Determination of the coefficient of friction in a screw joint loaded with a controlled torque

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Abstract. The aim of this article is mechanism description for the measuring the friction coefficient in the threads of threaded joint and consecutive experimental measuring of friction coefficient. The coefficient of friction in the threads of a bolt and nut depends on a number of factors, in particular the roughness of the surfaces, the properties of the lubricating film and the angle of the side of the thread. The coefficient is a function of the heat treatment, the quality of the surface protection substance, the size of the screw load and the pitch angle of the thread. The principal parameters of the measuring was fastening torque, which was choose by the torque wrench, axial strength, measured by axial force sensor, and calculated friction coefficient. The friction coefficient was calculated through the use of exponential equation of the torque balance in the screw. The value of the friction coefficient was examined on the threaded joint of size M20 without the plastic lubricants and with the plastic lubricants. Measured values of friction coefficient was close to values listed in the norm and makes argument that plastic lubricants can decrease the friction coefficient in the threads of threaded joint.

1. Introduction
Bolt joints rank among dismountable joints designed to connect diverse components. From the technical point of view, their function is based on threaded coupling. The thread is referred to as a functional element and to a high degree the threads are standardized. Consequently, according to a specific shape and based on profiles, several types of threads can be distinguished as follows – metric, Whitworth, pipe, knuckle, Panzergewinde, etc. Except for the respective use, the threads designed as structural parts of uncomplicated shapes of the individually connected components form a principle of an active screw-based mechanism referred to as a gear. It is used for changing the rotational motion to the linear or to the advanced one. However, in the practice, the most commonly employed thread coupling is in the form of connecting material. Bolted joints also include bolt nuts and screws of specific shape owing to which they meet general standards. The standards refer to position adjustment, pressing-out, assurance of tightness, stressing, etc.
Bolted joint designing includes designing of material and strength dimensioning. At the same time, requirements related to operation load must be taken into consideration as well. The bolted joint functions as required only if all mechanical properties of the individual elements are preserved along with degree of precision of the defined tolerated dimensions. In practice, the bolted joints are subjected to load tests according to specified calculations. The tests verify bolted joint efficiency, different deformations, thread strength, etc.
A primary role of the bolted joints is to grasp tightly the connected parts located between the bolt nut and the screw head. All inevitable forces are formed when the respective screw or bolt nut is tightened with the predefined torque. Apart from the force acting in the direction of the screw axis, the bolted joints induce other forces being perpendicular to its axis which is caused by friction forces. These forces occur especially in abutting areas of the connected parts. Friction force must be acting adequately to prevent shift of the connected parts and consequent stress of the screw by shear [09].

From the point of view of modern design engineering, assessment of carrying capacity, service life and meeting of functional requirements of the bolted joint is significantly influenced by correct definition of axial force $F_0$ when the screw or the bolt nut is tightened as well as by practical procedures inevitable for its achievement [06].

2. Bolted Joints Testing and Designing

Each designing process of the bolted joint, of its consequent structure, of strength dimension, and of material requires taking into consideration specified functional demands especially those which are operation load related. If the bolted joint must meet required criteria, it is inevitable to preserve prescribed mechanical properties of any of the bolted joint elements [03].

2.1. Ratio of Forces in the Bolted Joint

Ratio of forces in the screw is ration of forces on the inclined plane. It is relation between axial force $F_0$, driving force $F_1$ and other thread parameters.

2.1.1. Frictionless Motion

$$F_1 = F_0 \cdot \tan \gamma$$

Figure 1. Ratio of forces for frictionless motion

with $F_1$ - tangential force acting on mean diameter of the thread,
$F_0$ - axial force,
$F_N$ - normal force.

2.1.2. Motion with Friction - tightening

Figure 2. Ratio of forces for motion with friction (tightening)
\[
\sum F_\alpha = 0 \Rightarrow F_1 = F_N \cdot \sin \gamma + f \cdot F_N \cdot \cos \gamma
\]
\[
\sum F_\nu = 0 \Rightarrow F_Q = F_N \cdot \cos \gamma - f \cdot F_N \cdot \sin \gamma
\]
\[
\frac{F_1}{F_Q} = \frac{F_N \cdot \sin \gamma + f \cdot F_N \cdot \cos \gamma}{F_N \cdot \cos \gamma - f \cdot F_N \cdot \sin \gamma} \Rightarrow
\]
\[
F_1 = \frac{F_Q \cdot \sin \gamma + f \cdot \cos \gamma}{\cos \gamma - f \cdot \sin \gamma}
\]
\[
F_T = F_N \cdot f', \quad f' - \text{coefficient of friction.}
\]

When modified: \( F_1 = F_Q \cdot \frac{\tan \gamma + f}{1 - f \cdot \tan \gamma} \) \text{ resp. } \( F_1 = F_Q \cdot \frac{\tan \gamma + f \phi}{1 - f \cdot \tan \gamma \cdot \tan \phi} = F_Q \cdot \tan (\gamma + \phi) \)

2.2. Influencing Factors
The factors influencing relation between tightening torque and axial force in the screw can be classified as follows:
- \textit{geometrical} – thread shape and contact area between reciprocally rotating parts,
- \textit{tribological} – contact area friction [05].
Coefficient of friction \( f \) in the screw and bolt nut threads depends on a number of factors, especially on surface roughness, properties of greasing film, and on thread edge angle. Furthermore, \( f \) is a function of heat treatment, quality of material representing surface protection, magnitude \( F_O \) (screw load) and thread lead angle \( \gamma \) [07].
Character of the influence of the first group is highly deterministic one, however, the second group causes certain variance in a result and its global effect on the bolted joint must be defined by an experiment. Semi-empirical formula was derived for the screws through the aforementioned process.

2.3. Coefficient of Friction of the V-thread
Alike in friction, the flat thread premise is accepted and the moment equation is stemmed from, in case of which \( \phi \) or \( f \) is substituted by \( \phi' \) or \( f' \)
\[
T_A - F_Q \cdot \tan (\gamma + \phi') \frac{d_s}{2} = 0
\]
\[4\]
\[
T_A - F_Q \cdot (\tan \gamma + f') \frac{d_s}{2} = 0
\]
axial force in the screw
\[
F_O = \frac{2 \pi F_A l}{\pi f' \cdot d_s + s}
\]
coefficient of friction in the threads regardless of inclination angle of the thread
\[
f' = \frac{2 \pi T_A - F_O \cdot s}{\pi F_O \cdot d_s}
\]
coefficient of friction of the V-thread with \( \alpha \) standing for inclination angle of the thread
\[
f' = \frac{f}{\cos \frac{\alpha}{2}} \Rightarrow f' = f' \cdot \cos \frac{\alpha}{2}
\]
Influence of the \( \alpha \) angle results in increase of coefficient of friction \( f' \) in case of the V-thread with the increasing value \( \alpha \). The submitted paper deals with magnitude of coefficient of friction \( f' \).
3. Stand and Elements Essential for the Experiment
Laboratory measurement focused on determination of the coefficient of friction of the bolted joint with tightening torque and emerging axial force being under monitoring. The screw M20 x 100 STN EN 24017 was used as a sample in the experimental measurement. Prior to measurement, the screw was degreased to avoid measurement errors caused by impurities occurring on the thread surface, etc. Screw lead reached the value of $s = 2.5\ mm$ and mean diameter of the thread amounted to $d_s = 18.376\ mm$. The values serve for calculation of the coefficient of friction in the bolted joint.

Emerging axial force $F_o$ was monitored in the experimental measurement with the controlled tightening (axial) torque. Bolted joint load was monitored with the degreased meshing threads and threads greased with MOL Alubia AK2.

A stand was used for the practical part designed for monitoring of the axial force in the bolted joint. Measurement was performed in testing and monitoring centre of technical systems at Department of Technical Systems Design and Monitoring at the Faculty of Manufacturing Technologies TUKE.

Measurement was performed with the screw M20. The measurement required preparation of a measuring stand including pre-specified parts absence of which would make the measurement impossible. Measurement was performed with pre-defined values of axial torque. Consequently, the computer software displayed a graph which allowed reading off the axial force with individual axial torque values [02].

**Figure 3.** Stand designed for monitoring of bolted joints during controlled loading
A measuring stand consists of the following components: stand frame (1), axial force sensor (2) connected to a PC (3) through a converter (4), loaded and monitored screw (5), and measuring device for tightening (axial) torque (6). Tightening was performed manually to achieve desired tightening torque. Following the tightening the emerged axial force is transformed through the converter directly to the computer and consequently, the software forms dependence of axial force on time.

3.1. Digital Electronic Converter EMS650
Laboratory measurement was performed with a digital electronic converter Emsyst EMS650 with interface of USB 2.0. The converter is employed in digitalization of a signal produced by sensors working on the principle of a resistance bridge. A sensor of torque, of pressure, of force or of weight can serve as an example. The respective converter is not equipped with any auxiliary control units as all necessary set-ups or adjustments are performed by the computer or by the laptop. The EMS Center serves for the purposes of important data processing.
3.2. Tensometric Force Sensor
Laboratory measurement was performed with tensometric sensor EMS20 designed for monitoring of axial force with measurement range of up to $5\,kN$. It is a case of membrane type of tensometric sensor equipped with a full tensometric bridge. Measurement can be performed in the direction of pressure or tension [08]. The sensor is employed in all industries, in spheres of testing or in laboratories which measure force load. The sensor can be gripped with the use of external threads. In practice, the sensor is used for measuring of the forces on machines, in case of dynamometres or electronic scales.

3.3. Digital Torquemeter WRG3-135
A small digital torquemeter is designed for fast measuring and control of force during screw tightening. The torquemeter is installed directly onto a tightening key. The torquemeter is equipped with a digital display which shows actual measured values of axial torque or in case of maximum loading the display can show maximal value. Digital torquemeter WRG3-135 with measurement range from 6.8 up to 135 Nm serves for fast measuring and control of force during screw tightening with precision of $\pm\,2\%$ [05].

3.4. Software EMS Center
All laboratory measurement results of the controlled axial torque loading and of the monitoring of emerging axial force in case of particular bolted joint were evaluated by means of the EMS Center software. The software version is V1.02 and supports the operating system Windows 7, 8 and 10. The software is primarily designed for data collection by means of digital electric units by the company of EMSYST. The software offers graphical plotting of the selected developments and their consequent storage in files of desired formats.

4. Experimental Measurement

4.1. Dry Abrasion

Neither lubricating grease nor oils were used in this type of measurement. Coefficient of friction should thus reach the maximum values contrary to the following measurements in case of which lubricating grease was applied. The measured values are present in table 1 and in figure 7.

| No. of measurement | 1  | 2  | 3  | 4  | 5  | 6  |
|--------------------|----|----|----|----|----|----|
| Loading – tightening torque $M_{T_1}$ [Nm] | 11.8 | 20.0 | 31.2 | 40.2 | 50.7 | 60.3 |
| Emerging axial force $F_{Oa}$ [N] | 477.86 | 766.39 | 1175.90 | 1514.52 | 1824.24 | 2087 |

**Table 1.** Values measured in dry abrasion

![Figure 7. Dependence of emerging axial force $F_O$ on time from software EMS Center](image)

Calculated coefficients of friction $f'$ for the individual tightening torques in dry abrasion are as follows:

$$f'_{a1} = \frac{2\pi.M_{T_1} - F_{Oa1}.s}{\pi.F_{Oa1}.d_s} = \frac{2\pi.11.8 \text{ Nm} - 477.86 \text{ N}.0.0025 \text{ m}}{\pi.477.86 \text{ N}.0.018376 \text{ m}} = 2.644268$$

$$f'_{a2} = \frac{2\pi.M_{T_2} - F_{Oa2}.s}{\pi.F_{Oa2}.d_s} = \frac{2\pi.20 \text{ Nm} - 766.39 \text{ N}.0.0025 \text{ m}}{\pi.766.39 \text{ N}.0.018376 \text{ m}} = 2.796962$$
\[ f'_{a3} = \frac{2\pi M_{Ta3} - F_{Oa3}\cdot s}{\pi F_{Oa3}\cdot d_s} = \frac{2\pi \cdot 31.2 \, Nm - 1175.90 \, N \cdot 0.0025 \, m}{\pi \cdot 1175.90 \, N \cdot 0.018376 \, m} = 2.844469 \]

\[ f'_{a4} = \frac{2\pi M_{Ta4} - F_{Oa4}\cdot s}{\pi F_{Oa4}\cdot d_s} = \frac{2\pi \cdot 40.2 \, Nm - 1514.52 \, N \cdot 0.0025 \, m}{\pi \cdot 1514.52 \, N \cdot 0.018376 \, m} = 2.845579 \]

\[ f'_{a5} = \frac{2\pi M_{Ta5} - F_{Oa5}\cdot s}{\pi F_{Oa5}\cdot d_s} = \frac{2\pi \cdot 50.7 \, Nm - 1824.24 \, N \cdot 0.0025 \, m}{\pi \cdot 1824.24 \, N \cdot 0.018376 \, m} = 2.981553 \]

\[ f'_{a6} = \frac{2\pi M_{Ta6} - F_{Oa6}\cdot s}{\pi F_{Oa6}\cdot d_s} = \frac{2\pi \cdot 60.3 \, Nm - 2087 \, N \cdot 0.0025 \, m}{\pi \cdot 2087 \, N \cdot 0.018376 \, m} = 3.101356 \]

Actual coefficients of friction \( f \) for the individual tightening torques in dry abrasion are as follows:

\[ f_{a1} = f'_{a1}\cdot\cos\frac{\alpha}{2} = 2.644268\cdot\cos\frac{60^\circ}{2} = 2.290003 \]

\[ f_{a2} = f'_{a2}\cdot\cos\frac{\alpha}{2} = 2.796962\cdot\cos\frac{60^\circ}{2} = 2.42224 \]

\[ f_{a3} = f'_{a3}\cdot\cos\frac{\alpha}{2} = 2.844469\cdot\cos\frac{60^\circ}{2} = 2.463382 \]

\[ f_{a4} = f'_{a4}\cdot\cos\frac{\alpha}{2} = 2.845579\cdot\cos\frac{60^\circ}{2} = 2.464344 \]

\[ f_{a5} = f'_{a5}\cdot\cos\frac{\alpha}{2} = 2.981553\cdot\cos\frac{60^\circ}{2} = 2.582101 \]

\[ f_{a6} = f'_{a6}\cdot\cos\frac{\alpha}{2} = 3.101356\cdot\cos\frac{60^\circ}{2} = 2.685853 \]

4.2. Abrasion with the Use of Lubricating Grease MOL Alubia AK 2

Lubricating grease Alubia AK 2 is produced from high quality mineral oil and aluminium complex soap. The lubricating grease does not contain any additives. Its quality stems from positive properties of the Al-Kx soap and greasibility of mineral oils. It is of semi-soft consistence, of yellow-brown colour and with short-fibre structure. It is hot and cold-water resistant. The lubricating grease AK 2 ranks among the multi-use industrial grease types [01]. Primarily, it is suitable for slide and rolling-element bearings not exposed to high pressure or high rotations. Temperature range of use is from -30°C up to +100°C, and in case of regular additional lubricating the temperature ranges even up to +120°C. Table 2 and figure 8 show the measured values.

Table 2. Measured values in case of abrasion with lubricating

| No. of measurement | 1   | 2   | 3   | 4   |
|--------------------|-----|-----|-----|-----|
| Loading – tightening torque \( M_{Tb} \) [Nm] | 10.3 | 19.1 | 30.1 | 40.3 |
| Emerging axial force \( F_{Oa} \) [N] | 903.60 | 1563.30 | 2407.78 | 3139 |
Calculated coefficients of friction $f'$ for the individual tightening torques in abrasion with lubricating grease Alubia AK2 are as follows:

\[
\begin{align*}
    f'_1 &= \frac{2\pi M_{Tb1} - F_{Ob1} \cdot s}{\pi F_{Ob1} \cdot d_s} = \frac{2\pi \cdot 10.3 \ N m - 903.60 \ N \cdot 0.0025 \ m}{\pi \cdot 903.60 \ N \cdot 0.018376 \ m} = 1.197319 \\
    f'_2 &= \frac{2\pi M_{Tb2} - F_{Ob2} \cdot s}{\pi F_{Ob2} \cdot d_s} = \frac{2\pi \cdot 19.1 \ N m - 1563.30 \ N \cdot 0.0025 \ m}{\pi \cdot 1563.30 \ N \cdot 0.018376 \ m} = 1.286445 \\
    f'_3 &= \frac{2\pi M_{Tb3} - F_{Ob3} \cdot s}{\pi F_{Ob3} \cdot d_s} = \frac{2\pi \cdot 30.1 \ N m - 2407.78 \ N \cdot 0.0025 \ m}{\pi \cdot 2407.78 \ N \cdot 0.018376 \ m} = 1.317289 \\
    f'_4 &= \frac{2\pi M_{Tb4} - F_{Ob4} \cdot s}{\pi F_{Ob4} \cdot d_s} = \frac{2\pi \cdot 40.23 \ N m - 3139 \ N \cdot 0.0025 \ m}{\pi \cdot 3139 \ N \cdot 0.018376 \ m} = 1.354005
\end{align*}
\]

Actual coefficients of friction $f$ for the individual tightening torques in abrasion with lubricating grease Alubia AK2 are as follows:

\[
\begin{align*}
    f_b1 &= f'_1 \cos \frac{\alpha}{2} = 1.197319 \cdot \cos \frac{60^\circ}{2} = 1.036909 \\
    f_b2 &= f'_2 \cos \frac{\alpha}{2} = 1.286445 \cdot \cos \frac{60^\circ}{2} = 1.114094 \\
    f_b3 &= f'_3 \cos \frac{\alpha}{2} = 1.317289 \cdot \cos \frac{60^\circ}{2} = 1.140806 \\
    f_b4 &= f'_4 \cos \frac{\alpha}{2} = 1.354005 \cdot \cos \frac{60^\circ}{2} = 1.172603
\end{align*}
\]

Based on the given calculations, the coefficient of friction values were calculated. Consequently, according to the acquired results, the actual coefficients of friction for the individual tightening torques were calculated.
5. Results and evaluation of the experimental measurement

![Dependence of loading tightening torque on emerging axial force without greasing and with lubricating grease Alubia AK2](image)

**Figure 9.** Dependence of loading tightening torque on emerging axial force without greasing and with lubricating grease Alubia AK2

![Dependence of tightening torques on actual calculated coefficients of friction without greasing and with lubricating grease Alubia AK2](image)

**Figure 10.** Dependence of tightening torques on actual calculated coefficients of friction without greasing and with lubricating grease Alubia AK2

6. Conclusion

Calculated coefficients of friction in the thread are determined by laboratory testing and depend on a number of factors including an inrun of the bolted joint. Past a few tightening processes, it causes extension of axial force in the screw threads which is the main reason for variance of the measured values. Therefore, each measurement was followed by a complete unscrewing and re-screwing of the
screw to avoid encounter of the identical threads. Contrary to a linear theory, the actual dependence of the axial force on tightening torque has a progressive character. Based on the results of verifying experiments, the linear formula can be recommended for estimating a lower limit of axial force $F_0$ when tightening torque $M_T$ is applied. The actual value of $F_0$ can be higher even by 50%, especially in case of high values of $M_T$, which must be respected and taken into consideration when characteristic stress in screws is high because the areas of threads abrade. At the same time, to achieve reproducible values in a set of the uniform screws it is inevitable to pay particular attention to their identical greasing. The final part of the experiment can confirm the theory of lower values of coefficients of friction in the bolted joints in case of friction with lubricating. The values which have been measured and calculated are shown in the individual figures and plotted in the graphs.

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