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Experimental Analysis of Modern Screw Fasteners

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Abstract. This contribution describes analytical evaluation and experimental verification of the friction and force conditions in the prestressed bolted connections. In the case of using standard fasteners (bolts and nuts) there were evaluated mainly influence of advanced coatings using and lubricants into the threaded surfaces of bolted joints. To achieve the set goals modular design testing stand was designed. Achieved analytical findings and experimental verification will allow to refine the technological processes of assembly of bolted joints, which will have a major impact on the strength, durability and reliability of the screw connections (fasteners). Discovered knowledge is not currently available for design engineers during the designing of bolted joints. Design engineers typically use only recommendation of retailers and manufacturers when designing of bolted joints. In industrial practice, it is now very often required to calculate the screws according to the standard VDI 2230. [2] Standard VDI 2230 specifies a procedure for the strength calculation of prestressed screw connections. The calculation is usually done on a personal computer using the KissSoft program.

Introduction

The process of tightening threaded fastener assemblies, especially for critical bolted joints, involves controlling both input torque and angle of turn to achieve the desired result of proper preload of the bolted assembly. Understanding the role of friction in both the underhead and threaded contact zones is the key to defining the relationship between torque, angle, and tension. There can be as many as 200 or more factors that affect the tension created in a bolt when tightening torque is applied. Fortunately, torque-angle signature curves can be obtained for most bolted joints. By combining the torque-angle curves with a few simple calculations and a basic understanding of the engineering mechanics of threaded fasteners, you can obtain the practical information needed to evaluate the characteristics of individual fastener tightening processes. The torque-angle curves can also provide the necessary information to properly qualify the capability of tightening tools to properly tighten a given fastener. These findings were described by Shoberg. [1]

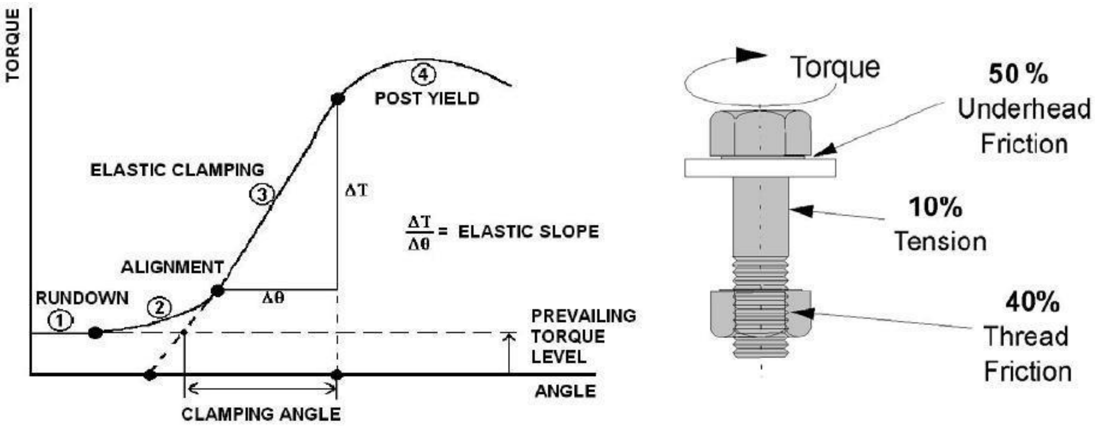

Fig. 1 Measured Torque-angle Curve. Four Zones of the Tightening Process. [1]

Prestressed Bolted Joints Theory

There are shown a prestressed bolted connection loaded with a centric axial force and diagram of prestressed bolted connection force - deformation in Fig. 2.

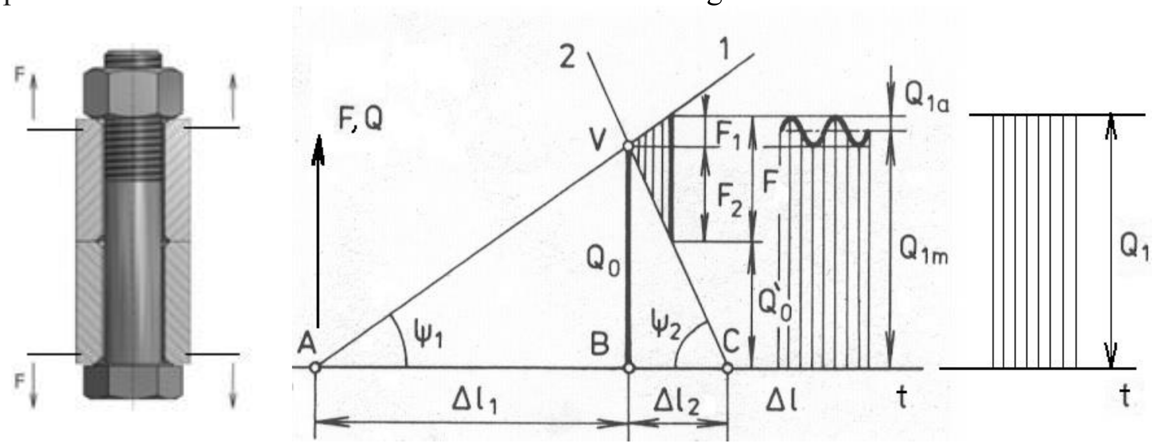

Fig. 2 Prestressed Bolted Connection Loaded with a Centric Axial Force (on the left side); Diagram of Prestressed Bolted Connection Force - Deformation (on the right side). [5]

The static strength calculation of the prestressed screw connection is performed according to the following equations (Eq. 1 through Eq. 17):

$$\gamma = arctg\,\frac{P}{\pi \cdot d_2} \tag{1}$$

$$f' \approx \frac{f}{\cos\beta} \tag{2}$$

$$M_{KK} = M_K + M_{TM} = Q_o \cdot \frac{d_2}{2} \cdot tg(\gamma + \varphi') + Q_o \cdot \rho_{TM} \cdot f_{TM} \tag{3}$$

$$Q_o = \frac{M_{KK}}{\frac{d_2}{2} \cdot tg\left(\gamma + \varphi'\right) + \rho_{TM} \cdot f_{TM}} \tag{4}$$

$$c = \frac{E \cdot S}{l} \tag{5}$$

$$\frac{1}{c_s} = \frac{1}{c_{sd}} + \frac{1}{c_{sz}} \tag{6}$$

$$\frac{1}{c_1} = \frac{1}{c_s} + \frac{2}{c_{lDa}} + \frac{1}{c_M} \tag{7}$$

$$c_2 = c_{lDb} \tag{8}$$

$$F_1 = \frac{c_1}{c_1 + c_2} \cdot F \tag{9}$$

$$F_2 = \frac{c_2}{c_1 + c_2} \cdot F \tag{10}$$

$$Q_1 = Q_o + F_1 \tag{11}$$

$$\sigma_{Q1} = \frac{Q_1}{S_3} = \frac{4 \cdot Q_1}{\pi \cdot d_3^2} \tag{12}$$

$$\tau_K = \frac{M_K}{W_K} = \frac{16 \cdot M_K}{\pi \cdot d_3^3} = \frac{16 \cdot Q_o \cdot \frac{d_2}{2} \cdot tg(\gamma + \varphi')}{\pi \cdot d_3^3} \tag{13}$$

$$\sigma_{red} = \sqrt{\sigma_{Q1}^2 + 3 \cdot \tau_K^2} \tag{14}$$

$$k_s = \frac{R_{p0,2}}{\sigma_{red}} \geq k_{s\min} = 1,2 \tag{15}$$

$$p_Z = \frac{Q_1}{\pi \cdot d_2 \cdot H_1 \cdot z} \geq p_{Zdov} \tag{16}$$

$$p_M = \frac{4 \cdot Q_1}{\pi \cdot (D^2 - d^2)} \geq p_{Mdov} \tag{17}$$

γ - thread pitch angle [°]; β - half angle of the thread profile [°]; φ' - friction angle in thread [°]; P - pitch [mm]; d_2 - flank diameter of the bolt thread [mm]; d_3 - core diameter of the bolt thread [mm]; ρ_{TM} - friction radius under the nut [mm]; f - coefficient of friction [1]; f' - coefficient of friction in thread [1]; f_{TM} - coefficient of friction under the nut [1]; M_{KK} - tightening torque [Nmm]; M_K - torque [Nmm]; M_{TM} - friction torque under the nut [Nmm]; Q_o - mounting - pretension force [N]; c - constants of stiffness [Nmm^{-1}]; E - Young's modulus of individual parts [Nmm^{-2}]; S - cross section of individual parts [mm^2]; l - length of individual parts [mm]; F - external axial force [N]; F_1, F_2 - components of external axial force [N]; Q_1 - maximum internal force of the bolt [N]; σ_{Q1} - tensile stress [Nmm^{-2}]; τ_K - share stress [Nmm^{-2}]; σ_{red} - equivalent stress [Nmm^{-2}]; $R_{p0,2}$ - yield point [Nmm^{-2}]; k_S - safety against yield point [1]; p_Z - contact pressure in the thread [MPa], p_M - contact pressure under the nut [MPa], D, d - outer and inner diameters of the replacement tube [mm].

There is defined the concept of controlled tightening of the screw connection in the technical support of the company Bossard. [3] This method of tightening the screw connection respects the variable value of the friction coefficient in the thread and the reduction of prestress of the screw connection after assembly. Actual tensile bolt prestress after controlled tightening ensures correct functioning of screw joints during operation. The tensile prestress value of the bolt must be greater than the minimum value in terms of the correct operation of the screw connection and at the same time tensile prestress value of the bolt must by less than the maximum permissible value in relation to the achieve the yield strength of the bolt (see Fig. 3).

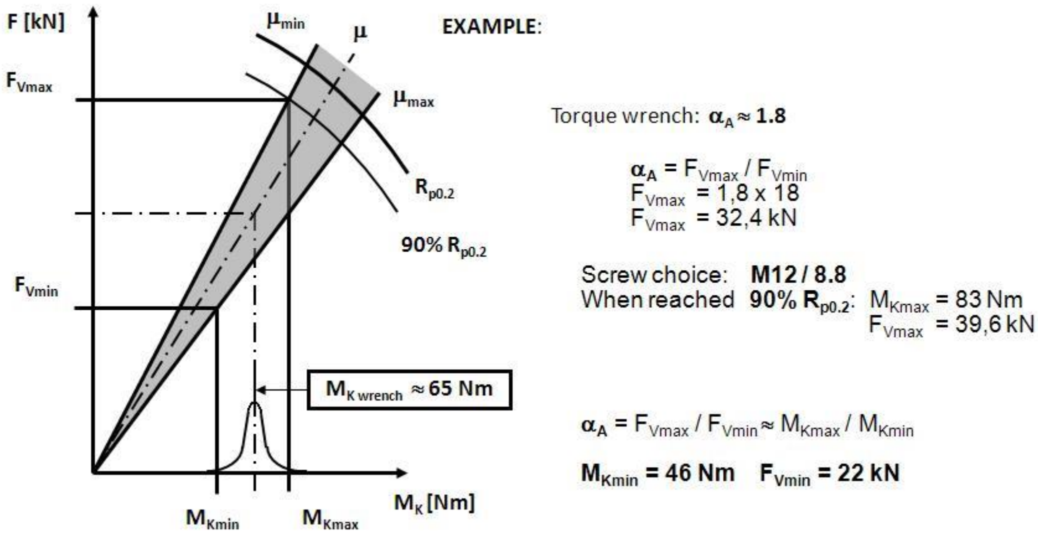

Fig. 3 Controlled Tightening Process of the Prestress Screw Joints. The Calculation Procedure of the Bolted Joints and these Diagrams are Presented in the [1,2,3]

Due to the contact of multiple surfaces with real surface roughness, the tension axial prestress is reduced after the screw connection is assembled. This phenomenon is caused by plastic deformation of individual contact surfaces. Reduction of the axial tensile stress is dependent on the number of contact surfaces of the screw joint and on their surface roughness (see Fig. 4).

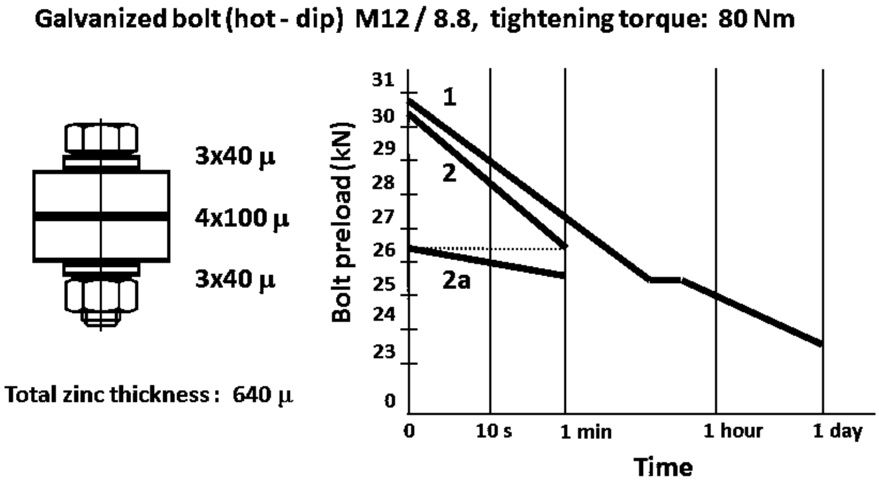

Fig. 4 Tension Axial Prestress Reduction of the Screw Joint after Assembly in Time. [2,3]

Experimental Analysis

The simple testing equipment for evaluation of threaded contact friction between the bolt and the nut was designed and manufactured at Department Designing and Machine Components of the Czech Technical University in Prague and simple experiments there were realized too. The results of these experiments are shown in Table 1.

Fig. 5 Simple Testing Equipment for Evaluation of Threaded Contact Friction, (on the left side), HBM Torque Sensor T20WN, 20 Nm, (on the right side). These photographs were taken by the corresponding author (2015, 2016)

These simple realized experiments verified the chosen measurement methodology. The aim of the experiments was to determine the magnitude of the friction coefficient in the thread depending on the surface (coating) of the screw and the nut. The experience gained in this way was used to design testing equipment for complex screw joint testing (see Fig. 6) The test equipment is currently being implemented by the prepared structural design.

Tab. 1 Table Presenting Measured and Calculated Values for Bolt Size M12. This table was prepared by the corresponding author (2016)

Table Presenting Measured and Calculated Values for Bolt Size M12
(Bolt: stainless steel A2-80, Nut: stainless steel A4-80, coating - Delta Seal Black)

Hinge mass:	2,86kg
Nut friction moment M_p:	0Nmm

Weight mass (including hinge) m [kg]	Tensile force Q_o [N]	Wrench torque moment M_{kk} [Nmm]	Wrench torque moment without nut friction moment M_k [Nmm]	Calculated thread friction angle φ' [°]	Calculated thread friction coefficient f'[1]	Calculated friction coefficient f [1]
0	0	0	0	0	0	0
161,51	1584,41	1000	1000	9,50769	0,16748	0,14504
220,46	2162,71	1750	1750	11,32404	0,20026	0,17343
240,14	2355,77	2500	2500	13,8561	0,24666	0,21362
245,51	2408,45	2500	2500	13,62506	0,24239	0,20991
Statistic evaluation			Sample average μ:	**12,08**	**0,214**	**0,186**
			Sample standard deviation σ:	**2,06**	**0,04**	**0,03**

New Testing Equipment for Complex Analysis of Screw Fasteners

On this testing equipment can be detected:
1) The value of the friction coefficient in the thread.
2) The value of the friction coefficient under screw head (under nut).
3) The tension axial prestress reducing after the screw connection is assembled.
4) To evaluate the characteristics of fastener tightening processes (Torque-angle curves).
5) Verifying the strength of the screw connection.

Technical parameters of this testing equipment:
Maximum testing torque moment 185 Nm
Maximum testing tension axial force 100 kN
Maximum testing rotation speed 97 min^{-1}
Maximum testing stroke 300 mm

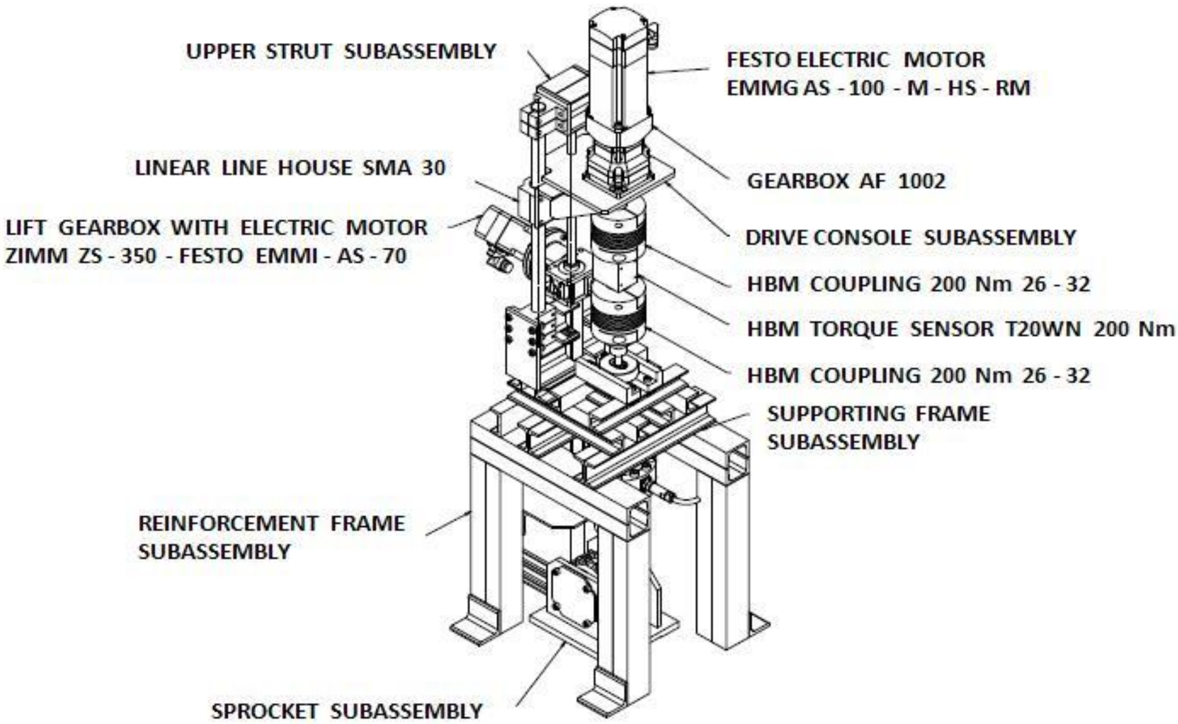

Fig. 6 Testing Equipment for Complex Analysis of Screw Fasteners. This image was processed by the corresponding author (2017)

Experimental Determination of the Friction Coefficient on the Tribometer

Tribo tests were performed to experimentally investigate the magnitude of the frictional coefficient of the selected material pair (see Table 2, Fig. 7 and Fig. 8).

Tab.2 Parameters of Tribometer Test (material pair - stainless steel A2-80/A4-80, with application of dry lubricant coating - “Gleitmo”). This table was prepared by the corresponding author (2016*)*

Tribo parameters

Tribometer module / Version 4.4.N	**Sample**	**Static partner**
Acquisition	– Coating : –	– Substrate : Steel
– Radius : 9,50 [mm]	– Substrate : –	– Cleaning : Acetone
– Lin. Speed : 6,03 [cm/s]	– Cleaning : Acetone	– Dimension : 6,00 [mm]
– Normal load : 10,00 [N]		– Geometry : Ball
– Stop condit. : 700,0 [lap]		
– Effective Stop : Laps		
– Acquisition rate : 10,0 [hz]		

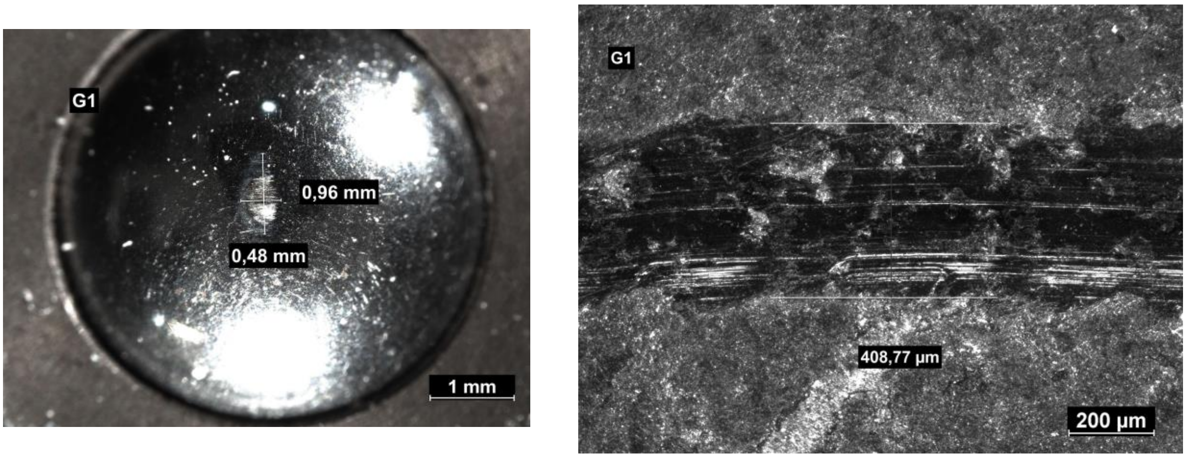

Fig. 7 Abrasive Wear of Selected Material Pair - Test Ball (A2-80) and Tested Surface (A4-80), with Application of dry lubricant coating - “Gleitmo”. This image was processed by the corresponding author (2017)

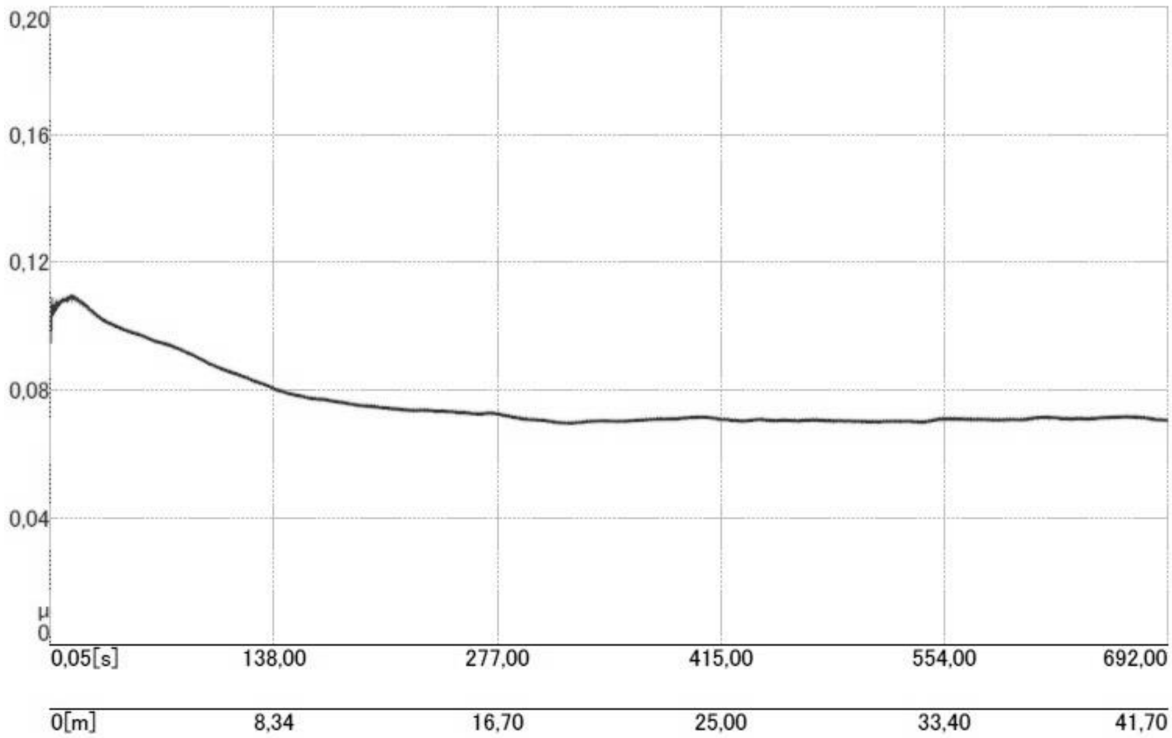

Fig. 8 Course of the Experimentally Determined Values of the Friction Coefficient of Selected Material Pair - test ball (A2-80) and tested surface (A4-80), with application of dry lubricant coating - “Gleitmo”. This image was processed by the corresponding author (2017)

Evaluation of Plastic Deformations of the Threaded Surfaces

Plastic deformations of the threaded surfaces of bolt and nut after tightening and loading were evaluated by using metallographic cuts too (see Fig. 9).

Fig. 9 Metallographic Cut of Threaded Surfaces of the M16 Nut (A4-80, with application of dry lubricant coating - "Gleitmo"). From the left side - 1. loaded thread, 2. loaded thread and 3. loaded thread. This photographs was processed by the corresponding author (2017)

Conclusions

Aim of the experiments was to determine the magnitude of the friction coefficient in the thread depending on the surface (coating) of the screw and the nut. Measured data are presented in the Table 1 (only one example). Experimentally determined value of the friction coefficient in the thread (0,214) corresponds to the value reported in the technical literature.

The simple realized experiments verified the chosen measurement methodology. The experience gained in this way was used to design testing equipment for complex screw joint testing. The test equipment is currently being implemented by the prepared structural design.

Tribo tests were performed to experimentally investigate the magnitude of the frictional coefficient of the selected material pairs and plastic deformations of the threaded surfaces of bolt and nut after tightening and loading were evaluated by using metallographic cuts too.

Acknowledgment

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