

Experimental study of friction in aluminium bolted joints

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Abstract. This study aims at developing an experimental tool useful to define accurately the friction coefficients in bolted joints and, therefore, at relating precisely the tightening torque to the bolt preloading force in some special components used in front motorbike suspensions. The components under investigation are some clamped joints made of aluminium alloy. The preloading force is achieved by applying a torque wrench to the bolt head. Some specific specimens have been appropriately designed and realized in order to study the tribological aspects of the tightening phase. Experimental tests have been performed by applying the Design of Experiment (DOE) method in order to obtain a mathematical model for the friction coefficients. Three replicas of a full factorial DOE at two levels for each variable have been carried out. The levels include cast versus forged aluminium alloy, anodized versus spray-painted surface, lubricated versus unlubricated screw, and first tightening (fresh unspoiled surfaces) versus sixth tightening (spoiled surfaces). The study considers M8x1.25 8.8 galvanized screws.

1 Introduction

Threaded fasteners are widely used in mechanical and structural applications because of their easiness to assembly and disassembly for maintenance and repair purposes. Both the level and the stability of the clamp loads, which are created by the tightening process, will govern the safety and reliability of bolted joints. In most of production applications, the fastener tension (preloading force) is achieved by using a torque wrench applied to the head or to the nut. The tribological aspects of the tightening phase are critical to define the actual torque-tension relationship [1, 2]. The tightening torque is mostly consumed in overcoming two friction components: the underhead (or bearing) friction due to the sliding of the fastener head on the flanges and the thread friction between the male and female thread. The residual torque component produces the fastener tension by generating the joint clamping force. Inaccuracies in determining the friction components may lead to an overestimation or underestimation of the bolted joint performances. The torque-preloading relationship is often simplified by using a constant K (Eq.1), known as torque coefficient (or nut factor): some Authors and Standards [3, 4, 5] provide an approximate value of 0.2 for the nut factor, but cautions against using it for critical joints shall be considered. Bickford [6] provides some mean values of the torque coefficient for various combinations of joint materials and surface conditions. However, the scatter in the torque coefficient is too great to provide a unique and reliable value, particularly in critical joints.

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$$T = K \cdot F_V \cdot d \quad (1)$$

T [Nmm] is the input tightening torque applied to the fastener head or nut, F_V [N] is the preloading force and d [mm] is the nominal thread diameter.

Motosh [7] and VDI2230 [8] provided a more accurate T - F_V relationship, reported in Eq.2, as addition of three different contributions: the pitch T_p , the thread T_t and the underhead T_u torque.

$$T = T_p(F_V, p) + T_t(F_V, \mu_t, d_2) + T_u(F_V, \mu_u, d_u) \quad (2)$$

$$T = F_V \cdot [0.16 \cdot p + 0.58 \cdot \mu_t \cdot d_2 + 0.5 \cdot \mu_u \cdot d_u]$$

p [mm] is the thread pitch, μ_t is the friction coefficient between male and female threads, d_2 [mm] is the mean thread diameter ($d_2 = d - 0.6495 \cdot p$), μ_u is the underhead friction coefficient and d_u [mm] is the underhead mean diameter. The pitch torque component T_p [Nmm] creates the fastener tension and the joint clamp load F_V . By considering a M8x1.25 bolt ($d_2 = 7.19$ mm, $d_u = 11$ mm) and a mean value for friction coefficients μ_t and μ_u equal to 0.15, it is easy to calculate that $T_p \approx 0.12T$, $T_t \approx 0.38T$ and $T_u \approx 0.50T$: the 88% of the total input torque T is consumed in overcoming friction (only 12% is converted in preloading force).

This study aims at developing an experimental tool and procedure useful to define accurately the friction coefficients in bolted joints and, therefore, at relating precisely the input bolt torque T to the bolt preloading force F_V . The components under investigation (Fig.1) are some clamped joints made of aluminium alloy used in front motorbike suspensions to connect the steering plates (forks) to the legs and the legs to the wheel pin: the tensile state of these components (maximum stress and coupling pressure) has been deeply studied by the Authors via Finite Elements Analysis (FEA) in a previous work [9], and it has been related to the preloading force. By leveraging the accurate knowledge of the friction coefficients, it is possible to extend the results presented in [9] using, as input parameter for calculation, the more appropriate tightening torque T (actually controlled during the clamping phase) instead of the preloading force F_V .

The aluminium alloy under investigation is realised by a casting or a forging process, afterwards anodized or spray-painted in surface.

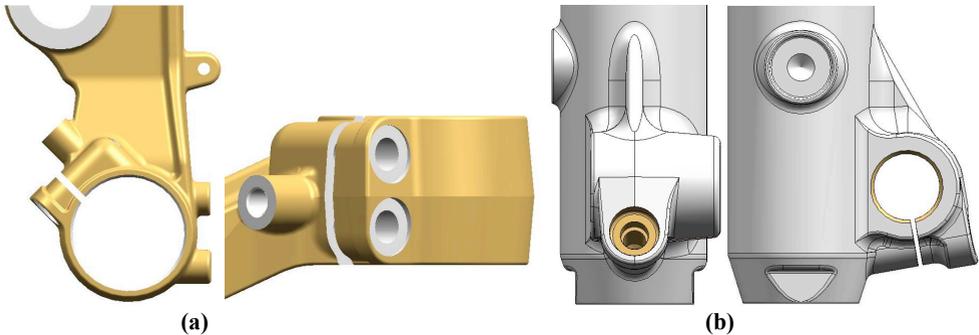


Fig. 1. Example of bolted joints in front motorbike suspensions: (a) steering plate-leg, (b) leg-wheel pin

2 Methodology and Results

In order to evaluate accurately the friction coefficients and to gather their effective mathematical expression, the Design of Experiment method has been applied. In detail, after some screening analyses, a full factorial plane, characterized by 4 variables with 2 levels each, has been designed. Three replicas have been carried out, in order to reduce the influence of noise (experimental error) and any non-investigated factors: a total of $3 \times 2^4 = 48$ experimental tests have been carried out. In Tab.1 the DOE parameters are summarized.

Table 1. The Design of Experiment (DOE) parameters: variables and levels.

<i>Variable</i>	<i>Low Level (0)</i>	<i>High level (1)</i>
A. Lubrication	Unlubricated	Lubricated
B. Process	Cast	Forged
C. Surface finishing	Spray-painted	Anodized
D. Tightening	First tightening (unspoiled surfaces)	Sixth tightening (spoiled surfaces)

According to VDI2230 [8] and DIN946 [10], Eq.2 has been rewritten into Eq.3, considering μ_t and μ_u equal to the same value μ_m in order to describe the overall friction behaviour of the bolt/nut assemblies.

$$T = F_V \cdot [0.16 \cdot p + 0.58 \cdot \mu_m \cdot d_2 + 0.5 \cdot \mu_m \cdot d_u]$$

$$\mu_m = \frac{T/F_V - 0.16 \cdot p}{0.58 \cdot d_2 + 0.5 \cdot d_u} \quad (3)$$

Each test planned by the DOE provides a value of the overall friction coefficient μ_m (Eq.3): in order to calculate μ_m some specific specimens, reported in Fig.2, have been appropriately designed and realized with the same process (cast or forged) and surface finishing (spray-painted or anodized) of the actual components (Fig.1). The study considers M8x1.25, SAE Standard 8.8, galvanized screws ($d_2=7.19\text{mm}$; $d_u=11\text{mm}$).

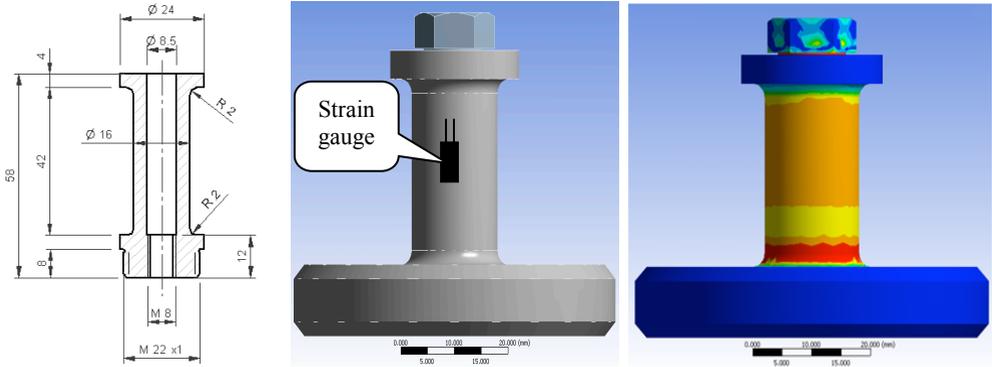


Fig.2 The specimen used for the friction coefficient μ_m definition

The total torque T is given by a calibrated torque wrench whereas the preloading force F_V has been evaluated by means of a strain gauge, located on the external surface of the specimen, which is able to provide the axial compression strain ϵ_C . The compression force F_C (Eq.4) acting on the specimen is equal, in magnitude, to the preloading force acting on the screw, since the system works like *series* of mechanical stiffness during the tightening phase.

$$|F_C| = F_V = |\epsilon_C| \cdot E \cdot A_{eq} \quad (4)$$

E [MPa] is the Young's modulus of the aluminium specimen (69.000MPa) and A_{eq} [mm^2] is the cylindrical equivalent cross section of the compressed region, when the external diameter of the bush ($D_A=16\text{mm}$) exceeds the bolt head diameter ($d_w=13\text{mm}$) as indicated in the sketch of Fig. 3.

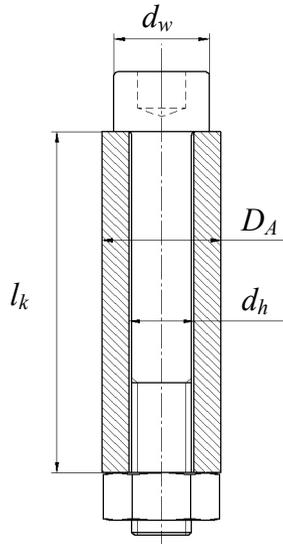


Fig.3 Sketch of a bolt-bush joint

In order to evaluate A_{eq} some formulae, as functions of different geometries (internal diameter of the specimen $d_h=8.5\text{mm}$, length of the specimen $l_k=4+42=46\text{mm}$), are proposed in [11]: the equivalent cross section (Eq.5) results equal to 143.6mm^2 .

$$A_{eq} = \frac{\pi}{4} \cdot (d_w^2 - d_h^2) + \frac{\pi}{8} \cdot d_w \cdot (D_A - d_w) \cdot \left[\left(\sqrt[3]{\frac{l_k \cdot d_w}{D_A^2} + 1} \right)^2 - 1 \right] = 143.6\text{mm}^2 \quad (5)$$

Since the specimen has been designed to be very similar to a thin bush, the equivalent cross section A_{eq} can be considered equal to the actual cross area A (Eq.6): the difference is equal to 0.5%.

$$A = \frac{\pi}{4} \cdot (D_A^2 - d_h^2) = 144.3\text{mm}^2 \approx A_{eq} \quad (6)$$

A Finite Element Analysis (FEA), reported in Fig.2, has demonstrated that the whole cross section (circular and hollow), in correspondence of the region where the strain gauge is located, has the same strain and, therefore, the same stress: the proposed tool (specimen and strain gauge) is able to provide an accurate estimation of the preloading force (Eq.4).

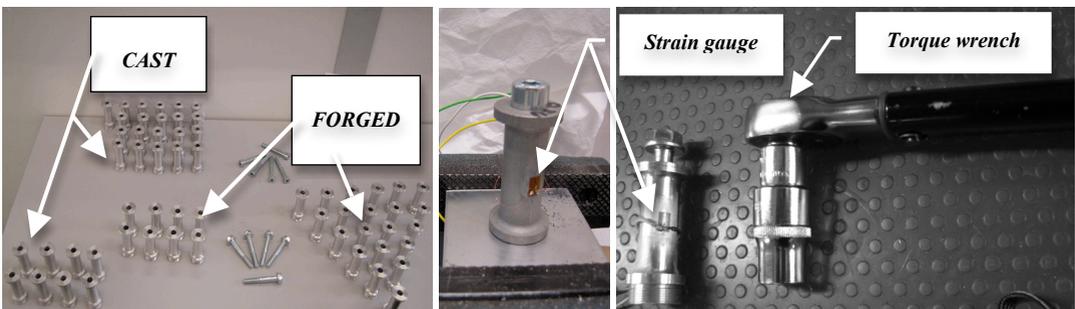


Fig.4 A set of the specimens and their testing tools

According to [12], experimental tests have been randomized: a total torque T equal to 15Nm has been applied to each specimen. The preloading force F_V has been evaluated, as reported in Fig. 4 and both the overall friction coefficient μ_m (Eq.3) and the torque coefficient K (Eq.1) have been calculated, as functions of the DOE variables and levels (Tab.1). The DOE plan and results (48 tests) are reported in Tab.2.

Table 2. DOE plan and results provided by experimental tests ($T=15Nm$)

ID	A. Lubrication	B. Process	C. Surface finishing	D. Tightening	F_V [N]	μ_m	K	ID	A.	B.	C.	D.	F_V [N]	μ_m	K
1	1	0	1	0	10102	0.13	0.19	13	1	1	1	1	10102	0.13	0.19
2	1	1	1	0	9092	0.15	0.21	16	0	1	1	1	3608	0.41	0.52
3	0	1	1	0	6783	0.21	0.28	15	1	0	0	1	15298	0.08	0.12
4	0	0	1	0	7504	0.19	0.25	10	1	1	0	1	18040	0.07	0.10
5	0	1	0	0	10391	0.13	0.18	14	1	0	1	1	15153	0.08	0.12
6	1	0	0	0	17751	0.07	0.11	11	0	0	1	1	4041	0.36	0.46
7	0	0	0	0	14865	0.08	0.13	12	0	0	0	1	10102	0.13	0.19
8	1	1	0	0	17895	0.07	0.10	9	0	1	0	1	9814	0.14	0.19
8	1	1	0	1	16019	0.08	0.12	17	1	1	1	0	9525	0.14	0.20
4	0	0	1	1	5051	0.29	0.37	18	0	0	1	0	6783	0.21	0.28
2	1	1	1	1	10679	0.12	0.18	19	0	1	0	0	11978	0.11	0.16
5	0	1	0	1	7793	0.18	0.24	20	1	1	0	0	16885	0.07	0.11
7	0	0	0	1	12267	0.11	0.15	21	0	0	0	0	11257	0.12	0.17
3	0	1	1	1	4185	0.35	0.45	22	0	1	1	0	4762	0.31	0.39
6	1	0	0	1	16019	0.08	0.12	23	1	0	1	0	9669	0.14	0.19
1	1	0	1	1	10824	0.13	0.18	24	1	0	0	0	9381	0.14	0.20
9	0	1	0	0	14432	0.09	0.13	18	0	0	1	1	4330	0.34	0.43
10	1	1	0	0	21648	0.05	0.09	21	0	0	0	1	9381	0.14	0.20
11	0	0	1	0	5484	0.26	0.34	22	0	1	1	1	2165	0.70	0.87
12	0	0	0	0	12989	0.10	0.14	23	1	0	1	1	8659	0.16	0.22
13	1	1	1	0	8515	0.16	0.22	19	0	1	0	1	8659	0.16	0.22
14	1	0	1	0	15009	0.08	0.12	17	1	1	1	1	9525	0.14	0.20
15	1	0	0	0	16885	0.07	0.11	24	1	0	0	1	9236	0.15	0.20
16	0	1	1	0	6206	0.23	0.30	20	1	1	0	1	15442	0.08	0.12

Table 3. Example of ANOVA Table results for μ_m

Effect (interaction)	Sum of Square	DoF	Mean Square	F_0
A – Lubrication	0.1610	1	0.1610	53.31
B – Process	0.0085	1	0.0085	2.83
C – Surface finishing	0.1776	1	0.1776	58.81
D – Number of tightening	0.0352	1	0.0352	11.66
AB	0.0114	1	0.0114	3.78
AC	0.0690	1	0.0690	22.85
AD	0.0320	1	0.0320	10.61
BC	0.0108	1	0.0108	3.58
BD	0.0030	1	0.0030	1.00
CD	0.0102	1	0.0102	3.38
ABC	0.0004	1	0.0004	0.14
ABD	0.0056	1	0.0056	1.87
ACD	0.0176	1	0.0176	5.84
BCD	0.0010	1	0.0010	0.33
Error	0.0997	33	0.0030	1.00

Once the whole 48 values of μ_m and K have been calculated, their results were studied by applying the Analysis Of VAriance (ANOVA) [12, 13]. This technique is based on a statistical approach and allows evaluating the effect of each variable and of their interaction, in order to identify those variables (or interactions) that are actually significant in changing the friction coefficients value. By means of the software Stagraphics® Plus, Release 5.1, the ANOVA table has been generated (an

example is reported in Tab.3) and the Fisher's test (F-Test) has been executed. F_0 value is determined subdividing the Mean Square of the single effect (or interaction) with the Mean Square of the Error [14]. The error probability α has been set equal to 0.10 (10%) and Fisher's value $F_{v_1;v_2;\alpha}$ has been obtained from Fisher's table [12, 13] (v_1 are the Degrees of Freedom of the source of variation and v_2 of the source of Error). The variables (or interactions) with F_0 higher than the corresponding $F_{v_1;v_2;\alpha}$ ($F_{1;17;10\%}=2.87$) are significant in the analysis (grey cells in Tab.3), whereas the other could be ignored in the response model (white cells in Tab.3), with a confidential level of $(1-\alpha)=90\%$. ANOVA and F-Test provide Eq. (7) and Eq. (8) in which the Regression Coefficients and, therefore, the mathematical models for μ_m and K are reported as functions of the significant investigated variables (or interactions).

$$\mu_m = 0.108 - 0.023 \cdot A + 0.103 \cdot C + 0.010 \cdot D - 0.007 \cdot A \cdot B - 0.063 \cdot A \cdot C + 0.017 \cdot A \cdot D + 0.053 \cdot B \cdot C + 0.117 \cdot C \cdot D - 0.153 \cdot A \cdot C \cdot D \quad (7)$$

$$K = 0.157 - 0.028 \cdot A + 0.123 \cdot C + 0.013 \cdot D - 0.008 \cdot A \cdot B - 0.075 \cdot A \cdot C + 0.015 \cdot A \cdot D + 0.065 \cdot B \cdot C + 0.138 \cdot C \cdot D - 0.180 \cdot A \cdot C \cdot D \quad (8)$$

Surface finishing (specimen spray-painted or anodized), lubrication (specimen lubricated or unlubricated), the interaction between surface finishing and lubrication, and finally the number of tightening are the most significant parameters (highest values of F_0 are highlighted by the bold style in Tab.3). In the bars diagrams of Fig. 5 and Fig. 6 some results are compared depending on the aforementioned parameters in case of forged specimens.

It is possible to highlight that the spray-painted specimens present the lower μ_m (the higher preloading forces F_v). For example, in presence of unspoiled surfaces, the overall friction coefficient μ_m decreases from the value of 0.26 in case of forged, anodized and unlubricated specimens to the value of 0.11 in case of forged, spray-painted and unlubricated ones, so that the preloading force increases of twice with the same tightening torque $T=15\text{Nm}$. Lubrication always increases the preloading forces: in presence of forged and unspoiled surfaces, the overall friction coefficient μ_m decreases from the value of 0.11 to 0.08 in case of spray-painted specimens, and from the value of 0.26 to 0.17 in case of anodized ones. Finally, considering the effect of the number of tightening and loosening (up to six maintenance operations in a standard motorbike lifecycle) the preloading force are affected by the tightening replicas mainly in case of unlubricated and anodized surfaces so that the preloading forces progressively decrease for the same tightening torque. As a matter of fact the surfaces are subjected to wear and spoiling (Fig.7) by increasing the number of tightening, while lubrication creates a sort of protective film. In presence of spoiled surfaces, the overall friction coefficient μ_m increases from the value of 0.26 to 0.39 in case of forged, anodized and unlubricated surfaces, whereas from the value of 0.16 to 0.17 in case of forged, anodized and lubricated surfaces.

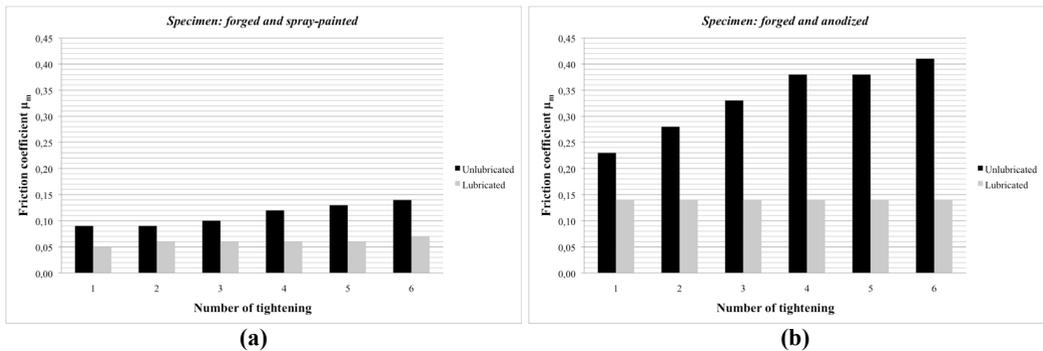


Fig.5 Bars diagrams of the friction coefficient μ_m values for forged specimens ((a): spray-painted (b): anodized) in case of tightening torque $T=15\text{Nm}$ (different series for lubricated and unlubricated specimens)

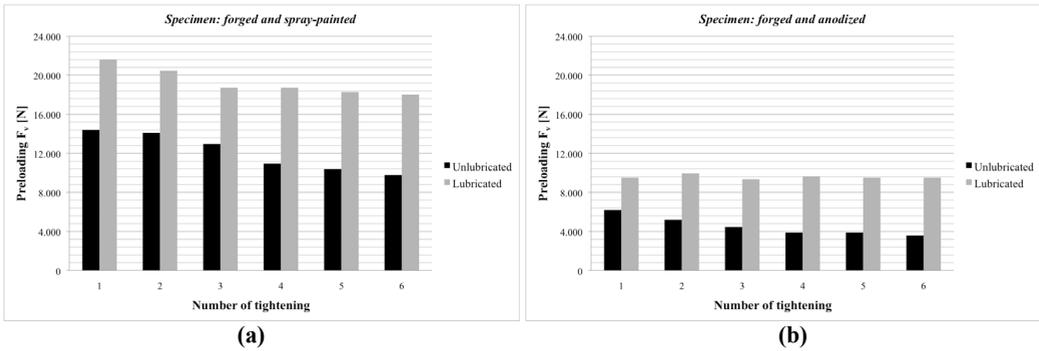


Fig.6 Bars diagrams of the preloading force F_p values for forged specimens ((a): spray-painted (b): anodized) in case of tightening torque $T=15\text{Nm}$ (different series for lubricated and unlubricated specimens)



Fig.7 Spray-painted specimens (a): unspoiled surfaces with D variable equal to 0 (b): spoiled surfaces with D variable equal to 1

3 Conclusion

The friction coefficient and the torque coefficient have been accurately calculated for some bolted joints of components used in front motorbike suspensions. For this purpose the authors have been designed and realised some specific specimens in order to evaluate differences between cast and forged aluminium alloy, between spray painted and anodized surfaces, between lubricated and unlubricated screw and, finally, between first tightening (fresh and unspoiled surfaces) and sixth tightening (spoiled surfaces). A total of 48 tests have been executed by applying the DOE method while the results have been analysed by the ANOVA and F-Test methods: friction conditions are strongly affected by surface finishing, lubrication and number of tightening and loosening; the forming process (forged or cast aluminium alloy) seems to have no significant influence on friction conditions. The mathematical models of the overall friction and torque coefficients have been derived as functions of the significant variables highlighted by the ANOVA and F-Test. The presented models are useful to estimate precisely the actual preloading force, deriving it directly from the tightening torque. The actual torque versus preloading force relationship for aluminium-steel bolted joints used in front motorbike suspensions can be effectively adopted for any type of maintenance operation.

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