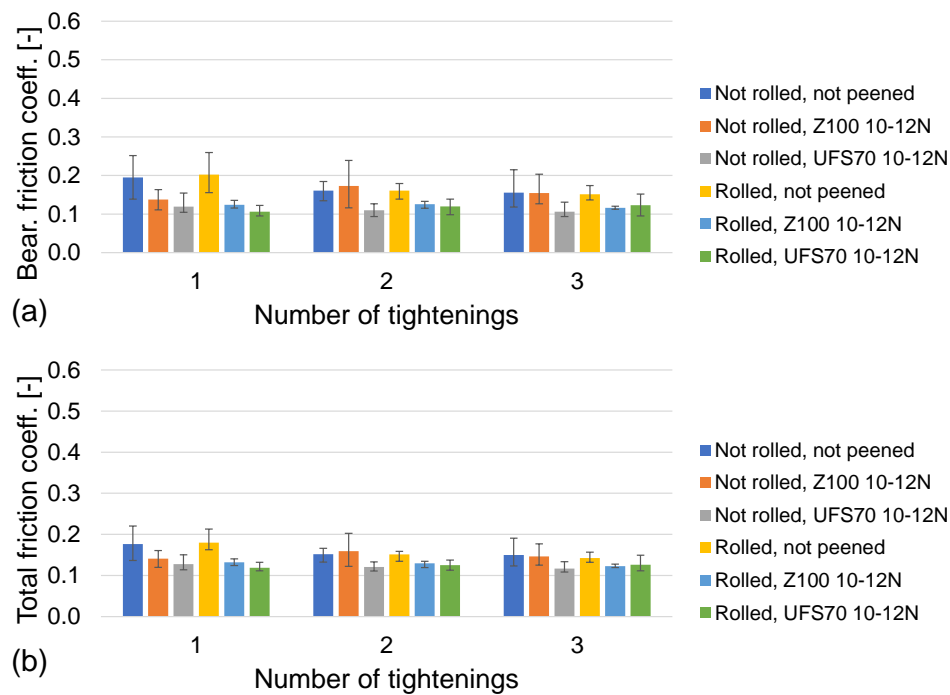


**Figure 4.** (a) Bearing and (b) friction coefficients plotted versus the number of tightenings for different peening treatments, with regard to the trials in dry conditions (data averaged regardless of deep-rolling execution).

It can be pointed out that the most beneficial treatment, which yields the lowest frictional coefficient throughout the three tightenings, is UFS70. It is worth mentioning that  $\mu_b$  and  $\mu_{tot}$  are decreased by

23% and 28%, respectively, with respect to untreated underhead, comparing the values upon the third tightening. The trend of friction coefficient versus tightenings is always monotonically increased, both for unpeened and for peened surfaces; however, in the latter case, the increase rate appears to be decreased, thus indicating a further beneficial effect arising from shot-peening.

The same analysis was conducted with regard to the test under lubrication, whose results, in terms of bearing and total frictional coefficients, are delivered in Figure 5a,b. Variation intervals were again appended, to highlight the ranges from minimum to maximum yields.



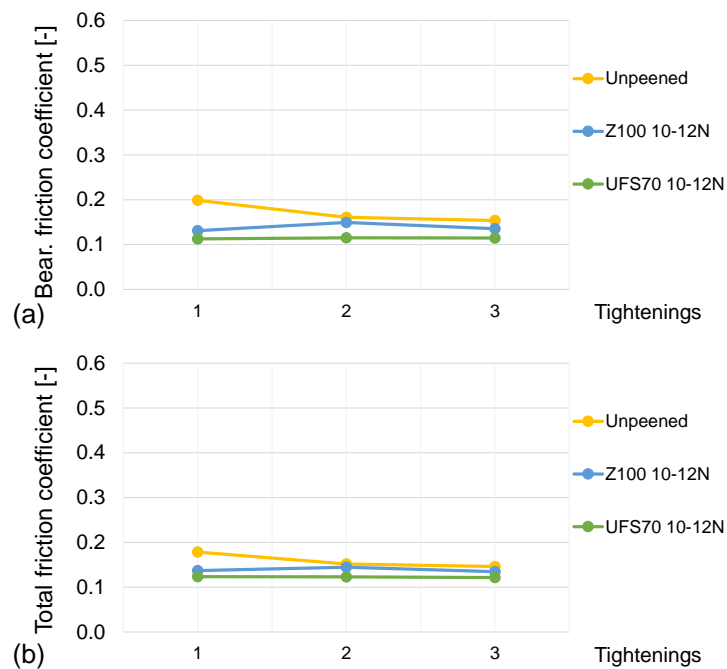
**Figure 5.** (a) Bearing and (b) total friction coefficients retrieved during the tests in grease lubricated conditions.

The three-factor ANOVA applied to both the bearing and the total friction coefficients (which referred to the friction coefficient at the underhead is provided in Table 8) confirmed that shot-peening does remarkably affect the tribological response; the  $p$ -value is in the order of  $10^{-12}$ , when considering  $\mu_b$ .

**Table 8.** ANOVA table with regard to the bearing friction coefficient ( $\mu_b$ ) in lubricated conditions.

Effects and Interactions, Error, and Total Variance	Sum of Squares	Degrees of Freedom	Mean Squares	Fisher Ratio	$p$ -Value
Deep-rolling	0.00191	1	0.00191	3.20	0.08
Shot-peening	0.04891	2	0.02446	40.95	$1 \cdot 10^{-12}$
Mult. tight.	0.00250	2	0.00125	2.09	0.13
Deep-rolling–Shot-peening interaction	0.00656	2	0.00328	5.49	$6 \cdot 10^{-3}$
Deep-rolling–Mult. tight. interaction	0.00014	2	0.00007	0.11	0.89
Shot-peening–Mult. tight. interaction	0.01110	4	0.00277	4.65	$2 \cdot 10^{-3}$
Three-factor-interaction	0.00280	4	0.00070	1.17	0.33
Error	0.04300	72	0.00060		
Total	0.11692	89	0.00131		

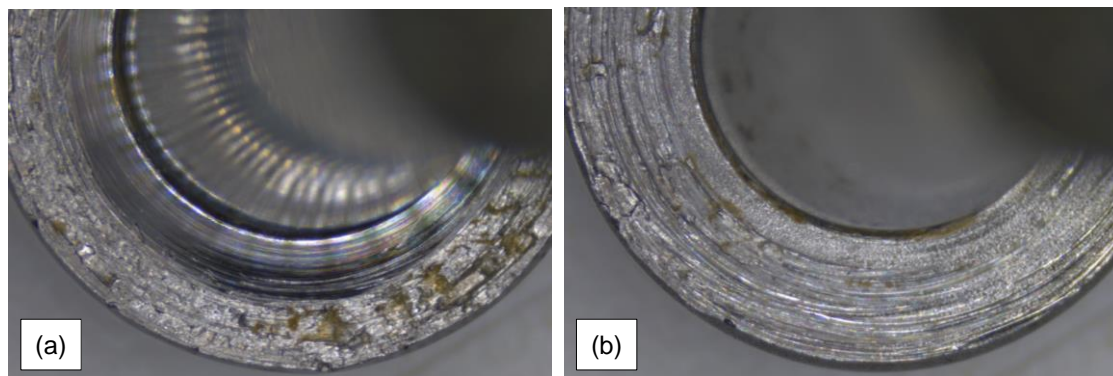
Repeated tightenings are in this case not significant, with a  $p$ -value in the order of 13%. Deep-rolling remains not significant, although in this case, the  $p$ -value is in the order of 8%, thus not far away from the significance threshold. Two interactions are significant in this case, highlighting that shot-peening has a slightly different effect at decreasing friction with and without deep rolling and for increasing number of tightenings. Particularly, the beneficial effect of shot-peening is more evident upon the first tightening. Then, friction at the interface is generally decreased in both the unpeened and peened conditions as an effect of lubricant spreading. As for unlubricated conditions, the study was deepened, plotting (Figure 6a,b) the averaged values of the friction coefficients for the unpeened surface and for the two peening treatments, with and without deep-rolling, versus repeated tightenings.



**Figure 6.** (a) Bearing and (b) friction coefficients plotted versus the number of tightenings for different peening treatments, with regard to the trials in lubricated conditions (data averaged regardless of deep-rolling execution).

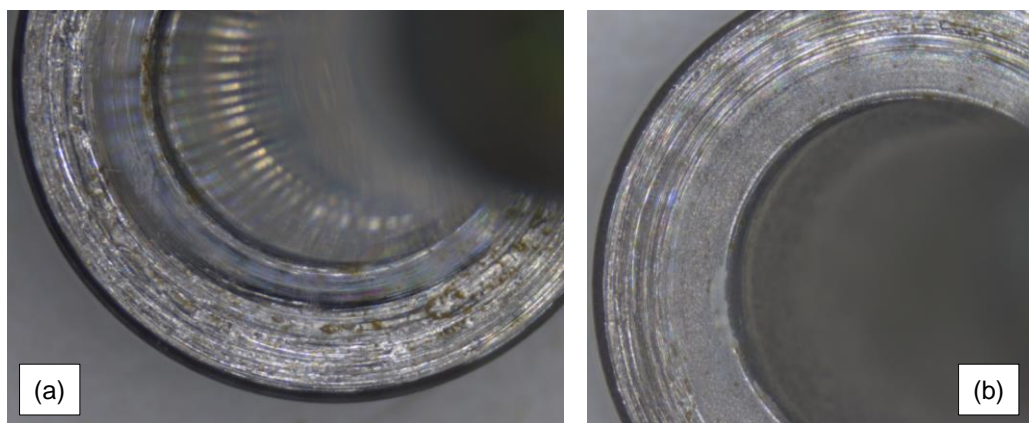
From a quantitative point of view, it is worth mentioning that, as an effect of shot-peening, with particular reference to UFS 70,  $\mu_b$  is reduced by 25% with respect to the untreated surface upon the third tightening. On the other hand, the beneficial effect is also confirmed by the trend of  $\mu_{tot}$ , which is decreased by 17% in the same condition. The distribution in this case is generally flat for both the untreated and peened surfaces. This is an important point, as it makes it possible to restore the same (initial) tribological properties upon subsequent tightenings. It can be highlighted that, in the first case, a friction decrease may be observed between the first and the second tightening; it is presumably because of grease lubricant being properly spread, thus covering the entire mating surface, upon the first tightening. Once the lubricant distribution is optimized, the friction remains constant. When the surface is previously shot-peened, friction remains at very low values (around 0.1) from the first to the last tightening, thus suggesting again a highly beneficial effect of shot-peening owing to the reasons highlighted above and to an additional hydrostatic effect arising from lubricant being trapped in the valleys.

The reported results may also be commented on in the light of the observation of the underhead surfaces at the end of the tests in dry or lubricated conditions, considering differently treated screws. It can be observed that, when considering screws that operated in dry conditions, the surfaces are damaged both for unpeened and for peened screws (Figure 7a,b).



**Figure 7.** Microscope images of the surfaces at the underhead after tribological tests in dry conditions with reference to (a) an unpeened and (b) a Z100 10-12N peened screw.

The high level of wear can explain the monotonically increasing trend of friction coefficients for increasing number of tightenings. Anyway, the level of wear can be classified as severe for untreated surfaces, whereas the peened screws (a Z100 10-12N treated one is depicted in Figure 7b) appear to be a bit less damaged. As for lubricated screws, consistent with that observed in [9], a much more reduced wear was observed. Moreover, again, the level of wear seems to be lower for the peened screws, if compared with the unpeened ones. Regarding this point, the surfaces at the underhead of an untreated and of a UFS70 treated screw are shown in Figure 8a,b, respectively.



**Figure 8.** Microscope images of the surfaces at the underhead after tribological tests in lubricated conditions with reference to (a) an unpeened and (b) a UFS70 10-12N peened screw.

## 6. Conclusions

Connecting rod screws may be regarded among the most loaded components in an engine. A literature survey has highlighted that improper fastening, with too high or too low preload, may be the primary reason for failures involving the bolt or the rod. Previous studies have indicated that friction properties, particularly at the underhead, do remarkably affect the achievable preload upon tightening. Further research pointed out that shot-peening has a beneficial effect at reducing friction, as an effect of dimple-related multiple contacts. However, no studies deal with applications on high strength screws and especially no qualitative or quantitative data are available in this field. The present study tackled this question, which can be regarded as its main novelty. An experiment was arranged, accounting for the effects of shot-peening at the underhead, and of deep-rolling, which is usually carried out at the underhead fillet to improve the fatigue strength. The effect of re-tightenings was considered as well, as subsequent tightenings are always run upon assembly and service of connecting rod screws.

The results indicate that deep-rolling does not affect friction, whereas shot-peening is highly beneficial. When considering grease lubricated surfaces, both the bearing and the total frictional

coefficients are significantly decreased by 25%. Moreover, the trend of friction coefficient versus the number of re-tightenings is flat, thus making it possible to restore the initial tribological conditions at every subsequent tightening. It is remarkable that shot-peening is beneficial even in dry conditions. In this case, friction coefficients are reduced by almost 30% and the increase rate versus re-tightenings is also reduced. The retrieved results for shot-peening can be justified by the more porous surface texture induced by this treatment, having the capability of retaining wear debris in the valleys. When lubrication is present, an additional hydrostatic effect contributes to a very low and steady friction trend, even under repeated tightenings. Conversely, deep-rolling has no effect on friction, as the plastic flow-induced undulations around the fillet do not significantly affect the underhead surface flatness. It is clear that deep-rolling cannot have any effect on the texture of the underhead surface far away from the fillet. This can also be regarded as a positive outcome, as it ensures that deep-rolling may be safely used to enhance the fatigue strength, without risking compromising the screw tribological response.

Underhead surface analyses highlighted that a peening treatment has the capability of reducing the wear level in both conditions, although without lubrication, wear remains high. Regarding the two investigated peening conditions, with ceramic and steel shots, the results are well comparable, with slightly better results, in terms of friction reduction, for the UFS 70 treatment involving 70 µm steel shots.

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