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Influence of Differential Thermochemical Treatment of Bolts on Tightening Parameters in a Bolted Joint

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This article presents the results of the research into the influence of heat treatment, with application of differential parameters and gas atmosphere, on the friction coefficient during the tightening of a bolted joint. The study consisted of several stages – it included metallographic examinations, hardness evaluation and joint tightening tests. This paper presents the research process, the obtained results and the analysis of the impact of thermochemical treatment on functional parameters, such as friction coefficient and torque, during the tightening of a bolted joint.

Keywords: thermochemical treatment, bolts, bolted joint, friction coefficient, torque.

Notation

D_0 – outer diameter of bearing surface, mm
D_b – diameter of bearing surface under bolt head for friction, mm
d_2 – basic pitch diameter of thread, mm
d_h – clearance hole diameter of washer or bearing part, mm
F – clamp force, N
F_d – proof load, N
K – torque coefficient (dimensionless)
P – thread pitch, mm
T – total torque, $\mathrm{N \cdot m}$
T_b – bearing torque, $\mathrm{N \cdot m}$
T_{th} – thread torque, $\mathrm{N \cdot m}$
μ_b – bearing friction coefficient (dimensionless)
μ_{th} – thread friction coefficient (dimensionless)
μ_{tot} – total friction coefficient (dimensionless)

Introduction. Bolts are the most commonly used fasteners, which, despite their relatively small sizes, play an important role in durability and reliability of machines, appliances, vehicles, structures or buildings. The variety of applications of fasteners entails relevant requirements for their quality and performance.

Bolt-forming methods are cold forging, hot forging and machining, while bolt-threading methods are roll threading and cut threading [1]. The most common method of bolts' manufacturing is cold forging with the following thread rolling, which allows one to obtain the advantageous mechanical properties of fasteners and at the same time to achieve material savings. The improvement of bolts' functional properties can also be achieved by the application of heat treatment [2, 3].

Thus, the functional properties of fasteners depend on various factor: the manufacturing method [4], the material used for production, the application of heat treatment and additional coatings during the manufacturing process [5], or aspects concerning assembly, such as joint design, bolt shape [6], lubrication, thread pitch, hole clearance, applied torque and clamping force, tightening speed, as well as the number of tightening and loosening cycles. Some of these have a greater influence on assembly effectiveness than others: e.g., study [7] shows that from the point of view of the parameters concerning fasteners' tightening, the value of friction coefficient under a bolt head has the largest impact on bolt tension. Clamping force is the most important factor affecting reliability and longevity of a bolted joint [8]. Clamping force is associated with such factors as torque [9] and friction coefficient. The essence is to control these parameters and minimize their uncertainty [10] in order to assure the proper assembly of the joint. This is especially important in case of strict safety requirements, in automotive or aeronautic industries.

Some experiments related to the influence of lubricants on tightening parameters were carried out. In research [11–14] and [15, 16] there are shown the results of the studies concerning the use of lubricants, the tightening speed as well as a number of performed tightening and loosening cycles. It was proven that the use of lubricants can stabilize the value of torque and friction coefficient during tightening of a bolted joint. Moreover, the authors in [12] suggest that the application of high pressure lubricants could reduce friction and torsional stress and consequently obtain preload value at the level of a new bolt nut pair. Regarding the tightening speed, its reduction to about 2 rpm causes a significant increase of friction coefficient. It should also be noticed that the reuse of fasteners entails changes in tightening parameters. The tightening torque and friction coefficient increase with the number of tightening cycles, the bolt extends during the tightening process and loses its initial properties. It is advisable not to reuse the dismantled fasteners but to install a new bolt nut pair.

The functional properties during tightening of a bolted joint are also dependent on coatings and the presence of washers. Works [17, 18–20] show the effects of the application of different bolt materials, washers (spring washers or Nordlock), coatings (such as zinc, chrome, copper, Geomet or Epilam) or sealants (Teflon tape). The application of these may improve the properties of the fasteners and lengthen the fatigue life of bolted joints.

The authors of works [11] and [21] also made some numerical models in order to simulate the behavior of a bolted joint during assembly, evaluate tightening parameters and optimize them. In the work [11] the influence of bolts tightening parameters on their self-loosening process is considered, whereas the work [21] contains a study about setting the installation torque of a bolted joint. In the paper [22] there was a research conducted about the influence of a thread angle on bolts tightening properties and their tendency to loosening during exploitation.

However, there are no research verifying the influence of the modified thermochemical treatment process on further bolt tightening parameters. This work aims to investigate if the changes of heat-treatment parameters could affect the properties of fasteners and therefore have influence on some aspects concerning tightening of a bolted joint.

Experimental Procedure. The aim of this research was to evaluate the influence of heat-treatment parameters modification on functional properties of bolts during the tightening process.

The assortment selected for testing were M10 × 70 bolts, property class 10.9, made from 30MnB4 steel, produced in accordance with DIN 931 standard. Testing fasteners made of the same material and of equal size guaranteed that these factors would not have any influence on the obtained results of the examination.

The experiment concerned five parts of specimens, each part contained 20 pieces of bolts. The heat treatment process consisted of the following steps:

(i) phosphates removal;
(ii) quenching;
(iii) tempering;
(iv) conservation.

The samples were heat-treated differentially. The applied parameters are shown in Table 1.

Table 1

Heat Treating Parameters

Parameter	Part number				
	1	2	3	4	5
Phosphates removal					
Phosphates cleaner	Yes	Yes	Yes	Yes	No
Quenching					
Quenching temperature (℃)	880	880	860	880	880
Carbon potential (%)	0.19	0.42	0.75	0.30	0.30
Quenching time (min)	60	83	65	60	60
Quenching fluid temperature (℃)	65	65	65	65	65
Tempering					
Tempering temperature (℃)	440	440	440	440	440
Tempering time (min)	75	75	75	75	75
Conservation					
Temperature (℃)	50	50	50	50	50
Emulsion concentration (%)	3	3	3	3	3
Additional conservation					
Emulsion concentration (%)	16.5	16.5	16.5	16.5	16.5

Additional conservation concerns 10 pieces of bolts in each sample of specimens which were extra coated with 16.5% emulsion.

Part 4 was produced in accordance with the technology currently used by the manufacturing company.

In order to verify that the modified heat-treatment process caused changes in the material microstructure, some microscopic metallographic examinations were made. Moreover, some microhardness tests on thread, core and bearing surfaces were conducted.

The experiments also included an investigation of the influence of differential heat treatment, and hence – changes in the material microstructure, on tightening parameters of a bolted joint. For this purpose, some tightening tests were performed. They were carried out in accordance with the guidelines contained in EN ISO 16047 standard [23].

The tightening tests were performed on a bolts measuring system SCHATZ® Analyse [24]. The device is shown in Fig. 1. The tests required the preparation of the fasteners and some additional equipment – plates, serving as washers. EN ISO 16047 standard allows the usage of two types of plates – through hardened (designated as HH) and of low hardness

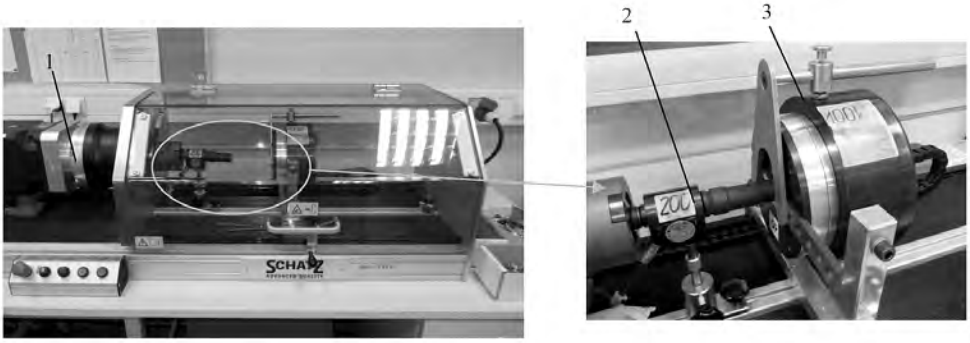

Fig. 1. Bolts measuring system: (*1*) drive motor and power unit, (*2*) torque/angle transducers, and (*3*) preload force/thread friction torque transducer.

Fig. 2. The plate used in tightening tests (d_h – clearance hole diameter and D_b – diameter of bearing surface).

(with HL designation). In the experiments, the HH through hardened plates were used. A plate can be seen in Fig. 2 – it shows a plate after tightening tests, with traces of friction on the bearing surface. The diameters d_h and D_b, which are marked in the picture, were entered into testXpert software to calculate the coefficients. A set of nuts was examined with a gauge and the proper ones were selected. Then the bolts and the plates were degreased and dried. After some preparatory steps, the fasteners were assembled in a measuring device. Figure 3 presents the method of attachment of a bolt, a nut and a plate in the appliance.

The tightening examinations were made as follows – in each set of samples 10 uncoated bolts and 10 pieces coated additionally with 16.5% emulsion were tested.

The clamping force was constant and equaled 36 kN. It had been calculated according to EN ISO 16047 standard [23], corresponding to the type and the size of the bolts. The tightening speed was 12 rpm.

The tests were performed under the normal conditions.

EN ISO 16047 standard [23] gives the method of calculating of the tightening coefficients.

The torque coefficient is determined from the tightening torque/clamp force relation using the following formula:

$$K = \frac{T}{F_d}.$$

The total friction coefficient μ_{tot} is determined from the tightening torque/clamp force ratio by the approximate formula:

$$\mu_{tot} = \frac{\frac{T}{F} - \frac{P}{2\pi}}{0.577 d_2 + 0.5 D_b}, \tag{1}$$

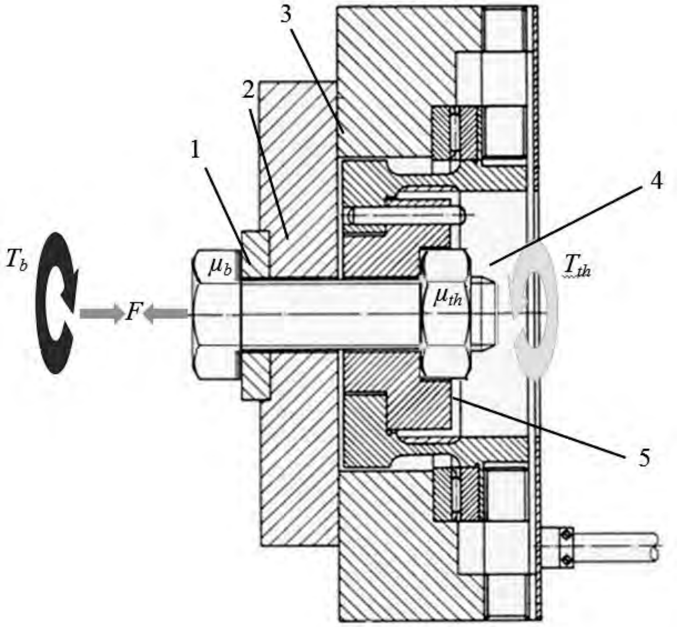

Fig. 3. The method of fixing the elements in the measuring device and the analyzed values: bearing torque T_b, bearing friction coefficient μ_b, thread torque T_{th}, thread friction coefficient μ_{th}, and clamp force F; (*1*) bolt, (*2*) plate, (*3*) plate adapter, (*4*) nut, and (*5*) nut adapter; based on [24].

where

$$D_b = \frac{D_0 + d_h}{2}. \tag{2}$$

The coefficient of friction between threads is determined from the thread torque/clamp force relation using the following approximate formula:

$$\mu_{th} = \frac{\frac{T_{th}}{F} - \frac{P}{2\pi}}{0.577 d_2}. \tag{3}$$

The thread torque may be calculated from the measurements of tightening torque and bearing surface friction torque as

$$T_{th} = T - T_b. \tag{4}$$

The friction coefficient between bearing surfaces is determined from the bearing surface friction torque/clamp force relation using the following approximate formula:

$$\mu_b = \frac{T_b}{0.5 D_b F}, \tag{5}$$

where D_b is calculated using formula (2).

The bearing surface friction torque may be calculated from the measurements of tightening torque and thread torque as

$$T_b = T - T_{th}. \tag{6}$$

Results and Discussion. To confirm that the differential heat treatment had caused changes in the material microstructure, microscopic observations were taken. The areas observed during the metallographic examinations are indicated in Fig. 4.

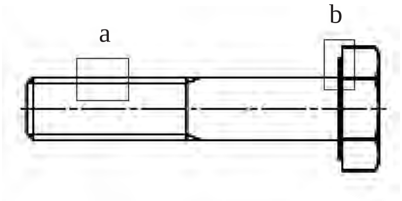

Fig. 4. The examined areas of the bolt: (a) material microstructure on the bolt thread; (b) material microstructure under the bolt head, on the bearing surface.

As was expected, the sample part 1, heat treated with carbon potential equal 0.19%C, had been decarburized, two parts of samples (2 and 3) had been carburized (the one treated with carbon potential 0.75%C more than the other one with carbon potential equal 0.42%C) and two other samples (4 and 5), made in the presence of carbon potential 0.30%C, normally used for this assortment, do not show any unexpected changes in the material microstructure – the difference between them is only the presence of a phosphates layer on the bolt surface.

All the aforementioned changes are shown in Figs. 5–9. Figure 5 shows part 1 of specimens, heat treated with carbon potential 0.19%C. There can be seen a slight decarburized layer of material. Figure 6 concerns part 2 of the bolts, which were heat treated with carbon potential 0.42%C. This caused a light carburization of the material at the surface of the bolt. In Fig. 7, which concerns the specimens heat treated with carbon potential 0.75%C (part 3), there can be noticed a greater decarburization. Part 4 of bolts, presented in Fig. 8, shows no changes in the material microstructure. It was manufactured in accordance to current technology, with carbon potential equal 0.3%C. The next set of specimens (part 5), shown in Fig. 9, also does not show any changes in the steel structure in comparison with part 4 presented on Fig. 8. However, not removing of the phosphates caused the formation of a thin layer on the bolt surface.

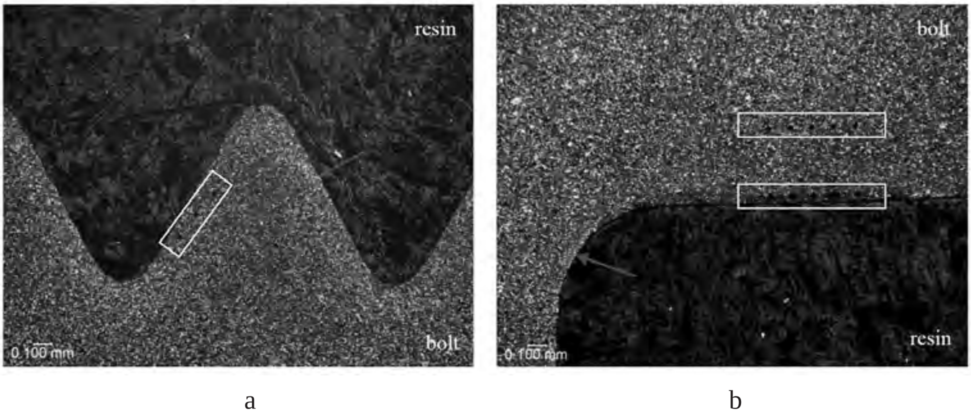

Fig. 5. Metallographic section (part 1) decarburized material.

The boundaries and areas of resulting changes in the material microstructure are marked with arrows in Figs. 5–9. The microscopic pictures show the structures of the bolt thread (a) and bearing surface (b).

Subsequently, some microhardness tests were conducted. The measuring points were established in the bolt core, on the thread surface and on the bearing surface, under the bolt head (in distances 0.04 and 0.4 mm from the surface under the bolt head, on two sides). They are marked with ◆ signs, highlighted in Fig. 5 with rectangles.

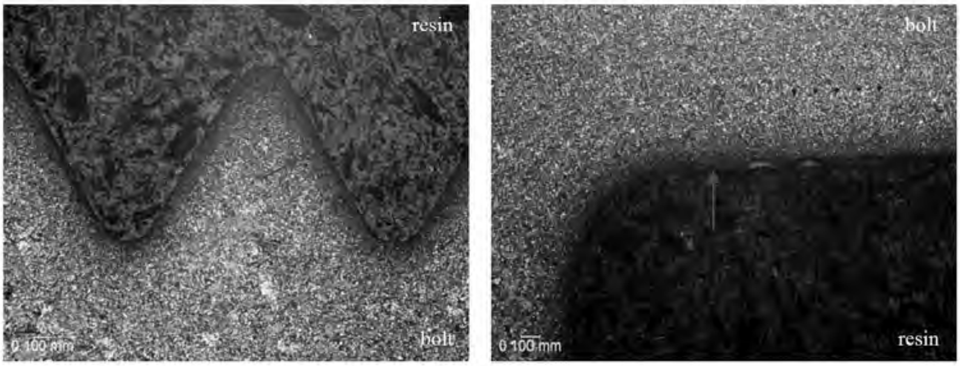

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Fig. 6. Metallographic section (part 2) carburization of the material (0.42%C).

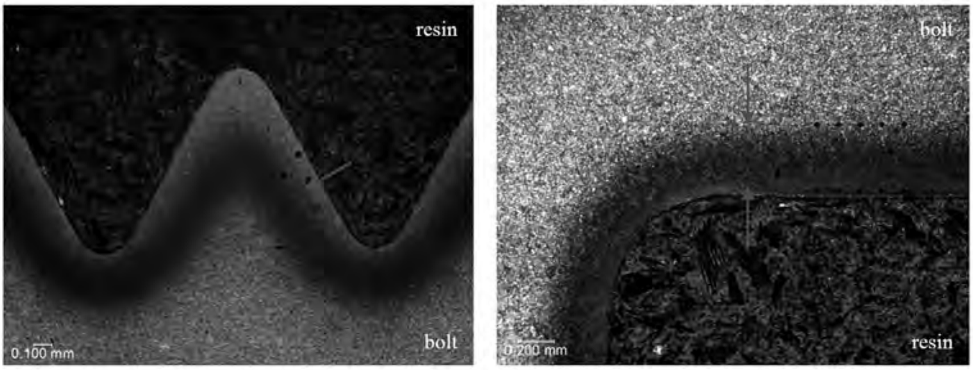

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Fig. 7. Metallographic section (part 3) carburization of the material (0.75%C).

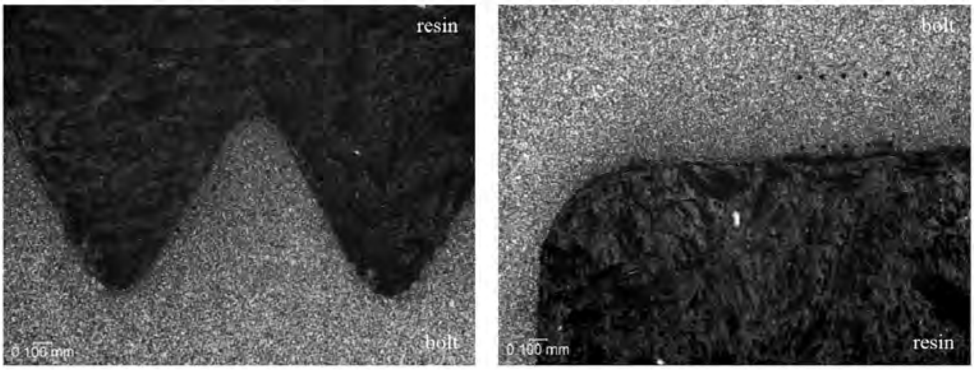

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Fig. 8. Metallographic section (part 4) produced according to standards.

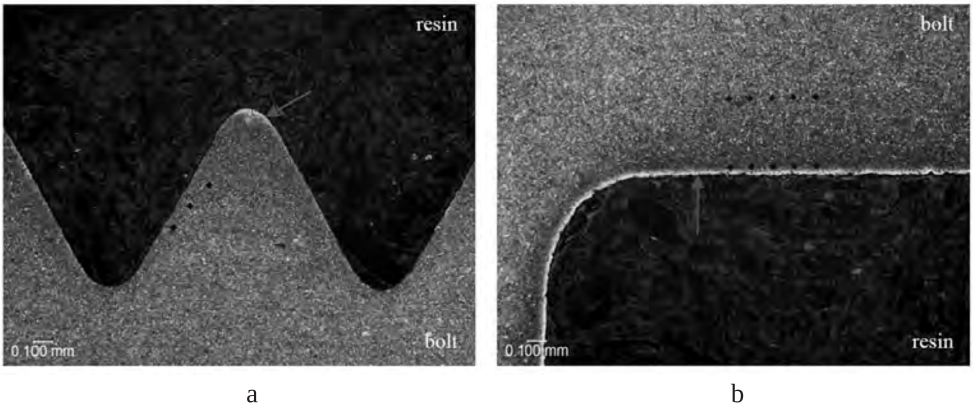


Fig. 9. Metallographic section (part 5) no changes in the material microstructure in comparison with part 4; a visible layer of not removed phosphates.

The surface measurements were made with a load equal to 10,000 gf, while the core and the bearing surface hardness tests were taken with a load equal 300 gf.

Table 2 contains the results of the hardness measurements. All the values are given in Vickers scale.

Table 2

Average HV Hardness Values of the Bolts

Part number	Core hardness	Surface hardness	Bearing surface hardness (distance 0.04 mm, side I)	Bearing surface hardness (distance 0.4 mm, side I)	Bearing surface hardness (distance 0.04 mm, side II)	Bearing surface hardness (distance 0.4 mm, side II)
1	378	355	306	342	311	340
2	361	377	400	384	402	384
3	362	451	453	392	477	398
4	352	379	389	388	376	377
5	357	384	381	393	388	386

It can be seen that in case of carburized bolts (especially with higher carbon potential) the thread hardness and the bearing surface hardness (in distance 0.04 mm) are higher than in case of the fasteners treated normally, with carbon potential equal 0.3%C. Similarly, decarburized bolts show lower hardness values compared to the pieces from part 4 – only the core hardness has risen. The presence of the phosphates layer does not significantly affect the bolt hardness.

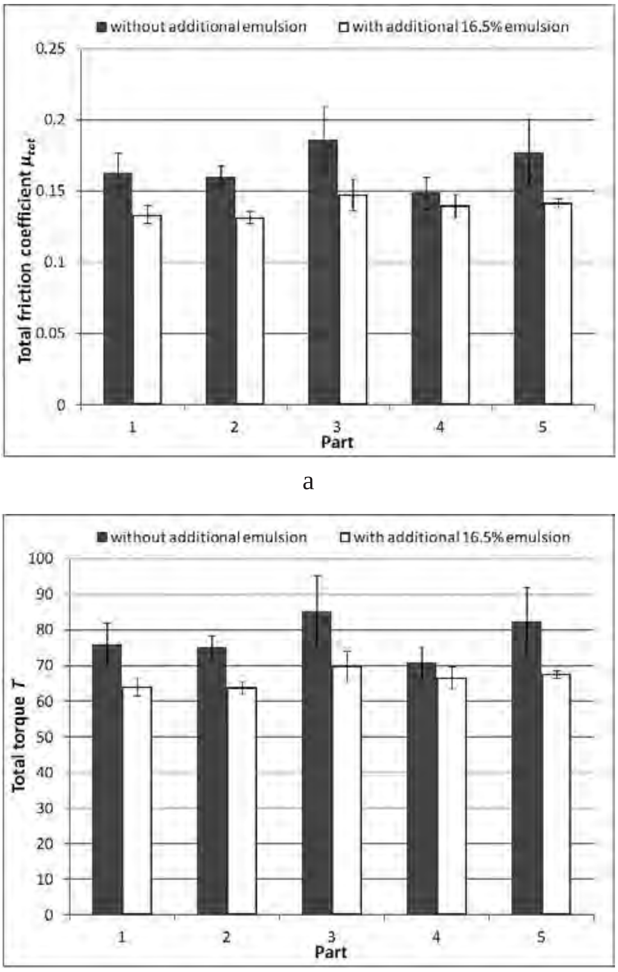
The research also included testing fasteners parameters during tightening. The clamping force equaled 36 kN. The following values were measured: total torque T, thread torque T_{th}, bearing torque T_b, total friction coefficient μ_{tot}, thread friction coefficient μ_{th}, and bearing friction coefficient μ_b. Table 3 presents the results of the bolts examination – mean value $\bar{x}$, standard deviation *SD*, minimum value *Min* and maximum value *Max* of the total tightening torque T and the total friction coefficient μ_{tot}.

Table 3

Tightening Coefficients Obtained in the Tests of Bolts

Part number	Coefficient	Bolts without additional coating		Bolts coated with 16.5% emulsion	
		T, N·m	μ_{tot}	T, N·m	μ_{tot}
1	$\bar{x}$	76.26	0.163	64.21	0.134
	SD	5.73	0.014	2.66	0.006
	Min	67.98	0.143	61.09	0.127
	Max	87.12	0.189	69.14	0.146
2	$\bar{x}$	75.26	0.160	63.91	0.132
	SD	3.36	0.008	1.72	0.004
	Min	72.19	0.153	61.63	0.127
	Max	81.61	0.176	66.84	0.139
3	$\bar{x}$	85.54	0.186	70.00	0.148
	SD	9.81	0.024	4.35	0.011
	Min	74.50	0.159	62.51	0.130
	Max	105.09	0.233	78.93	0.170
4	$\bar{x}$	70.88	0.149	66.80	0.140
	SD	4.63	0.011	3.25	0.008
	Min	64.40	0.133	62.58	0.129
	Max	79.44	0.169	71.46	0.151
5	$\bar{x}$	82.51	0.178	67.72	0.142
	SD	9.61	0.023	1.16	0.003
	Min	71.90	0.152	66.02	0.137
	Max	101.36	0.223	69.66	0.146

The graphs in Fig. 10 show the comparison of the results obtained during the tightening tests. It can be seen that the modification of the thermochemical treatment parameters has a certain influence on the values of torque and friction coefficient during tightening of a threaded joint. The greatest change caused carburization with higher carbon potential (0.75%C) – the mean total friction coefficient and the mean total torque rose respectively by 25 and 20% compared to part 4, which had been treated normally. Also in this case, the standard deviation is the highest. Equally, high values dispersion occurs in the case of not removing phosphates before the heat treatment process. Moreover, the mean total friction coefficient and the mean total torque are higher by 20 and 16%. In other cases the changes are slighter, they equal about 6–9%. Also the values dispersion is smaller in reference to the fasteners from parts 3 and 5. Nonetheless, in some cases, where requirements for bolted joint tightening parameters are strict, they may not be complied because of greater values dispersion and unpredictability of these. This research shows that the application of more concentrated emulsion during the manufacturing process could stabilize the tightening parameters. This applies both to differently heat treated fasteners and specimens within one part. As could be seen in Fig. 10, bolts additionally coated with 16.5% emulsion show less dispersion of functional parameters. The difference between



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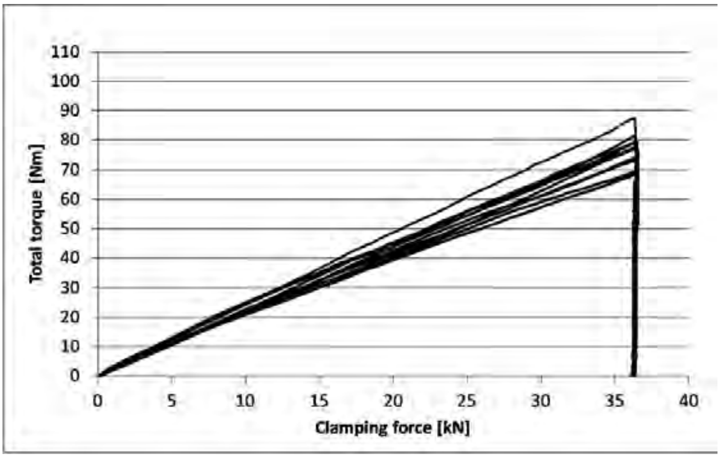
b

Fig. 10. The comparison of the obtained results for uncoated bolts and bolts additionally coated with 16.5% emulsion: (a) total friction coefficient μ_{tot}; (b) total torque T.

variously heat treated fasteners does not exceed ±5%, both in the mean total friction coefficient and the mean total torque. Likewise, the standard deviation values in each part of the samples are smaller than in case of the bolts without the presence of more concentrated emulsion. With respect to the bolted joint assembly process, for the bolts coated additionally with 16.5% emulsion, the lower torque is sufficient to obtain the required clamping force. However, it should be noticed that the friction coefficient values also decrease, which, in some cases, may lead to improper fixing of the joint and, consequently, loosening bolts during the operation.

Figures 11–15 present the spread of measured total torque versus clamping force during the tightening process. It can also be seen that the dispersion of torque and friction coefficient values is smaller in the case of additionally coated bolts. Furthermore, fasteners tightening is performed more smoothly, in a more repetitive and predictable way.

Applying a more concentrated emulsion does not require any significant modifications of the manufacturing process, except for changing the proportion of components of the emulsion, and can bring benefits in the form of stabilization and better repeatability of fasteners tightening parameters.



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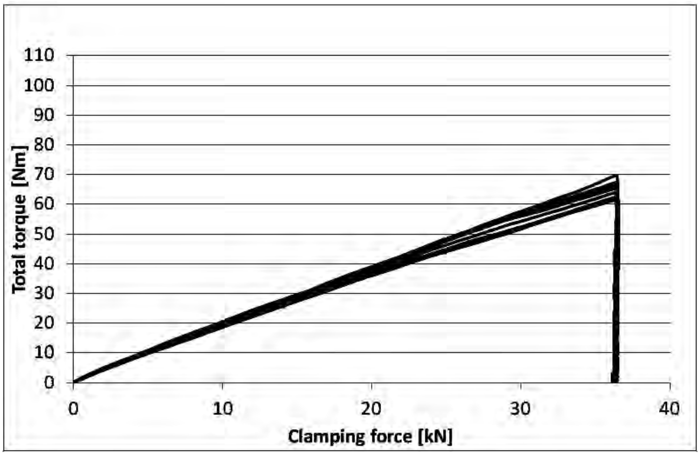

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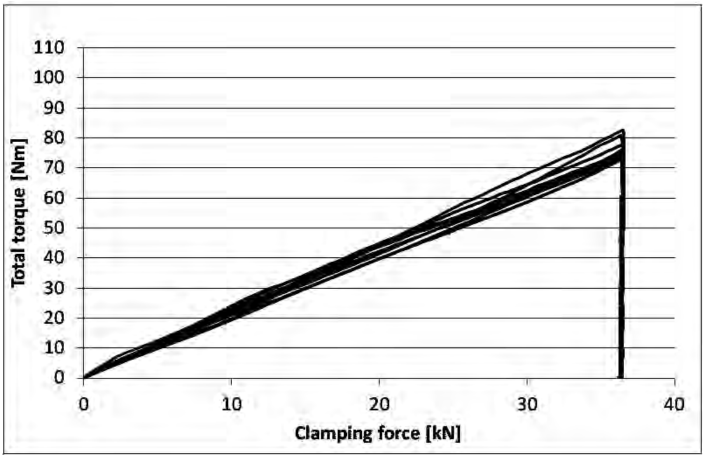
Fig. 11. Spread of measured total torque versus clamping force during tightening process (for part 1). Here and in Figs. 12–15: (a) bolts without additional coating; (b) bolts coated additionally with 16.5% emulsion.



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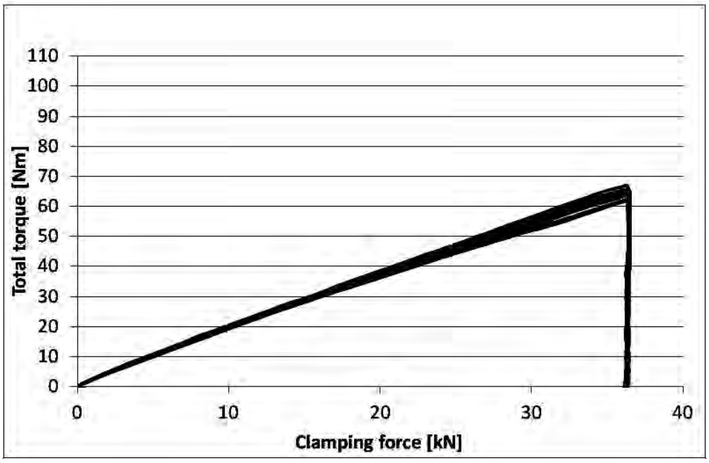

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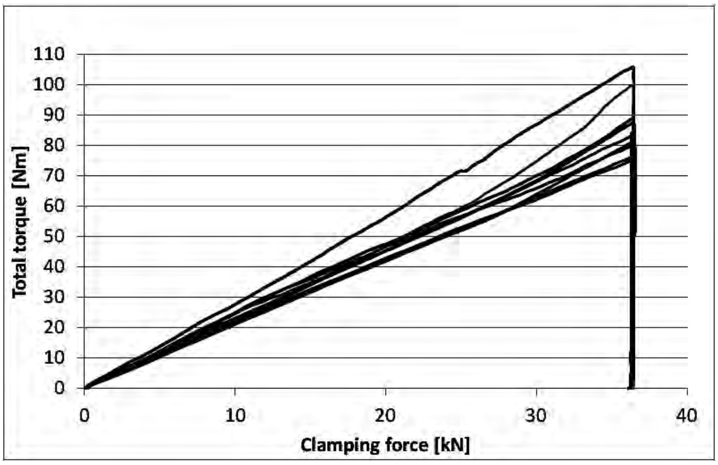
Fig. 12. Spread of measured total torque versus clamping force during tightening process (for part 2).



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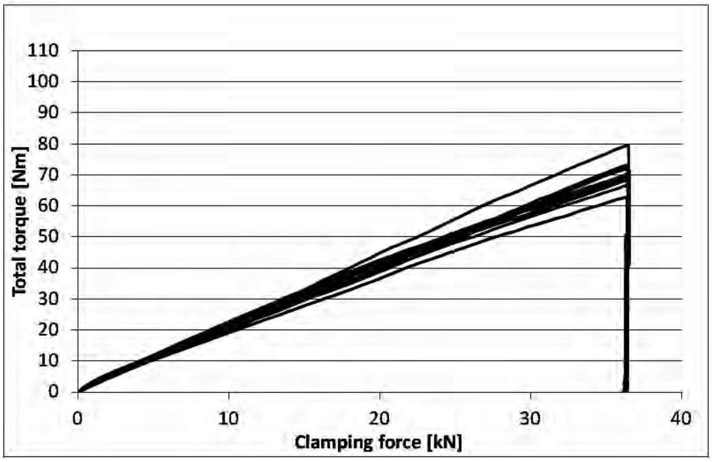

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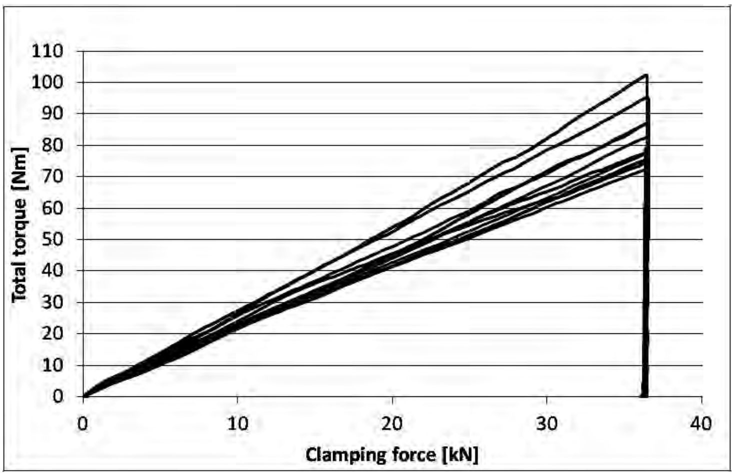
Fig. 13. Spread of measured total torque versus clamping force during tightening process (for part 3).



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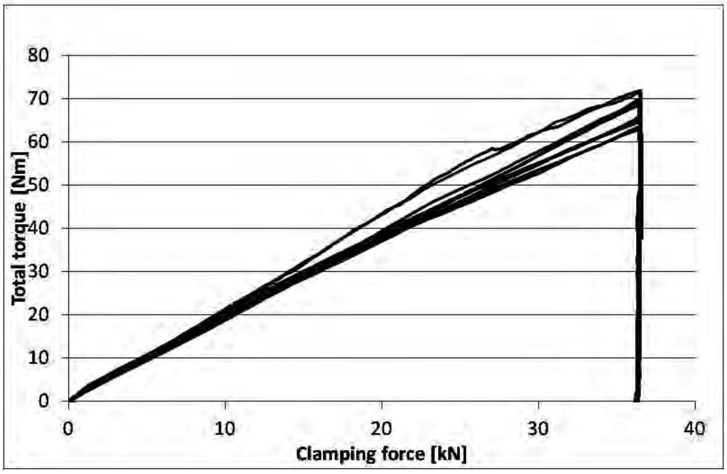

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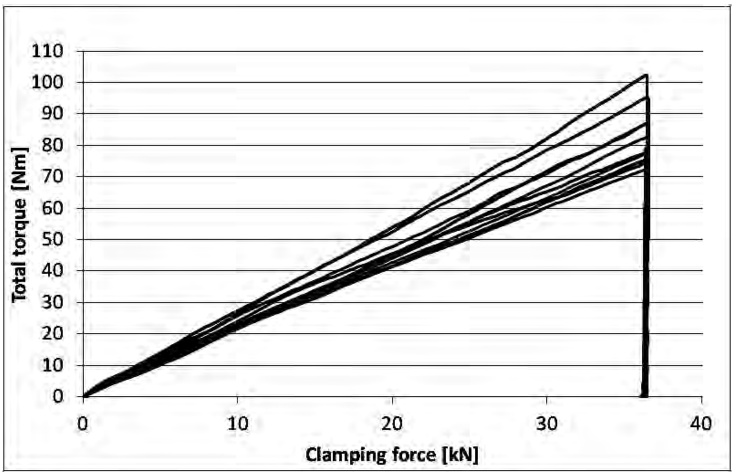
Fig. 14. Spread of measured total torque versus clamping force during tightening process (for part 4).



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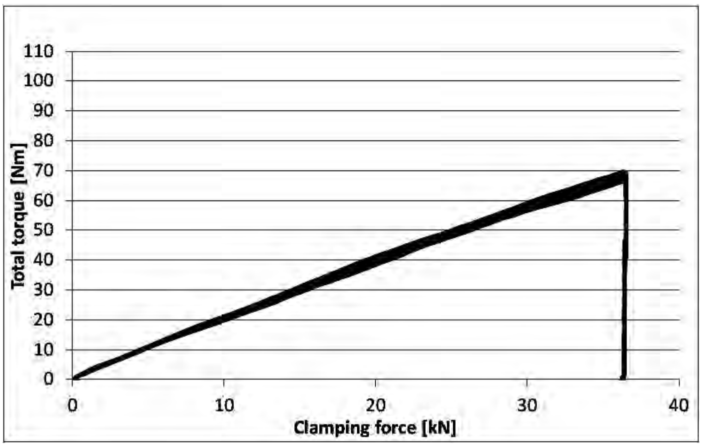

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Fig. 15. Spread of measured total torque versus clamping force during tightening process (for part 5).

Conclusions. This paper presents the research concerning the influence of differential thermochemical treatment of bolts on tightening parameters of a bolted joint. To sum up, the conclusions are as follows:

1. The modification of thermochemical treatment conditions has a certain influence on the material microstructure, the surface hardness as well as the functional parameters during tightening of a bolted joint.

2. The changes in heat treatment process cause greater dispersion of total torque and total friction coefficient values, both in differently heat treated parts of fasteners and within a single set of bolts.

3. The most significant changes in the total torque and the total friction coefficient values were observed in the case of the fasteners carburized with carbon potential equal to 0.75%C. Also the fasteners with not removed phosphates showed changes at a similar level as pieces carburized with higher carbon potential.

4.The application of a more concentrated emulsion (at a 16.5% concentration) caused the stabilization of the bolted joint tightening parameters and eliminated the influence of the changes in the material microstructure occurring during the heat-treatment process, on the functional properties of bolts.

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