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Frictional behavior of bolted joints during impact tightening

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Abstract
Impact tightening is widely used in industrial assembly of bolted joints. Friction plays a decisive role in the impact tightening process of bolted joints, yet the dynamic frictional behavior during this process remains insufficiently understood. While previous studies have focused on single bolt sizes, this work expands the experimental investigation to M10, M16, and M20 bolted joints, revealing scale-dependent frictional mechanisms. The influences of bolt diameter, impact wrench power, socket length and preload level on the distribution of coefficients of thread and bearing friction are analyzed. Results show that both bolt diameter and impact wrench power significantly influence the dynamic coefficients of friction, with smaller bolted joints exhibiting higher coefficients and greater scatter. These transitions indicate changes in real contact conditions and stick–slip behavior under impulsive torque input. These insights advance the understanding of frictional dynamics in impact tightening and provide quantitative input for improving predictive models of impact tightening and preload estimation, supporting the development of more reliable industrial assembly processes.

Keywords Bolted joint, Impact wrench, Coefficient of friction, Impact friction

1 Introduction

Due to their flexibility, ease of assembly and disassembly, bolted joints are among the most commonly used mechanical component connections in technical applications [1]. Bolted joint connections are usually designed on a specific preload. Therefore, the height and scatter of the preload achieved during tightening is an important reliability factor [2]. The preload is primarily influenced by friction in the thread and under the bolt head [3, 4]. During the tightening process, approximately 80% of the applied torque is dissipated by overcoming friction, making tribological behavior a decisive factor for the integrity of the connection. Different frictional behavior can lead to significant deviations in the resulting preload, which affect safety, durability and material efficiency [5].

For tightening bolted joints, tangential impact wrenches are often used in industrial assembly processes. Impact wrenches tighten bolted joints with short high torque pulses. They allow the application of high torques with minimal reaction force on the operator and high tightening speed [6]. However, due to their impulsive torque, these tools typically exhibit high preload variation, leading to uncertainties in tightening. According to VDI 2230 [7], the tightening factor of mechanical impact wrenches is significantly higher than the tightening factor of conventional torque-controlled tools. Due to the higher tightening factor, more or larger bolted joints are often required if the bolted joints are tightened with an impact wrench. Due to uncertainties in the tightening process, impact tightening is not allowed in some critical bolted joint connections [8]. Despite this limitation, impact wrenches remain popular due to their ergonomic and productive advantages.

Previous research has investigated influences such as surface coatings, lubrication and tool speed on thread and bearing friction. However, experimentally validated friction data for impact tightened bolted joints remain limited, particularly with respect to preload dependent behavior of multiple bolt sizes [9–11]. In general, the dynamic coefficients of friction of impact tightened bolted joints cannot be directly compared with continuously tightened bolted joints. For continuously tightened bolted joints, the coefficient of friction is tested at 75% of est preload FP. For impact tightened bolted joints, the bolted joints are rotated for a few degrees with every torque impact. After the impact, the bolted joint stops and the static friction has to be overcome again. There is no direct connection between the preload at a specific time and the tightening torque at the same time [12, 13]. Therefore, the coefficients of friction and their scatter have to be analyzed for several preload levels during the tightening process.

Recent studies show that the coefficient of thread friction during impact tightening can be up to 70% higher than during continuous tightening [14]. Furthermore, it remains unclear whether friction in the thread and under the bolt head behaves similarly under impact conditions for different bolt sizes [14]. The lack of validated macro-level friction models makes it difficult to accurately predict the preload in tangential impact tightening processes [15].

The problem is that the development of more accurate simulation models of impact tightened bolted joints requires a better understanding of the frictional behavior. Therefore, the influence of bolt diameter, impact wrench power and socket length on the dynamic coefficients of friction is not yet understood. Understanding these influences will help to improve the simulation models. These models can help to adapt future assembly strategies [16]. Investigating frictional behavior at the thread and bolt head can support the creation of cross-scaling models that accurately simulate real-world tightening scenarios [16].

This study aims to improve the understanding of the influences on frictional behavior of impact tightened bolted joints by systematically analyzing the dynamic coefficients of friction. A novel high-speed experimental setup is used to measure dynamic friction in real time for different and larger bolt diameters and higher tightening torques. The influence of bolt size, impact wrench force and socket length are investigated to quantify their effects on frictional behavior.

The results provide preload dependent experimental insight into dynamic thread and bearing friction during impact tightening and enable a differentiated assessment of their respective contributions and scatter. By identifying when during the tightening process and under which tightening conditions tribologically relevant changes occur, the study supplies quantitative input for the calibration of predictive tightening and multibody simulation models. The overall objective is to support more reliable preload estimation and to reduce the need for empirically oversized bolted joint designs in industrial assembly.

Based on these objectives, the research is guided by the following research questions:

1. Does the dynamic coefficient of friction decrease during the impact tightening process of bolted joints for different bolt diameters, impact wrench power and socket length?
2. How do different bolt sizes influence the coefficients of dynamic friction during the impact tightening of bolted joints?
3. How do different impact wrench power levels and socket lengths influence the coefficients of dynamic friction during the impact tightening of bolted joints?
4. Is there a difference between dynamic thread and bearing friction in impact tightened bolted joints?

2 Materials and methods

In the following the study design, the new test rig, the utilized bolted joints and their preparation, the post-processing of the data and the statistical analysis are described.

2.1 Study design

In this study blank grade fully threaded bolted joints [17], nuts [18] and washers [19] are used. The hardness of the bolted joint lies between 250 and 320 HV according to DIN EN ISO 898–1 [20]. The hardness of the nut lies between 200 and 302 HV according to DIN EN ISO 898–2 [21] and the hardness of the washer is 140 HV. The chemical composition of the bolts and nuts follows DIN EN ISO 898–1 and DIN EN ISO 898–2 [20, 21]. The interchangeable bearing torque support surface has a hardness of 190 HV. The impact wrench (manufacturer: HILTI AG, product: SIW 8–22 ½, nominal maximum torque 1000 Nm) was disassembled and a mechatronic trigger is added for an automated start and stop of the impact wrench. This was done to reduce the influence of the user holding the tool. The original control unit is used, but connected to the measurement system to be able to stop the tightening process when reaching the target force. For M10 the target preload level is 44 kN, for M16, the target preload level is 73 kN for M20 the target preload level is 114 kN. The parameters bolt diameter, impact wrench power and socket length are varied in this study. The factor levels and descriptions are provided in Table 1. For M10 only impact wrench power level 1 has been used as the harder torque impacts from power level 2 can damage and break the small bolts.

The impact wrench is triggered at 100%. For each bolt size the tightening process is stopped automatically, when the preset test preload is reached. According to DIN 898-1 the test preload is 56.3 kN for M10 12.9, 91 kN for M16 8.8 and 147 kN for M20 8.8 bolted joints [20].

The following bolts, nuts and washers and sockets were utilized as described in Table 2. For each bolt size, bolted joints, washers and nuts are taken from the same batch. M10 12.9 bolted joints have been used as M10 8.8 bolted joints would have deformed plastically. Damaged parts are removed.

2.2 Experimental setup and procedure

Based on a split Hopkinson bar [22] and the setup used for M10 bolted joints in [16] a new improved test rig was developed. The new test rig is able to measure the dynamic

Table 1 Parameters and factor levels of the study

	Bolt diameter	Power level of impact wrench Hilti SIW 8–22 ½	Socket length	Number of tests (repetitions)
Factor level	M20	Level 1: impact frequency 2500 1/min	Short: Hilti SI-S 1/2″–30 S Long: Hilti SI-S 1/2″–30 L	Σ80 (20 repetitions each)
		Level 2: impact frequency 2950 1/min	Short: Hilti SI-S 1/2″–30 S Long: Hilti SI-S 1/2″–30 L	
	M16	Level 1: impact frequency 2500 1/min	Short: Hilti SI-S 1/2″–24 S Long: Hilti SI-S 1/2″–24 L	Σ80 (20 repetitions each)
		Level 2: impact frequency 2950 1/min	Short: Hilti SI-S 1/2″–24 S Long: Hilti SI-S 1/2″–24 L	
	M10	Level 1: impact frequency 2500 1/min	Short: Hilti SI-S 1/2″–17 S Long: Hilti SI-S 1/2″–17 L	Σ40 (20 repetitions each)

Table 2 Bolted joints, washers and nuts used for tightening tests

	M10	M16	M20
Bolted joint (DIN 933)	Fully threaded, 12.9, blank, M10 × 90	Fully threaded, 8.8, blank, M16 × 90	Fully threaded, 8.8, blank, M20 × 90
Washer (DIN 125/ISO 7089)	Steel, blank, A, 10, 300 HV	Steel, blank, A, 16, 200 HV	Steel, blank, A, 20, 200 HV
Nut (DIN 934)	M10, 12, blank	M16, 8, blank	M20, 8, blank

bearing and thread friction independently for impact tightened M10, M16 and M20 bolted joints on the same test rig. M20 nuts are directly fit clearance-free in the test rig. For M10 and M16 bolted joints a nut holder is inserted in the test rig.

In contrast to continuous tightening, impact wrenches tighten bolted joints with short high torque pulses, e.g. in this study the torque pulses endure up to 0.5 ms with a maximum of 600 Nm at a hammering frequency of 2500 1/min for impact wrench level 1. For impact wrench level 2, the torque pulses endure up to 0.5 ms with a maximum of 1000 Nm at a hammering frequency of 2950 1/min. Between two impulses of the impact wrench, there is a dwell phase with zero input torque. This has to be considered in the experimental setup for measuring bearing and thread friction during impact tightening. Therefore, the experimental setup was developed focusing on the following requirements:

- Multiple bolt sizes have to be tested with the same test rig to improve the comparability of the measurements.
- Bearing and thread torque have to be measured independently to isolate interactions in the measured values.

- Bearing and thread torque impacts have to be measured with a high frequency up to 1 MHz.
- Nut and bearing torque support surface have to be changeable in order to be able to replace wearing parts and carry out the tests in a reproducible manner.
- For ideal impulse wave transmission, the connection has to be clearance-free and the cross sections have to be continuous.

Based on the requirements and experience with existing systems, a new test bench for higher torque impacts, higher and changeable bolt sizes was developed based on a test rig described in [16] Fig. 1.

The test bench contains an inner solid (1) bar for thread torque measurement and an outer hollow bar (2) for bearing torque measurement, connected via a cap (3). Both bars (steel 1.7225) are equipped with full-bridge strain gauges (MICRO-MEASUREMENTS CEA-06-062UV-350) for dynamic torque measurement. The inner bar incorporates a clearance-free nut fixture with exchangeable brackets (1a) for different bolt sizes. The cap houses a load cell (HBM KMR+/400 kN) with force introduction washers (3a) and an axial needle bearing (3b) to decouple the measured thread and bearing torque. The outer bar engages the cap through a dog clutch(2a), with PTFE-lubricated sliding bearings (4) between bars. The assembly is mounted in vibration-damped steel blocks (5). For damping, rubber layers (5a) are used between the steel blocks and the measuring shafts. The idealized closed force loop is added as a red line. The torque flow is added as a green line. The applied torque on the bolt head separates into bearing torque and thread torque. The bearing torque is transmitted via the cap (3) and the outer shaft (2). The thread torque is transmitted via the nut, the bracket (1a) and the inner shaft (1) to the steel block (5).

2.3 Preparation of bolted joints

In order to be able to analyze dry friction and to see larger effects, the bolted joint connections must be degreased before the tightening tests. All bolted joints, washers and nuts are cleaned in an ultrasonic bath with a 5% solution of brake cleaner (Wekem WS 1000) in water at 30 °C for 10 min. The parts are dried on lint-free paper to prevent fiber

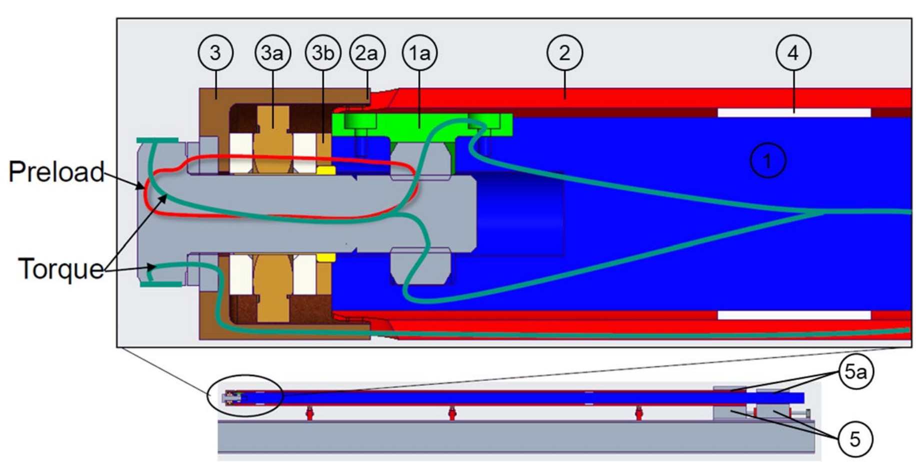

Fig. 1 Test bench for the separated measurement of the preload, thread and bearing torque course in bolted joints of different sizes during impact tightening. Preload is measured in a closed force loop. Torque is measured separately as bearing and thread torque

contamination. To minimize the risk of corrosion, the tightening tests were done shortly after cleaning. For each bolt size, bolted joints, washers and nuts are taken of the same batch. Damaged parts are sorted out.

2.4 Post-processing of data

Preload, thread and bearing torque are measured with LTT 24 of Labortechnik Tasler GmbH at a measuring frequency of 1 MHz. The high measuring frequency is used because of the very dynamic tightening process of bolted joints. The measured data is filtered with a Butterworth fifth order low-pass filter of 100 kHz. The filter frequency of 100 kHz has been chosen due to the short duration of the torque impacts up to 0.5 ms and high frequency of the torque pulses. To check the influence of the filter on the coefficients of friction, the filtered and unfiltered data has been compared showing no relevant differences in the evaluated results.

The thread torque peaks and bearing torque peaks are detected for every impact. Additional conditions of increasing the preload and a minimum time gap between two impacts were used to prevent misdetection. The preload used for further calculation is determined in the steady state before each detected impact. Figure 2 shows the preload, bearing, thread and total torque during impact tightening of an M20 bolted joint. The bolted joint is tightened with the impact wrench on power level 1 and a short socket. The peak values are marked with a blue x.

The dynamic coefficients of thread and bearing friction are calculated for each of the peaks according to ISO 16,047 [23] and Kellermann and Klein [24]. The dynamic coefficients of friction result from the measured preload, the bearing and thread torque impacts and the geometric and mechanical relationships as follows:

$$\mu_{t,peak}\left(n_{peak}\right)=\frac{\frac{T_{t,peak}(n_{peak})}{F_{peak}(n_{peak})}-\frac{P}{2*\pi}}{.577*d_2} \quad (1)$$

$$\mu_{b,peak}\left(n_{peak}\right)=2*\frac{T_{b,peak}\left(n_{peak}\right)}{D_b*F_{peak}\left(n_{peak}\right)} \quad (2)$$

$$D_{b,measured}=\frac{D_{O,measured}+d_{h,measured}}{2} \quad (3)$$

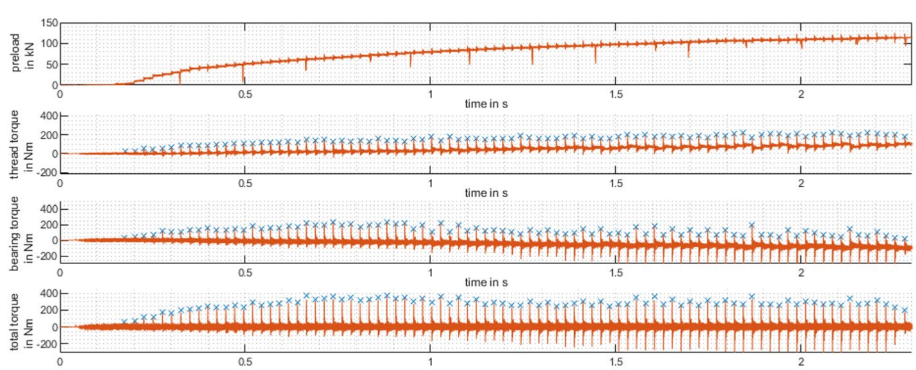

Fig. 2 Course of preload, thread torque, bearing torque and total tightening torque during impact tightening of an M20 bolted joint with a short socket on impact wrench power level 1. The results show the typical progressive increase of preload and torque components, with oscillations arising at every torque impact from the impact wrench

$D_{b,measured}$ is calculated using the measured values $D_{O,measured}$ and $d_{h,measured}$ according to DIN EN ISO 16,047 [23]. For M10, $D_{b,measured}$ is 14.87 mm², for M16 $D_{b,measured}$ is 21,45 mm² and for M20 $D_{b,measured}$ is 26.47 mm².

Preload is evaluated between 0.05*test preload (F_P) and 0.75 F_P in 0.05 F_P steps. F_P is used according to DIN 898-1 [20].

2.5 Statistical analysis

SPSS27 is used for all performed statistical tests. The dynamic coefficients of thread and bearing friction are analyzed with respect to bolt diameter, impact wrench power level, socket length and preload level.

For the statistical analysis, the coefficients of friction are evaluated at preload levels between 0.05*test preload (F_P) and 0.75 F_P in 0.05 F_P steps. F_P is used according to DIN 898-1 [20]. For the dynamic coefficients of thread and bearing friction the data is separated in 150 groups. The groups differ between the factor levels bolt diameter, power level of impact wrench, socket length and preload level.

For determining the statistical tests, normal distribution and homogeneity of variances are tested using a Shapiro Wilk test ($\alpha = 0.05$) and Levene's test. As shown in Table 3 not all groups can be assumed normally distributed.

The homogeneity of variances is tested using Levene's test ($\alpha = 0.05$) For both μ_{th} and μ_b equal variances could not be assumed ($p < 0.001$).

As several groups violate the assumption of normal distributed and equal variances cannot be assumed, non-parametrical statistical tests are performed. The influence of bolt diameter on the coefficients of friction is analyzed with the Kruskal–Wallis test, followed by pairwise Mann–Whitney U tests with Bonferroni correction for each preload level. The influence of socket length and impact wrench power are tested with Mann–Whitney U tests for each preload level. The influence of preload level on the dynamic coefficient of thread and bearing friction is tested with Friedman test for repeated measurements. Additionally, the dynamic coefficients of thread and bearing friction are shown as separate boxplots for M10, M16 and M20 bolted joints during tightening with short and long sockets and two impact wrench power levels.

3 Results

In this chapter, the results of the study are shown. First, the coefficients of thread friction during the impact tightening are shown for different bolt diameters, impact wrench power and socket length. Afterwards, the result for the dynamic coefficient of bearing friction are shown.

3.1 Analysis of the dynamic coefficient of thread friction

Figure 3 shows the dynamic coefficients of thread friction at 25%, 50% and 75 % of maximum test preload. For each preload level, the dynamic coefficients of thread friction are measured for M10, M16 and M20 bolted joints during tightening with short and long

Table 3 Shapiro Wilk test for testing for normal distribution

Shapiro Wilk	μ_{th}	μ_b
Number of groups	150	150
Number of groups with p(Shapiro-Wilk) > = 0.05	137	72
Percentage that can be assumed normally distributed	91%	48%

sockets and two impact wrench power levels. Each combination is shown in a separate boxplot.

During the tightening process both the dynamic coefficients of thread friction and the scatter of the dynamic coefficient of thread friction decrease. Based on the statistical procedure described in Chap. 2.5 the influence of bolt diameter on the dynamic coefficient of thread friction is additionally analyzed using the Kruskal–Wallis test across preload levels from 0.05 F_P to 0.75 F_P. For all preload levels, bolt diameter has a significant effect on thread friction (H = 124.1–166.7, df = 2, $p < 0.001$). Post-hoc pairwise Mann–Whitney U tests confirms significant differences in the dynamic coefficient of thread friction between all bolt diameters across preload levels from 0.05 to 0.75 F_P. M10 bolted joints consistently exhibited higher dynamic coefficients of thread friction than both M16 (U = 0–187, Z = − 8.907 to − 7.866, $p < 0.001$) and M20 bolted joints (U = 0–60, Z = − 8.91 to − 8.57, $p < 0.001$). M16 bolted joints also show significantly higher coefficients of dynamic thread friction than M20 bolted joints (U = 110–870, Z = − 10.55 to −7.95, $p < 0.001$), although the difference was smaller than between M10 and M20.

The Mann–Whitney U test indicates that impact wrench power level significantly influences the dynamic coefficient of thread friction at preload levels between 0.05 F_P and 0.65 F_P (U = 3014–3931, Z = − 2.17 to − 4.45, p = 0.030 to < 0.001). The higher impact wrench power level results in lower dynamic coefficients of thread friction. At higher preload levels (0.70 F_P and 0.75 F_P), the effect of the impact wrench power level is no longer significant (p = 0.070–0.191). This indicates that the influence of impact wrench power decreases with increasing preload.

Both Fig. 3 and the Mann–Whitney U test indicate no significant influence of socket length on the dynamic coefficient of thread friction at any preload level (U = 4546–4999, Z = − 0.04 to − 1.11, p = 0.267–0.998).A comparison between the preload levels in Fig. 3 shows that the dynamic coefficient of thread friction significantly decreases with increasing preload. This is supported by Friedman test which indicates a significant effect ($\chi^2(14) = 2172.28$, $p < 0.001$).

3.2 Analysis of the dynamic bearing friction

The dynamic coefficient of bearing friction is illustrated for three preload levels. Figure 4 shows the dynamic coefficients of thread friction at 25%, 50% and 75% of maximum test preload. For each preload level, the dynamic coefficients of thread friction are measured for M10, M16 and M20 bolted joints during tightening with short and long sockets and two impact wrench power levels. Each combination is shown in a separate boxplot.

The results show consistent with the statistical analysis that the bolt diameter significantly influences the dynamic coefficient of bearing friction across all preload levels (Kruskal–Wallis H = 91.3–124.0, df = 2, $p < 0.001$). M10 bolted joints exhibit substantially higher coefficients of bearing friction and greater scatter compared to M16 (U = 0–60, Z = − 8.91 to − 8.25, $p < 0.001$) and M20 bolted joints (U = 0–118, Z = − 8.91 to − 8.57, $p < 0.001$). M16 bolted joints display moderately higher dynamic coefficients of bearing friction than M20 bolted joints (U = 1242–2143, Z = − 6.68 to − 3.61, $p < 0.001$).

The Mann–Whitney U test indicates that lower impact wrench power level only affects dynamic coefficient of bearing friction at very low preload levels between 0.10 FP and 0.25 F_P (U = 3599–3922, Z = − 2.99 to − 2.19, p = 0.003–0.029. The higher impact wrench power levels lead to lower dynamic coefficients of friction. At 0.05 F_P (p = 0.068) and at

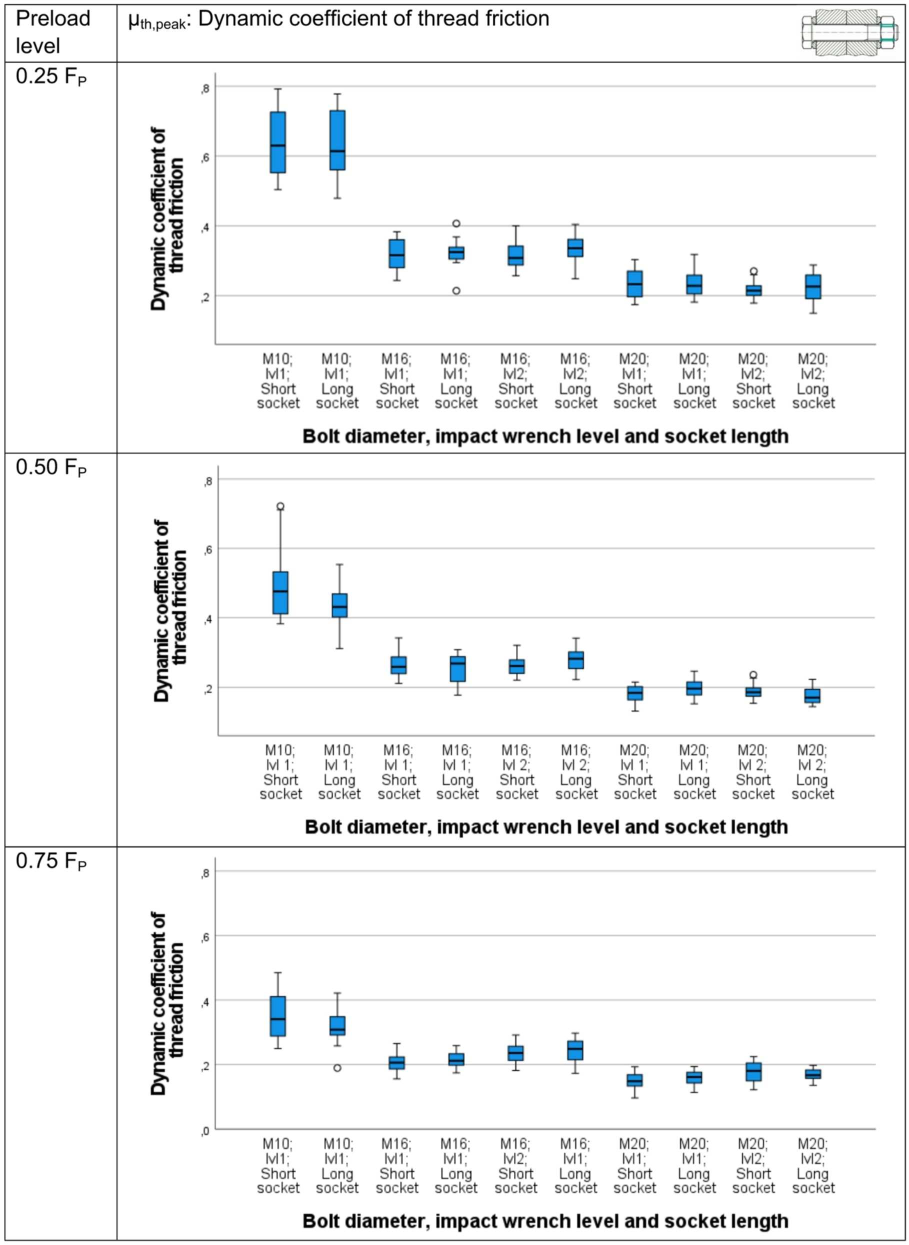

Fig. 3 Dynamic coefficients of thread friction at three preload levels (0.25 F_P, 0.5 F_P and 0.75 F_P) of impact tightened bolted joints. The dynamic coefficients of thread friction are compared for M10, M16 and M20 bolted joints, short and long sockets and two impact wrench power levels. Higher preload levels cause lower dynamic coefficients of thread friction. The higher impact wrench power level tends to lead to lower dynamic coefficients of thread friction

preload levels above 0.30 F_P ($p = 0.120–0.980$), no significant influence of power level is detected. Thus, the impact wrench power level influences bearing friction only in the very early stages of tightening.

For dynamic coefficient of bearing friction, socket length showed no significant effect across preload levels up to 0.65 FP (U = 4216–4982, Z = – 0.04 to – 1.92, $p = 0.055–0.965$). At higher preload levels between 0.7 and 0.75 F_P, a small but significant influence was observed (U = 3733–3806, Z = – 3.10 to –2.92, $p = 0.002$ to 0.004;).

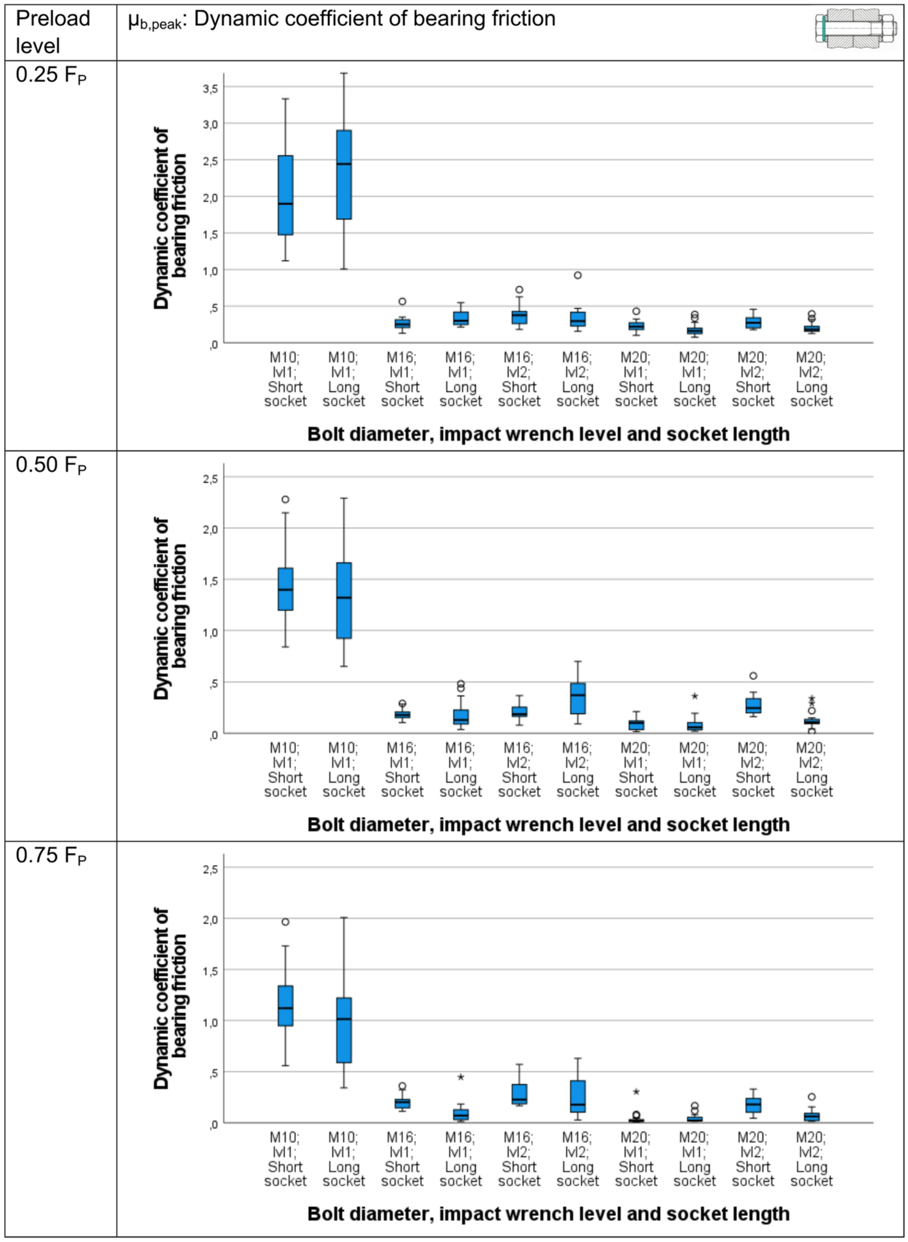

Fig. 4 Dynamic coefficients of bearing friction at three preload levels (0.25 FP, 0.5 FP and 0.75 FP) of impact tightened bolted joints. The dynamic coefficients of bearing friction are compared for M10, M16 and M20 bolted joints, short and long sockets and two impact wrench power levels. Higher preload levels cause lower dynamic coefficients of bearing friction. A higher impact wrench power level leads to lower dynamic coefficients of bearing friction

A comparison between the preload levels in Fig. 4 shows that the dynamic coefficient of bearing friction decreases with increasing preload. This is supported by Friedman test which indicates a significant effect ($\chi^2(14) = 1400.28$, $p < 0.001$).

Overall, dynamic coefficients of bearing friction values are higher and have a higher scatter than dynamic coefficients of thread friction, particularly for the investigated M10 bolted joints.

4 Discussion

This study investigated the dynamic frictional behavior of impact tightened bolted joints, focusing on the influence of bolt diameter, impact wrench power level and socket length. A constant interfacial contact condition throughout the tightening process was assumed. In general, higher impact conditions such as longer sockets, high impact torques of the impact wrench and low preload levels increase the risk of intermittent separation or micro lift off between the contact surfaces in the bolted joint connection. However, no indications for interface separation such as negative normal force or torque spikes uncorrelated with rotation were detected.

Beyond the parametric findings, the results provide new insights into the dynamic coefficients of thread and bearing friction, their scatter, and their dependence on preload. On the basis of the results, the research questions can be answered as follows:

4.1 Decrease of friction during the impact tightening process of bolted joints for different bolt diameters, impact wrench power and socket length

Both the dynamic coefficient of thread friction and the dynamic coefficient of bearing friction decrease during the impact tightening process for different bolt diameters, impact wrench power levels and socket lengths. This effect has also been observed in a previous study of lubricated impact-tightened M10 bolted joints and can now be confirmed for larger bolt sizes under dry friction conditions. A primary reason for the decrease of the dynamic coefficients of thread and bearing friction is that the surface pressure is higher at higher preload levels and the tightening speed gets lower. The contact surfaces of the bolted joints flatten during the tightening process, increasing the real contact area. It is further hypothesized that the contact surfaces are already partly flattened at higher preload levels. This observation highlights that the frictional behavior during impact tightening is not static but evolves dynamically with changing surface conditions and local contact pressures.

The observed preload-dependent decrease of both the dynamic coefficient of thread and bearing friction is consistent with rate-and-state friction models. In these models, friction depends on both normal load and the evolving state of the contact surfaces. For higher preload levels, the micro-slip amplitudes are lower. More stable contact conditions lead to lower dynamic coefficients of friction and lower scatter. Similar preload dependent behavior is also seen in Iwan models where increasing preload raises tangential stiffness and slip thresholds of micro contacts [25]. This behavior is further associated with a redistribution of impulse energy from frictional dissipation to elastic transmission at higher preload levels. At higher preload levels, the contact stiffness at the thread and bearing interfaces increases. The increased contact stiffness limits microslip. Therefore, a larger part of the impulse energy is transmitted elastically through the bolted joint rather than being dissipated by friction.

4.2 Influence of bolt size on the coefficients of dynamic friction during impact tightening of bolted joints

Smaller bolt sizes lead to higher dynamic coefficients of friction. For larger bolts, the number of torque impacts and the tightening angle is higher. Therefore, levelling effects in the surfaces occur less. To verify this, a surface analysis of the bolted joint before and after tightening will be done in future studies.

For M10 bolted joints with a higher strength class both the dynamic coefficients of thread and bearing friction are much higher than for M16 and M20. The M10 bolted joints have carried the load under the bolt head more on the outer part of the contact area. A similar effect of the distribution of the load under the bolt head on the coefficient of friction has been shown for continuously tightened bolted joints [26]. Another contributing factor is that the harder M10 bolted joints need a smaller tightening angle and less time for tightening. Therefore, the levelling of the bolted joints could be less advanced and the coefficient of friction is higher. These results confirm a scale-dependent frictional behavior, driven by geometry, stiffness, and surface levelling effects. The observed bolt-size dependence can be interpreted within Iwan models, which represent the interface as a distribution of micro-slip elements [25]. Larger bolt diameters are tightened with a higher number of impacts and smaller tightening angle per impact, leading to more progressive activation and stabilization of contacts. This results in reduced coefficients of friction and scatter, consistent with a narrower effective slip threshold distribution in hysteresis-based models of bolted joints.

4.3 Influence of impact wrench power levels and socket length on the coefficients of dynamic friction during the impact tightening of bolted joints

The impact wrench power level influenced dynamic friction, but its effect was preload-dependent. For the dynamic coefficient of thread friction, a high impact wrench power level consistently lowered the coefficients up to a preload of 0.65 F_P, after which the influence diminished. For bearing friction, the effect was limited to the very early stages of tightening (≤ 0.25 F_P). A possible explanation is that stronger torque impacts reduce stick–slip phases by overcoming static friction more effectively, leading to lower dynamic coefficients of friction. As preload increases, the relative effect of pulse energy becomes less significant compared to the increasing normal forces in the bolted joint. These findings highlight that tool settings can influence early tightening behavior, but their effect on final preload scatter may be limited depending on the tightening strategy of the impact wrench.

The socket length showed no significant influence on the dynamic coefficient of thread friction at any preload level. Only a small influence on dynamic coefficient of bearing friction could be detected at very high preload levels (≥ 0.7 F_P). This indicates that variations in torsional compliance of the tool–socket system have negligible impact on tribological behavior in the bolted joint. This result contrasts with some earlier suggestions [9], but aligns with industrial experience that socket choice has little effect compared to bolt size or lubrication. The influence of impact wrench power and socket length can be interpreted using rate-dependent friction concepts and hysteresis models. Higher impulse energy of the impact wrench leads to a more reproduceable overcoming of static friction. This reduces sensitivity to local variations at low preload levels in the beginning of the tightening process. In microslip-based models, increased impulse amplitude leads to a more complete activation of micro-slip elements during low preload level at early tightening stages [25]. This reduces variability in the friction response. With increasing preload level in the macro slip part of the tightening process, the influence of impulse amplitude diminishes as contact stiffness dominates the frictional behavior [25].

4.4 Cause of difference between thread and bearing friction

The dynamic coefficients of bearing friction were not only higher but also exhibited greater scatter compared to the dynamic coefficients of thread friction. This aligns with previous studies for lubricated M10 bolted joints [16] and emphasizes that the bearing surface introduces more variability, possibly due to uneven contact surfaces of the impact tightened bolted joints. This difference between the dynamic coefficients of thread and bearing friction should be considered when developing predictive models for impact tightened bolted joints. The higher scatter observed for bearing friction compared to thread friction is consistent with microslip hysteresis models that account for a not constant pressure distribution and distributed slip thresholds. Bearing interfaces are more sensitive to local uneven surfaces and pressure gradients. This can lead to a broader activation spectrum of micro-slip elements. In hysteresis-based frameworks, such as Iwan models, this leads to increased energy dissipation variability and friction scatter [25]. While these frameworks provide useful interpretation of the observed effects, the present study applies a macroscopic coulomb friction evaluation.

5 Conclusion

This research experimentally characterized the dynamic frictional behavior of impact tightened bolted joints under dry conditions. Both thread and bearing coefficients of friction decreased during tightening, with bolt diameter identified as the dominant factor: smaller bolts exhibited higher dynamic coefficients of friction and greater scatter. Impact wrench power influenced friction primarily at early preload stages, while socket length had negligible effect. Bearing friction consistently exhibited higher values and greater scatter than thread friction.

Friction plays a crucial role in achieving consistent and reliable preload levels in impact tightened bolted joints. Since preload directly determines the functional integrity and safety of the assembly, understanding and consideration of frictional behavior is essential for industrial tightening processes. Variations in friction influence the achieved preload, which can compromise the performance, durability, and reliability of the assembly.

These findings provide quantitative evidence that bolt size and tool power must be considered in predictive models of the impact tightening process and preload estimation, contributing to more accurate and reliable assembly processes.

6 Outlook

The results generated in this research provide a foundation for developing more reliable multibody simulation models that represent the dynamic interaction of wrench, fastener, and clamped parts. For the application of multibody simulation models, for each preload level, friction coefficients are calculated depending on bolt size, number of impacts, tightening angle and socket length. With this the tightening process can be simulated for each torque impact of the torque wrench.

Future work should expand the research to coated and lubricated bolted joints, varying the limited bolt grades and different surface hardness levels to make the findings transferable to a wider range of applications. Additionally, systematic surface analyses before and after tightening will be essential to clarify the role of wear and roughness evolution in the tribological mechanisms of impact tightening. These investigations of the contact surfaces will be supported by laser doppler vibrometry and high-speed imaging of a partly cut bolted joint connection to directly observe interface kinematics. In this research, the bolted joints have been tightened once. For future investigation of repeated tightening, we expect higher coefficients of dynamic thread and bearing friction.

Nomenclature

$D_{b,measured}$	Measured bearing surface diameter mm
$D_{O,measured}$	Outer bearing surface diameter mm
$d_{h,measured}$	Measured bearing hole diameter mm
D	Bolt diameter mm
d_2	Effective thread diameter mm
F_P	Maximum test preload kN
F_{peak}	Preload at impact kN
F	Preload kN
P	Thread pitch mm
p	Probability value -
s	Standard deviation -
T_b	Bearing torque in Nm
$T_{b,peak}$	Bearing peak torque Nm
T_{th}	Thread torque Nm
$T_{th,peak}$	Thread peak torque Nm
α	Significance level -
μ_b	Coefficient of bearing friction -
$\mu_{b,peak}$	Coefficient of bearing friction at peak torque -
μ_{th}	Coefficient of thread friction -
$\mu_{th,peak}$	Coefficient of thread friction at peak torque -

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Author contributions
Tobias Kretschmer: Writing – original draft, Formal analysis, Methodology, Conceptualization, Software, Investigation. Markus Doellken: Writing – editing and review, Supervision. Patrick Haberkern: Writing – review and editing. Felix Leitenberger: Writing – review and editing. Niklas Frank: Writing – review and editing. Albert Albers: Writing – review and editing. Sven Matthiesen: Writing – review and editing, Supervision.

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Data availability
The dataset generated and analyzed during the current study has been made publicly available at https://doi.org/10.35097/yjdmucmycjkbm09g .

Declarations

Ethical approval
Not applicable.

Consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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