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Original Research

The Influence of the Friction Coefficient on the Clamping Force of a Bolted Joint

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Abstract

Clamping force is the most important factor influencing the reliability and durability of a bolt connection. Therefore, it is important to form the correct clamping force when tightening the bolt joint. In connection with the above, the article reviews the literature in the aspect of factors influencing the tribological properties of fasteners. The research part focuses on, not discussed by the other authors, determining the influence of the material of counterpart on the value of the clamping force of the bolted joint, formed in the joint during tightening. Due to the requirements of the automotive industry, where manufacturers expect universal fasteners that can be used with both steel and aluminum counterparts, both of these counterparts' materials were selected for research. The influence of top coats on the value of the clamping force of the bolt joint during tightening was also studied. Using a top coat on fasteners reduces the coefficient of friction during tightening by more than 30%. If a top coat is not applied to electrolytically galvanized fasteners, the friction coefficient increases three times compared to the friction coefficient obtained with top-coated bolts. In this case, the clamping force of the bolted joint is reduced by more than 60% when tightening the bolts.

Keywords: coefficient of friction, clamping force, bolted joint

Nomenclature

F	clamping force
R	dispersion (difference between maximum and minimum value)
s	standard deviation
T	torque
Step #1	first step of the tightening procedure
Step #2	second step of the tightening procedure
x	average value
Zn8/Cn/T0	the electrolytic zinc with a minimum thickness of 8μm/thick-layer passivation/without top coat
Zn8/Cn/T2yL	the electrolytic zinc with a minimum thickness of 8μm/thick-layer passivation/ with top coat stabilizing the friction coefficient
Greek symbols	
μ_b	coefficient of friction on the bearing surface of bolt
μ_{tot}	total coefficient of friction
μ_{th}	coefficient of friction on the thread surface

1. Introduction

The continuous development of the automotive industry results in increased requirements for the quality of fasteners, which include not only the bolt material, but also its geometry, surface preparation method and protective coating.

Clamping force is the most important factor of a bolted joint, influencing its reliability and durability (Esmaeili et al., 2014). It is closely related to factors such as friction coefficient and torque. Controlling these parameters is crucial to ensuring correct assembly of the joint. This is particularly important in the case of safety requirements. With the development of the automotive industry, the requirements for fasteners are increasing. Car manufacturers expect universal bolted products, that is, those that can be installed in steel and aluminum or painted elements. Due to the fact that different friction conditions (Mokhtar, 1982; Nassar & Sun, 2007) occur on the aluminum surface and different on the steel or painted surface, this requirement is difficult to meet. It is important to know the influence of the substrate and friction conditions between the bolt's bearing surface and the substrate into which the bolt is screwed on the obtained clamping force of the joint. Therefore, the article focuses on a literature review in terms of factors influencing the tribological properties of fasteners, and then the research part focuses on determining the influence of the type of substrate and protective coating on the value of the clamping force of a bolted joint.

Croccolo et al. (2017) and Zou et al. (2007) studied the effect of different types of lubricants on the coefficient of friction and torque obtained during bolt tightening. Zou et al. (2007) also considered the effect of thread pitch, tightening speed and the number of tightening repetitions on the coefficient of friction and torque. Croccolo et al. (2017) and Zou et al. (2007) considered the coefficient of friction on the thread and on the bearing surface of the bolt‘s head. However, the influence of the substrate into which the fasteners are assembled was not analyzed. The authors report that lubricants have an extremely large effect on the obtained friction values and assembly torque. The solid lubricant of the lubricating paste type, used by Zou et al. (2007) caused the most significant reduction in the friction values on the thread and on the bearing surface of the bolt‘s head. Thus, the same tightening torque resulted in a higher clamping force of the bolted joint than in the case of no lubricant paste. Zou et al. (2007) reported that similar effects on the tribological properties were observed for greases and oils. However, at low tightening speeds, the use of grease resulted in lower friction values than in the case of oils. Croccolo et al. (2017) tested mineral oil and ceramic paste as lubricants. Interflon ceramic paste proved to be very effective in reducing friction. The friction coefficient was reduced by 32% compared to dry conditions, that is, without lubricants and by 17% compared to oil lubrication.

Ma (2020) analyzed the effect of protective coating on the tribological properties of the bolts, taking into account the separate effects of each of the protective coating layers, that is, electrolytic zinc, passivation layer (thin, coherent coating made of chromium oxides) and top coat layer (layer of additionally applied lubricant). The author determined the effect of individual protective coating layers on the total coefficient of friction, the coefficient of friction on the thread and on the bearing surface of the bolt‘s head. The analysis also took into account the effect of the substrate into which the bolt is screwed, the effect of nut lubrication and the effect of temperature. Based on research written by Ma (2020), it was shown that top coats play the greatest role in stabilizing the total coefficient of friction. The use of top coats significantly reduces the total coefficient of friction. The black passivation layer combined with the top coat allows for obtaining lower values of the total coefficient of friction, the coefficient of friction on the thread and on the bearing surface, than in the case of a silver passivation layer. The immersion time and passivation bath concentration do not have a significant effect on the obtained friction coefficient values. The thickness of the coating layer has a marginal effect on the obtained friction coefficient values, while heating the bolts at a temperature higher than 182°C for more than 1 hour significantly increases the friction coefficient value. Ma (2020) also showed that when bolts were tightened into an aluminum substrate, the obtained friction coefficient values significantly exceeded the friction coefficient values obtained when tightening bolts in steel. However, the extent to which this affects the obtained clamping force value was not considered.

De Agostinis et al. (2015), Eccles et al. (2010), Jiang et al. (2002) and Liu et al. (2020) analyzed the effect of repeated tightening and loosening on the tribological properties of fasteners coated with protective coatings. The authors observed significant changes in the contact surfaces of the external/internal thread and on the bearing surface of the bolt‘s head due to repeated tightening and loosening. Surface wear due to repeated tightening and loosening causes an increase in the coefficient of friction. The increase in the coefficient of friction causes a decrease in the clamping force intended for the joint after tightening to a specific torque value. The reduction in the clamping force is significant, with the clamping force at the sixth re-tightening usually being half of the force obtained at the first tightening. The use of appropriate lubricants allows for obtaining stable values of the coefficient of friction also during re-use of the bolts.

According to Nassar et al. (2007) during repeated tightening and loosening at tightening speeds lower than 30 rpm, the friction coefficient for zinc-coated bolts increases significantly. As a result of repeated tightening and loosening, the roughness of the hard galvanized washer surface increases significantly. An increase in the roughness of the bolt head bearing surface is also observed, but to a lesser extent than in the case of the washer roughness. This is directly related to the detaching of the zinc layer from the hard washer surface due to the lower adhesion of the zinc layer to the originally smoother surface than in the case of the bolt head bearing surface. In the case of using top coats, the effect of repeated tightening is observed, but it is not as significant (Jiang et al., 2002). For higher tightening speeds, the effect of repeated tightening can be neglected.

The literature review proposed by Croccolo et al. (2023) discusses several types of damage characteristic of threaded fastener. Uncertainty regarding the clamping force is the main cause of failures occurring during the assembly stage of fasteners. Another key issue resulting from the review (Croccolo et al., 2023) is the need for appropriate selection of the fastener material depending on its purpose. The analysis of material selection should take into account the effect of the manufacturing process on the texture and microstructure of the material. As Croccolo et al. (2023) stated, special attention should be paid to the interaction between the bolt's material and the material of the fastened elements. For example, differences in the thermal expansion coefficients of materials can result in damage to threaded fasteners connections even with small changes in temperature. The authors emphasize how important it is to properly design bolt's connections. The loads under which the joint operates can lead to damage due to overload. This phenomenon is closely related to the coefficient of friction, and properly selected lubricants play a key role here. From the study written by Croccolo et al. (2023), it can be concluded that various mechanisms usually combine and ultimately lead to joint failure, leaving the actual cause of failure initiation difficult to determine.

2. Experimental procedures

The tests were performed using M6×75 bolts (Fig. 1) with a T30 hexalobular socket in strength class 8.8 in accordance with ISO 898-1:2013 (International Organization for Standardization, 2013) used by the Volkswagen group. The used test methodology is presented in Table 1.

Fig. 1. Tested bolt.

Table 1. Experimental procedures for test bolt M6×75 8.8 according to ISO 898-1:2013 (International Organization for Standardization, 2013).

Task	**Samples quantity, pcs**		
1. Taking samples after the forging and heat treatment process	50		
2. Carrying out protective electrolytic zinc coating with thick-layer passivation (Zn8/Cn/T0)	50		
2.1. Applying of top coat (T2yL)	30		
3. Tests	**variant I** Zn8/Cn/T0	**variant II** Zn8/Cn/T2yL	**Purpose of the study**
3.1. Yield point-controlled tightening	-	10	determining the level of the friction coefficient and the tightening torque for further stages
3.2. Torque-controlled tightening into the steel counterpart	10	10	determining the effect of the friction coefficient on the clamping force and therefore how high the risk is of not achieving sufficient clamping force if the products are not lubricated when tightening into the steel
3.3. Torque-controlled tightening into the aluminum counterpart	10	10	determining the effect of the friction coefficient on the clamping force and therefore how high the risk is of not achieving sufficient clamping force if the products are not lubricated when tightening into the aluminum

The fasteners are made of 23MnB4+Cr material in accordance with EN 10263-4:2017 (European Committee for Standardization, 2017). The chemical composition of the material is presented in Table 2.

Table 2. Chemical composition (wt.%) of 23MnB4+Cr according to EN 10263-4:2017 (European Committee for Standardization, 2017).

C	Mn	Cr	B	Si	P	S	Al	Ti
0.22	0.97	0.27	0.003	0.1	0.01	0.006	0.027	0.048

These bolts are manufactured by cold forging, then the thread is obtained in the rolling process, which results in a profitable (due to exploitation) fibrous structure. After the bolt forming process, the heat treatment process takes place, thanks to which the fasteners obtain the appropriate mechanical properties. The heat treatment process is a two-stage process. In the first stage, heating to a temperature of 880°C takes place, followed by rapid cooling in oil to harden the fasteners. In the second stage, the products must be tempered in order to obtain a structure that provides optimal mechanical properties. In this research work, in order to determine the effect of the friction coefficient on the obtained clamping force of the connection, the first batch of bolts was covered with electrolytic zinc Zn8/Cn/T0 (without top coat), while the second batch of bolts was covered with Zn8/Cn/T2yL (additional top coat with lubricating properties). The friction coefficient and clamping force were tested using a Schatz-Kistler Tribology Tester (Fig. 2), a measuring device for threaded connections offering the ability to measure total torque in the range of 0÷200 Nm, clamping force in the range of 0÷100 kN and thread torque in the range of 0÷150 Nm.

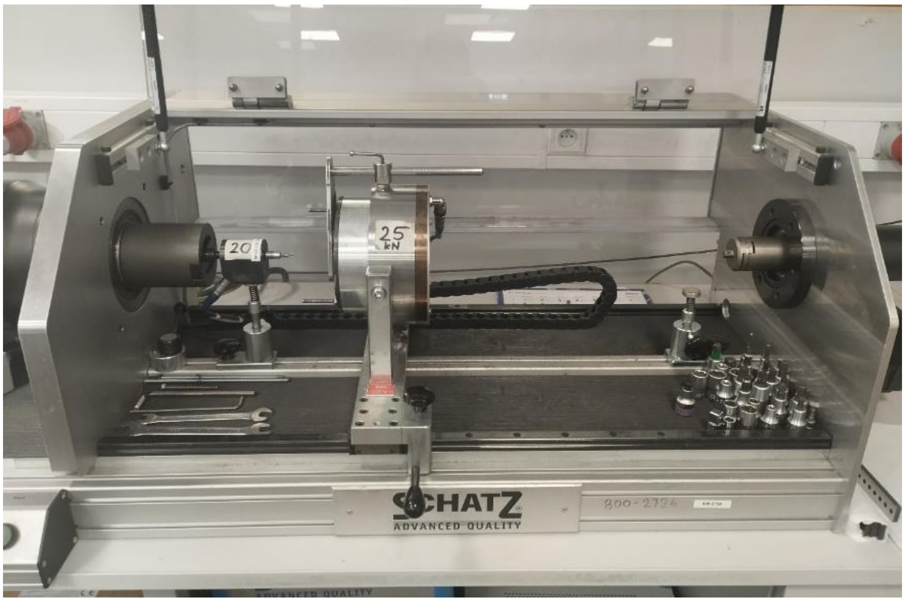

Fig. 2. Schatz-Kistler tribological tester.

The bolts were tightened into steel counterparts and aluminum strips, due to the fact that it reflects the real assembly conditions. The assembly steps are shown in the diagram in Figure 3a. This study allowed us to confirm what friction coefficient values we obtain when using electrolytic zinc with an additionally applied lubricant layer (top coat). For the needs of the next stage of the research work, a torque-controlled tightening procedure was developed (Fig. 3b), in which the tightening torque obtained in the first stage of the research work was used. The tightening was carried out at a constant speed of 12 rpm until the previously determined tightening torque was obtained and the clamping force generated in the joint as a result of the applied torque was calculated. In the last tightening phase, the bolts were loaded over the entire length of the thread. The obtained results showed the influence of the lubricant on the obtained value of the joint clamping force.

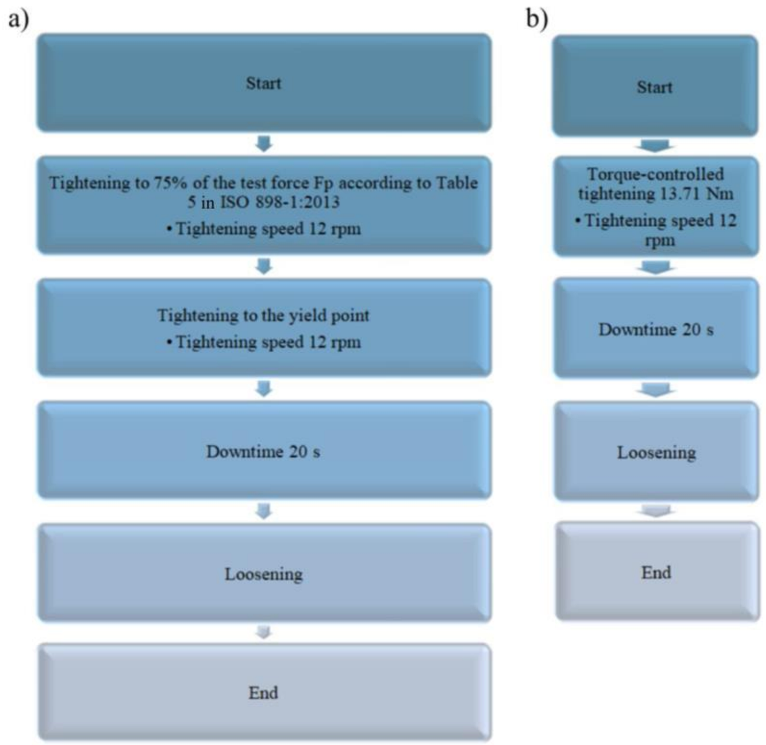

Fig. 3. a) yield point-controlled and b) torque-controlled tightening procedure.

3. Results and discussion

3.1. Determination of the friction coefficient and torque during tightening in steel according to the first procedure

In this part of the research, in accordance with the experimental procedure presented in Table 1, M6×75 bolts were tightened into the steel washer. The tightening procedure was carried out in two stages. In the first step, the bolt was tightened to 8.7 kN, which is 75% of the test force according to Table 5 in ISO 898-1:2013 (International Organization for Standardization, 2013), and then in the second step, the yield point was achieved. The system calculates the force value at which plastic deformation occurs based on monitoring the torque/angle curve. The yield point is reached when the system records a 3% decrease in the slope of the torque/angle curve. Then the bolt is unscrewed. The clamping force, tightening torque and friction coefficient were calculated for the first and second steps of the tightening procedure. Based on the results in Table 3, it can be seen that the friction coefficient is the same for the first and second steps. The obtained results indicate the stability of the tightening process, which was probably achieved thanks to the lubricant used.

As a result of the conducted test, a tightening torque of 13.71 Nm was obtained, which was used in the next stage of the test, during torque-controlled tightening.

Table 3. Results from yield point-controlled tightening (task 3.1, Table 1) - steel counterpart —coating electrolytic zinc with top coat Fe/Zn8/Cn/T2yL.

Parameter	First tightening program (task 3.1, Table 1) - steel counterpart - coating Fe/Zn8/Cn/T2yL													
	F, Step #1	F, Step #2	T, Step #1	T, Step #2	Tb, Step #1	T_b, Step #2	T_{th}, Step #1	T_{th}, Step #2	μ_{tot}, Step #1	μ_{tot}, Step #2	μ_{th}, Step #1	μ_{th}, Step #2	μ_b, Step #1	μ_b, Step #2
unit	kN	kN	Nm	Nm	Nm	Nm	Nm	Nm	-	-	-	-	-	-
x	8.70	14.70	8.28	13.71	3.85	6.38	4.43	7.33	0.10	0.10	0.11	0.11	0.09	0.09
s	0.00	0.16	0.18	0.29	0.16	0.27	0.07	0.10	0.00	0.00	0.00	0.00	0.00	0.00
min.	8.70	14.38	8.00	13.18	3.55	5.84	4.30	7.08	0.10	0.10	0.11	0.10	0.09	0.09
max.	8.71	14.95	8.55	14.22	4.08	6.83	4.57	7.43	0.11	0.10	0.12	0.12	0.10	0.10
R	0.01	0.57	0.55	1.04	0.53	0.99	0.27	0.35	0.01	0.00	0.01	0.02	0.01	0.01

3.2. The influence of the top coat on the clamping force of the joint during the torque-controlled tightening into a steel washer

The use of a top coat stabilizes the friction coefficient values, which is directly related to the stability of the obtained joint clamping force. The test showed minimal friction coefficient scatter at the level of 0.01 for both the bolt head bearing surface, thread surface and the total friction coefficient (Table 4). The lubricant used brought the expected result and fully stabilized the tightening process, which is also confirmed by the obtained joint clamping force. In this test, the average clamping force value was 14.42 kN, and the obtained value scatter was at the level of 1.01 kN. Based on the results presented in Table 4, it can be stated that a properly selected top coat (lubricant film) ensures tightening stability also in the case of using torque-controlled tightening.

Table 4. Results from torque-controlled tightening (task 3.2, Table 1) - steel counterpart - coating electrolytic zinc with top coat Fe/Zn8/Cn/T2yL.

Parameter	Second tightening program (task 3.2, Table 1) - steel counterpart - coating Fe/Zn8/Cn/T2yL							
	Angle, Step #1	F, Step #1	T, Step #1	T_b, Step #1	T_{th}, Step #1	μ_b, Step #1	μ_{th}, Step #1	μ_{tot}, Step #1
unit	°	kN	Nm	Nm	Nm	-	-	-
x	255.30	14.42	13.71	6.44	7.27	0.09	0.11	0.10
s	42.36	0.32	0.00	0.15	0.15	0.00	0.00	0.00
min.	225.25	14.03	13.71	6.24	7.03	0.09	0.11	0.10
max.	361.00	15.04	13.71	6.69	7.48	0.10	0.12	0.10
R	135.75	1.01	0.00	0.45	0.45	0.01	0.01	0.01

Lack of top coat with lubricant has a very strong influence on the loss of stability of the friction coefficient value. In the test, the results of which are presented in Table 5, the friction coefficient spreads were obtained at the level of 0.05 for the bolt head bearing surface, 0.16 for the thread surface, and 0.07 for the total friction coefficient. The lack of lubricant caused the lack of stability of the connection, and the proper clamping force of the joint was not achieved. According to ISO 16047:2005 (International Organization for Standardization, 2005) and ISO 898-1:2013 (International Organization for Standardization, 2013), for the M6 bolt in class 8.8 during tightening, the minimum clamping force that should be achieved in the connection is 8.7 kN. During the experiment, only 5 kN of clamping force was obtained, which is only 58% of the minimum required clamping force.

Table 5. Results from the torque-controlled tightening (task 3.2, Table 1) - steel counterpart - coating electrolytic zinc without top coat Fe/Zn8/Cn/T0.

Parameter	Second tightening program (task 3.2, Table 1) - steel counterpart - coating Fe/Zn8/Cn/T0							
	Angle, Step #1	F, Step #1	T, Step #1	T_b, Step #1	T_{th}, Step #1	μ_b, Step #1	μ_{th}, Step #1	μ_{tot}, Step #1
	°	kN	Nm	Nm	Nm	-	-	-
x	120.78	5.01	13.72	6.78	6.93	0.29	0.40	0.33
s	8.17	0.30	0.00	0.37	0.37	0.01	0.05	0.02
min.	108.25	4.53	13.71	5.94	6.36	0.27	0.34	0.30
max.	130.75	5.51	13.72	7.36	7.78	0.31	0.50	0.37
R	22.50	0.99	0.01	1.42	1.43	0.05	0.16	0.07

3.3. The influence of the top coat on the clamping force of the joint during the torque-controlled tightening into an aluminum washer

Also in the case of tightening into an aluminum counterpart, the use of a lubricant stabilized the friction coefficient values (Table 6). The test obtained very small spreads of the friction coefficient at the level of 0.01÷0.02. The lubricant used brought the expected result and fully stabilized the tightening process also into an aluminum substrate. Based on the tests performed and the analysis of the results, it can be concluded that the applied protective coating would be suitable for applications for tightening into steel as well as aluminum. However, a standard tightening test into an aluminum counterpart should be performed in accordance with VW 01131:2018 (VW Group Standard, 2018), to be able to confirm the above.

Table 6. Results from the torque-controlled tightening (task 3.2, Table 1) - aluminum counterpart - coating electrolytic zinc with top coat Fe/Zn8/Cn/T2yL.

Parameter	Second tightening program (task 3.3, Table 1) - aluminum counterpart - coating Fe/Zn8/Cn/T2yL							
	Angle, Step #1	**F, Step #1**	**T, Step #1**	**T_b, Step #1**	**T_{th}, Step #1**	**μ_b, Step #1**	**μ_{th}, Step #1**	**μ_{tot}, Step #1**
unit	°	kN	Nm	Nm	Nm	-	-	-
x	210.50	12.81	13.71	7.17	6.55	0.12	0.11	0.12
s	5.63	0.45	0.00	0.18	0.18	0.01	0.00	0.00
min.	203.00	12.17	13.71	6.77	6.28	0.11	0.11	0.11
max.	217.00	13.50	13.72	7.43	6.95	0.13	0.12	0.12
R	14.00	1.33	0.01	0.66	0.67	0.02	0.01	0.01

The lack of a top coat with lubricant has a very strong impact on the lack of stability of the friction coefficient value also when tightening into an aluminum counterpart. The study obtained friction coefficient scatters of 0.06 for the bolt head bearing surface, 0.10 for the thread surface and 0.05 for the total friction coefficient. The lack of lubricant caused the lack of stability of the connection and the proper clamping force of the joint was not achieved. According to ISO 16047:2005 (International Organization for Standardization, 2005) and ISO 898-1:2013 (International Organization for Standardization, 2013), for an M6 bolt in class 8.8, during tightening, the minimum clamping force that should be generated in the connection is 8.7 kN. During the experiment, only 4.81kN of clamping force was obtained (Table 7), which is only 55% of the minimum expected clamping force.

Table 7. Results from the torque-controlled tightening (task 3.2, Table 1) - aluminum counterpart - coating electrolytic zinc without top coat Fe/Zn8/Cn/T0.

Parameter	Second tightening program (task 3.3, Table 1) - Aluminum counterpart - coating Fe/Zn8/Cn/T0							
	Angle, Step #1	**F, Step #1**	**T, Step #1**	**T_b, Step #1**	**T_{th}, Step #1**	**μ_b, Step #1**	**μ_{th}, Step #1**	**μ_{tot}, Step #1**
unit	°	kN	Nm	Nm	Nm	-	-	-
x	105.03	4.81	13.72	7.01	6.70	0.31	0.40	0.35
s	5.72	0.22	0.00	0.27	0.28	0.02	0.03	0.02
min.	97.50	4.46	13.71	6.52	6.29	0.27	0.35	0.32
max.	118.25	5.13	13.72	7.42	7.20	0.33	0.44	0.37
R	20.75	0.67	0.01	0.89	0.91	0.06	0.10	0.05

3.4. Comparison of the friction coefficient of the bolt joint obtained during the torque-controlled tightening with the use of top coat and without top coat for tightening in steel and aluminum counterpart

The use of a top coat with lubricant significantly reduces the coefficient of friction, as indicated in Figures 4-6. The greatest reduction in the coefficient of friction was achieved on the bearing surface of the bolt head (Fig. 4). When tightening into a steel counterpart, the coefficient of friction under the bolt head was reduced by 33% by using top coat compared to the coefficient of friction obtained for bolts without top coat. On the other hand, when tightening into an aluminum counterpart, the coefficient of friction on the bearing surface of the bolt head was reduced by 39% compared to the coefficient of friction obtained for bolts without lubricant. Which is becoming extremely important for the developing branch of the automotive industry, where in many applications fasteners are tightened into aluminum.

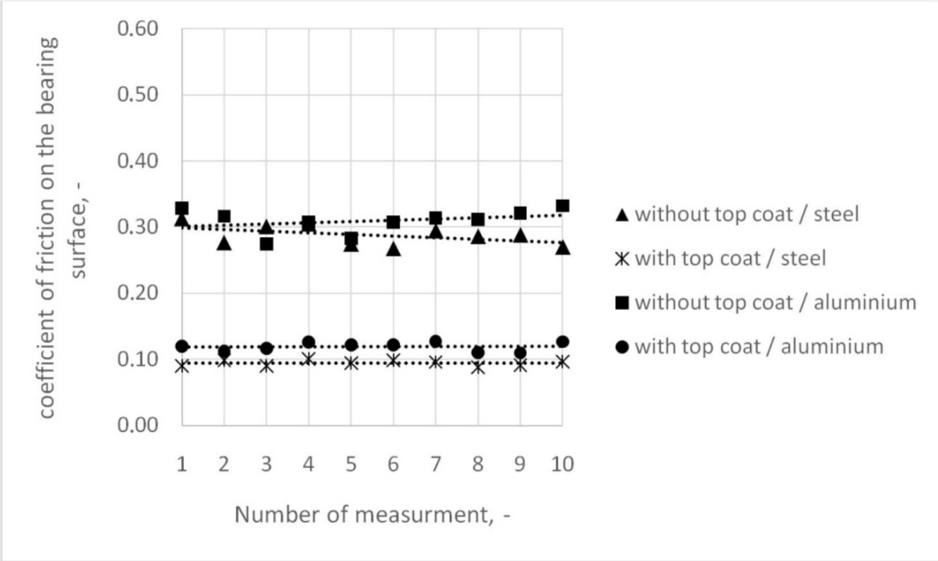

Fig. 4. Comparison of the friction coefficient under the bolt's head obtained during the torque-controlled tightening with and without a top coat for tightening in steel and aluminum counterpart.

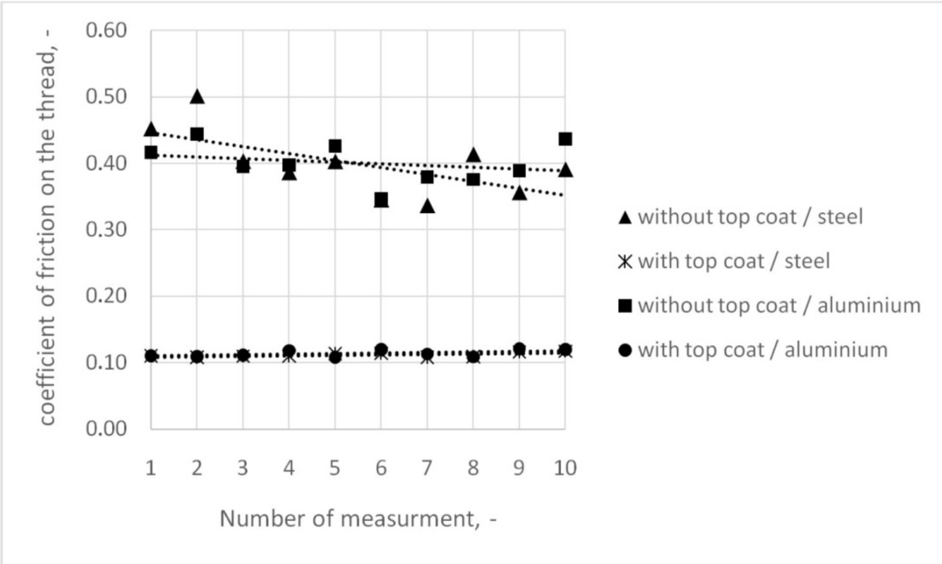

Fig. 5. Comparison of the friction coefficient on the thread surface obtained during the torque-controlled tightening with and without a top coat for tightening in steel and aluminum counterpart.

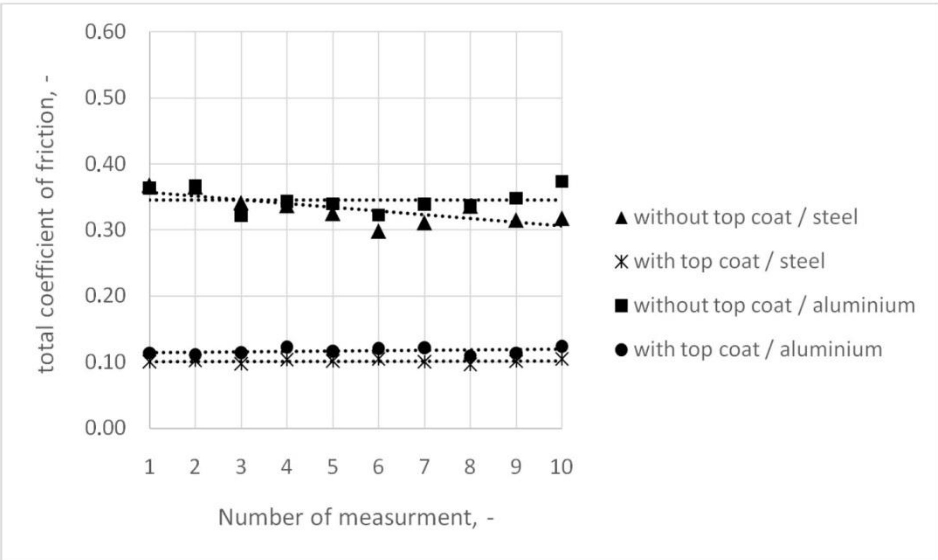

Fig. 6. Comparison of the total friction coefficient obtained during the torque-controlled tightening with and without a top coat for tightening in steel and aluminum counterpart.

3.5. Comparison of clamping force of the bolted joint obtained during the torque-controlled tightening with and without a top coat for tightening in steel and aluminum counterpart

The clamping force of the bolted joint obtained during torque-controlled tightening of bolts without top coat compared to the clamping force of the bolted joint obtained during torque-controlled tightening of bolts with top coat is almost three times lower (Fig. 7). This dependence exists for both steel and aluminum. This means that in the first case, when tightening into a steel counterpart in the absence of lubricant, a 65% lower clamping force was obtained than in the case of using lubricant. On the other hand, in the second case, when tightening into an aluminum counterpart in the absence of lubricant, a 62% lower clamping force was obtained than in the case of using lubricant. Therefore, the risk of loosening the connection due to the lack of generating the appropriate clamping force is huge.

3.6. Comparison of the effect of the friction coefficient on the obtained clamping force of bolted joints for steel and aluminum counterparts

According to the results obtained in the experiment, an increase in the friction coefficient from 0.10 to 0.33 causes a decrease in the obtained clamping force of the bolted joint from 14.42 kN to 5.01 kN in the case of tightening into a steel counterpart (Fig. 8). On the other hand, in the case of tightening bolts into an aluminum counterpart, an increase in the friction coefficient from 0.12 to 0.35 causes a decrease in the obtained clamping force of the bolted joint from 12.81 kN to 4.81 kN. In the case of tightening bolts into an aluminum counterpart, slightly lower values of the clamping force of the bolted joint were obtained than in the case of tightening bolts into a steel counterpart, which is directly related to the level of the friction coefficient obtained for both cases.

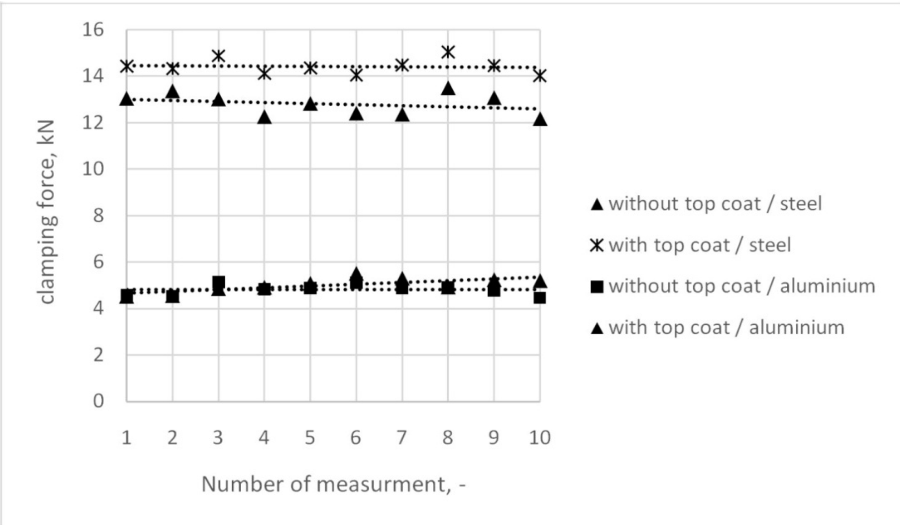

Fig. 7. Comparison of the clamping force obtained during the torque-controlled tightening with and without a top coat for tightening in steel and aluminum counterpart.

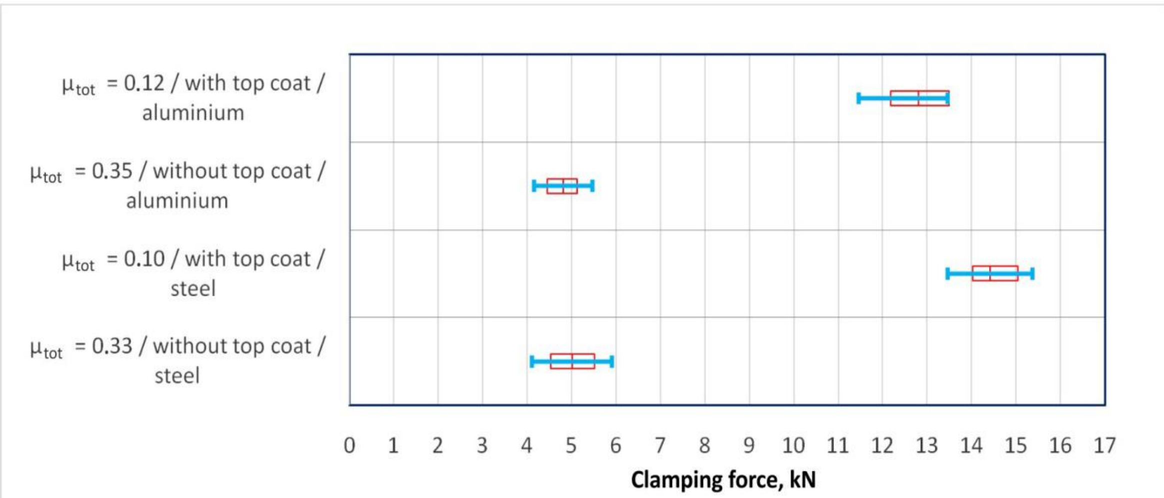

Fig. 8. Comparison of the effect of the friction coefficient on the obtained clamping force of bolted joints for steel and aluminum counterpart.

4. Conclusions

The following conclusions can be reached:

1) Applying protective coatings to fasteners using a top coat with a lubricant helps to stabilize the tightening process, that is, to achieve stable values of the friction coefficient and the clamping force of the bolted joint.
2) An increase in the friction coefficient value causes a decrease in the clamping force of the bolted joint.
3) The use of a top coat with lubricant significantly reduces the coefficient of friction. The greatest reduction in the coefficient of friction was achieved on the bearing surface of the bolt.
4) When tightening into a steel counterpart, the coefficient of friction under the bolt's head was reduced by 33% compared to the coefficient of friction obtained for bolts without lubricant.
5) When tightening into an aluminum counterpart, the coefficient of friction on the bearing surface of the bolt was reduced by 39% compared to the coefficient of friction obtained for bolts without lubricant.
6) When tightening into a steel counterpart in the case of electrolytic zinc without lubricant, the clamping force of the bolted joint was 65% lower than when lubricant was used.
7) When tightening into an aluminum counterpart in the case of electrolytic zinc without lubricant, the clamping force of the bolted joint was 62% lower than when lubricant was used.
8) Therefore, the risk of loosening the threaded connection due to lack of adequate clamping force is very high.
9) The use of protective coatings with an additionally applied layer of lubricant (top coat) together with the appropriate geometry of the bearing surface, enabling the proper value of the contact surface, contributes to a significant reduction of friction, especially on the bearing surface. This is extremely important in solutions used in the automotive industry, where fasteners are often screwed into an aluminum counterpart.

The conducted tests and obtained results emphasize how important the correct execution of protective coating is. Supervision of the process of making protective coatings is crucial in ensuring the correct working conditions of the threaded connections. In the case of assembly of fasteners using the torque-controlled method without supervision of the obtained clamping force, the risk of loosening the bolted joint due to generating too low clamping force is very high. In the case of more precise tightening methods, e.g., tightening to the yield point, in the case of improperly selected friction conditions, it is probable that the bolt will break during assembly due to exceeding its strength.

Based on the obtained results, it can be stated with high probability that the tested electrolytic zinc coating with an additionally applied lubricant layer will be suitable for applications in the automotive industry when screwing into an aluminum counterpart. The above statement must be confirmed by tests of this type of protective coating in accordance with the Volkswagen Group procedure VW 01131:2018 (VW Group Standard, 2018), which defines how to test the coefficient of friction of fasteners screwed into an aluminum counterpart.

The continuation of the research contained in this article would concern screwing in accordance with VW 01131:2018 (VW Group Standard, 2018) into an aluminum counterpart and into a steel counterpart painted using the cataphoresis method (KTL). These studies would clearly answer whether the described electrolytic zinc coating with an additionally applied lubricant layer would be a universal solution for the production of fasteners supplied to the VW group, which must meet both the friction conditions in aluminum and in painted steel counterpart.

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Wpływ Współczynnika Tarcia na Siłę Zacisku Połączenia Śrubowego

Streszczenie

Siła zacisku jest najważniejszym czynnikiem wpływającym na niezawodność i trwałość połączenia śrubowego. Niezwykle istotnym jest wytworzenie prawidłowej siły zacisku podczas dokręcania złącza śrubowego. W związku z powyższym w artykule dokonano przeglądu literatury w aspekcie czynników wpływających na właściwości tribologiczne elementów złącznych. W części badawczej przedstawiono, nieporuszany przez innych autorów, wpływ rodzaju materiału podłoża, w które wkręcana jest śruba na wartość siły zacisku złącza śrubowego powstającej w złączu podczas dokręcania. Ze względu na wymagania branży motoryzacyjnej, w której producenci oczekują uniwersalnych wyrobów śrubowych, które mogą zostać zastosowane zarówno w podłożu stalowym jak i aluminiowym, oba te materiały podłoża zostały wybrane do badań eksperymentalnych. Opracowano również wpływ powłoki nawierzchniowej na wartość siły zacisku złącza śrubowego podczas dokręcania. Zastosowanie powłoki nawierzchniowej na elementach złącznych zmniejsza współczynnik tarcia podczas dokręcania o ponad 30%. Jeżeli nie zastosuje się powłoki nawierzchniowej na elementach złącznych ocynkowanych elektrolitycznie, współczynnik tarcia wzrasta trzykrotnie w porównaniu do współczynnika tarcia otrzymanego dla śrub pokrytych powłoką nawierzchniową. W takim przypadku siła zacisku połączenia śrubowego zmniejsza się o ponad 60% podczas dokręcania śrub.

Słowa kluczowe: współczynnik tarcia, siła zacisku, połączenie śrubowe