INSTITUTE FOR
Metal and Lightweight Structures
Prof. Dr.-Ing. habil. Natalie Stranghöner

UNIVERSITÄT DUISBURG ESSEN
Open-Minded

Universitätsstr. 15 | 45141 Essen | Phone: +49 (0)201 183-2757 | Fax: +49 (0)201 183-2710
E-Mail: iml@uni-due.de | www.uni-due.de/iml

Preloading procedures to achieve a reduced preloading level in the elastic range of the bolt material with sufficient reliability

Deliverable report D1.5

WP 1 – Task 1.5

Prof. Dr.-Ing. habil. Natalie Stranghöner
natalie.stranghoener@uni-due.de

Christoph Abraham B.Sc.
christoph.abraham@uni-due.de

Dominik Jungbluth M.Sc.
dominik.jungbluth@uni-due.de

Part of the RFCS Research Project

"SIROCO"
Execution and reliability of slip-resistant connections for steel structures using CS and SS

RFCS Project No.:	RFSR-CT-2014-00024
Project No.	410410007-20003
Report No.:	2018-09

30.03.2018

Table of contents Page

1 Introduction

1.1 General remarks

This deliverable report deals with Work Package 1, Task 1.5 from the RFCS Research Project SIROCO, "Execution and reliability of slip resistant connections for steel structures using CS and SS". Work Package 1 of the project deals with improving test procedure for the determination of slip factors and closing the lack of undefined or unclear defined rules given in the test procedure of Annex G of EN 1090-2.[1]

According to EN 1090-2, if a bolting assembly is tightened to the minimum preload $F_{p,C}$ and later untightened, it must be removed and the whole assembly discarded. Reuse is not possible. In some cases, there is a need for reuse of the bolts and/or the nuts. Preloading in the elastic range would offer the possibility for reusability of the assemblies or parts of them – implied that the bolts/nuts are not damaged due to the previous use.

For this reason, in this task existing preloading procedures (torque and combined method) will be experimentally tested with the aim to specify specific parameters (lubrication, tightening steps etc.) in order to be able to achieve guaranteed preload levels in the elastic range with sufficient reliability. Thus, tightening tests acc. to EN ISO 16047 [2] resp. EN 14399-2 [3] will be performed for HV and HR bolts, property classes 10.9 and 8.8 of two bolt dimensions each: M24 and M36. Due to the fact that the main influencing parameter in the tightening process is the lubrication of the nut, various lubrication types will be tested.

The evaluation of the tightening tests for preloading procedures to achieve a reduced preloading level in the elastic range of the bolt material with sufficient reliability is based on the German modified torque method and the modified combined method according to DIN EN 1993-18/NA. [4] The target level of preloading for these tightening methods is $F_{p,C}^* = 0.7\ f_{yb}\ A_s$ and based on the 0.2 % remaining strain level of the bolt material instead of the ultimate stress level. In the following, the tested HR and HV bolting assemblies will be systematically investigated regarding the achieved preloads including statistical evaluation.

Furthermore, background information to the existing tightening methods and other data from literature will be part of the research.

1.2 Objectives

This deliverable report deals with the work carried out in Work Package 1 – Task 1.5 "Preloading procedures to achieve a reduced preloading level in the elastic range of the bolt material with sufficient reliability".

1.3 Reference to Technical Annex

The Technical Annex of RFCS SIROCO project defines the Work Package 1 – Task 1.5 as follows:

<u>Task 1.5 Development of preloading procedures to achieve a reduced preload level on the basis of the 0,2% remaining strain level (UDE, TUD)</u>

Background: There is a need to measure the preload of bolts in existing structures. For example: A lot of existing bridges needs an evaluation of the present structural status in view of the remaining life time under increasing traffic loading conditions.

This is important for making decisions whether the bridge can remain as it is or needs to be strengthened (upgraded) or even to be replaced by a new structure. In this evaluation, knowledge about the actual level of preload of the bolts in slip-resistant connections is vital.

In literature some research on this topic is reported but the results show a large scatter. The interpretation of the measured signals from the testing is influenced by several aspects, such as the clamped plate package, massiveness of the surrounding structure, etc.

A suggestion is to develop appropriate tightening procedures for slip-resistant connections where the preload level is based on the 0,2% remaining strain level of the bolt material (i.e. 70 % of the yield strength level of the bolt material) instead of the ultimate stress level of the bolt material. With this preload level the bolt assemblies would be loaded in the elastic range only.

In some cases, there is a need for reuse of the bolts and/or the nuts. Preloading in the elastic range would offer the possibility for reusability of the assemblies or parts of them – implied that the bolts/nuts are not damaged due to the previous use.

For this reason, in this task existing preloading procedures (torque and combined method) will be experimentally tested with the aim to specify specific parameters (lubrication, tightening steps etc.) in order to be able to achieve guaranteed preload levels in the elastic range with sufficient reliability. Thus, tightening tests acc. to EN ISO 16047 resp. EN 14399-2 with the tightening torque testing machine in the laboratory of UDE will be performed for HV and HR bolts, grade 10.9 and 8.8 of two bolt dimensions each: M24 and M36. Due to the fact that the main influencing parameter in the tightening process is the lubrication of the nut, various lubrication types will be tested.

Test specimens for tightening tests:

2 types of bolts (HV and HR), grade 10.9 for HV-bolts and grades 8.8 and 10.9 for HR-bolts, 2 bolt dimensions (M24 and M36), four lubrication types, 10 tightening tests per configuration

-> 1 x 2 x 4 x 10 + 2 x 2 x 4 x 10 = 80 + 160 = 240 tightening tests

All experimental tightening tests will be performed at UDE. The results will be discussed and evaluated by UDE and TUD.

Results and deliverables:

- Preloading procedures to achieve a reduced preload level in the elastic range of the bolt material with sufficient reliability (Amndm. to EN 1090-2)

2 State of the art

2.1 General

Firstly, a short overview of non-preloaded and preloaded carbon steel bolting assemblies is provided, based on the harmonized standards EN 15048-1 [5] (subchapter 2.2.1) and EN 14399-1 [6] (subchapter 2.2.2). Categories of bolted connections acc. to EN 1993-1-8 [7] are explained as well as the related target levels of preloading, see subchapter 2.2.3.

An introduction to force-deformation relationships of bolted connections is presented in subchapter 2.3.1. The mechanical behaviour of bolting assemblies and bolted connections is essential, and for this reason the load-bearing behaviour of bolting assemblies under mono-axial tensile load is presented as well in subchapter 2.3.2.

The applicability of tightening methods is directly connected to the quality of calibrated bolting assemblies in their delivered condition. To achieve and guarantee a specified preload level, appropriate tightening methods are required and underline the importance of adjusted, calibrated lubrication and k-classes. For this reason, the k-value, as a parameter for predominant friction conditions and quality of lubrication, is introduced according to EN 14399-2 as well as the related k-classes K0, K1, and K2 acc. to EN 14399-1 [6].

Looking at the tightening and basic preloading behaviour of HV/HR bolting assemblies, not only the tightening itself is of interest, but the whole procedure including all necessary tightening parameters and criteria: the level of suitable preloading, the associated lubrication, the tightening procedure (see subchapter 2.4) itself and the evaluation criteria.

For this reason, the test procedure and suitability test for preloading according to EN 14399-2 are presented as well as the to be measured and/or to be determined parameters according to EN ISO 16047 (see subchapter 2.6 and 2.7). The criteria to evaluate the ductility of bolting assemblies according to EN 14399-2, EN 14399-3 [8] and EN 14399-4 [9] are summarized in subchapter 2.7.

2.2 Standards and categories of bolted connections

Bolting assemblies used in the steel construction industry are based on two European harmonized standards (CPR 305/2011), summarized in Figure 1:

- **Non-preloaded bolting assemblies** (categories A, D) refers to *EN 15048-1: 2007-07* and can be divided into standard bolts for metal construction (EN ISO 4014, 4016, 4017 and 4018) and german bolts for steel construction (DIN 7990 and DIN 7968).
- **Preloaded bolting assemblies** (categories B, C, E) according to *EN 14399-1:2015-04* include preloaded special bolts "H" like system HR acc. EN 14399-3 and HV acc. EN 14399-4 [9] (as examples of suitable bolting assemblies refered to the scope of EN 14399-1). Preloading of standard bolts acc. EN ISO 4014 [10] and EN ISO 4017 [11] is also possible.

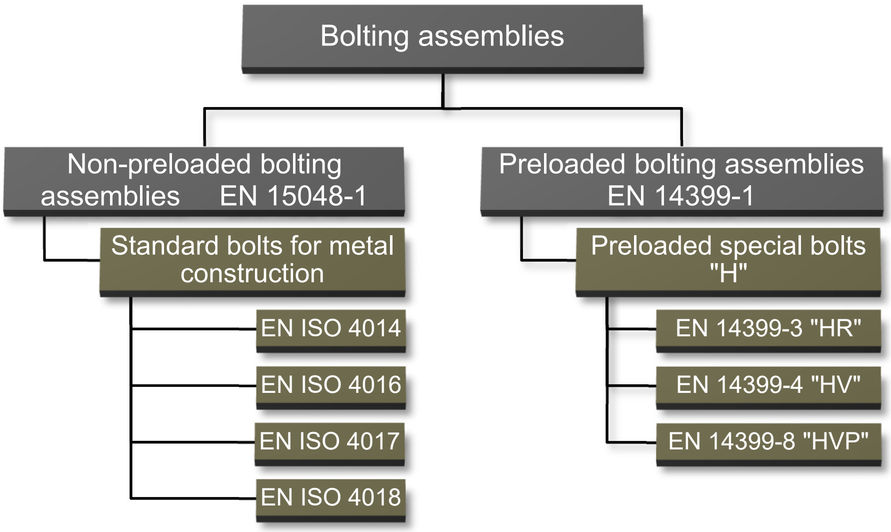


Figure 1 Overview of bolting assemblies and harmonized standards used in the steel construction industry [12][13]

2.2.1 Harmonized Standard EN 15048-1: Non-preloaded structural bolting assemblies

The European harmonized standard EN 15048-1:2007-07 [14] "Non-preloaded structural bolting assemblies – Part 1: General requirements" contains all technical requirements for bolting assemblies without referring to individual products in steel construction and is open-designed, meaning that various bolting assemblies must fulfil central claims like dimensions and tolerances in accordance to international or European standards, deliverable in bolting assemblies, CE certification of the manufacturer, and structural bolting (SB) marking [12].

Standard bolts for metal construction (EN ISO 4014, 4016, 4017 and 4018) are presented in a comparative overview in Table 1 together with German bolts according to DIN 7990 and DIN 7968 also fulfilling the criteria of EN 15048-1. The advantages of these standard bolts for metal construction are that only a narrow stock range is necessary, and from a technical viewpoint, the selection is easy for the planning engineer and washers are not prescribed when normal round holes are used without special conditions. On the other hand, the shear load capacity of bolts with the thread in the clamped package is lower and deformations are a bit larger in shear/hole bearing connections. The normative references, main characteristics, and differences of nuts and washers for non-preloaded structural bolting assemblies are summarized in Table 2 and Table 3 [12].

Table 1 Overview of non-preloaded structural bolting assemblies acc. EN 15048-1:2007-07 (based on [12])

Designation	Product standard	Thread length	Shank diameters	Wrench width	Product class	Strength class
Standard bolts for metal construction	EN ISO 4014	medium long: b ≈ (2.2 to 2.5) · d	normal: d_{sh} = d	normal: s ≈ (1.5 to 1.6) · d	A/B 1)	5.6, 8.8, 10.9
	EN ISO 4016				C	4.6
	EN ISO 4017	long: b ≈ 1	normal: d_{sh} = d	normal: s ≈ (1.5 to 1.6) · d	A/B 1)	5.6, 8.8, 10.9
	EN ISO 4018				C	4.6
German bolts for steel construction	DIN 7990	particularly short: b ≈ (1.2 to 1.6) · d	normal: d_{sh} = d	normal: s ≈ (1.5 to 1.6) · d	C	4.6, 5.6
	DIN 7968	particularly short: b ≈ (1.2 to 1.5) · d	Pass-: d_{sh} = d + 1	normal: s = (1.5 to 1.6) · d	C	5.6

1) ≤ M24 / > M24

Table 2 Overview of applicable nuts for non-preloaded structural bolting assemblies acc. EN 15048-1 (based on [12])

Designation	Product standard	Height of the nut	Wrench width	Product class	Strength class
Standard bolts for metal construction	EN ISO 4032	medium: m ≈ 0.9 · d	normal: s ≈ (1.5 to 1.6) · d	A/B 1)	6, 8, 10
	EN ISO 4034	medium: m ≈ 0..9 · d	normal: s ≈ (1.5 to 1.6) · d	C	4, 5
	EN ISO 4033	medium: m ≈ 1.0 · d	normal: s ≈ (1.5 to 1.6) · d	A/B 1)	9, 12

1) ≤ M16 / > M16

Table 3 Overview of applicable washers for non-preloaded structural bolting assemblies acc. EN 15048-1 [14] (based on [12])

Designation	Product standard	Thickness 1)	Outside diameter 1)	Inside diameter 1)	Chamfer	Product class	Hardness
Standard bolts for metal construction	EN ISO 7089	thin: h = 2.5 to 5.0 mm	d_a = e + (3 to 5) mm	d_i = d +1 mm	no	A	200/300 HV
	EN ISO 7090				outside		200/300 HV
	EN ISO 7091				no	C	100 HV
German bolts for steel construction	DIN 7989-1	thick: h = 8 mm		d_i = d + (2 to 3) mm	no	C	100 HV
	DIN 7989-2					A	

1) Range: minimum value: M12 / maximum value: M36

Two types of bolting assemblies are possible [12]:

- *Standard bolting assemblies for metal construction* with EN ISO 4014 or 4017 bolts combined with ISO 4032 hexagon nuts and washers acc. to ISO 7089.
- *German bolting assemblies for steel construction* with DIN 7990 or DIN 7968 bolts, hexagon nuts acc. to EN ISO 4032, and washers acc. to DIN 7989 (only standardised in Germany).

2.2.2 Harmonized Standard EN 14399-1: High-strength structural bolting assemblies for preloading

The European harmonized standard EN 14399-1 “High-strength structural bolting assemblies for preloading – Part 1: General requirements” contains all technical requirements for bolting assemblies for preloading. The normative references, main characteristics, and differences of nuts and washers for preloaded structural bolting assemblies are summarized in Table 4, Table 5 and Table 6. Chapter 4.2.1 of EN 14399-1 describes two types of bolting assemblies for preloaded bolted connections:

- **Type HR** (including System HR acc. EN 14399-3 and System HRC acc. EN 14399-10) is structurally designed so that *ductility is predominantly achieved by plastic elongation of the bolt*. For this, the minimum height of the hexagon nut must be ≥ 0.9 *D* and the thread length of the bolt is acc. ISO 888:2012-04.
- **Type HV** is structurally designed so that ductility is *predominantly achieved by the plastic deformation of the paired threads*, realized by nut height ≈ 0.8 *D* and bolts with short thread length.

The special characteristics of HRC bolting assemblies with reference to EN 14399-10 and Direct Tension Indicators (DTI) according to EN 14399-9 are not explained here (see Deliverable report D3.3). Furthermore, preloading of standard bolting assemblies for metal construction in property class 8.8 according to EN ISO 4014 [21] and EN ISO 4017 [22] is also possible.

Compared to EN ISO 4014 and EN ISO 4017 bolting assemblies, high-strength structural bolting assemblies for preloading in System HR and HV are characterized by a larger wrench width, the height of the nut is equal to ISO 4017 (m ≈ 0.9 · d) and System HV bolt heads are larger than EN ISO 4014/4017 bolt heads.

Table 4 Overview of preloaded high-strength structural bolts acc. EN 14399-1 (based on [12])

Designation	Product standard	Thread length	Shank diameter	Wrench width	Product class	Strength class
Preloaded special bolts "H"	EN 14399-4 "HV"	short: b ≈ (1.4 to 1.9) · d	normal: d_{sch} = d	large: s ≈ (1.6 to 1.7) · d	B	10.9
	EN 14399-8 "HVP"	extremly short: b ≈ (1.2 to 1.5) · d	Pass-: d_{sch} = d + 1	large: s ≈ (1.6 to 1.7) · d	B	10.9
	EN 14399-3 "HR "	medium: b ≈ (2.2 to 3.3) · d	normal: d_{sch} = d	large: s ≈ (1.6 to 1.7) · d	B	8.8, 10.9
Preloaded standard bolts for metal construction	EN 14399-1 + EN ISO 4014	medium: b ≈ (2.2 to 2.5) · d	normal: d_{sch} = d	normal: s ≈ (1.5 to 1.6) · d	A/B[1)]	8.8
	EN 14399-1 + EN ISO 4017	long: b ≈ 1	normal: d_{sch} = d	normal: s ≈ (1.5 to 1.6) · d	A/B[1)]	8.8

[1)] ≤ M24 / > M24

Table 5 Overview of preloaded high-strength nuts acc. EN 14399-1 (based on [12])

Designation	Product standard	Height of the nut	Wrench width	Product class	Strength class
Preloaded special bolts "H"	EN 14399-4 "HV"	small: m ≈ 0.8 . d	large: s ≈ (1.6 to 1.7) · d	B	10
	EN 14399-3 "HR"	medium: m ≈ 0.9 . d	large: s ≈ (1.6 to 1.7) · d	B	8, 10
Preloaded standard bolts for metal construction	EN 14399-1 + EN ISO 4032	medium: m ≈ 0.9 . d	normal: s ≈ (1.5 to 1.6) · d	A/B[1)]	8

[1)] ≤ M16 / > M16

Table 6 Overview of preloaded high-strength washers acc. EN 14399-1 (based on [12])

Designation	Product standard	Thickness[1)]	Outside diameter[1)]	Inside diameter[1)]	Chamfer	Product class	Hardness
Preloaded special bolts "H"	EN 14399-5	medium: h = 3.0 to 6.0 mm	$d_a = e$	$d_i = d$ +1 mm	no	A	300 to 370 HV
	EN 14399-6				inside + outside		
Preloaded standard bolts for metal construction	EN 14399-1 + DIN 34820	thin: h = 2.5 to 5.0 mm	$d_a = e$ + (3 to 5) mm	$d_i = d$ +1 mm		A	300 HV

[1)] Range: minimum value: M12 / maximum value: M36

2.2.3 Categories of bolted connections and preloading target levels

The primary distinction of bolted connections is between shear connections and tension connections, categorized based on the type of loading perpendicular or running parallel to the bolt axis, see Figure 2. Based on the primary distinction, the Eurocode EN 1993-1-8 [7] classifies bolted connections into categories A to E, presented in Table 7 and Figure 3.

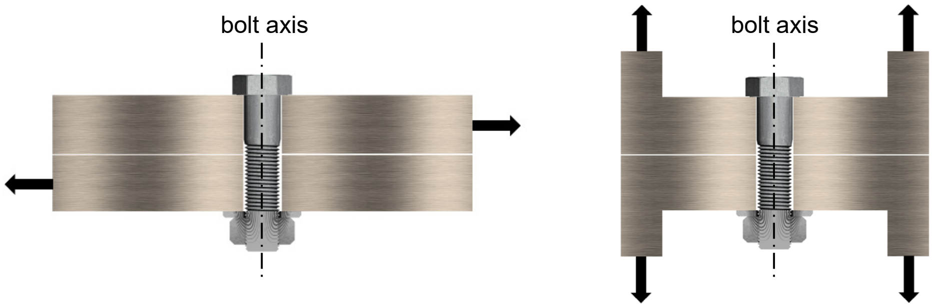


Figure 2 Bolted shear connection (left) and tension connection (right)

Table 7 Categories of bolted connections acc. EN 1993-1-8:2010-12

Category	Design criterion	Annotations
Shear connections		
A bearing type	$F_{v,Ed} \leq F_{v,Rd}$ $F_{v,Ed} \leq F_{b,Rd}$	No preloading required. Bolt classes from 4.6 to 10.9 may be used.
B slip resistant at serviceability	$F_{v,Ed,ser} \leq F_{s,Rd,ser}$ $F_{v,Ed} \leq F_{v,Rd}$ $F_{v,Ed} \leq F_{b,Rd}$	Preloaded 8.8 or 10.9 bolts should be used.
C slip resistant at ultimate	$F_{v,Ed} \leq F_{s,Rd}$ $F_{v,Ed} \leq F_{b,Rd}$ $\sum F_{v,Ed} \leq N_{net,Rd}$	Preloaded 8.8 or 10.9 bolts should be used.
Tension connections		
D non-preloaded	$F_{t,Ed} \leq F_{t,Rd}$ $F_{t,Ed} \leq B_{p,Rd}$	No preloading required. Bolt classes from 4.6 to 10.9 may be used.
E preloaded	$F_{t,Ed} \leq F_{t,Rd}$ $F_{t,Ed} \leq B_{p,Rd}$	Preloaded 8.8 or 10.9 bolts should be used.

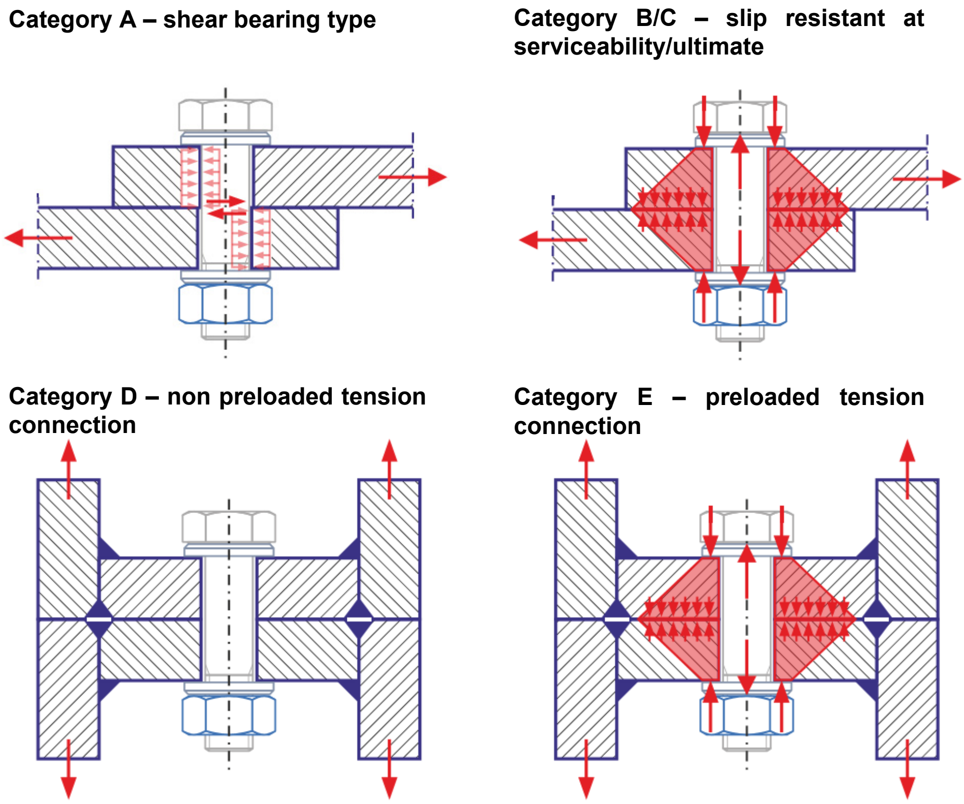


Figure 3 Visualization of categories of bolted connections [© IML]

The preloading of high-strength, structural bolting assemblies can serve different purposes. The type of bolted connection must be considered, as well as the relevance of the security, which has of course the highest priority. From this perspective, further distinguishing between two target levels of preloading in steel construction is useful to take into account the required inspection of installation and testing accuracy:

- ***Target level I*** – *Guarantee structural safety:* slip-resistant connections in categories B and C as well as preloaded tension connections in category E which are often used in fatigue loaded applications. In all cases, the preload must be sufficiently and safely guaranteed over the entire service life and periodical inspections are required.

  ➢ *Specified preload in EN 1090-2:* $F_{p,C} = 0.7 \cdot f_{ub} \cdot A_s$,

  unless otherwise specified.

with	$F_{p,C}$	specified preloading level (see also EN 1090-2)
	f_{ub}	nominal tensile strength ($R_{m,nom}$) of the bolt
	A_s	nominal stress area of the bolt (see EN ISO 898-1 [14])

- ***Target level II*** – *Improvement of serviceability:* the shear-bearing connection in category A, as well as the non-preloaded tension connection in category D, can be executed as preloaded connections to improve the serviceability (e.g. slip minimisation, increasing the stiffness, reduction of deformations).

  ➢ *Posssible preload:* $F_p \leq F_{p,C}$, *e. g.* $F_{p,C}^* = 0.7 \cdot f_{yb} \cdot A_s$

  with $F_{p,C}^*$ reduced preloading level (see exemplary German Technical

Annex, DIN EN 1993-1-8/NA [15])

f_{yb} nominal yield strength ($R_{m,nom}$) of the bolt

A_s nominal stress area of the bolt (see EN ISO 898-1)

The execution of preloaded bolted connections is summarized in Table 8 with a focus on the discussed target levels of preloading, normative references, tightening methods, and inspection requirements.

Table 8 Execution of preloaded bolted connections acc. to EN 1090-2 and DIN EN 1993-1-8/NA [16]

Target level preload	Category (according to design)	Preload (according to execution)		Bolting assemblies: product standard	Bolting assemblies: strength class	k-cl.	Tightening methods³⁾	Tightening parameters⁴⁾	Control requirements
I Quantitative improvement ultimate state	B¹⁾ C	relevant for design	$F_{p,C}$	EN 14399-1	10.9 8.8⁵⁾	K2 K1	CM	EN 1090-2	EN 1090-2
	E		$F_{p,C}$						
			$F_v < F_{p,C}$	specifications required²⁾					
			$F_{p,C}^*$	Tab. NA.A.2⁶⁾	10.9	K1	MCM MTM CWM	Tab. NA.A.2⁶⁾ Tab. NA.A.3⁶⁾	EN 1090-2
				Tab. NA.A.1⁶⁾	8.8		MTM CWM	Tab. NA.A.1⁶⁾	
			$F_v < F_{p,C}^*$	Tab. NA.A.2⁶⁾	10.9		MTM CWM	proportional to Tab. NA.A.2⁶⁾	
				Tab. NA.A.1⁶⁾	8.8			proportional to Tab. NA.A.1⁶⁾	
II Qualitative improvement serviceability	A D	not relevant for design	$F_{p,C}$	EN 14399-1	10.9 8.8⁵⁾	K2 K1	CM	EN 1090-2	EN 1090-2
			$F_v < F_{p,C}$	specifications required²⁾					
			$F_{p,C}^*$	Tab. NA.A.2⁶⁾	10.9	K1	MCM MTM CWM	Tab. NA.A.2⁶⁾ Tab. NA.A.3⁶⁾	EN 1090-2 – please note Quelle 1
				Tab. NA.A.1⁶⁾	8.8		MTM CWM	Tab. NA.A.1⁶⁾	
			$F_v < F_{p,C}^*$	Tab. NA.A.2⁶⁾	10.9		MTM CWM	proportional to Tab. NA.A.2⁶⁾	
				Tab. NA.A.1⁶⁾	8.8			proportional to Tab. NA.A.1⁶⁾	

¹⁾ In this case to guarantee serviceability. ²⁾ Specifications regarding preload level. ³⁾ Abbreviations of tightening methods: CM – combined method; TM – torque method; CWM – calibrated wrench method; MTM – modified torque method; MCM – modified combined method. ⁴⁾ e.g. reference tightening torques. ⁵⁾ The use of bolts in strength class 8.8 is not recommend. ⁶⁾ Tables acc. Annex NA.A. of DIN EN 1993-1-8

2.3 Tightening behaviour of HV/HR bolting assemblies made of carbon steel

The load-bearing behaviour of structural bolting assemblies can be divided into two fundamentally different types of loading: rapid tensile loading and cyclic, alternate fatigue loading. This separation is necessary due to different failure modes and the importance of notches. Thomala and Kloos [17] emphasize that strength behaviour, in particular for notched components, is influenced mainly by the load-time function; and that structurally related notches can improve the load-bearing behaviour of components under rapid tensile load (sufficient ductility assumed) but is reduced under cyclic, alternate loading. First, focusing on rapid tensile loading, the force-deformation-relationships of concentrically clamped single-bolted connections is introduced. Second, the load-bearing behaviour of bolting assemblies under rapid tensile load is discussed.

2.3.1 Force-deformation relationships

When tightened the nut respective to the bolt head, the preload F_M is created in the bolting assembly depending on friction conditions, the tightening method, surface roughness of the clamped parts, and many additional factors. In principle, when tightened, the bolt elongates in the amount of f_{SM} while the clamp package is compressed by the value $f_{PM.}$ For reasons of balance, the preload F_M is equal to the clamp force F_K. The unequal length changes and forces that take place are schematically visualized in Figure 4 and can be calculated by the equations 2-1 and 2-2 (see explanations regarding δ below):

$$f_{SM} = \delta_S \cdot F_M \ , \tag{2-1}$$

$$f_{PM} = \delta_P \cdot F_M \ . \tag{2-2}$$

When an axial operating load F_A is acting, it is proportionally transmitted via the clamped region and via the bolt. The additional axial bolt load F_{SA} is the difference between the operating load F_A and the applied preload F_M and loads the bolt, whereas the remaining proportion F_{PA} relieves the clamped sections, depending on the elastic behaviour of the bolt connection, as well as the location of the action of the forces. The result is the residual clamp load F_{KR}. It is important to note that the operating force F_A also leads to length changes f_{SA} and f_{PA}. All forces and length changes can be illustrated in a joint diagram, presented in Figure 5.

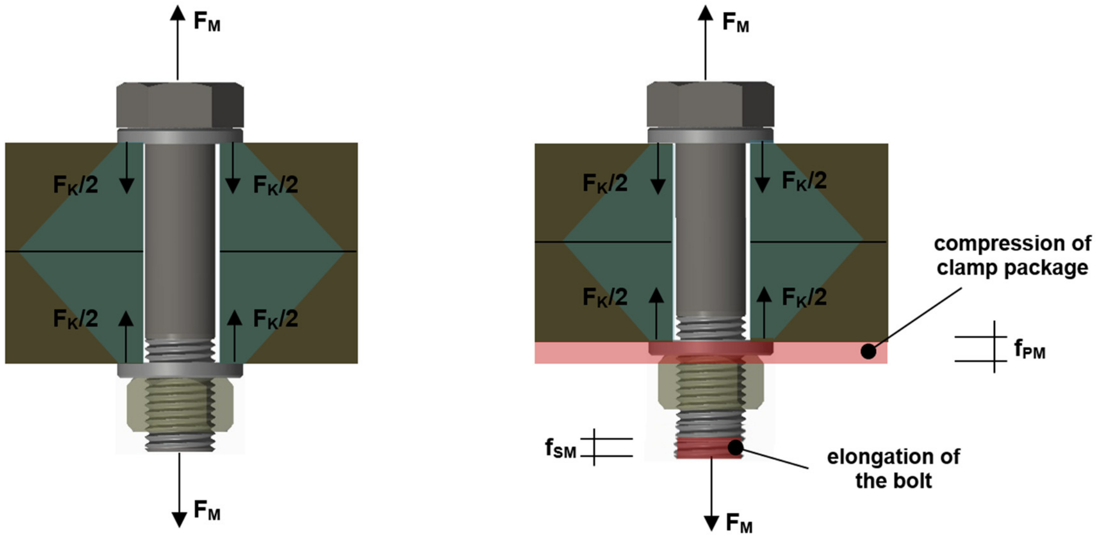


Figure 4 Schematic visualisation of length changes of the bolt (f_{SM}) and clamp package (f_{PM}) [17]) when tightened; see also [18]

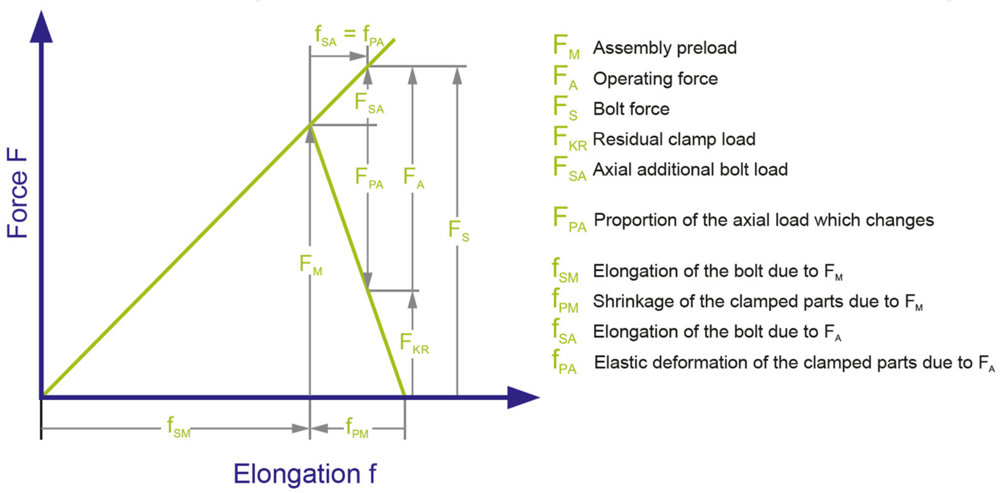


Figure 5 Joint diagram of a bolted connection to illustrate forces and length changes (© IML).

Significantly influenced by the elastic behaviour of the connection in the immediate surroundings of the bolt axis, forces and axial deformations can be described by axial deformations of the bolt and deformations of the clamped package. Based on Hooke's law, the elastic resiliencies can be calculated:

$$\varepsilon = \frac{\sigma}{E} \rightarrow \frac{f}{l} = \frac{F}{A \cdot E} \rightarrow \frac{f}{F} = \frac{l}{E \cdot A} = \delta \ . \qquad (2\text{-}3)$$

For calculating the elastic axial bolt resilience δ_S, the bolt and connecting elements can be seen as a row of arranged and connected cylindrical elements, visualized in Figure 6. In equation 2-4, the elastic bolt resilience is the sum of individual resiliencies of cylindrical elements (δ_1, δ_2, …) within the clamp length, including the resilience of the bolt head (δ_{SK}), the resilience of the engaged thread part (δ_{Gew}), and nut or the tapped hole region (δ_{GM}). VDI 2230 Part 1 [19] states more precisely that "δ_{GM} is composed of the resilience at the minor diameter δ_G of the engaged bolt thread and the resilience of the nut or tapped thread region δ_M".

$$\delta_S = \delta_{SK} + \delta_1 + \delta_2 + \ldots + \delta_{Gew} + \delta_{GM} \ \wedge \ \delta_{GM} = \delta_G + \delta_M \qquad (2\text{-}4)$$

On the other hand, the elastic resilience δ_P of the clamp package is more difficult to calculate due to three-dimensional stress and deformation states. In particular, problems arise when compression stresses radially decrease in the cross section and the transverse dimensions of the bolted parts exceed the diameter of the bolt head surface. VDI 2230 Part 1:2015-11 offers two equations to determine the elastic resilience δ_P, depending on assumptions made. If contact resilience is not taken into account and micro-structures and conditions of the surface are neglected, equation 2-5 describes the elastic resilience δ_P of the clamp package by using a substitutional deformation cone of the same resilience:

$$\delta_P = \int_{y=0}^{y=l_k} \frac{dy}{E(y) \cdot A(y)} \ . \qquad (2\text{-}5)$$

If there is, in addition to the deformation cone, a deformation sleeve in the bolted connection (criterium: $D_A < D_{A,Gr}$ with $D_{A,Gr} = d_w + w \cdot l_k \cdot \tan\varphi$), then the elastic resilience δ_P of the clamp package is determined by equation 2-6 (w = 1 for through-bolt joints, w = 2 for tapped thread joints):

$$\delta_P = \frac{2\ln\left[\frac{(d_w + d_h)\cdot(d_w + w\cdot l_k\cdot\tan\varphi - d_h)}{(d_w - d_h)\cdot(d_w + w\cdot l_k\cdot\tan\varphi + d_h)}\right]}{w\cdot E_P\cdot\pi\cdot d_h\cdot\tan\varphi}. \qquad (2\text{-}6)$$

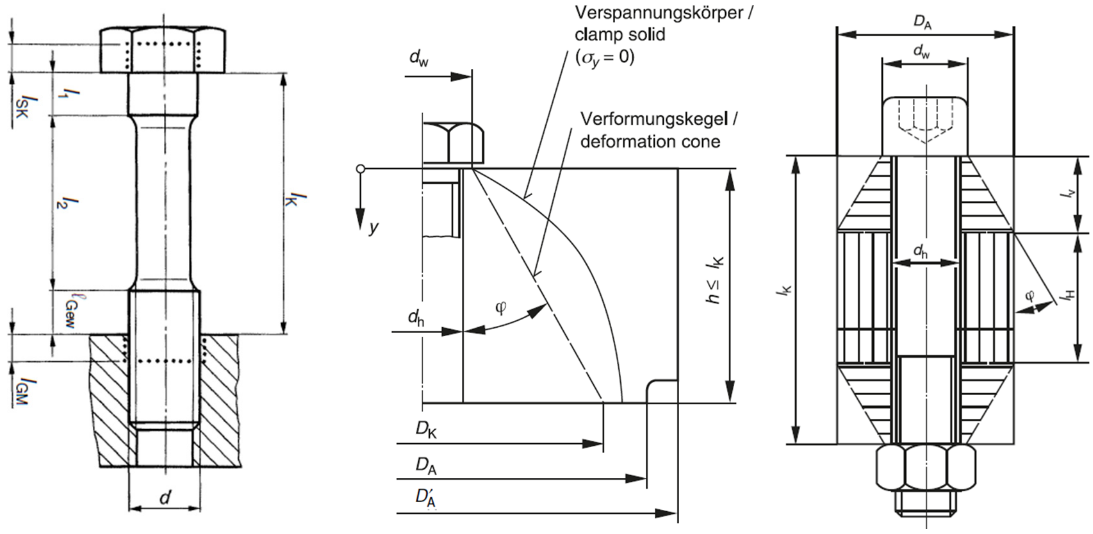


Figure 6 Division of bolt into individual cylindrical elements (left), clamp solid and calculation model (middle), and cylindrical deformation cone plus sleeve acc. VDI 2230 Part 1 [25].

2.3.2 Tensile loaded bolting assemblies and notch effects

The load-bearing behaviour of bolting assemblies under tensile load focuses on the question of converting a tightening torque to a useable and reliable preload. The total tightening torque M_A is composed of the preload producing torque M_{GSt} (which is, due to friction, only 10% of the total tightening torque), thread torque M_{GR}, and the nut respective to the bolt head bearing torque M_{KR} (terminology from [17]). In the elastic range and with constant friction assumed, the relationship between tightening torque and the achieved preload is linear.

$$M_A = M_{GSt} + M_{GR} + M_{KR} = M_G + M_{KR} \qquad (2\text{-}7)$$

Derived from the equilibrium conditions for the inclined plane as a fundamental principle, the relationship between the preload and the torsional moment acting in the thread can be obtained. Considering the pitch diameter d_2, the pitch P, and flank angle α = 60° (ISO threads), the equation for thread torque can be simplified as:

$$M_G = F_V\,(0.159P + 0.577\,d_2\,\mu_G). \qquad (2\text{-}8)$$

The nut respective to the bolt head bearing torque for overcoming the friction is calculated by equation 2-9 with an adopted constant surface pressure and D_{Km} as friction diameter:

$$M_{KR} = F_V\,\mu_K\,\frac{D_{Km}}{2} \wedge D_{Km} = \frac{(d_w + d_h)}{2}. \qquad (2\text{-}9)$$

The tightening torque can finally be determined by the following equation:

$$M_A = F_V \left(0.159\,P + 0.577\,d_2\,\mu_G + \frac{D_{Km}}{2}\mu_K \right). \quad (2\text{-}10)$$

Figure 7 summarizes the occurring forces, torques, and frictions in a bolted connection when tightened (here, exemplary nut sided), the distribution in load-bearing paired threads, and the flow of forces.

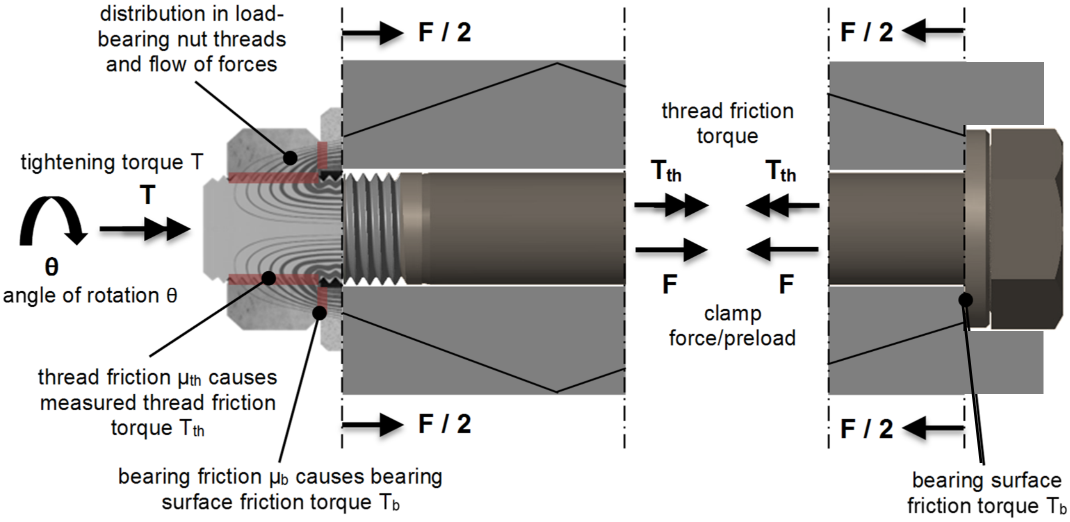


Figure 7 Forces, torques and friction conditions in a bolted HV connection when tightened [17][18]

The design of bolts in the context of load-bearing behaviour can be different depending on the required applications and target failure mode. For example, System HR bolts, according to EN 14399-3, are structurally designed with the aim that ductility is predominantly achieved through plastic elongation of the bolt. For this, the minimum height of the hexagon nut must be ≥ 0.9 D, so that fracture occurs in the free loaded thread of the bolt. Related to security aspects, plastic deformations give notice of upcoming fracture. On the contrary, system HV bolts acc. EN 14399-4 achieve ductility through plastic deformation of the paired threads, realized by a nut height of ≈ 0.8 D and bolts with short thread lengths. The failure principle is the stripping of the hexagon nut.

Bolts are highly notched connecting elements and under tension load, local stresses can significantly increase. Figure 8 shows the ratio $\sigma_{max}/\sigma_{nom}$ (form factor α_K) and displays places with high notch stresses at borders, like the bolt head-shank transition, in the free loaded thread of the bolt, and especially at the first load-bearing thread of the nut. It can be used to design failure modes of bolts, e.g. the different height of the System HR and System HV nuts to modify local stresses.

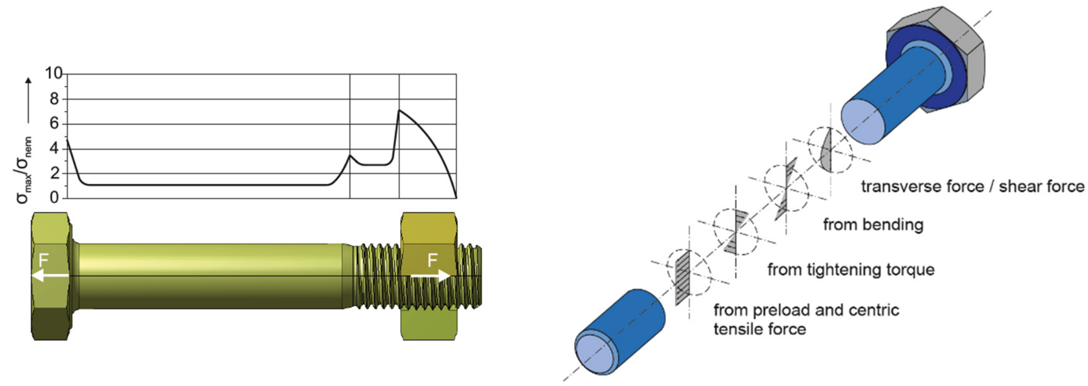
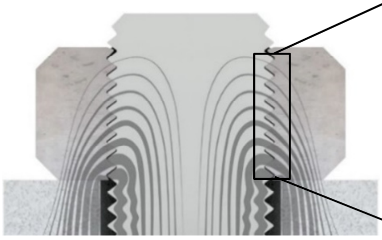


Figure 8 Distribution and form factors α_K of notches in a bolt (left) and stresses in bolt shank (right) (© IML for left and right Figure).

Thomala and Kloos [17] emphasize that multiaxial stress states, which result from restricted transversal contractions (Poisson's ratio), are significantly influential on the load-bearing behaviour of bolts in rapid tensile load depending on the material toughness. When the material toughness is sufficient, high stresses lead to better load-bearing behaviour due to notched strengthening, but also ductility and deformability decreases. On the other hand, notch softening as a strength-reducing effect occurs when material toughness drops below a limit value. The different (not multiaxial) stresses in the bolt shank are also shown in Figure 8. Furthermore, forces at load-bearing paired threads are unequally distributed, see Figure 9. Numerical investigations at the IML indicate that local plasticizing occurs already at a specified preload of $F_{p,C}^* = 0.7 \cdot f_{yb} \cdot A_s$. [20]



Thread	%	% Sum
1	34%	34%
2	23%	55%
3	16%	71%
4	11%	82%
5	9%	91%
6	7%	98%

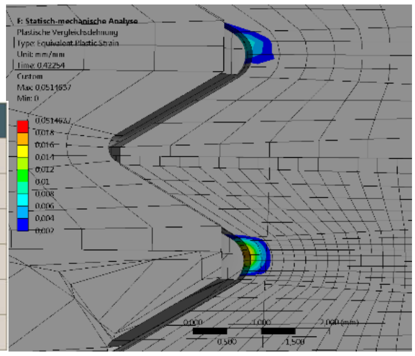


Figure 9 Load distribution in the paired threads (left/middle) and plasticising at $F_{p,C}^*$ (right).

2.4 Tightening methods and calibrated lubrication / k-classes

Tightening methods are required to achieve the specified preload in high-strength structural bolting assemblies with sufficient reliability. The accuracy of the achieved preload (respective to clamping load) depends on the following factors and demonstrates the importance of nearly constant conditions:

- friction conditions and lubrication,
- geometrical conditions of the bolted connection, like tolerances of the threads and the flexibility of the bolting assembly and clamped parts,
- tightening method.

Because there is still a degree of uncertainty regarding the preload achieved, the tightening factor $\alpha_A = F_{max}/F_{min}$ is used to describe the scatterings depending on the tightening method. Practically, the tightening factor α_A helps to avoid mechanical overload of the tightened bolting assemblies by increasing the designed and selected bolt area as a multiplication factor. A high tightening factor indicates a tightening method with low quality and high spreading[17].

Although a wide-range of tightening methods exist, like torsion free tightening for specific applications, EN 1090-2 focuses on tightening methods which include the rotation of the nut or bolt head (in exceptional cases with reference to Annex H, or additional testing done acc. EN to 14399-2), the combined method and torque method. Other tightening methods (e.g. torsion- free axial preloading with hydraulic pressure) can be applied, too, but must be calibrated in accordance to recommendations from the manufacturer. If a bolt assembly is tightened up to the minimum preload $F_{p,C}$ and later untightened, it must be removed and the whole assembly must be discarded.

The applicability of tightening methods is connected to the quality of lubricated bolting assemblies in their delivered condition. For this reason, the k-value, as a measure for predominant friction conditions, is defined according to EN 14399-2, as well as k-classes K0, K1, and K2 defined acc. to EN 14399-1:

$$k_i = \frac{M_i}{F_{p,C} \cdot d}\,.$$

For k-class K0, there are no special requirements for the k-value. The manufacturer only ensures that the delivered bolting assemblies are lubricated, while for k-class K1, the manufacturer must guarantee that the bolting assemblies are in a special range between 0.10–0.16, but additional statistical evaluations are not required. Finally, k-class K2 has the most demanding requirements, namely a special mean k-value k_m and low coefficient of variation; a summary about classification of k-classes is presented in Table 9.

Table 9 Classification of k-classes K0, K1, and K2 according to EN 14399-1:2015-04

k-class	Information to be supplied	Criteria according EN 14399-3:2015 and -4
K0	No requirements for k-factor	—
K1	Range of individual test value k_i	$0.10 \le k_i \le 0.16$
K2	Mean test value k_m	$0.10 \le k_m \le 0.23$
	Coefficient of variation of k-factor V_k	$V_k \le 0.06$

The application of the *torque method* acc. to EN 1090-2 requires k-class K2. For the *combined method* acc. to EN 1090-2, k-class K1 or K2 are prescribed. The *combined method,* with reference to chapter 8.5.4 of EN 1090-2, consists of two steps:

- *First a torque-controlled tightening step* with a torque wrench in a suitable operating range to a tightening torque value of 0.75 $M_{r,i}$. This first tightening must be completed for all bolts in the connection before starting the second step. The torque reference values are calculated as:
  - $M_{r,2} = k_m \cdot d \cdot F_{p,C}$ with k_m for k-class K2
  - $M_{r,1} = k_m \cdot d \cdot F_{p,C}$ with k_m for k-class K1 ∧ k_m = 0.13
- *Second an angle of rotation-controlled tightening step* where a specified part turn is applied to the turned part of the assembly. The position of the nut relative to the bolt should be marked after the first step. The additional rotation

angles are dependent on the bolt diameter and total nominal thickness of parts to be connected, including all packs and washers.

A schematic overview of the first and second tightening steps is presented in Figure 10 by Schmidt and Stranghöner [12]. Starting with 75% of the reference tightening torque (depending on the k-class K1 or K2), and depending on the curve form in the bolt force-tightening torque-curve (left), a specific bolt force is reached for each bolting assembly. After additional rotation (e.g. 90° for 2d ≤ t < 6d), a new bolt force is achieved. Due to individual scattering, the achieved bolt forces may vary for each tightened bolting assembly.

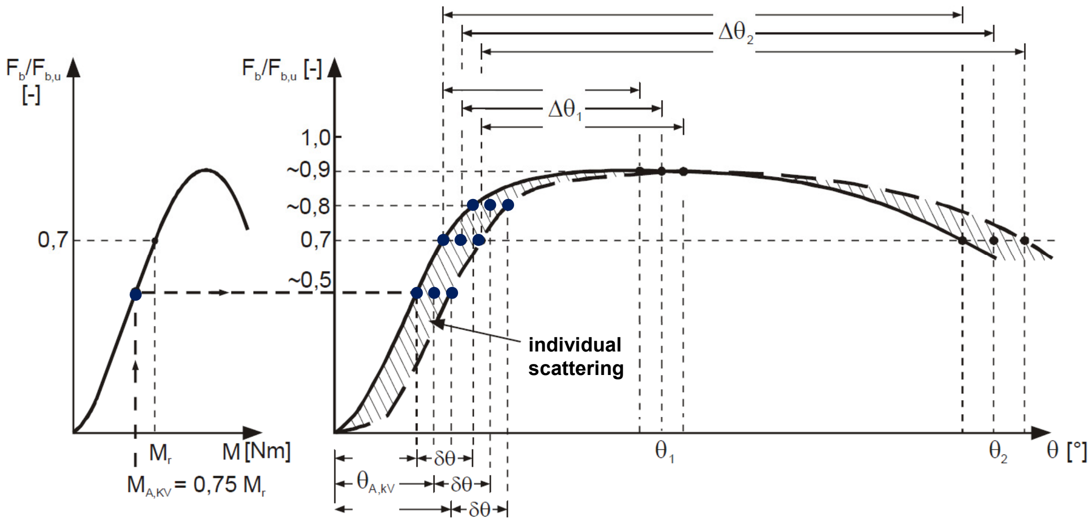


Figure 10 Schematical overview of first and second tightening step of combined method acc. EN 1090-2:2011-10 [12] (© IML)

2.5 Test procedure and suitability for preloading acc. to EN 14399-2

According to EN 14399-2, "High-strength structural bolting assemblies for preloading – Part 2: Suitability for preloading", "the purpose of the tightening test is to check the behaviour of the bolting assembly to ensure that the required preload can be reliably obtained by the tightening methods specified in EN 1090-2 with sufficient margins against over tightening and against failure". Focusing on normative references, Table 10 summarizes some primary aspects of System HR and System HV bolting assemblies.

Table 10 Systems of bolt/nut/washer assemblies according to EN 14399-1:2015-04

	Bolt/nut/washer assembly System HR		**Bolt/nut/washer assembly System HV**
General requirements	EN 14399-1		
Bolt/nut assembly	EN 14399-3		EN 14399-4
Marking	HR		HV
Property classes	8.8/8	10.9/10	10.9/10
Washer(s)	EN 14399-5 or EN 14399-6		EN 14399-5 or EN 14399-6
Marking	H		H
Suitability test for preloading	EN 14399-2		EN 14399-2

To ensure that the required preload is reliably achieved, the tightening procedure according to EN 14399-2 with test bolting assemblies is positioned such that:

- a washer of the assembly according to EN 14399-5 is placed under the hexagon nut, and plain chamfered washer according to EN 14399-6 may be placed under the bolt head;
- the clamp length Σt, including shims and washer(s), is the minimum allowed in the relevant product standard;
- neither the bolt nor washer under the nut rotates during the test;
- the number of shims does not exceed four, with defined characteristics shown in Table 11 and presented in Figure 11 and Figure 12 as examples;
- and the test apparatus is made of steel and the including stiffness of the test setup as high as practicable.

Table 11 Characteristics of shims according to EN 14399-2

Nominal bolt diameter	Hole diameter	Outside diameter	Thickness	Hardness for the outside shim	Parallelism
$d \leq$ M14	$d + 1$	Not less than the outside assembly washer diameter and sufficient to distribute load adequately to the device	≥ 2	$\geq$ 45 HRC through hardened	≤ 1 %
M14 $< d \leq$ M24	$d + 2$				
$d >$ M24	$d + 3$				

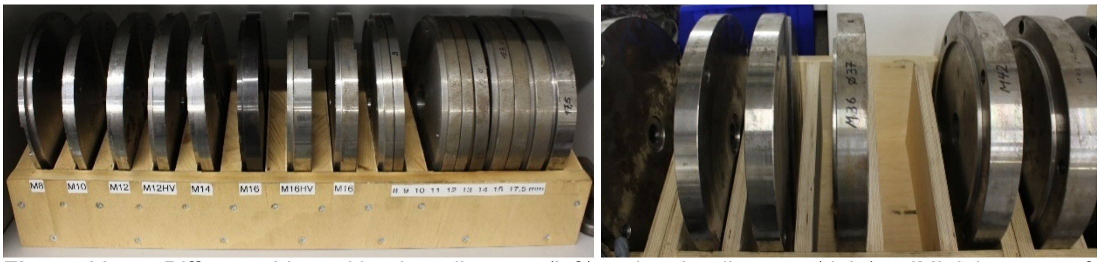


Figure 11 Different shims with minor diameter (left) and major diameter (right) at IML laboratory of University of Duisburg-Essen

The tightening is completed through rotation of the nut in a continuous manner with the speed of rotation between 1 min^{-1} and 10 min^{-1} and an ambient temperature between 10–35° C.

The suitability for preloading of high-strength structural bolting assemblies and the tightening test procedure are typically regulated by EN 14399-2 and valid for System HR (EN 14399-3) and System HV (EN 14399-4). The main aspects of the test procedure and criteria of evaluation are summarized below. To ensure that the required preload can be reliably obtained, the tightening procedure must be performed as follows:

- The tightening procedure with test assemblies shall be positioned such that
  - a washer of the assembly is placed under the nut, and if possible placed under the bolt head;
  - the clamp length including shims and washer(s) is the minimum allowed in the relevant product standard.
- The tightening shall be carried out by rotation of the nut in a continuous manner with speed of rotation between 1 min^{-1} and 10 min^{-1}.
- The test shall be stopped when one of the following conditions is first satisfied:
  - the angle of nut rotation exceeds (Θ_{pi} + $\Delta\Theta_{2i,min}$);
  - the bolt force drops to $F_{p,C}$;
  - bolt failure by fracture occurs.
- For each of the bolting assemblies, determination of the *rotation/bolt force relationship* and *torque/bolt force relationship*, and additionally the *elongation/bolt force relationship* if required.

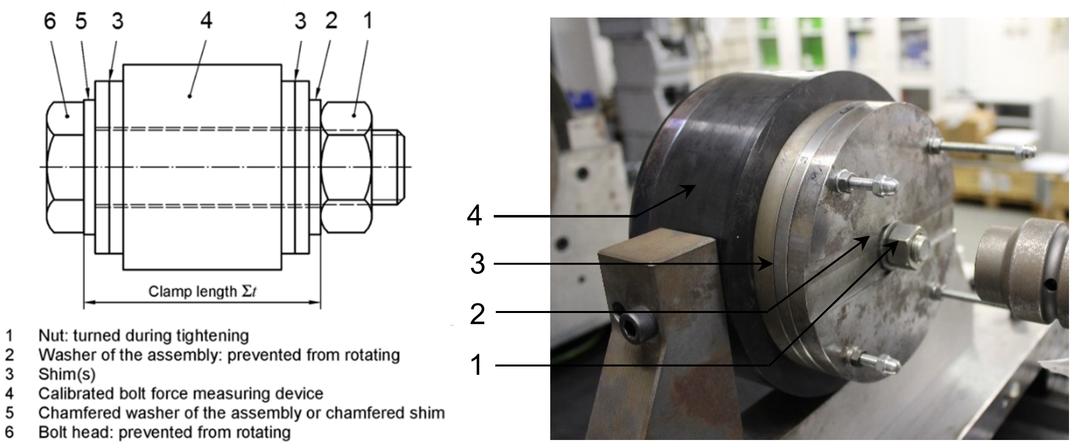


Figure 12 Test setup for tightening tests at IML-UDE (exemplarily)

Figure 13 schematically visualizes a typical bolt force-angle of rotation curve and bolt force-tightening torque curve and defines relevant tightening and evaluation values like the maximum individual value of bolt force $F_{bi,max}$, the preloading level $F_{p,C}$, and the angle differences $\Delta\Theta_{1i}$ and $\Delta\Theta_{2i}$. Furthermore, the determination of the k-value is graphically displayed.

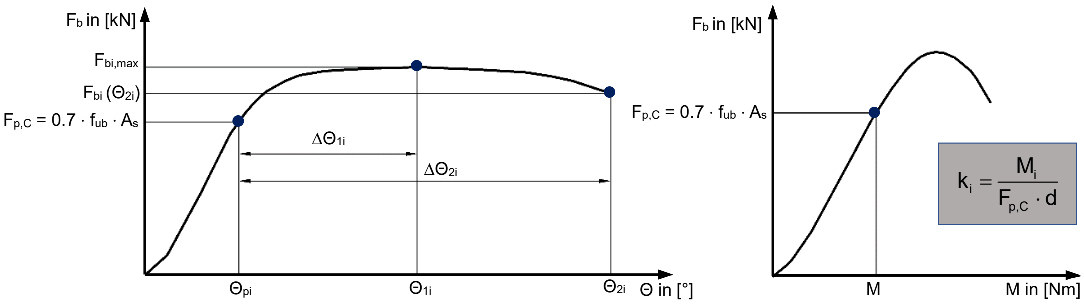


Figure 13 Tightening curves and criteria of evaluation acc. EN 14399-2

The criteria of evaluation of high-strength structural bolting assemblies for preloading according to EN 14399-3 (System HR bolting assemblies made of carbon steel) are defined in subchapter 2.7 and 2.8.

2.6 Measured and determined parameters acc. to EN ISO 16047

Tightening of a bolted connection by a continuously applied tightening torque generates a clamp force/preload F in the bolted connection. By the influence of these two measured parameters, further tightening characteristics can be measured or determined, which characterize the tightening properties of the bolted connection. According to EN ISO 16047 the following tightening parameters are defined

- torque coefficient K (K-factor),
- coefficient of total friction μ_{tot},
- coefficient of friction between threads μ_{th},
- coefficient of friction between bearing surfaces μ_b,
- yield clamp force F_y,
- yield tightening torque T_y,
- ultimate clamp force F_u, and
- ultimate tightening torque T_u.

For testing bolts/nuts under standard conditions, specified test components shall be used, either a test-bearing plate or a test washer of high (through-hardened, type HH) or low (type HL) hardness as well as suitable test nuts or test bolts. All traces of grease, oil or other contaminations shall be removed before testing.

The connecting element to be tested is either a nut or a bolt and is assembled with the corresponding test components, a test nut or test bolt to the entire bolted connection. The connecting element to be tested is supported by a test-bearing plate or a test washer. The specimen shall be assembled in the fixture (either the head of the test bolt or the test nut shall be fixed), and nut or bolt head, whichever is free to rotate, shall be driven by applying the tightening torque.

The tightening characteristics, which are not directly available as measured values, are determined by the following equations (2-11 to 2-15). The relationship between tightening characteristics and the parameters that have to be measured during the tightening are shown in Table 12.

Table 12 Parameters that have to be measured to obtain respective tightening characteristics

Tightening characteristics which may be determined		Parameters to be measured			
		Clamp force F	Tightening torque T	Thread torque T_{th}	Rotation angle Θ
Bearing surface friction torque	T_b	–	•	•	–
K-factor	K	•	•	–	–
Coefficient of total friction	μ_{tot}	•	•	–	–
Coefficient of friction between threads	μ_{th}	•	–	•	–
Coefficient of friction between bearing surfaces	μ_b	•	•	•	–

Determination of bearing surface friction torque T_b

$$T_b = T - T_{th} \quad [\text{Nm}] \qquad (2\text{-}11)$$

with T: tightening torque,
defined as torque acting on a nut or a bolt during tightening,
T_{th}: thread torque,
defined as torque acting on paired threads on the bolt shank,
T_b: bearing surface friction torque,
defined as torque acting on the bearing surfaces on the clamped parts during tightening.

Determination of torque coefficient K (K-factor)

$$K = \frac{T}{F \cdot d} \quad [\text{Nm}] \qquad (2\text{-}12)$$

with T: tightening torque,
F: clamp force/preload,
d: nominal thread diameter.

Unless otherwise specified, the determination of the K-factor is carried out under standard conditions and shall include the point with the clamp force at 75% of the proof load (0.75 F_p) of the test part, or the part to be tested, whichever is lower.

Determination of coefficients of total friction μ_{tot}

$$\mu_{tot} = \frac{\frac{T}{F} - \frac{P}{2\pi}}{0{,}578 \cdot d_2 + 0{,}5 \cdot D_b} \quad [-] \qquad (2\text{-}13)$$

with $D_b = \frac{D_o + d_h}{2}$ [mm]

T: tightening torque,
F: clamp force/preload,

P: pitch of the tread,
d_2: basic pitch diameter of the thread,
D_b: diameter of bearing surface under nut or bolt head for friction (theoretical or measured),
D_o: outer diameter of bearing surface, $d_{w,min}$ or $d_{k,min}$ (see product standards)
d_h: clearance hole diameter of washer or bearing part as nominal value

Unless otherwise specified, the determination of the total friction μ_{tot} is carried out under standard conditions and should include the point with the clamp force at 75% of the proof load (0.75 F_p) of the test part, or the part to be tested, whichever is lower.

Determination of coefficient of friction between threads μ_{th}

$$\mu_{th} = \frac{\frac{T_{th}}{F} - \frac{P}{2\pi}}{0{,}578 \cdot d_2} \qquad [-] \qquad (2\text{-}14)$$

with T_{th}: thread torque,
F: clamp force/preload,
P: pitch of the tread,
d_2: basic pitch diameter of the thread,
T: tightening torque,
T_b: bearing surface friction torque.

Unless otherwise specified, the determination of the thread friction μ_{th} is carried out under standard conditions and should include the point with the clamp force at 75% of the proof load (0.75 F_p) of the test part, or the part to be tested, whichever is lower.

Determination of coefficient of friction between bearing surfaces μ_b

$$\mu_b = \frac{T_b}{0{,}5 \cdot D_b \cdot F} \qquad [-] \qquad (2\text{-}15)$$

with T_b: bearing surface friction torque,
D_b: diameter of bearing surface under nut or bolt head for friction (theoretical or measured),
F: clamp force/preload,
T: tightening torque,
T_{th}: thread torque.

Unless otherwise specified, the determination of thread friction μ_{th} is carried out under standard conditions and should include the point with the clamp force at 75% of the proof load (0.75 F_p) of the test part, or the part to be tested, whichever is lower.

Determination of further tightening characteristics

The equations and methods for determining further tightening characteristics like the yield clamp force F_y, yield tightening torque T_y, ultimate clamp force F_u and ultimate tightening torque T_u according to EN ISO 16047 are not given in this summary.

In addition to EN ISO 16047, the statistical evaluation of the results of the tightening test is based on the following equations (2-16 to 2-19):

Mean value

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{2-16}$$

with $\bar{x}$: mean value,
n: number of tested specimens,
x_i: individual measured value.

Standard deviation

$$s = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^{n} (x_i - \bar{x})^2} \tag{2-17}$$

with s: standard deviation,
$\bar{x}$: mean value,
n: number of tested specimens,
x_i: individual measured value.

Range

$$R = max - min \tag{2-18}$$

with s: range,
max: highest measured value,
min: lowest measured value.

Coefficient of variation

$$\nu = \frac{s}{\bar{x}} \tag{2-19}$$

with ν: coefficient of variation,
s: standard deviation,
$\bar{x}$: mean value.

2.7 Evaluation of basic preloading behavior and ductility regarding EN 14399-2

The requirements regarding sufficient ductility of carbon steel HV and HR bolting assemblies are specified in EN 14399-4 and EN 14399-3. HR bolting assemblies are characterised by a longer thread and a higher nut than HV bolting assemblies. The criteria of evaluation are presented in (2-20) to (2-24). From these four criteria, only requirements (2-21) and (2-23/24) have to be fulfilled on $F_{p,C}$-level in the suitability test for preloading acc. to EN 14399-2/3.

- $F_{p,C} = 0.7 \cdot f_{ub} \cdot A_s$ (2-20)

$F_{p,C}$ specified preloading level (see also EN 1090-2)
f_{ub} nominal tensile strength ($R_{m,nom}$) of the bolt
A_s nominal stress area of the bolt (see EN ISO 898-1)

- $F_{bi,max} \geq 0.9 \cdot f_{ub} \cdot A_s$ (2-21)

  $F_{bi,max}$ individual value of the maximum bolt force reached during the test
  f_{ub} nominal tensile strength ($R_{m,nom}$) of the bolt
  A_s nominal stress area of the bolt

- $\Delta\Theta_{1i} \geq \Delta\Theta_{1,min} = 90° / 120° / 150°$ (depending on the clamp length) (2-22)

  $\Delta\Theta_{1i}$ individual angle difference of the nut from the first time the preload $F_{p,C}$ is exceeded to the individual value of the maximum bolt force $F_{bi,max}$

- $\Delta\Theta_{2i} \geq \Delta\Theta_{2,min} = 210° / 240° / 270°$ (depending on the clamp length) for HR bolting assemblies (2-23)

- $\Delta\Theta_{2i} \geq \Delta\Theta_{2,min} = 180° / 210° / 240°$ (depending on the clamp length) for HV bolting assemblies (2-24)

  $\Delta\Theta_{2i}$ individual angle difference of the nut from the first time the preload $F_{p,C}$ is exceeded to the angle when bolt force drops below $F_{p,C}$ again

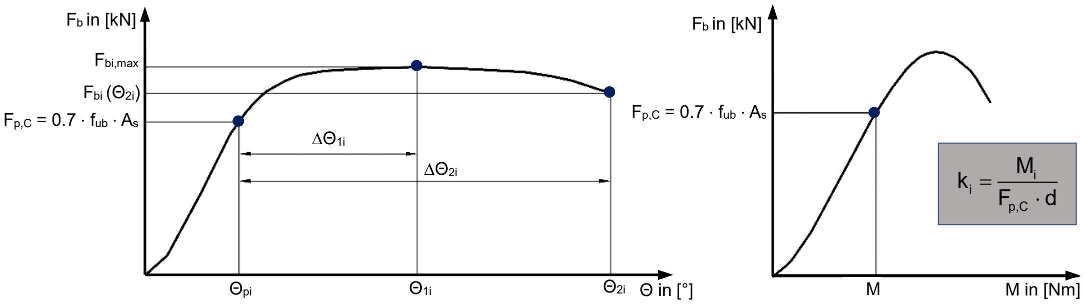


Figure 14 Schematic bolt force-angle of rotation curve (left) and bolt force-tightening torque curve (right) according to EN 14399-2

3 Experimental investigations

3.1 Test equipment and test setup

Bolt force-tightening torque tests were carried out with the tightening torque testing machine (maximum torque: 15000 Nm and maximum bolt force: 1800 kN) at the Institute of Metal and Lightweight Structures of the University Duisburg-Essen, see also Figure 15. The torque and rotation are automatically generated by an electric gear motor. The tightening speed is set manually via an adjusting gear before starting the tightening test and was constant for all tests 5.0 rpm. The tightening torque testing machine is equipped with sensors for recording measurements from the company Schatz GmbH, Remscheid, Germany.

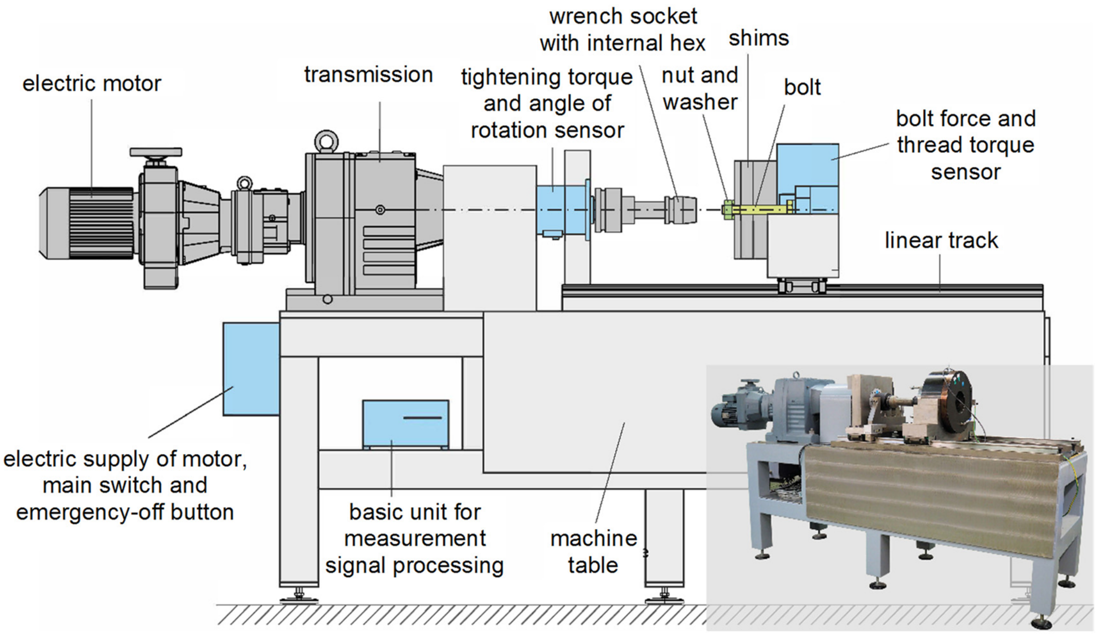


Figure 15 Tightening torque testing machine of Institute for Metal and Lightweight Structures of University of Duisburg-Essen

3.2 Test programme

Experimental tightening tests of bolting assemblies were performed at the Institute for Metal and Lightweight Structures, University of Duisburg-Essen (UDE). All tightening tests of System HR and System HV bolting assemblies for bolt dimension M24 and M36 are finished. The test programme is given in Table 13. The test matrix for tightening tests shows the bolt type (HR and HV), bolt dimension, property classes of the bolts, and the lubrication used. For each series, 10 bolting assemblies were tested and the obtained results evaluated.

Table 13 Task 1.5 – Test matrix for System HR and HV bolting assemblies

Lubrication	System HR / EN 14399-3:2015				System HV / EN 14399-4:2015	
	M24 8.8	M24 10.9	M36 8.8	M36 10.9	M24 10.9	M36 10.9
Factory provided	10/10	10/10	10/10	10/10	10/10	10/10
Gleitmo WSP 5040	10/10	10/10	10/10	10/10	10/10	10/10
Molykote 1000 spray	10/10	10/10	10/10	10/10	10/10	10/10
Microgleit HV-paste LP440	10/10	10/10	10/10	10/10	10/10	10/10

Concluded tightening tests	**240** / 240 tests required acc. Technical Annex

In total, 24 series and 240 bolting assemblies were tested at UDE using the Institute's tightening torque testing machine, divided into 160 assemblies for System HR (strength class 8.8 and 10.9), and 80 assemblies for System HV (strength class 10.9). All tightening tests were performed according to EN 14399-2:2015-04 and EN ISO 16047:2013-01. The test series are named according to the following designation system:

Myy-zz

Myy: Bolt diameter

zz: Sequential number of bolt
Pos. 01 – 10: Factory provided
Pos. 11 – 20: Gleitmo WSP 5040
Pos. 21 – 30: Molykote 1000 spray
Pos. 31 – 40: HV-paste LP440

3.3 Lubrication

The target development of tightening procedures for slip-resistant connections where the preload level is based on the 0.2 % remaining strain level of the bolt material instead of the ultimate stress level is related to the required experimental tightening tests. To achieve guaranteed preload levels in the elastic range with sufficient reliability, specific parameters (lubrication, tightening steps etc.) must be investigated in detail. In reference to the technical annex, and because the main influencing parameter in the tightening process is the lubrication of the nut, various lubrication types were tested (see Figure 16).

Factory provided	Fuchs Lubritech gleitmo® WSP 5040 grease paste	Dow Corning Molykote® 1000 Spray	Microgleit HV-paste LP440

Figure 16 Task 1.5 – Types of lubrication

3.4 Tightening test results and evaluation of System HR bolting assemblies made of carbon steel acc. EN 14399-3

The tightening test results of HR bolting assemblies according to EN 14399-3 will not be presented here in greater detail. All tested series of System HR bolting assemblies are presented in Annex A. The results and discussion of the tightening test results is presented in subchapter 3.6; the evaluation refers to EN 14399-3. Additionally, subchapter 3.6 presents the evaluation on the basis of 0.2% remaining strain level and recommendation of tightening methods to achieve a reduced preload level in the elastic range of the bolt material with sufficient reliability.

3.5 Tightening test results and evaluation of System HV bolting assemblies made of carbon steel acc. EN 14399-4

The tightening test results of HV bolting assemblies according to EN 14399-4 will be presented here as examples in shortened and partially incomplete form to give an overview about the main tightening and basic preloading behaviour. All tested series of System HV bolting assemblies are presented in Annex B. The results and discussion of the tightening test results is presented in subchapter 3.6 including comparisons of the applied lubricants; the evaluation refers to EN 14399-4. Additionally, subchapter 3.6 also presents the evaluation on the basis of 0.2% remaining strain level and recommendation of tightening methods to achieve a reduced preload level in the elastic range of the bolt material with sufficient reliability.

3.5.1 M24x100 HV 10.9 bolting assemblies

M24 HV	Bolts:	M24x100 – tZn – HV 10.9, manufactured by August Friedberg GmbH
	Nuts:	Hexagon nut M24 AF – 10Z – A8 – HV
	Washers:	M24 AF – HV according to EN 14399-6

In the context of bolt dimension M24, tightening tests of carbon steel bolts M24x100 in strength class 10.9 were done with four different lubrications: Factory delivered, Fuchs Lubritech Gleitmo WSP 5040, DOW Corning Molykote 1000 spray and Microgleit HV-paste LP440. The clamp length $\sum t$ was set to 67.0 mm (clamp length/bolt diameter ratio of 2.8) in reference to EN 14399-4, and the bolting assemblies were tightened nut sided with constant speed of rotation 2.0 1/min. The tightening tests were stopped when the bolt force dropped to $F_{p,C}$ after reaching $F_{p,C}$ to allow more detailed investigation of basic preloading behaviour and the influence of different lubrications.

3.5.1.1 M24x100 HV 10.9 – Factory provided

The test results of M24x100 HV bolting assemblies in property class 10.9 and factory provided lubrication to achieve k-class K1 are summarized in Table 14 and Table 15 including statistical evaluation. Referring to the criteria of EN 14399-4, all bolting assemblies reached $F_{p,C}$, $\Delta\Theta_{1i,min}$ and $\Delta\Theta_{2i,min}$. In contrast, none of the tested bolting assemblies achieved $F_{bi,max} \geq 0.9 \cdot f_{ub} \cdot A_s$. The k-values lie between k = 0.14 and k = 0.17. In total, 4 of 10 bolting assemblies achieved k-class K1, k-class K2 was not accomplished. For further information and summarized criteria see Table 16. In addition, the tightening curves are shown in Figure 18 and Figure 19.

Table 14 Test results of M24 HV - Factory provided

Legende		$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k (F_{p,C^*})	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---						---	---	0,16					0,16			
min			317,7						120	210	0,10					0,10			
	M24x100-01	247,1	<305,8	1509,5	211	313	549	247,0	178	414	>0,17	0,137	0,147	0,127	222,4	>0,17	1003,1	912,4	1369,3
	M24x100-02		<317,0	1421,7	180	280	575	246,9	174	469	0,14	0,108	0,119	0,098		0,14	818,6	734,5	1172,0
	M24x100-03		<312,6	1164,2	197	296	472	246,9	175	350	0,14	0,110	0,132	0,089		0,14	827,9	754,7	1078,1
	M24x100-04		<306,3	1172,7	182	285	531	246,9	179	425	0,16	0,125	0,134	0,115		0,16	924,2	836,9	1160,0
	M24x100-05		<282,5	1245,8	176	243	383	247,0	143	283	>0,17	0,134	0,163	0,106		>0,17	982,7	890,3	1180,3
	M24x100-06		<308,8	1086,1	192	289	580	246,8	173	464	0,14	0,114	0,142	0,088		0,15	857,9	785,5	1052,2
	M24x100-07		<299,7	1565,2	227	331	539	247,0	180	388	>0,17	0,140	0,154	0,127		>0,18	1025,8	939,0	1251,0
	M24x100-08		<311,8	1167,7	184	283	533	246,8	174	423	>0,16	0,130	0,138	0,122		>0,17	960,1	883,7	1158,7
	M24x100-09		<293,0	1324,0	187	262	399	246,8	151	289	>0,17	0,140	0,168	0,114		>0,18	1027,7	935,9	1244,8
	M24x100-10		<301,4	1384,8	183	269	508	246,9	158	398	>0,16	0,131	0,136	0,126		>0,17	965,5	890,8	1195,7

Table 15 Statistical evaluation of M24 HV - Factory provided

M24x100 n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k (F_{p,C^*})	M ($F_{bi,max}$) Nm
max	317,0	1565,2	227	331	580	247,0	180	469	0,140	0,168	0,127	1027,7	0,17	939,0	0,18	1369,3
min	282,5	1086,1	176	243	383	246,8	143	283	0,108	0,119	0,088	818,6	0,14	734,5	0,14	1052,2
R	34,5	479,1	51	88	197	0,2	37	186	0,032	0,049	0,039	209,1	0,03	204,5	0,04	317,1
$\bar{x}$	303,9	1304,2	192	285	507	246,9	169	390	0,127	0,143	0,111	939,4	0,16	856,4	0,16	1186,2
s	10,2	162,4	16	25	69	0,1	13	65	0,012	0,015	0,015	79,0	0,01	74,5	0,01	89,8
v	3,37	12,46	8,30	8,76	13,52	0,03	7,72	16,63	9,60	10,44	13,70	8,41	8,33	8,70	9,17	7,57

n: number; R: range; $\bar{x}$: mean value; s: standard deviation; v: coefficient of variation in [%]

Table 16 Evaluation of test results of M24 HV - Factory provided according to EN 14399-4

	n	$F_{p,C}$	$F_{bi,max}$	$\Delta\Theta_{1i,min}$	$\Delta\Theta_{2i,min}$	k-values	k-class K1	k-class K2	
Series	**[-]**	**247.1 kN**	**≥ 317.7 kN**	**≥ 120°**	**≥ 210°**	**[-]**	**0.10 ≤ k_i ≤ 0.16**	**0.10 ≤ k_m ≤ 0.23**	**V_k ≤ 0.06**
M24 HV - Factory provided	10	10/10	0/10	10/10	10/10	0.14 – 0.17	4/10	0.16	0.08

Figure 17 M24 HV - Factory provided test specimen after tightening

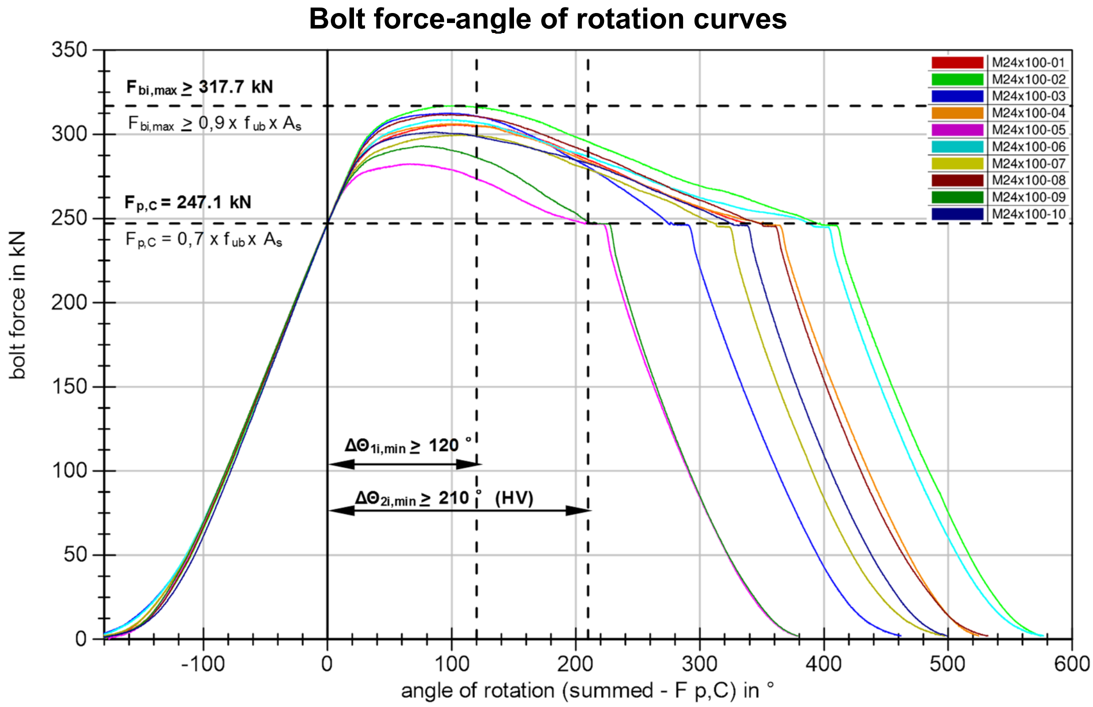


Figure 18 M24 HV - Factory provided Bolt force-angle of rotation curves

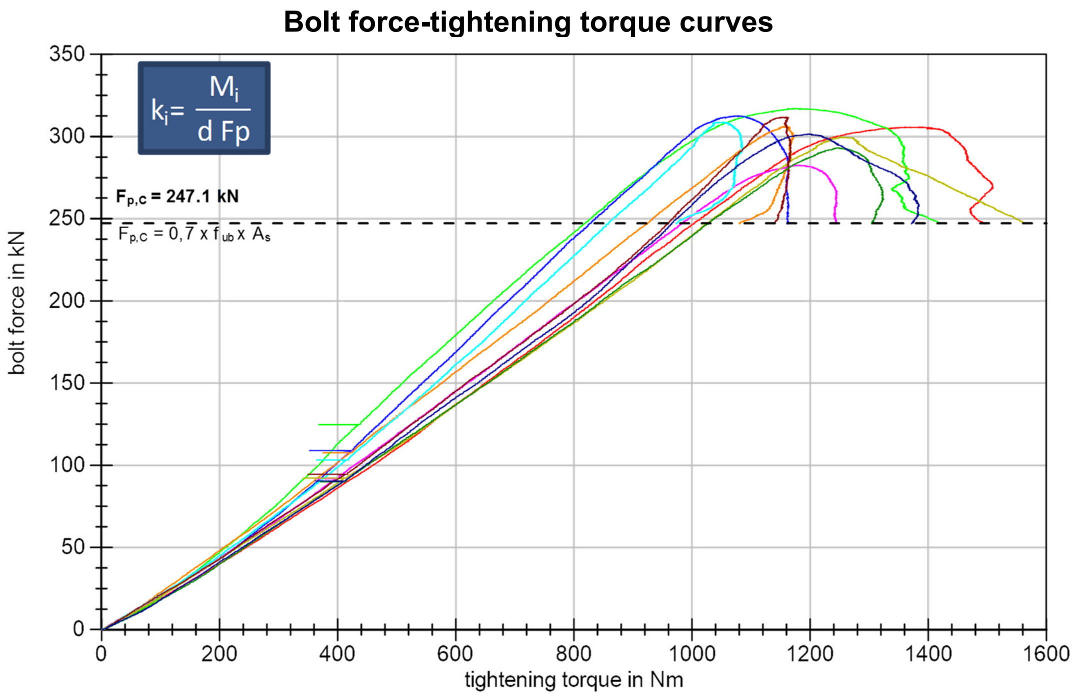


Figure 19 M24 HV - Factory provided Bolt force-tightening torque curves

3.5.1.2 M24x100 HV 10.9 – Gleitmo WSP 5040

Table 17, Table 18 and Table 19 summarize the test results and evaluation of M24 HV bolting assemblies with Gleitmo WSP 5040 lubrication. Statistical evaluation as well as an overview of fulfilled and failed criteria according to EN 14399-4 are also presented. Furthermore, Figure 21 and Figure 22 show the related tightening graphs. Similar to M24 HV – Factory provided, all bolting assemblies reached $F_{p,C}$, $\Delta\Theta_{1i,min}$ and $\Delta\Theta_{2i,min}$. Effectively and in respect of measuring inaccuracy, all tested bolting assemblies fulfilled criteria for maximum bolt force $F_{bi,max} \geq 0.9 \cdot f_{ub} \cdot A_s$. The k-values are between k = 0.15 and k = 0.16 so that nearly all of the 5 tested bolts did reach k-class K1, k-class K2 was accomplished with a noticeable low coefficient of variation V_k at 3 %.

Table 17 Test results of M24 HV - Gleitmo WSP 5040

Legende		$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C}$*)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---						---	---	0,16					0,16			
min			317,7						120	210	0,10					0,10			
	M24x100-17	247,1	<317,4	1467,5	179	291	560	247,0	185	454	0,15	0,119	0,105	0,133	222,4	0,15	889,2	821,7	1061,4
	M24x100-18		319,5	1244,8	189	301	593	247,0	186	478	0,15	0,119	0,114	0,123		0,15	887,8	813,9	1097,0
	M24x100-19		323,2	1221,4	214	319	634	246,9	180	495	0,15	0,118	0,109	0,126		0,15	878,9	805,0	1118,7
	M24x100-20		322,0	1684,2	176	290	592	247,0	188	489	0,15	0,121	0,104	0,138		0,16	904,0	827,7	1146,5
	M24x100-21		337,4	1148,0	219	354	648	246,8	209	503	>0,16	0,132	0,110	0,152		>0,17	971,5	895,7	1114,1

Table 18 Statistical evaluation of M24 HV - Gleitmo WSP 5040

M24x100_Gleitmo WSP 5040 n = 5	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C}$*)	M ($F_{bi,max}$) Nm
max	337,4	1684,2	219	354	648	247,0	209	503	0,132	0,114	0,152	971,5	0,16	895,7	0,17	1146,5
min	317,4	1148,0	176	290	560	246,8	180	454	0,118	0,104	0,123	878,9	0,15	805,0	0,15	1061,4
R	20,0	536,2	43	64	88	0,2	29	49	0,014	0,010	0,029	92,6	0,01	90,7	0,02	85,1
$\bar{x}$	323,9	1353,2	195	311	605	246,9	190	484	0,122	0,108	0,134	906,3	0,15	832,8	0,16	1107,5
s	7,9	220,1	20	27	35	0,1	11	19	0,006	0,004	0,011	37,6	0,00	36,2	0,01	31,3
ν	2,43	16,27	10,20	8,59	5,86	0,04	5,93	3,93	4,77	3,72	8,53	4,14	2,94	4,34	5,73	2,83

n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Table 19 Evaluation of test results of M24 HV - Gleitmo WSP 5040 according to EN 14399-4

	n	$F_{p,C}$	$F_{bi,max}$	$\Delta\Theta_{1i,min}$	$\Delta\Theta_{2i,min}$	k-values	k-class K1	k-class K2	
Series	**[-]**	**247.1 kN**	**≥ 317.7 kN**	**≥ 120°**	**≥ 210°**	**[-]**	**0.10 ≤ k_i ≤ 0.16**	**0.10 ≤ k_m ≤ 0.23**	**V_k ≤ 0.06**
M24 HV - Gleitmo WSP 5040	5	5/5	4/5	5/5	5/5	0.15 – 0.16	4/5	0.15	0.03

Figure 20 M24 HV - Gleitmo WSP 5040 test specimen after tightening

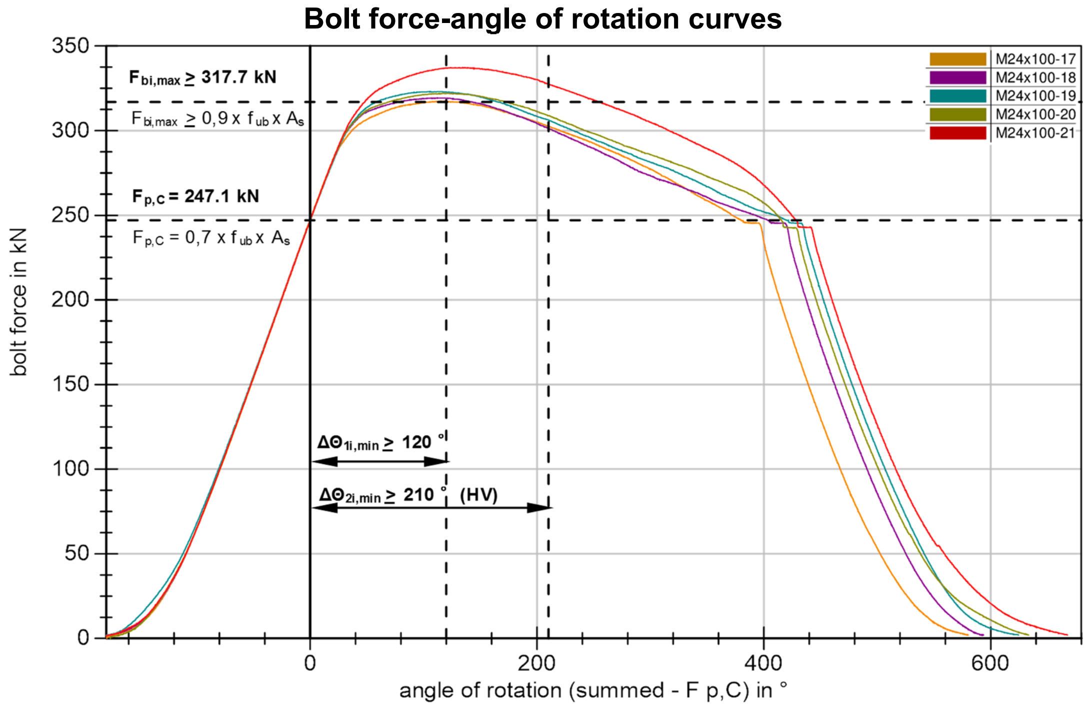


Figure 21 M24 HV - Gleitmo WSP 5040 Bolt force-angle of rotation curves

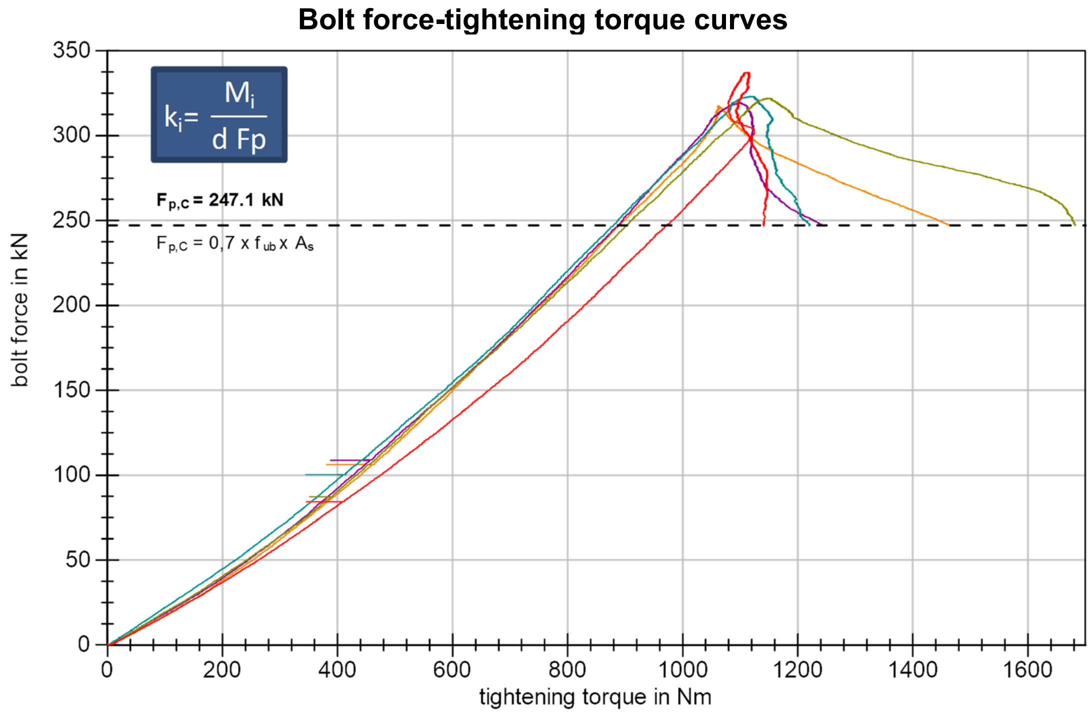


Figure 22 M24 HV - Gleitmo WSP 5040 Bolt force-tightening torque curves

3.5.1.3 M24x100 HV 10.9 – Molykote 1000 spray

The test results of M24 HV – Molykote 1000 spray bolting assemblies with property class 10.9 are presented in Table 20 and Table 21 including statistical data and evaluation. Referring to EN 14399-4, all bolting assemblies reached the specified preload of $F_{p,C} = 0.7 \cdot f_{ub} \cdot A_s = 247.1$ kN and additionally, 5 of 5 bolts achieved $F_{bi,max} \geq 0.9 \cdot f_{ub} \cdot A_s = 317.7$ kN. Due to the well pronounced plastic range, all tested bolts reached $\Delta\Theta_{1i,min} = 120°$ and $\Delta\Theta_{2i,min} = 210°$. The k-values lie between k = 0.14 and k = 0.15. In total, 5 of 5 bolting assemblies achieved k-class K1, k-class K2 was accomplished with low coefficient of variation V_k (3 %). For further information and summarized criteria see Table 22. In addition, the tightening curves are shown in Figure 24 and Figure 25.

Table 20 Test results of M24 HV - Molykote 1000 spray

Legende		$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---						---	---	0,16					0,16			
min			317,7						120	210	0,10					0,10			
	M24x100-22	247,1	331,1	990,4	227	360	570	246,9	210	419	0,14	0,110	0,110	0,110	222,4	0,14	830,4	762,3	983,1
	M24x100-23		330,4	1179,0	210	335	584	246,9	198	447	0,14	0,107	0,084	0,128		0,14	810,9	726,2	1147,7
	M24x100-24		329,6	1214,1	221	347	638	247,0	201	493	0,15	0,122	0,104	0,138		0,15	907,0	825,6	1206,3
	M24x100-25		341,4	1183,8	217	363	582	247,0	219	438	0,14	0,109	0,090	0,127		0,14	826,1	741,9	1142,9
	M24x100-26		330,3	1019,9	232	362	598	246,9	206	442	0,14	0,114	0,126	0,103		0,15	858,0	786,8	1013,6

Table 21 Statistical evaluation of M24 HV - Molykote 1000 spray

M24x100_Molykote 1000 spray n = 5	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C*}$)	M ($F_{bi,max}$) Nm
max	341,4	1214,1	232	363	638	247,0	219	493	0,122	0,126	0,138	907,0	0,15	825,6	0,15	1206,3
min	329,6	990,4	210	335	570	246,9	198	419	0,107	0,084	0,103	810,9	0,14	726,2	0,14	983,1
R	11,8	223,7	22	28	68	0,1	21	74	0,015	0,042	0,035	96,1	0,01	99,4	0,01	223,2
$\bar{x}$	332,6	1117,4	221	353	594	246,9	207	448	0,112	0,103	0,121	846,5	0,14	768,6	0,14	1098,7
s	5,0	103,9	9	12	26	0,1	8	27	0,006	0,017	0,014	37,9	0,00	39,1	0,01	95,6
ν	1,49	9,30	3,87	3,43	4,43	0,02	3,98	6,12	5,29	16,20	11,80	4,47	3,15	5,09	3,80	8,70

n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Table 22 Evaluation of test results of M24 HV - Molykote 1000 spray according to EN 14399-4

Series	n	$F_{p,C}$	$F_{bi,max}$	$\Delta\Theta_{1i,min}$	$\Delta\Theta_{2i,min}$	k-values	k-class K1	k-class K2	
	[-]	247.1 kN	≥ 317.7 kN	≥ 120°	≥ 210°	[-]	$0.10 \leq k_i \leq 0.16$	$0.10 \leq k_m \leq 0.23$	$V_k \leq 0.06$
M24 HV - Molykote 1000	5	5/5	5/5	5/5	5/5	0.14 – 0.15	5/5	0.14	0.03

Figure 23 M24 HV - Molykote 1000 spray test specimen after tightening

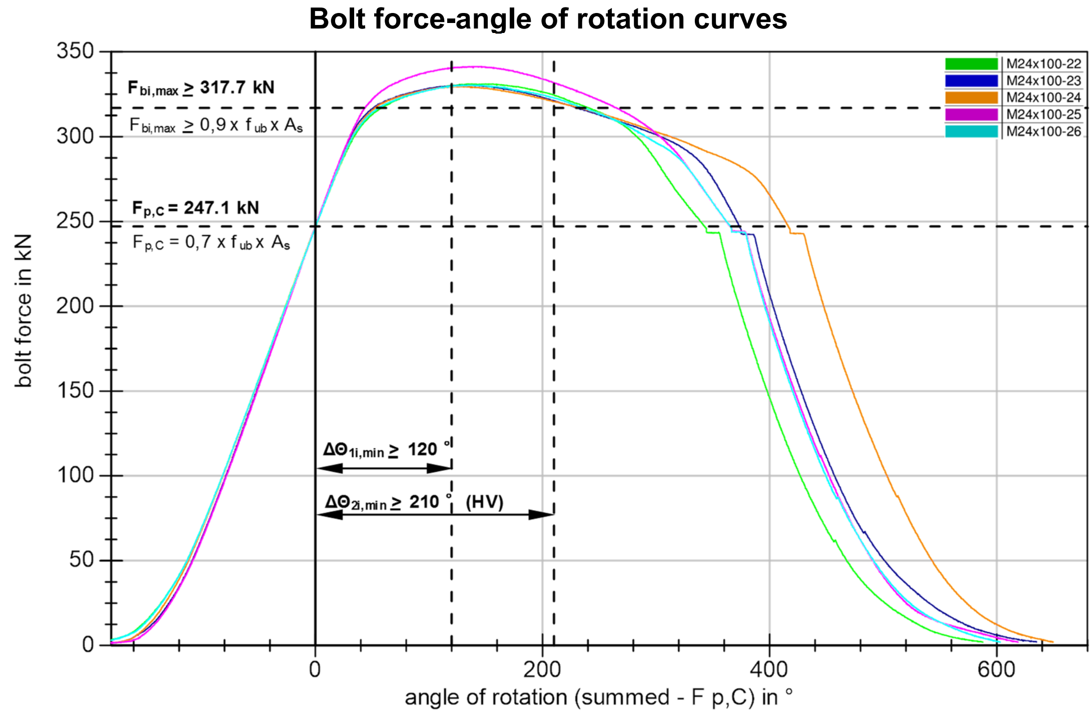


Figure 24 M24 HV - Molykote 1000 spray Bolt force-angle of rotation curves

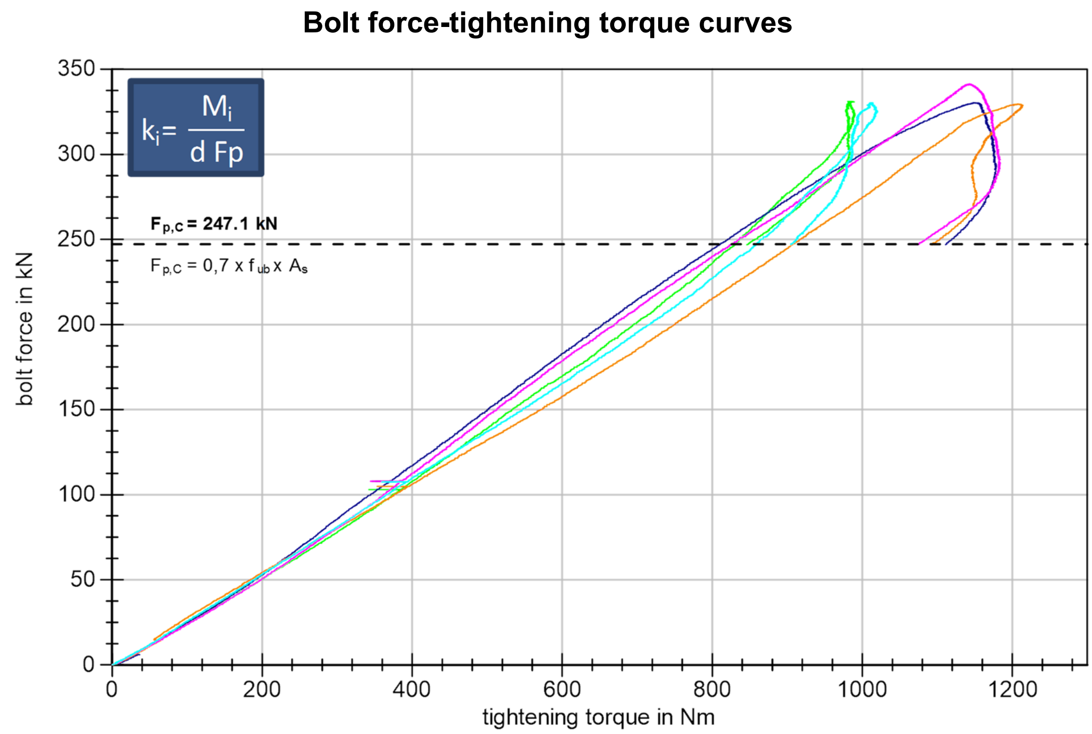


Figure 25 M24 HV - Molykote 1000 spray Bolt force-tightening torque curves

3.5.1.4 *M24x100 HV 10.9 – Microgleit HV-paste LP440*

The test results of M24x100 HV 10.9 bolting assemblies lubricated with Microgleit HV-paste LP440 are summarized in Table 23, Table 24 and Table 25 showing statistical evaluation as well as the summarized fulfilled and failed criteria according to EN 14399-4. In addition, Figure 27 and Figure 28 show the tightening graphs for these bolting assemblies. Referring to the criteria of EN 14399-4, all bolting assemblies reached $F_{p,C}$, $\Delta\Theta_{1i,min}$ and $\Delta\Theta_{2i,min}$. Effectively and in respect of measuring inaccuracy, all tested bolting assemblies achieved $F_{bi,max} \geq 0.9 \cdot f_{ub} \cdot A_s$. Caused by high k-values between k = 0.17 and k = 0.21, none of the tested bolting assemblies achieved criteria for k-class K1. K-class K2 was not accomplished as well, which was caused by higher coefficient of variation V_k of about 10 %.

Table 23 Test results of M24 HV - Microgleit HV-paste LP440

Legende		$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k (F_{p,C^*})	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---						---	---	0,16					0,16			
min			317,7						120	210	0,10					0,10			
	M24x100-27	247,1	335,1	1733,1	223	347	626	246,9	201	480	>0,17	0,138	0,120	0,155	222,4	>0,17	1013,1	908,5	1519,9
	M24x100-28		336,5	1557,7	221	346	584	246,9	202	439	>0,17	0,141	0,127	0,154		>0,17	1030,7	932,1	1517,2
	M24x100-29		<317,5	1690,2	248	358	664	246,9	187	492	>0,21	0,172	0,123	0,218		>0,20	1228,7	1049,0	1577,0
	M24x100-30		318,3	1785,3	212	314	623	246,9	178	487	>0,20	0,166	0,137	0,193		>0,20	1193,6	1059,7	1686,3
	M24x100-31		326,8	1558,0	180	298	557	247,0	194	452	>0,19	0,157	0,118	0,193		>0,19	1131,7	1017,5	1390,2

Table 24 Statistical evaluation of M24 HV - Microgleit HV-paste LP440

M24x100_Microgleit n = 5	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k (F_{p,C^*})	M ($F_{bi,max}$) Nm
max	336,5	1785,3	248	358	664	247,0	202	492	0,172	0,137	0,218	1228,7	0,21	1059,7	0,20	1686,3
min	317,5	1557,7	180	298	557	246,9	178	439	0,138	0,118	0,154	1013,1	0,17	908,5	0,17	1390,2
R	19,0	227,6	68	60	107	0,1	24	53	0,034	0,019	0,064	215,6	0,04	151,2	0,03	296,1
$\bar{x}$	326,8	1664,9	217	333	611	246,9	192	470	0,155	0,125	0,183	1119,6	0,19	993,4	0,19	1538,1
s	9,0	103,3	25	25	41	0,0	10	23	0,015	0,008	0,028	95,9	0,02	69,0	0,02	107,4
v	2,74	6,21	11,31	7,63	6,76	0,02	5,23	4,94	9,68	6,01	15,12	8,56	9,52	6,94	8,15	6,98

n: number; R: range; $\bar{x}$: mean value; s: standard deviation; v: coefficient of variation in [%]

Table 25 Evaluation of test results of M24 HV - Microgleit HV-paste LP440 according to EN14399-4

Series	n	$F_{p,C}$	$F_{bi,max}$	$\Delta\Theta_{1i,min}$	$\Delta\Theta_{2i,min}$	k-values	k-class K1	k-class K2	
	[-]	247.1 kN	≥ 317.7 kN	≥ 120°	≥ 210°	[-]	$0.10 \leq k_i \leq 0.16$	$0.10 \leq k_m \leq 0.23$	$V_k \leq 0.06$
M24 HV - Microgleit HV	5	5/5	4/5	5/5	5/5	0.17 – 0.21	0/5	0.19	0.10

Figure 26 M24 HV - Microgleit HV-paste LP440 test specimen after tightening

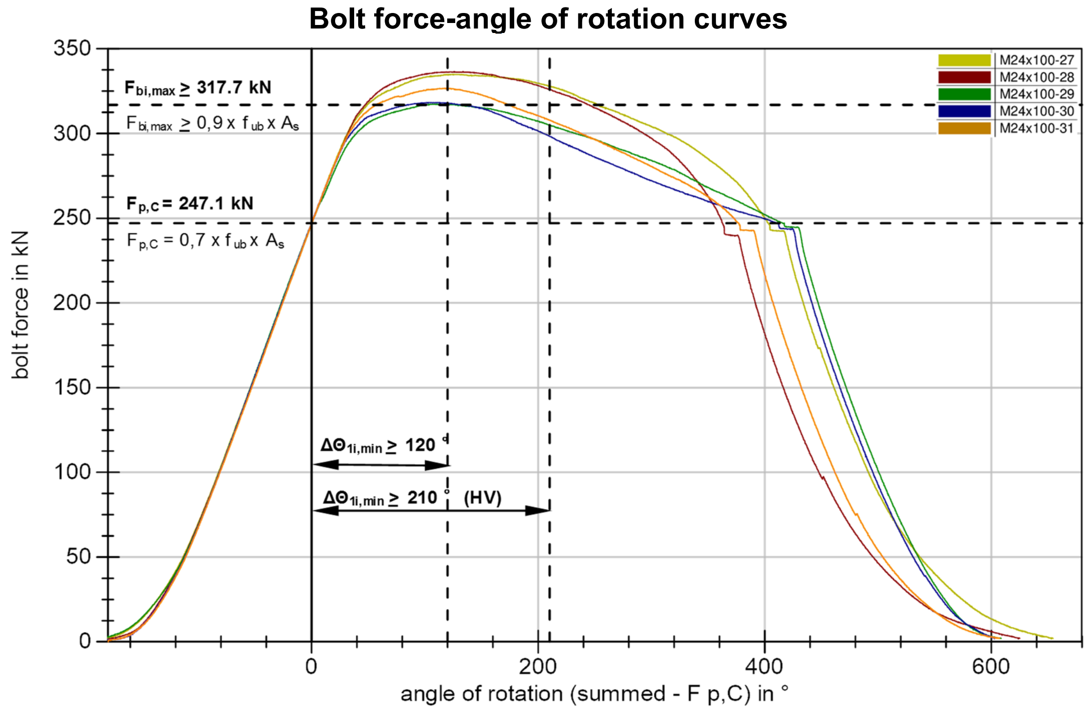


Figure 27 M24 HV - Microgleit HV-paste LP440 Bolt force-angle of rotation curves

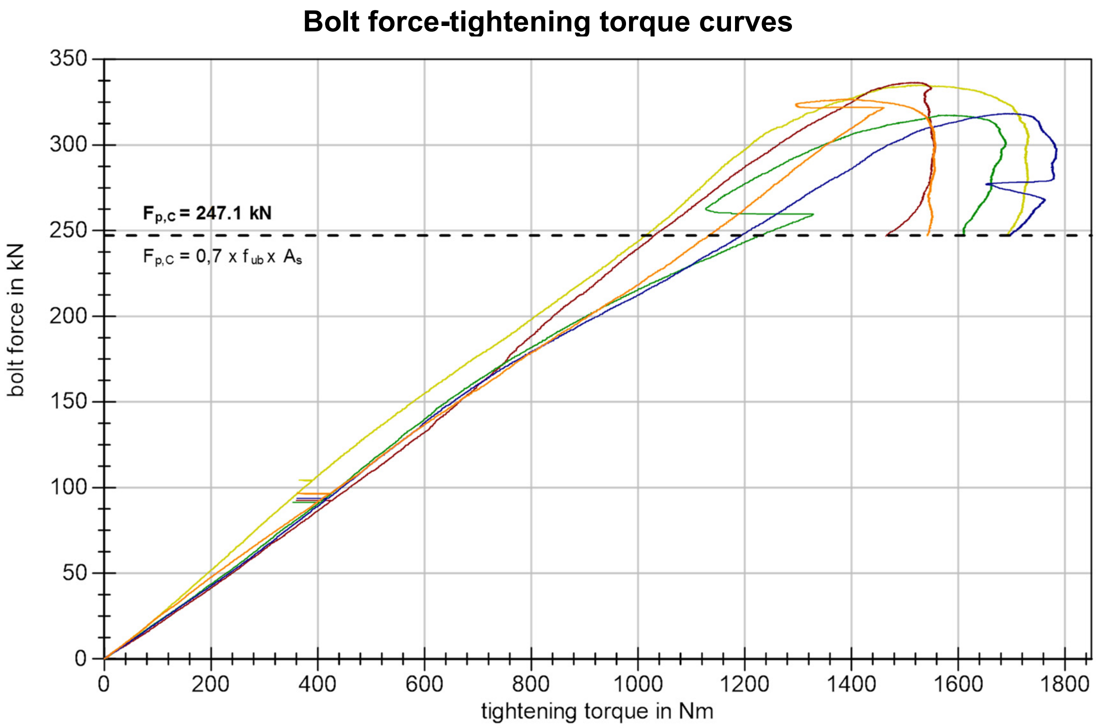


Figure 28 M24 HV - Microgleit HV-paste LP440 Bolt force-tightening torque curves

3.5.2 M36x160 HV 10.9 bolting assemblies

M36 HV	Bolts:	M36x160 – tZn – HV 10.9 – CE A (7), manufactured by August Friedberg GmbH
	Nuts:	Hexagon nut M36 AF – 10Z – A13 – HV – CE
	Washer:	M36 AF HV CE according to EN 14399-6

Congruent with bolt dimension M24, tightening tests of carbon steel bolts M36x160 in property class 10.9 were carried out using the same four different lubrications: Factory provided, Gleitmo WSP 5040, Molykote 1000 spray and Microgleit HV-paste LP440. The clamp length ∑t was set to 114.0 mm (clamp length/bolt diameter ratio of 3.2) in reference to EN 14399-4, and the bolting assemblies were tightened nut sided with constant speed of rotation 2.0 1/min. Again, the tightening tests were stopped when the bolt force dropped to $F_{p,c}$ after reaching $F_{p,c}$ to allow more detailed investigation of basic preloading behaviour and the influence of different lubrications.

3.5.2.1 M36x160 HV 10.9 – Factory provided

The test results of M36x160 HV bolting assemblies in property class 10.9 and factory provided lubrication are summarized in Table 26 and Table 27 including statistical evaluation. Fracture did occur in every tested bolt, see Figure 29. Referring to the criteria of EN 14399-4, all bolting assemblies reached $F_{p,C}$ and $\Delta\Theta_{1i,min}$ while 5 of 6 tested bolts reached $\Delta\Theta_{2i,min}$. In contrast, only one of the tested bolting assemblies achieved $F_{bi,max} \geq 0.9 \cdot f_{ub} \cdot A_s$. The k-values lie between k = 0.16 and k = 0.22 and show a noticeable high scattering. In total, none of the tested bolting assemblies achieved k-class K1, k-class K2 was not accomplished as well. For further information and summarized criteria see Table 28. In addition, the tightening curves are shown in Figure 30 and Figure 31.

Table 26 Test results of M36 HV - Factory provided

Legende		$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---						---	---	0,16					0,16			
min			735,3						120	210	0,10					0,10			
	M36x160-01	571,9	745,4	5122,7	246	366	-	-	208	-	>0,16	0,120	0,122	0,118	514,7	>0,16	3341,1	2965,5	5120,7
	M36x160-02		<729,8	6666,6	263	386	626	571,2	211	451	>0,19	0,144	0,153	0,137		>0,19	3946,7	3580,9	5695,7
	M36x160-03		<719,0	6360,9	239	365	592	571,5	215	441	>0,18	0,132	0,167	0,105		>0,18	3658,3	3343,6	4961,9
	M36x160-04		<712,6	6456,4	247	364	545	571,1	205	386	>0,19	0,140	0,169	0,116		>0,19	3840,6	3490,2	5833,0
	M36x160-05		<728,7	6982,8	241	389	642	571,4	235	489	>0,22	0,169	0,134	0,197		>0,21	4568,9	3980,2	6968,6
	M36x160-21		<734,8	6673,1	318	461	677	570,9	231	447	>0,20	0,147	0,167	0,131		>0,19	4020,3	3560,2	6074,2

Table 27 Statistical evaluation of M36 HV - Factory provided

M36x160 n = 6	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C*}$)	M ($F_{bi,max}$) Nm
max	745,4	6982,8	318	461	677	571,5	235	489	0,169	0,169	0,197	4568,9	0,22	3980,2	0,21	6968,6
min	712,6	5122,7	239	364	545	570,9	205	386	0,120	0,122	0,105	3341,1	0,16	2965,5	0,16	4961,9
R	32,8	1860,1	79	97	132	0,6	30	103	0,049	0,047	0,092	1227,8	0,06	1014,7	0,05	2006,7
$\bar{x}$	728,4	6377,1	259	389	616	571,2	218	443	0,142	0,152	0,134	3896,0	0,19	3486,8	0,19	5775,7
s	11,6	650,9	30	37	50	0,2	13	37	0,016	0,020	0,033	409,5	0,02	331,6	0,02	722,9
ν	1,59	10,21	11,63	9,58	8,16	0,04	5,76	8,34	11,55	13,04	24,54	10,51	10,53	9,51	8,75	12,52

n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Table 28 Evaluation of test results of M36 HV - Factory provided according to EN 14399-4

	n	$F_{p,C}$	$F_{bi,max}$	$\Delta\Theta_{1i,min}$	$\Delta\Theta_{2i,min}$	k-values	k-class K1	k-class K2	
Series	**[-]**	**571.9 kN**	**≥ 735.3 kN**	**≥ 120°**	**≥ 210°**	**[-]**	**$0.10 \leq k_i \leq 0.16$**	**$0.10 \leq k_m \leq 0.23$**	**≤ 0.06**
M36 HV - Factory provided	6	6/6	1/6	6/6	5/6	0.16 – 0.22	0/6	0.19	0.11

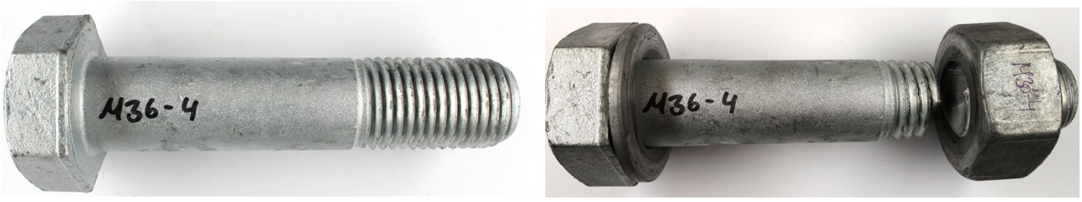


Figure 29 M36 HV - Factory provided test specimen before and after tightening

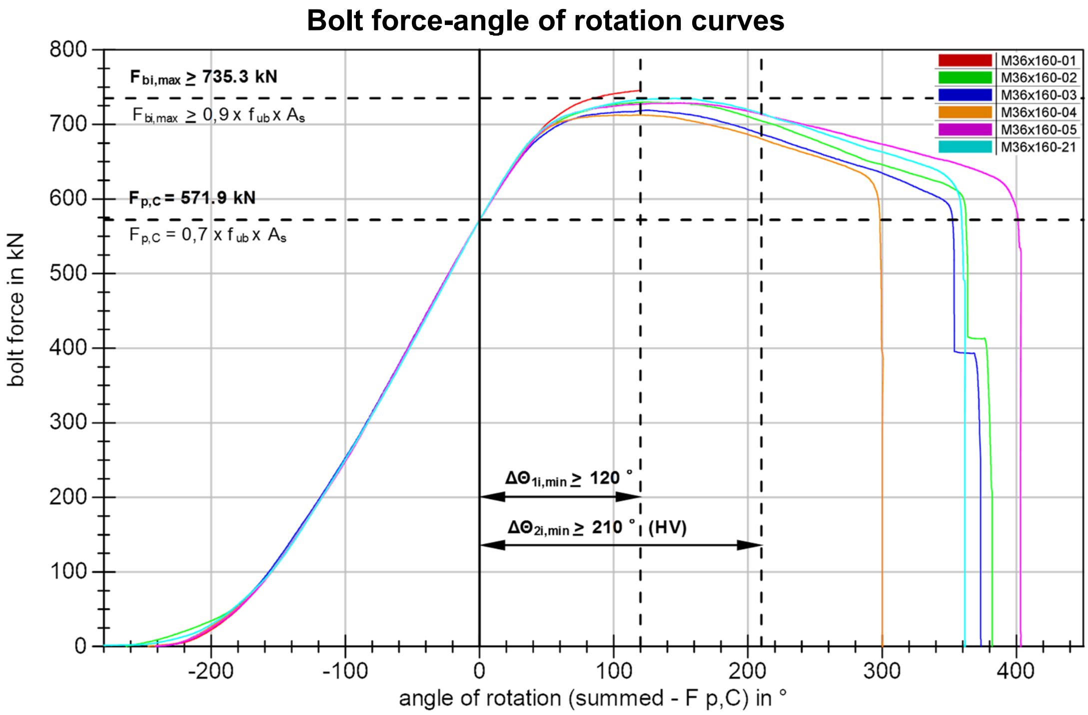


Figure 30 M36 HV - Factory provided Bolt force-angle of rotation curves

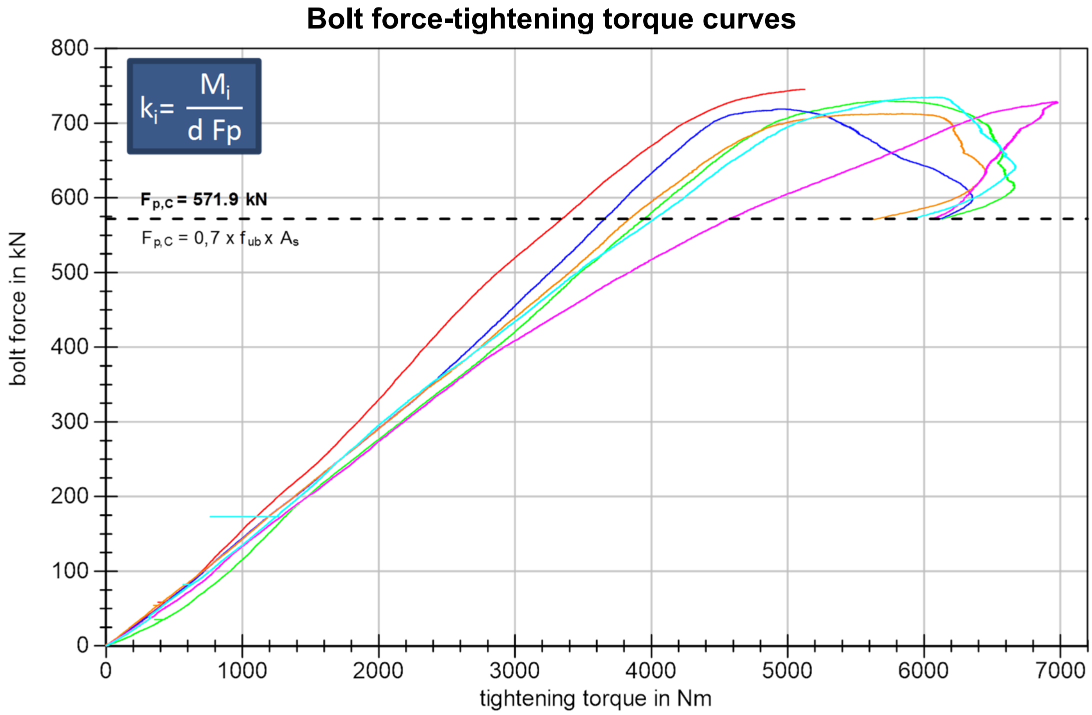


Figure 31 M36 HV - Factory provided Bolt force-tightening torque curves

3.5.2.2 M36x160 HV 10.9 – Gleitmo WSP 5040

Table 29, Table 30 and Table 31 summarize the test results and evaluation of M36 HV bolting assemblies with Gleitmo WSP 5040 lubrication. Statistical evaluation is also presented together with an overview of fulfilled and failed criteria according to EN 14399-4. Furthermore, Figure 33 and Figure 34 show the related tightening graphs. All bolting assemblies reached the specified preload of $F_{p,C} = 0.7 \cdot f_{ub} \cdot A_s = 571.9$ kN and additionally, 10 of 10 bolts achieved $F_{bi,max} \geq 0.9 \cdot f_{ub} \cdot A_s$. Because of the well pronounced plastic range, all tested bolts reached $\Delta\Theta_{1i,min} = 120°$ and $\Delta\Theta_{2i,min} = 210°$. The k-values lie between k = 0.13 and k = 0.15. In total, 10 of 10 bolting assemblies achieved k-class K1, k-class K2 was accomplished with low coefficient of variation V_k (5 %).

Table 29 Test results of M36 HV - Gleitmo WSP 5040

Legende		$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---						---	---	0,16					0,16			
min			735,3						120	210	0,10					0,10			
	M36x160-06	571,9	811,5	5526,9	251	431	608	571,4	267	444	0,14	0,101	0,100	0,103	514,7	0,14	2886,5	2664,0	3902,1
	M36x160-07		786,8	5874,1	269	437	595	571,9	256	414	0,14	0,105	0,112	0,100		0,15	2980,4	2702,7	4938,2
	M36x160-08		799,5	5495,3	248	397	578	571,8	234	415	0,13	0,096	0,081	0,108		0,14	2751,6	2525,1	3884,0
	M36x160-09		765,6	4392,9	273	419	671	571,8	234	486	0,14	0,104	0,114	0,096		0,15	2953,6	2705,8	3797,9
	M36x160-10		793,9	6559,8	242	406	621	571,8	250	465	0,15	0,106	0,110	0,102		0,15	2997,8	2713,7	4742,5
	M36x160-26		771,8	6304,6	254	386	599	571,9	218	431	0,14	0,103	0,098	0,107		0,14	2931,4	2672,6	4686,2
	M36x160-27		804,9	6003,2	298	476	649	571,8	262	436	0,14	0,104	0,104	0,105		0,15	2962,9	2738,8	4576,6
	M36x160-28		802,4	4631,8	270	424	576	571,8	238	390	0,13	0,095	0,093	0,097		0,14	2740,4	2526,6	3778,8
	M36x160-29		805,2	6048,9	267	428	594	572,0	244	411	0,14	0,098	0,088	0,106		0,14	2799,6	2549,5	4423,5
	M36x160-30		798,1	3929,5	289	465	619	571,9	261	415	0,13	0,097	0,093	0,100		0,14	2772,8	2547,9	3553,1

Table 30 Statistical evaluation of M36 HV - Gleitmo WSP 5040

M36x160_Gleitmo WSP 5040 n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C}$*)	M ($F_{bi,max}$) Nm
max	811,5	6559,8	298	476	671	572,0	267	486	0,106	0,114	0,108	2997,8	0,15	2738,8	0,15	4938,2
min	765,6	3929,5	242	386	576	571,4	218	390	0,095	0,081	0,096	2740,4	0,13	2525,1	0,14	3553,1
R	45,9	2630,3	56	90	95	0,6	49	96	0,011	0,033	0,012	257,4	0,02	213,7	0,01	1385,1
$\bar{x}$	794,0	5476,7	266	427	611	571,8	246	431	0,101	0,099	0,102	2877,7	0,14	2634,7	0,14	4228,3
s	15,0	876,0	18	28	30	0,2	16	28	0,004	0,011	0,004	101,5	0,01	86,6	0,01	495,0
ν	1,89	15,99	6,74	6,56	4,95	0,03	6,31	6,59	4,03	10,92	4,04	3,53	4,58	3,29	3,59	11,71

n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Table 31 Evaluation of test results of M36 HV - Gleitmo WSP 5040 according to EN 14399-4

	n	$F_{p,C}$	$F_{bi,max}$	$\Delta\Theta_{1i,min}$	$\Delta\Theta_{2i,min}$	k-values	k-class K1	k-class K2	
Series	**[-]**	**571.9 kN**	**≥ 735.3 kN**	**≥ 120°**	**≥ 210°**	**[-]**	**0.10 ≤ k_i ≤ 0.16**	**0.10 ≤ k_m ≤ 0.23**	**≤ 0.06**
M36 HV - Gleitmo WSP 5040	10	10/10	10/10	10/10	10/10	0.13 – 0.15	10/10	0.14	0.05

Figure 32 M36 HV - Gleitmo WSP 5040 test specimen after tightening

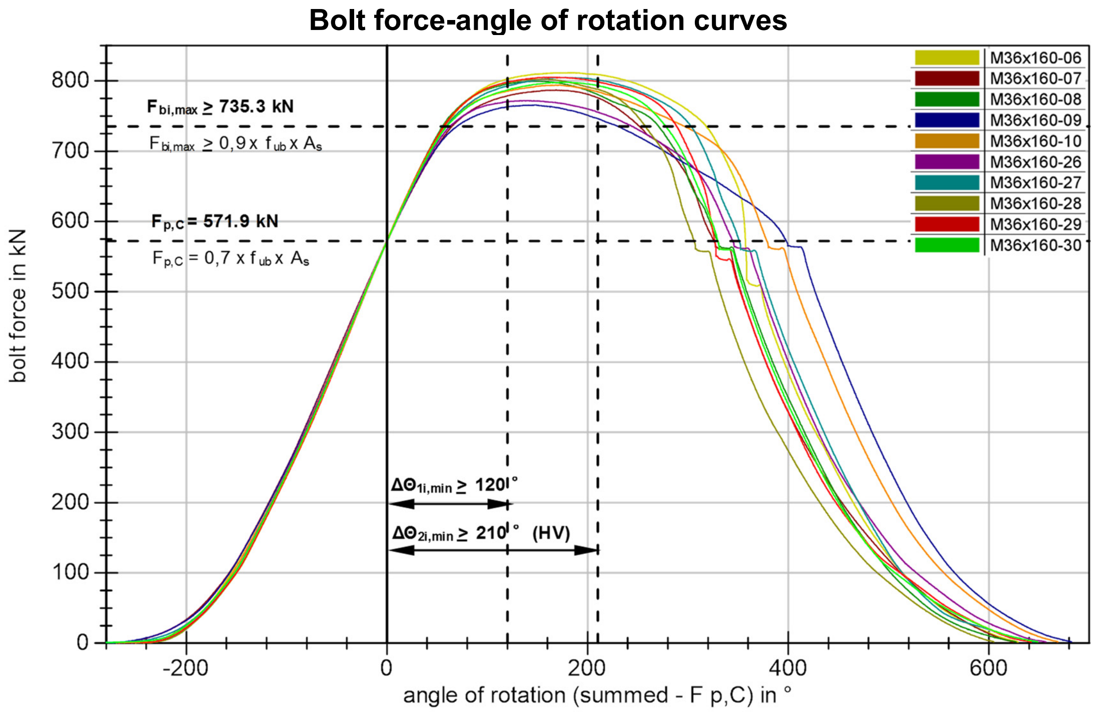


Figure 33 M36 HV - Gleitmo WSP 5040 Bolt force-angle of rotation curves

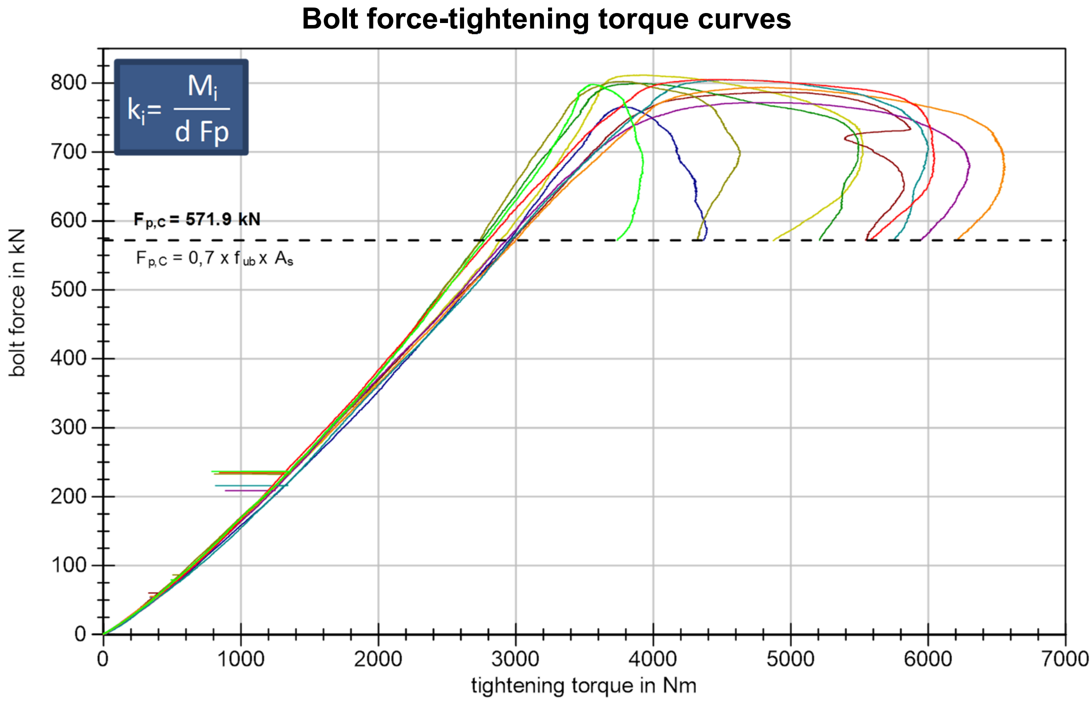


Figure 34 M36 HV - Gleitmo WSP 5040 Bolt force-tightening torque curves

3.5.2.3 M36x160 HV 10.9 – Molykote 1000 spray

The test results of M36x160 HV bolting assemblies in property class 10.9 and Molykote 1000 spray as lubrication are summarized in Table 32 and Table 33 including statistical evaluation. Referring to the system HV criteria of EN 14399-4, all bolting assemblies reached $F_{p,C}$, $\Delta\Theta_{1i,min}$ and $\Delta\Theta_{2i,min}$. Furthermore, all tested bolting assemblies achieved $F_{bi,max} \geq 0.9 \cdot f_{ub} \cdot A_s$. The k-values lie between k = 0.14 and k = 0.16 and are characterized by low scattering (only specimen M36x160-15 shows a higher k-value in amount of 0.16). In total, all bolting assemblies achieved k-class K1 and k-class K2 was accomplished as well. For further information and summarized criteria see Table 34. In addition, the tightening curves are shown in Figure 36 and Figure 37.

Table 32 Test results of M36 HV - Molykote 1000 spray

Legende		$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---						---	---	0,16					0,16			
min			735,3						120	210	0,10					0,10			
(blue)	M36x160-11	571,9	808,1	4598,1	249	446	582	571,6	285	421	0,14	0,098	0,083	0,111	514,7	0,14	2814,7	2629,1	3711,9
(orange)	M36x160-12		799,7	3564,4	270	439	594	571,9	256	410	0,14	0,098	0,093	0,102		0,14	2796,6	2554,3	3497,3
(magenta)	M36x160-13		784,6	4735,4	281	449	621	571,8	258	430	0,14	0,101	0,093	0,108		0,14	2877,9	2666,4	3791,6
(cyan)	M36x160-14		768,5	4603,6	254	392	547	571,8	224	379	0,14	0,100	0,092	0,106		0,14	2849,4	2563,8	4039,4
(yellow)	M36x160-15		756,2	4770,9	263	404	576	571,8	230	401	>0,16	0,118	0,110	0,124		>0,16	3297,7	2995,4	4247,7

Table 33 Statistical evaluation of M36 HV - Molykote 1000 spray

M36x160_Molykote 1000 spray n = 5	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M (F_{p,C^*}) Nm	k (F_{p,C^*})	M ($F_{bi,max}$) Nm
max	808,1	4770,9	281	449	621	571,9	285	430	0,118	0,110	0,124	3297,7	0,16	2995,4	0,16	4247,7
min	756,2	3564,4	249	392	547	571,6	224	379	0,098	0,083	0,102	2796,6	0,14	2554,3	0,14	3497,3
R	51,9	1206,5	32	57	74	0,3	61	51	0,020	0,027	0,022	501,1	0,02	441,1	0,02	750,4
$\bar{x}$	783,4	4454,5	263	426	584	571,8	251	408	0,103	0,094	0,110	2927,3	0,14	2681,8	0,14	3857,6
s	21,4	503,5	13	26	27	0,1	24	20	0,008	0,010	0,008	209,4	0,01	181,3	0,01	291,8
ν	2,74	11,30	4,84	6,14	4,62	0,02	9,77	4,82	8,24	10,38	7,60	7,15	6,21	6,76	6,21	7,56

n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Table 34 Evaluation of test results of M36 HV - Molykote 1000 spray according to EN 14399-4

	n	$F_{p,C}$	$F_{bi,max}$	$\Delta\Theta_{1i,min}$	$\Delta\Theta_{2i,min}$	k-values	k-class K1	k-class K2	
Series	[-]	571.9 kN	≥ 735.3 kN	≥ 120°	≥ 210°	[-]	$0.10 \le k_i \le 0.16$	$0.10 \le k_m \le 0.23$	≤ 0.06
M36 HV - Molykote 1000	5	5/5	5/5	5/5	5/5	0.14 – 0.16	4/5	0.14	0.06

Figure 35 M36 HV - Molykote 1000 spray test specimen after tightening

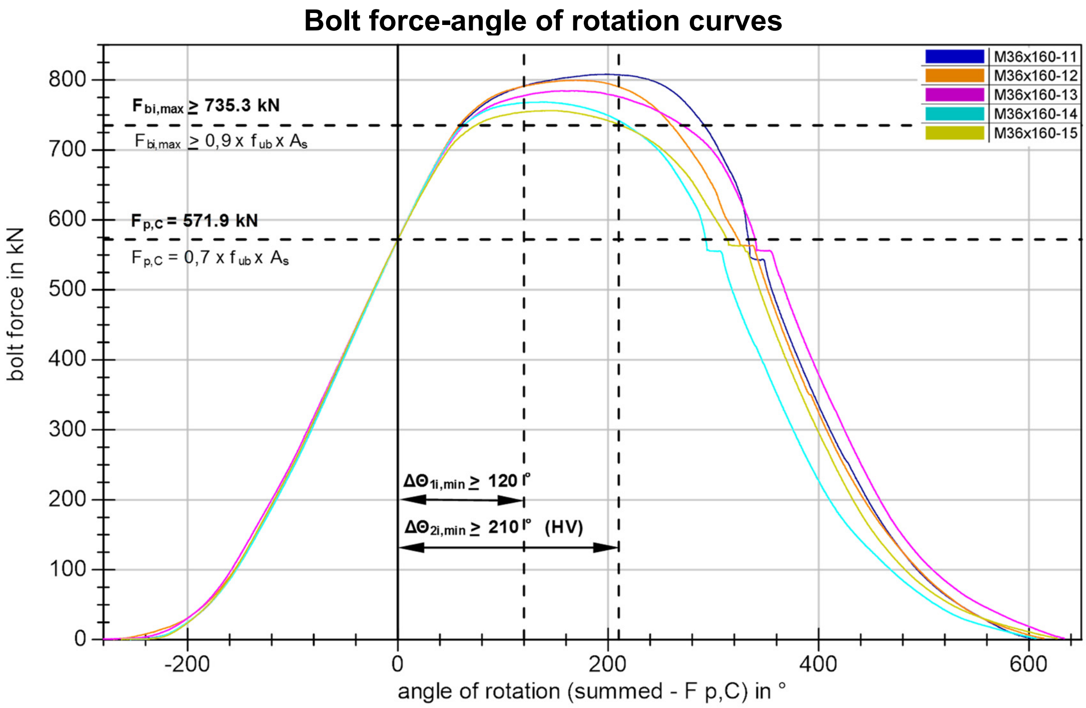


Figure 36 M36 HV - Molykote 1000 spray Bolt force-angle of rotation curves

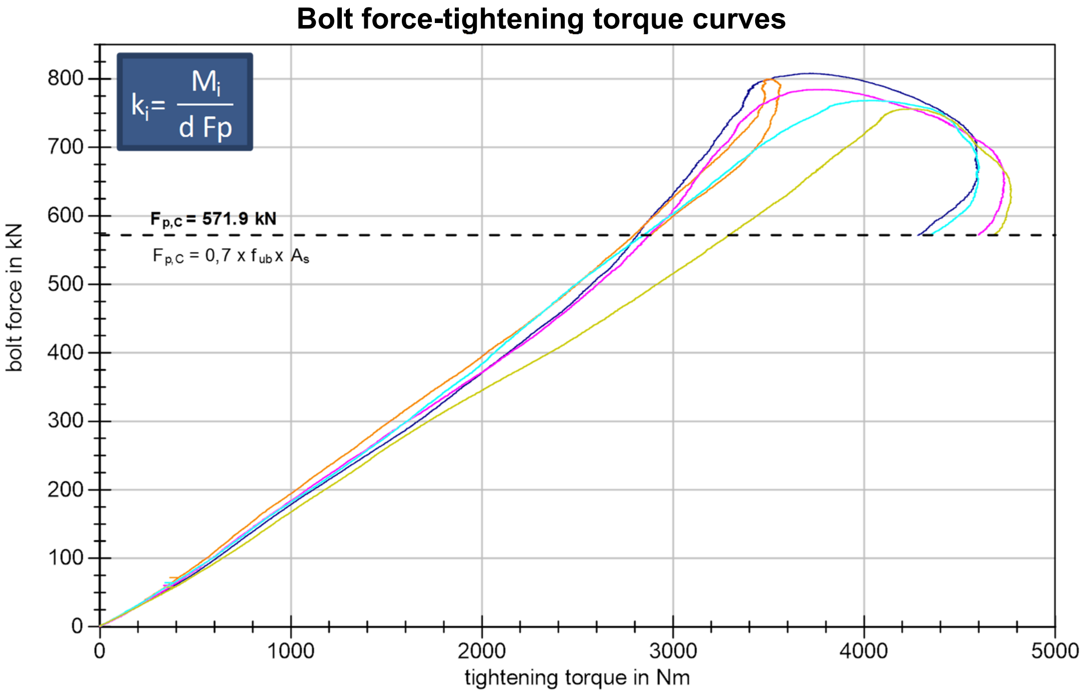


Figure 37 M36 HV - Molykote 1000 spray Bolt force-tightening torque curves

3.5.2.4 M36x160 HV 10.9 – Microgleit HV-paste LP440

Table 35, Table 36 and Table 37 present the test results and evaluation of M36 HV bolting assemblies with Microgleit HV-paste LP440. Statistical evaluation is given together with an overview of fulfilled and failed criteria according to EN 14399-4. Furthermore, Figure 39 and Figure 40 show the related tightening graphs. All bolting assemblies reached the specified preload of $F_{p,C} = 0.7 \cdot f_{ub} \cdot A_s = 571.9$ kN and $F_{bi,max} \geq 0.9 \cdot f_{ub} \cdot A_s = 735.3$ kN. Because of the again well pronounced plastic range, all tested bolts reached $\Delta\Theta_{1i,min} = 120°$ and $\Delta\Theta_{2i,min} = 210°$. In contrast, the k-values lie remarkably high between k = 0.20 and k = 0.22. As a result, 0 of 5 bolting assemblies achieved k-class K1, but k-class K2 was accomplished with low coefficient of variation V_k (4 %).

Table 35 Test results of M36 HV - Microgleit HV-paste LP440

Legende		$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C}$*)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---						---	---	0,16					0,16			
min			735,3						120	210	0,10					0,10			
	M36x160-16	571,9	770,6	6242,6	276	461	691	571,9	272	501	>0,20	0,152	0,127	0,172	514,7	>0,19	4149,9	3579,4	6227,6
	M36x160-17		754,7	6293,9	278	457	676	571,6	268	486	>0,22	0,168	0,119	0,206		>0,22	4532,6	4028,4	6280,5
	M36x160-18		764,0	5987,7	265	387	577	571,6	208	398	>0,20	0,150	0,110	0,181		>0,20	4089,1	3731,7	5613,7
	M36x160-19		750,1	6068,2	272	405	603	571,8	219	416	>0,20	0,154	0,124	0,178		>0,20	4198,0	3720,6	6014,5
	M36x160-20		767,2	6213,4	267	416	686	571,8	235	505	>0,21	0,160	0,118	0,193		>0,21	4339,3	3826,4	6150,3

Table 36 Statistical evaluation of M36 HV - Microgleit HV-paste LP440

M36x160_Microgleit n = 5	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k (F_{p,C^*})	M ($F_{bi,max}$) Nm
max	770,6	6293,9	278	461	691	571,9	272	505	0,168	0,127	0,206	4532,6	0,22	4028,4	0,22	6280,5
min	750,1	5987,7	265	387	577	571,6	208	398	0,150	0,110	0,172	4089,1	0,20	3579,4	0,19	5613,7
R	20,5	306,2	13	74	114	0,3	64	107	0,018	0,017	0,034	443,5	0,02	449,0	0,03	666,8
$\bar{x}$	761,3	6161,2	272	425	647	571,7	240	461	0,157	0,120	0,186	4261,8	0,21	3777,3	0,20	6057,3
s	8,6	128,2	6	33	53	0,1	29	50	0,007	0,007	0,014	177,3	0,01	165,8	0,01	267,4
ν	1,13	2,08	2,06	7,66	8,16	0,02	11,94	10,92	4,65	5,44	7,28	4,16	4,34	4,39	5,59	4,42

n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Table 37 Evaluation of test results of M36 HV - Microgleit HV-paste LP440 according to EN 14399-4

Series	n	$F_{p,C}$	$F_{bi,max}$	$\Delta\Theta_{1i,min}$	$\Delta\Theta_{2i,min}$	k-values	k-class K1	k-class K2	
	[-]	571.9 kN	≥ 735.3 kN	≥ 120°	≥ 210°	[-]	$0.10 \leq k_i \leq 0.16$	$0.10 \leq k_m \leq 0.23$	≤ 0.06
M36 HV - Microgleit HV	5	5/5	5/5	5/5	5/5	0.20 – 0.22	0/5	0.21	0.04

Figure 38 M36 HV - Microgleit HV-paste LP440 test specimen after tightening

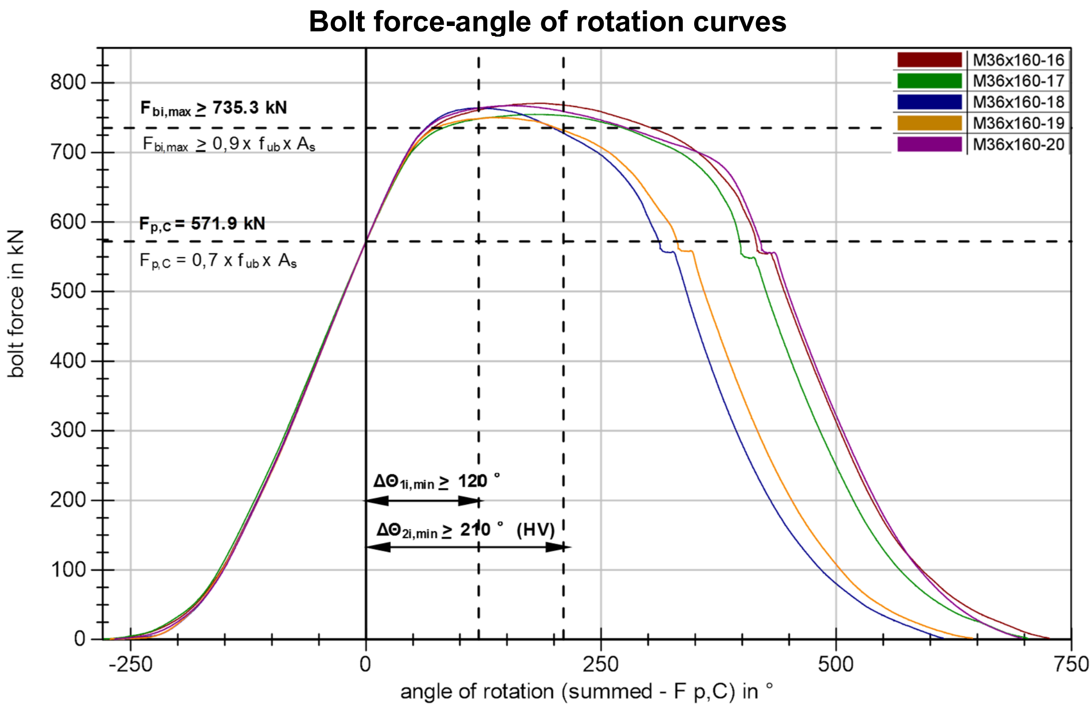


Figure 39 M36 HV - Microgleit HV-paste LP440 Bolt force-angle of rotation curves

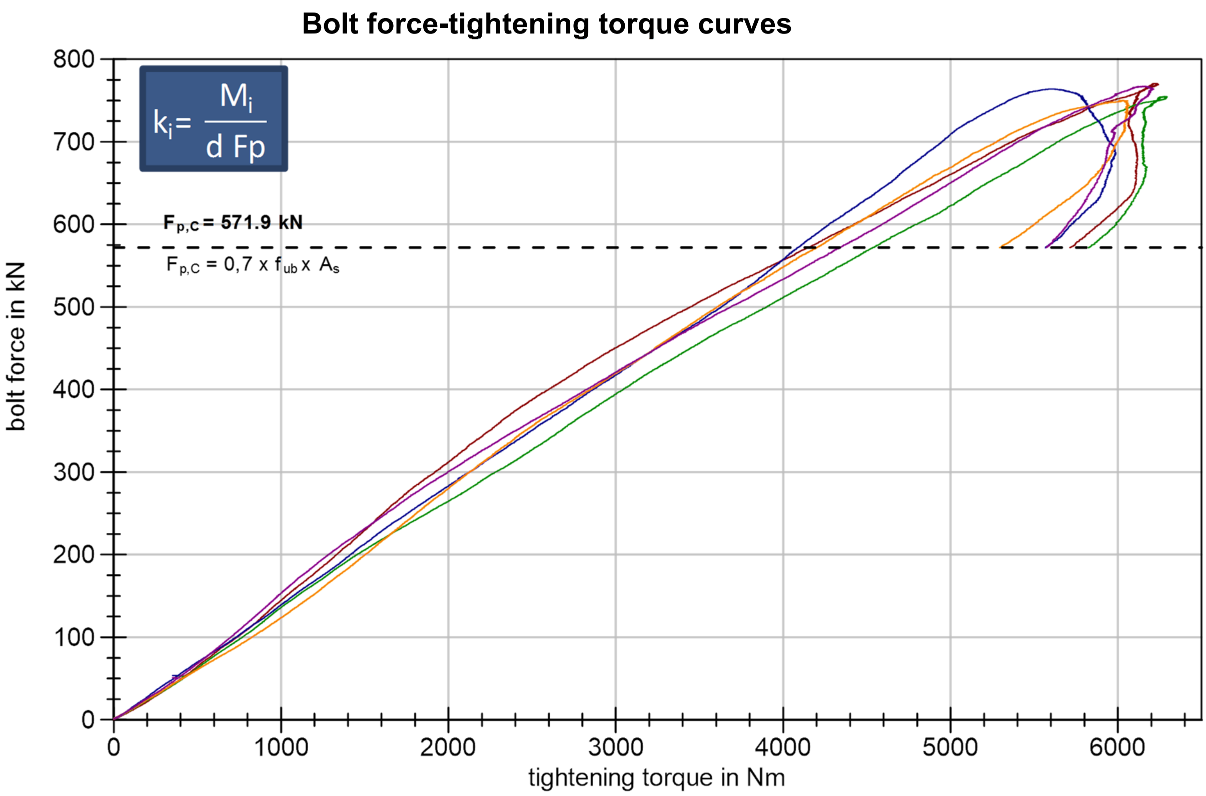


Figure 40 M36 HV - Microgleit HV-paste LP440 Bolt force-tightening torque curves

3.6 Results and Discussion

3.6.1 Evaluation of tightening tests for System HR/HV acc. EN 14399-3 and EN 14399-4

Table 38 shows a summary of the evaluation of the tested M24/M36 System HR and HV bolting assemblies after finishing tightening tests for Task 1.5. In addition, Table 39 summarizes the friction coefficients at specified preload level $F_{p,C}$ for each tested series and lubrication. The main conclusions are as follows:

The various lubrication types show different tightening behaviour and can be characterized in the context of preloading:

- All three lubrications used reached the specified preload of $F_{p,C}^* = 0.7 \cdot f_{yb} \cdot A_s$, as well as $F_{p,C} = 0.7 \cdot f_{ub} \cdot A_s$.
- All factory provided series reached $F_{p,C}^*$ and $F_{p,C}$, with the exception of HR M36 8.8 series, where 7 of 10 bolts achieved both preload levels.
- The results for the criteria of maximum individual bolt force $F_{bi,max} \geq 0.9 \cdot f_{ub} \cdot A_s$ are unequally distributed. Although all HR M24x100 bolting assemblies in property class 8.8 and 10.9 achieved the prescribed criteria of $F_{bi,max}$, the HR M36x160 8.8 and 10.9 series only partially fulfilled the criteria. It is striking that the factory provided series failed completely, as well as Microgleit HV-paste

LP440 failed mainly. For HV M36x160 10.9 bolting assemblies, all tested series achieved the criteria of maximum individual bolt force (again, except for the factory provided series). For HV M24x160 10.9 tested series, in each case, 8 of 10 bolts achieve criteria $F_{bi,max} \geq 0.9 \cdot f_{ub} \cdot A_s$, while the factory provided bolting assemblies failed completely.

- Regarding the criteria of sufficient ductility $\Delta\Theta_{1i}$ and $\Delta\Theta_{2i}$, the test results tend to show two groups: HV M24x100, HV M36x160, HR M24x100 8.8 and HR M24 10.9 series are characterised by high ductility behaviour and mostly achieved the criteria of nut rotation $\Delta\Theta_{1i}$ and $\Delta\Theta_{2i}$. HR M36x160 8.8 and HR M36x160 10.9 series are characterized by lower ductility when using factory provided or Gleitmo WSP 5040 lubrication, though using Molykote 1000 spray or Microgleit HV-paste LP440 significantly increased the ductility behaviour and consequently the angles of rotation $\Delta\Theta_{1i}$ and $\Delta\Theta_{2i}$.

Table 38 Summary of the evaluation of tightening tests acc. EN 14399-3 and EN 14399-4

Tested series	n [-]	$F_{p,C}^*$	$F_{p,C}$	$F_{bi,max}$	$\Delta\Theta_{1i,min}$	$\Delta\Theta_{2i,min}$	k-values [-]	k-class K1 $0.10 \leq k_i \leq 0.16$	k-class K2 $0.10 \leq k_m \leq 0.23$	k-class K2 $V_k \leq 0.06$	Fracture
System HR: M24x100 8.8											
Factory provided	10	100%	100%	100%	100%	100%	0.12 – 0.14	100%	0.130	0.029	0%
Gleitmo WSP 5040	10	100%	100%	100%	100%	100%	0.13 – 0.15	100%	0.141	0.045	0%
Molykote 1000 spray	10	100%	100%	100%	100%	100%	0.12 – 0.14	100%	0.128	0.047	0%
Microgleit HV-paste LP440	10	100%	100%	100%	100%	100%	0.14 – 0.16	100%	0.148	0.058	40%
System HR: M24x100 10.9											
Factory provided	10	100%	100%	100%	100%	100%	0.12 – 0.14	100%	0.129	0.053	0%
Gleitmo WSP 5040	10	100%	100%	100%	100%	100%	0.13 – 0.15	100%	0.136	0.043	0%
Molykote 1000 spray	10	100%	100%	100%	100%	100%	0.12 – 0.14	100%	0.127	0.044	0%
Microgleit HV-paste LP440	10	100%	100%	100%	100%	100%	0.13 – 0.15	100%	0.139	0.052	0%
System HR: M36x160 8.8											
Factory provided	10	100%	70%	0%	20%	30%	0.12 – 0.14	0%	0.287	0.147	30%
Gleitmo WSP 5040	10	100%	100%	30%	80%	90%	0.15 – 0.18	50%	0.166	0.067	30%
Molykote 1000 spray	10	100%	100%	90%	100%	100%	0.14 – 0.17	40%	0.161	0.066	0%
Microgleit HV-paste LP440	10	100%	100%	10%	100%	100%	0.21 – 025	0%	0.227	0.069	50%
System HR: M36x160 10.9											
Factory provided	10	100%	100%	0%	40%	0%	0.22 – 0.37	0%	0.267	0.157	20%
Gleitmo WSP 5040	10	100%	100%	40%	60%	80%	0.14 – 0.19	80%	0.153	0.099	20%
Molykote 1000 spray	10	100%	100%	80%	90%	100%	0.14 – 0.17	90%	0.151	0.069	10%
Microgleit HV-paste LP440	10	100%	100%	20%	90%	100%	0.17 – 0.23	0%	0.199	0.094	50%
System HV: M24x100 10.9											
Factory provided	10	100%	100%	0%	100%	100%	0.14 – 0.17	40%	0.158	0.085	10%
Gleitmo WSP 5040	10	100%	100%	80%	100%	100%	0.14 – 0.16	80%	0.152	0.042	0%
Molykote 1000 spray	10	100%	100%	80%	70%	100%	0.14 – 0.16	90%	0.146	0.057	0%
Microgleit HV-paste LP440	10	100%	100%	80%	100%	100%	0.16 – 0.21	10%	0.180	0.086	0%
System HV: M36x160 10.9											
Factory provided	10	100%	100%	30%	100%	90%	0.13 – 0.22	10%	0.184	0.125	40%
Gleitmo WSP 5040	10	100%	100%	100%	100%	100%	0.13 – 0.15	100%	0.140	0.035	0%
Molykote 1000 spray	10	100%	100%	100%	100%	100%	0.12 – 0.16	90%	0.134	0.087	0%
Microgleit HV-paste LP440	10	100%	100%	100%	100%	100%	0.16 – 0.22	0%	0.192	0.096	0%

Considering the evaluation results acc. to EN 14399-3 (System HR) and EN 14399-4 (System HV), as well as the analysis of friction coefficients (see Table 39), a comparison between various lubrications leads to the following conclusions:

- In terms of HV bolting assemblies, best results were achieved with Gleitmo WSP 5040 and Molykote 1000 spray. The k-values at $F_{p,C}$ stand out due to low scatterings (0.12–0.16) and low coefficients of variation V_k.
  - Gleitmo WSP 5040 and Molykote 1000 spray significantly decrease the frictions μ_{tot} and μ_{th} and lead to k-values in a narrow range (e.g. 0.14–0.16 for M24x100 10.9 series). k-class K2 is accomplished (with

the exception of HV M36x160 10.9 series and Molykote 1000 spray due to coefficient of variation V_k = 8.7% > 6%).

- In terms of HR bolting assemblies, a distinction must be made between bolt dimension M24 and M36:
  - For bolt dimension M24, every tested lubrication showed satisfactory test results, in addition to the factory provided bolting assemblies. k-class K1 and K2 are accomplished in each tested series with low coefficients of variation V_k (2.9–5.8%). Bolt fracture occurred only in one series, and only when turning off the hexagon nut after the end of the test procedure.
  - For bolt dimension M36, k-class K2 failed in each tested series, while k-class K1 and other criteria acc. to EN 14399-3:2015-04 were only partially accomplished. Bolt fracture occurred in nearly all tested HR M36 series. In this context, better tightening test results were achieved by using Molykote 1000 spray lubrication.

Table 39 Summary of the friction coefficients of tested HR and HV series

Tested series	μ_{tot} ($F_{p,C}$)			μ_{th} ($F_{p,C}$)			μ_b ($F_{p,C}$)		
	min	max	Vk [%]	min	max	Vk [%]	min	max	Vk [%]
System HR: M24x100 8.8									
Factory provided	0.086	0.097	**3.28**	0.089	0.119	**9.97**	0.076	0.088	**5.30**
Gleitmo WSP 5040	0.091	0.111	**5.29**	0.097	0.118	**5.52**	0.081	0.115	**9.96**
Molykote 1000 spray	0.080	0.096	**5.26**	0.083	0.104	**8.03**	0.075	0.090	**6.53**
Microgleit HV-paste LP440	0.095	0.119	**6.67**	0.108	0.131	**5.76**	0.078	0.119	**11.11**
System HR: M24x100 10.9									
Factory provided	0.084	0.100	**6.35**	0.098	0.129	**8.62**	0.068	0.088	**7.60**
Gleitmo WSP 5040	0.089	0.106	**5.22**	0.095	0.118	**6.56**	0.080	0.107	**11.10**
Molykote 1000 spray	0.082	0.099	**5.34**	0.085	0.106	**7.21**	0.073	0.106	**11.52**
Microgleit HV-paste LP440	0.091	0.109	**6.03**	0.101	0.120	**6.53**	0.081	0.100	**7.16**
System HR: M36x160 8.8									
Factory provided	0.182	0.272	**15.77**	0.123	0.268	**28.49**	0.186	0.282	**17.87**
Gleitmo WSP 5040	0.109	0.136	**7.63**	0.102	0.163	**15.39**	0.101	0.126	**5.90**
Molykote 1000 spray	0.103	0.129	**7.56**	0.085	0.113	**8.26**	0.108	0.144	**9.87**
Microgleit HV-paste LP440	0.158	0.191	**7.54**	0.113	0.169	**13.06**	0.169	0.210	**8.50**
System HR: M36x160 10.9									
Factory provided	0.170	0.291	**16.81**	0.125	0.324	**29.67**	0.181	0.264	**13.26**
Gleitmo WSP 5040	0.099	0.139	**11.14**	0.086	0.176	**21.77**	0.097	0.118	**5.52**
Molykote 1000 spray	0.097	0.122	**7.77**	0.090	0.127	**12.56**	0.089	0.136	**14.68**
Microgleit HV-paste LP440	0.128	0.170	**10.32**	0.102	0.161	**11.61**	0.125	0.199	**13.34**
System HV: M24x100 10.9									
Factory provided	0.108	0.141	**9.70**	0.118	0.168	**10.60**	0.088	0.127	**13.91**
Gleitmo WSP 5040	0.112	0.132	**4.80**	0.092	0.121	**7.79**	0.123	0.152	**5.88**
Molykote 1000 spray	0.107	0.130	**6.56**	0.068	0.126	**19.61**	0.103	0.158	**13.72**
Microgleit HV-paste LP440	0.128	0.172	**9.62**	0.089	0.137	**12.07**	0.147	0.218	**12.23**
System HV: M36x160 10.9									
Factory provided	0.096	0.169	**13.88**	0.098	0.170	**16.56**	0.098	0.170	**21.93**
Gleitmo WSP 5040	0.095	0.106	**4.02**	0.081	0.114	**10.93**	0.096	0.108	**4.00**
Molykote 1000 spray	0.086	0.118	**10.06**	0.064	0.110	**15.80**	0.083	0.124	**10.30**
Microgleit HV-paste LP440	0.121	0.168	**10.55**	0.096	0.127	**8.43**	0.142	0.206	**13.24**

Furthermore, Figure 41 and Figure 42 show exemplary tightening curves of HR M24x100 8.8 series comparing factory provided lubrication (black) and Molykote® 1000 spray (yellow), and are characterised by slightly reduced scattering and more congruent tightening curves.

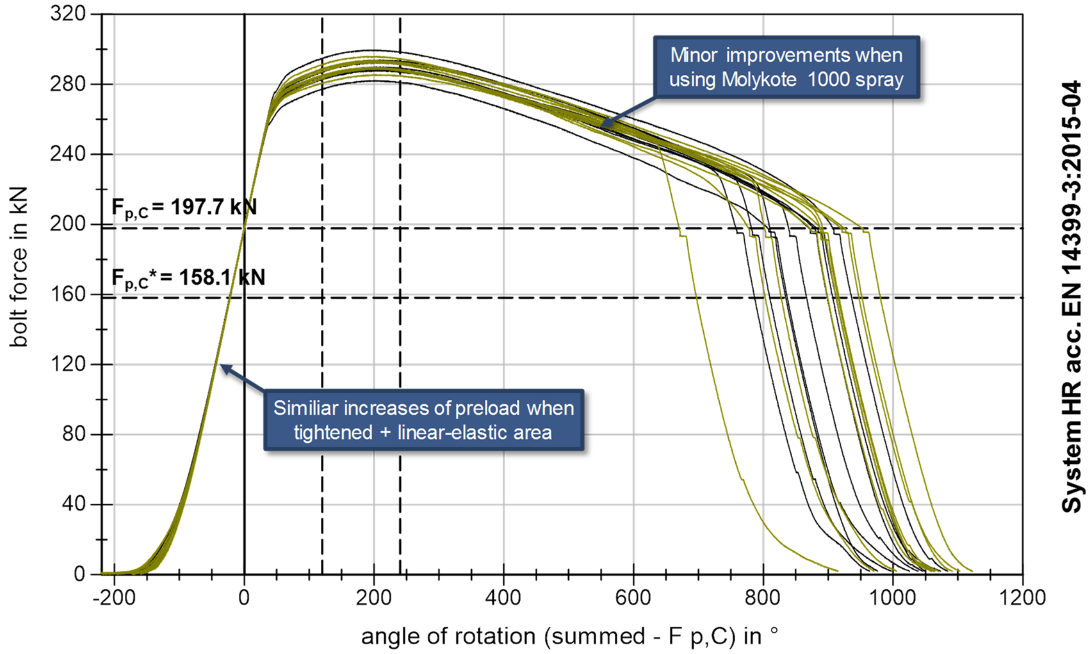


Figure 41 Comparison of bolt force-angle of rotation curves between HR M24x100 8.8 – factory provided (black) and Molykote 1000 spray (yellow)

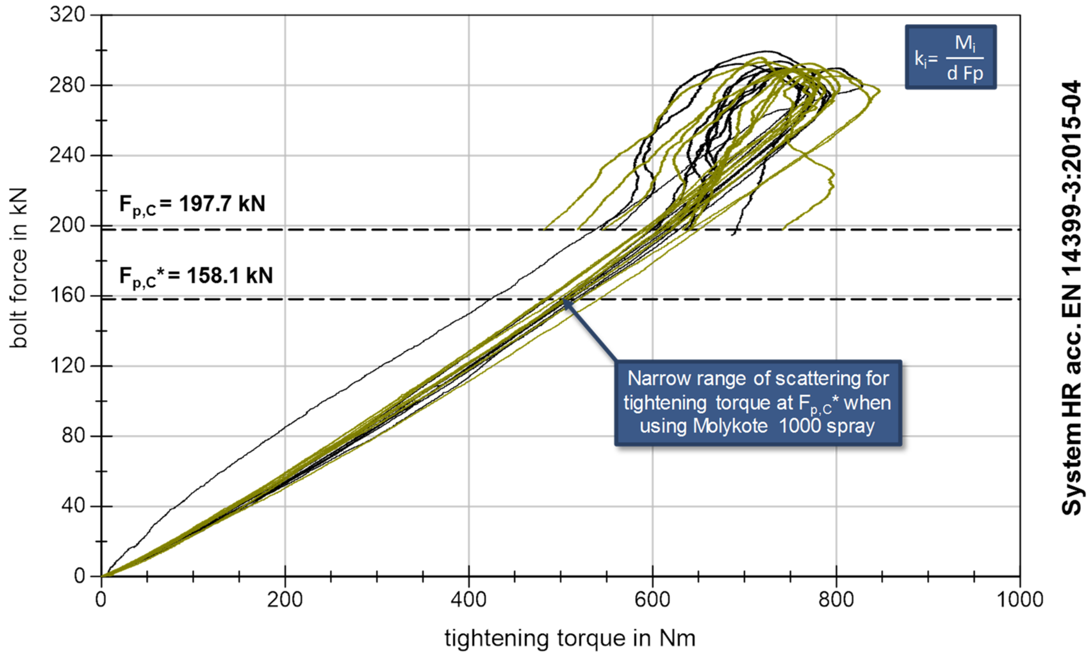


Figure 42 Comparison of bolt force-tightening torque curves between HR M24x100 8.8 – factory provided (black) and Molykote 1000 spray (yellow)

In addition, Figure 43 and Figure 44 show tightening curves of HR M36x160 10.9 series comparing factory provided lubrication and Gleitmo® WSP 5040 lubrication. The positive effects of alternative lubrication are a significant improvement of ductility, and hence the criteria of maximum individual bolt force $F_{bi,max}$ and angles of rotation $\Delta\theta_{1i}$ and $\Delta\theta_{2i}$.

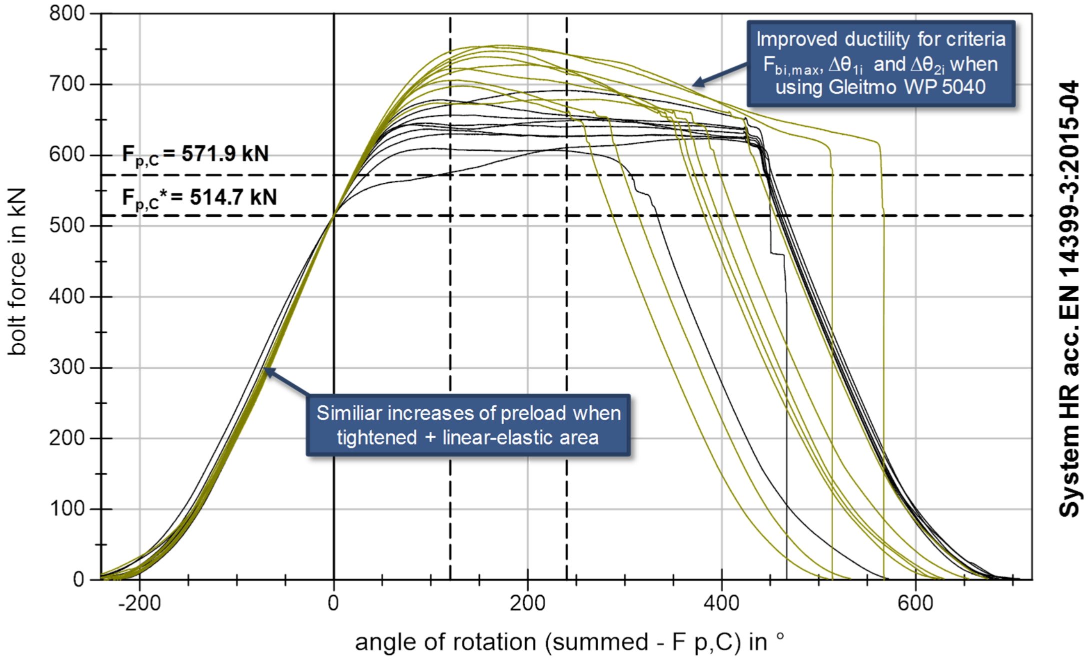


Figure 43 Comparison of bolt force-angle of rotation curves between HR M36x160 10.9 – factory provided (black) and Molykote 1000 spray (yellow)

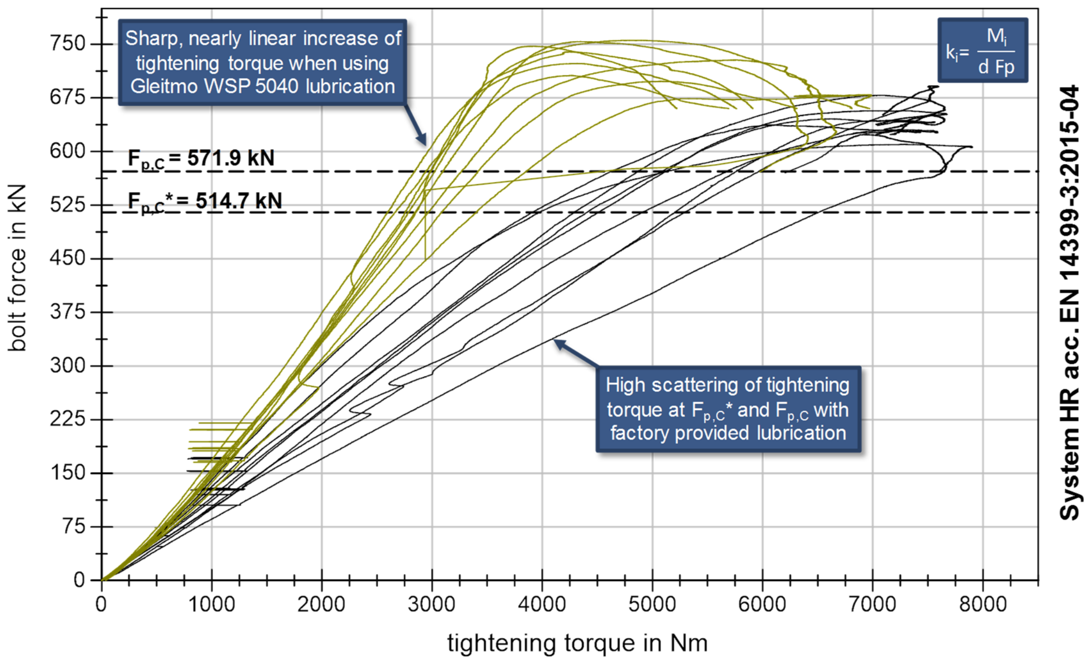


Figure 44 Comparison of bolt force-tightening torque curves between HR M36x160 10.9 – factory provided (black) and Molykote 1000 spray (yellow)

3.6.2 Evaluation on the basis of the 0.2% remaining strain level

The applicability of tightening methods is connected to the quality of lubricated bolting assemblies in their delivered condition. For this reason, the k-value—as a measure of the predominant friction conditions—is defined according to EN 14399-2, as well as k-classes K0, K1, and K2 defined according to EN 14399-1. The application of the torque method requires k-class K2. For the combined method, k-class K1 or K2 is prescribed. Clearly defined tightening torques and a constant level of friction coefficients μ_{tot}, μ_{th} and μ_b are required to achieve guaranteed preload levels in the elastic range with sufficient reliability. For this reason, a detailed summary of tightening torques at specified preload levels $F_{p,C}$*, $F_{p,C}$ and at maximum individual bolt force $F_{bi,max}$ is presented in Table 40. Additionally, k-values at $F_{p,C}$* and $F_{p,C}$ and $\Delta\Theta_{1i}$ and $\Delta\Theta_{2i}$ are summarized in Table 41. It can be seen that the coefficients of variation of k-values as well as tightening torques M_i at $F_{p,C}$* and $F_{p,C}$ are close to each other and underscore the importance of the type of lubrication and effectivity of lubrication during tightening. Especially Gleitmo WSP 5040 and Molykote 1000 spray are characterised by low coefficients of variation of tightening torque at $F_{p,C}$* and $F_{p,C}$. A comparison of coefficients of variation of μ_{th} and μ_b is presented in Figure 45. Furthermore, a comparison of coefficients of variation of (total) tightening torque at $F_{p,C}$* and $F_{p,C}$ can be seen in Figure 46.

Table 40 Summary of tightening torque at different preloading levels

Tested series	M_i ($F_{p,C}$*) in [Nm]				M_i ($F_{p,C}$) in [Nm]				M_i ($F_{bi,max}$) in [Nm]			
	min	max	range	Vk [%]	min	max	range	Vk [%]	min	max	range	Vk [%]
System HR: M24x100 8.8												
Factory provided	486.9	532.3	45.4	**2.41**	590.1	653.2	63.1	**2.79**	692.5	792.8	100.3	**3.42**
Gleitmo WSP 5040	512.8	605.8	93.0	**4.76**	618.4	732.4	114.0	**4.50**	702.4	855.5	153.1	**6.06**
Molykote 1000 spray	444.7	541.4	96.7	**5.18**	551.9	649.1	97.2	**4.63**	715.3	803.4	88.1	**3.45**
Microgleit HV-paste LP440	526.0	626.8	100.8	**5.55**	641.2	777.6	136.4	**5.74**	900.5	1114.7	214.2	**6.85**
System HR: M24x100 10.9												
Factory provided	659.3	757.9	98.6	**5.44**	724.9	837.5	112.6	**5.34**	957.0	1120.9	163.9	**5.24**
Gleitmo WSP 5040	692.7	799.6	106.9	**4.37**	759.0	877.4	118.4	**4.34**	912.6	1019.7	107.1	**3.40**
Molykote 1000 spray	645.4	750.5	105.1	**4.41**	709.3	830.6	121.3	**4.45**	960.1	1076.3	116.2	**3.72**
Microgleit HV-paste LP440	690.5	806.1	115.6	**5.09**	770.8	899.1	128.3	**5.16**	1043.6	1257.3	213.7	**4.77**
System HR: M36x160 8.8												
Factory provided	2958.5	4160.9	1202.4	**10.74**	3939.8	5734.3	1794.5	**14.68**	4673.7	6371.3	1697.6	**9.58**
Gleitmo WSP 5040	2079.3	2443.8	364.5	**5.36**	2477.6	3007.6	530.0	**6.68**	3027.0	3813.8	786.8	**9.00**
Molykote 1000 spray	1963.7	2358.2	394.5	**6.22**	2349.6	2872.0	522.4	**6.68**	2900.2	4183.8	1283.6	**10.10**
Microgleit HV-paste LP440	2814.6	3283.3	468.7	**6.23**	3455.4	4121.2	665.8	**6.89**	4632.4	5839.8	1207.4	**7.05**
System HR: M36x160 10.9												
Factory provided	3906.4	6505.9	2599.5	**16.35**	4620.7	7634.2	3013.5	**15.63**	6087.1	7578.1	1491.0	**6.30**
Gleitmo WSP 5040	2596.9	3402.5	805.6	**8.46**	2840.1	3849.6	1009.5	**9.92**	3894.2	6920.4	3026.2	**19.83**
Molykote 1000 spray	2506.3	3100.2	593.9	**6.81**	2782.3	3416.8	634.5	**6.83**	3739.7	5022.9	1283.2	**10.21**
Microgleit HV-paste LP440	3234.0	4160.7	926.7	**9.21**	3577.2	4623.6	1046.4	**9.45**	4785.4	6651.3	1865.9	**9.02**
System HV: M24x100 10.9												
Factory provided	541.6	694.3	152.7	**8.55**	816.9	1027.7	210.8	**8.48**	1052.2	1369.3	317.1	**7.57**
Gleitmo WSP 5040	605.0	699.6	94.6	**4.30**	844.8	971.1	126.3	**4.17**	1061.4	1257.0	195.6	**5.00**
Molykote 1000 spray	532.3	619.8	87.5	**5.39**	810.9	961.4	150.5	**5.66**	983.1	1266.0	282.9	**7.99**
Microgleit HV-paste LP440	614.5	714.6	100.1	**5.44**	945.5	1228.7	283.2	**8.55**	1340.0	1686.3	346.3	**7.47**
System HV: M36x160 10.9												
Factory provided	887.2	1247.4	360.2	**8.96**	2754.8	4568.9	1814.1	**12.54**	4223.0	6968.6	2745.6	**13.47**
Gleitmo WSP 5040	943.0	1029.7	86.7	**3.51**	2740.4	2997.8	257.4	**3.51**	3553.1	4938.2	1385.1	**11.71**
Molykote 1000 spray	821.1	959.5	138.4	**4.98**	2497.0	3297.7	800.7	**8.73**	3070.3	4247.7	1177.4	**10.64**
Microgleit HV-paste LP440	969.0	1249.1	280.1	**7.18**	3381.1	4538.9	1157.8	**9.58**	5142.6	6280.5	1137.9	**7.00**

Table 41 Summary of k-values at $F_{p,C}$*, $F_{p,C}$ and angles of nut rotation at $F_{p,C}$

Tested series	k ($F_{p,C}$*)			k ($F_{p,C}$)			$\Delta\Theta_{1i}$ in [°]			$\Delta\Theta_{2i}$ in [°]		
	min	max	Vk [%]	min	max	Vk [%]	min	max	Vk [%]	min	max	Vk [%]
System HR: M24x100 8.8												
Factory provided	0.128	0.140	**2.41**	0.124	0.140	**2.88**	199	214	**2.65**	659	907	**9.05**
Gleitmo WSP 5040	0.135	0.160	**4.84**	0.130	0.150	**4.52**	173	203	**5.63**	498	885	**17.24**
Molykote 1000 spray	0.117	0.143	**5.24**	0.116	0.140	**4.72**	191	208	**2.99**	670	953	**9.93**
Microgleit HV-paste LP440	0.139	0.165	**5.47**	0.135	0.160	**5.79**	150	181	**5.30**	682	770	**4.51**
System HR: M24x100 10.9												
Factory provided	0.124	0.142	**5.27**	0.122	0.140	**5.28**	148	184	**6.99**	373	836	**24.35**
Gleitmo WSP 5040	0.130	0.150	**4.37**	0.128	0.150	**4.30**	163	203	**6.76**	451	828	**19.91**
Molykote 1000 spray	0.121	0.141	**4.53**	0.120	0.140	**4.44**	165	196	**5.55**	414	837	**16.44**
Microgleit HV-paste LP440	0.129	0.151	**5.14**	0.130	0.150	**5.24**	134	173	**7.15**	655	748	**4.71**
System HR: M36x160 8.8												
Factory provided	0.225	0.316	**10.76**	0.239	0.350	**14.68**	35	258	**69.83**	82	398	**44.20**
Gleitmo WSP 5040	0.158	0.185	**5.29**	0.150	0.180	**6.72**	98	242	**31.39**	224	582	**29.13**
Molykote 1000 spray	0.149	0.179	**6.24**	0.143	0.170	**6.62**	200	291	**13.30**	401	691	**23.00**
Microgleit HV-paste LP440	0.214	0.249	**6.25**	0.210	0.250	**6.86**	161	269	**20.36**	382	684	**22.52**
System HR: M36x160 10.9												
Factory provided	0.211	0.351	**16.34**	0.224	0.370	**15.67**	68	276	**55.93**	273	498	**14.32**
Gleitmo WSP 5040	0.140	0.184	**8.53**	0.138	0.190	**9.94**	106	240	**29.53**	220	544	**29.89**
Molykote 1000 spray	0.135	0.167	**6.82**	0.135	0.170	**6.85**	119	235	**21.77**	305	654	**23.81**
Microgleit HV-paste LP440	0.175	0.225	**9.26**	0.174	0.230	**9.43**	102	229	**25.63**	269	585	**24.71**
System HV: M24x100 10.9												
Factory provided	0.138	0.170	**8.45**	0.138	0.173	**8.48**	143	180	**7.66**	283	469	**16.64**
Gleitmo WSP 5040	0.143	0.159	**4.05**	0.143	0.164	**4.17**	180	209	**5.61**	454	535	**5.06**
Molykote 1000 spray	0.138	0.159	**5.44**	0.137	0.162	**5.66**	106	219	**29.65**	349	493	**29.65**
Microgleit HV-paste LP440	0.160	0.199	**7.43**	0.159	0.207	**8.55**	178	202	**4.59**	439	543	**5.92**
System HV: M36x160 10.9												
Factory provided	0.133	0.221	**12.51**	0.134	0.222	**12.54**	74	234	**29.69**	257	489	**20.60**
Gleitmo WSP 5040	0.135	0.147	**3.50**	0.133	0.146	**3.51**	218	267	**6.29**	390	486	**6.59**
Molykote 1000 spray	0.120	0.155	**7.99**	0.121	0.160	**8.73**	174	285	**18.25**	295	430	**14.25**
Microgleit HV-paste LP440	0.163	0.220	**9.62**	0.164	0.220	**9.58**	145	272	**22.36**	323	505	**15.96**

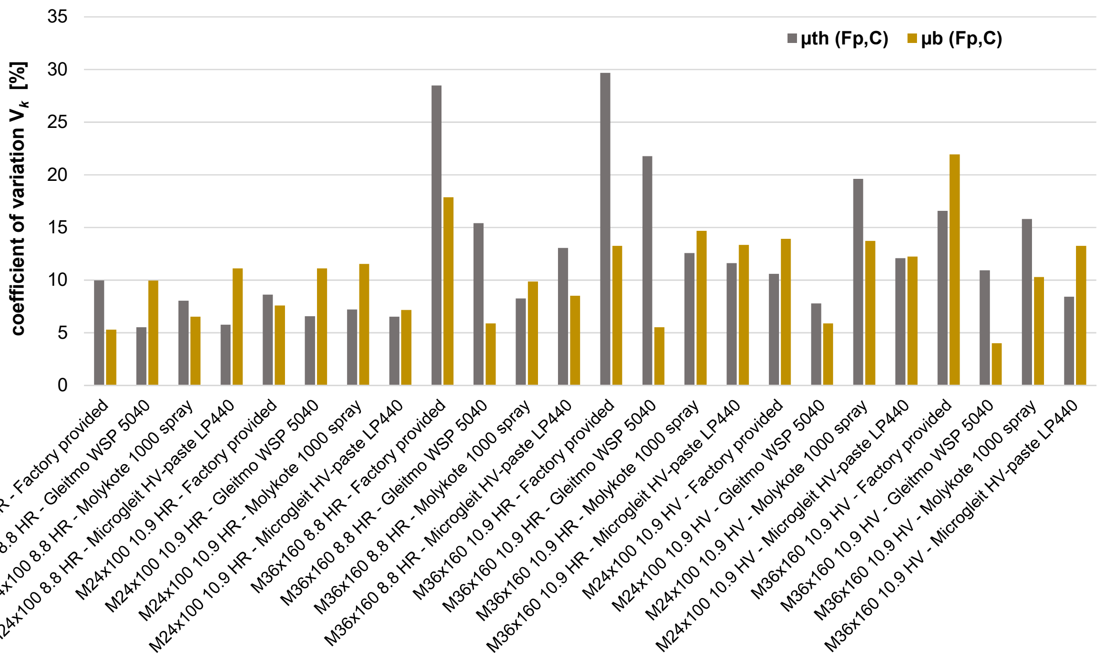


Figure 45 Summary of coefficients of variation μ_{th} and μ_b at $F_{p,C}$

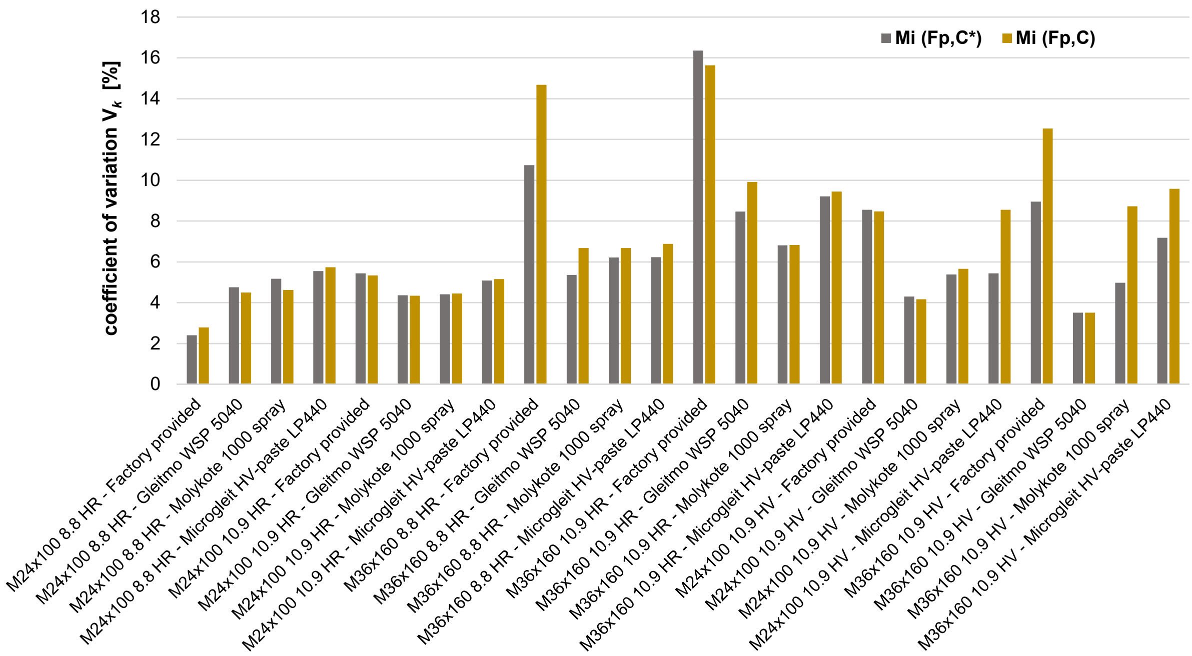


Figure 46 Summary of coefficients of variation of tightening torque at $F_{p,C}$* and $F_{p,C}$

3.7 Recommendation of tightening methods to achieve a reduced preloading level in the elastic range of the bolt material with sufficient reliability

The evaluation of the tightening tests for preloading procedures to achieve a reduced preload level in the elastic range of the bolt material with sufficient reliability is based on the German modified torque method and the modified combined method according to DIN EN 1993-1-8/NA. The target level of preload for these tightening methods is $F_{p,C}* = 0.7\ f_{yb}\ A_s$ and based on the 0.2 % remaining strain level of the bolt material instead of the ultimate stress level.

The test procedure of the modified torque method consists of the following two steps:

1. The first tightening step can be selected as required. This first tightening step must be completed for all the bolting assemblies in a bolted connection before the second tightening step is started.
2. The second tightening step means the application of the tightening torque of Table NA.A.1 for property class 8.8 or Table NA.A.2 for strength class 10.9 according to DIN EN 1993-1-8/NA to achieve the reduced specified preload $F_{p,C}* = 0.7\ f_{yb}\ A_s$. If the required preload is smaller than $F_{p,C}$*, the tightening torque must be reduced proportionally.

This method allows any gradual preloading of connections with many bolting assemblies as well as re-tightening, which serves as a control measure or as a compensation of preload losses after a few days.

The test procedure of the modified combined method is comparable to the *combined method* acc. to EN 1090-2. However, the tightening torque of the first torque-controlled tightening step is modified by Table NA.A.2 of DIN EN 1993-1-8/NA. Additionally, the second angle of rotation-controlled tightening step is modified by Table NA.A.3 of DIN EN 1993-1-8/NA by different additional rotation angles, which are dependent on the bolt diameter and total nominal thickness of parts to be connected, including all packs and washers.

It must be pointed out, that these tightening torques and angles of rotation according to DIN EN 1993-18/NA are not considering the various lubricants. For this reason and regarding the performed tightening tests of HR and HV bolting assemblies, the evaluation of tightening methods based on the German National Annex can only give a first insight whether the required preload level $F_{p,C}$* = 0.7 f_{yb} A_s based on the 0.2 % remaining strain level of the bolt material is achieved or not when using standard torques and angles of rotation. It is to note that the required tightening torques, and additional angle of rotations must be determined experimentally for each specific lubrication in a tightening test. The scattering of tightening parameters must be considered as well as the maximum preload level to avoid overtightening of the bolting assemblies, especially when re-use of the bolting assemblies is intended. Table 42 shows the summary of the evaluation of the modified torque method and modified combined method acc. to DIN EN 1993-1-8/NA for all tested carbon steel HR/HV bolting assemblies. Additionally, Figure 47 and Figure 48 visualize comparisons of the achieved preloads of HR and HV bolting assemblies.

Table 42 Summary of the evaluation of the modified torque method and modified combined method acc. to DIN EN 1993-1-8/NA for all tested carbon steel HR/HV bolting assemblies

Tested series	Modified torque method acc. DIN EN 1993-1-8/NA					Modified combined method acc. DIN EN 1993-1-8/NA				
	$F_{p,C}$* achieved?	Minimum achieved bolt force	Maximum achieved bolt force	range	Vk [%]	$F_{p,C}$* achieved?	Minimum achieved bolt force	Maximum achieved bolt force	range	Vk [%]
System HR: M24x100 8.8	M_A = 600 Nm acc. Table NA.A.1					not valid for strength class 8.8				
Factory provided	100%	180,2	201,6	21,4	3,13	-	-	-	-	-
Gleitmo WSP 5040	90%	156,4	190,6	34,2	5,52	-	-	-	-	-
Molykote 1000 spray	100%	178,8	214,9	36,1	5,20	-	-	-	-	-
Microgleit HV-paste LP440	80%	151	182,9	31,9	5,73	-	-	-	-	-
System HR: M24x100 10.9	M_A = 800 Nm acc. Table NA.A.2					$M_{A,MKV}$ = 600 Nm + ϑ_{MKV} = 60°				
Factory provided	100%	235,2	275,8	40,6	5,62	100%	278,4	304,6	26,2	3,42
Gleitmo WSP 5040	100%	222,9	261,3	38,4	4,69	100%	268,0	296,1	28,1	2,89
Molykote 1000 spray	100%	236,7	281,9	45,2	4,64	100%	285,1	309,3	24,2	2,19
Microgleit HV-paste LP440	90%	221,0	255,9	34,9	4,71	100%	270,2	300,9	30,7	3,42
System HR: M36x160 8.8	M_A = 2100 Nm acc. Table NA.A.1					not valid for strength class 8.8				
Factory provided	0%	197,7	260,3	62,6	9,69	-	-	-	-	-
Gleitmo WSP 5040	10%	303,1	370,7	67,6	6,11	-	-	-	-	-
Molykote 1000 spray	30%	318,7	396,4	77,7	7,08	-	-	-	-	-
Microgleit HV-paste LP440	0%	225,9	278,3	52,4	6,95	-	-	-	-	-
System HR: M36x160 10.9	M_A = 2800 Nm acc. Table NA.A.2					$M_{A,MKV}$ = 2100 Nm + ϑ_{MKV} = 60°				
Factory provided	0%	236,0	408,0	172,0	15,30	0%	355,8	483,0	127,2	9,60
Gleitmo WSP 5040	40%	427,1	563,4	136,3	8,34	90%	498,7	572,9	74,2	3,97
Molykote 1000 spray	40%	463,6	575,6	112,0	7,24	100%	535,3	608,8	73,5	4,57
Microgleit HV-paste LP440	0%	339,5	448,6	109,1	9,42	0%	433,4	510,7	77,3	5,22
System HV: M24x100 10.9	M_A = 800 Nm acc. Table NA.A.2					$M_{A,MKV}$ = 600 Nm + ϑ_{MKV} = 60°				
Factory provided	30%	186,3	241,5	55,2	10,28	100%	244,7	287,9	43,2	5,71
Gleitmo WSP 5040	10%	190,7	230,2	39,5	5,07	100%	244,4	270,5	26,1	3,00
Molykote 1000 spray	60%	200,8	244,3	43,5	6,19	100%	259,4	291,7	32,3	4,34
Microgleit HV-paste LP440	0%	178,6	205,8	27,2	5,26	100%	240,7	265,9	25,2	3,32
System HV: M36x160 10.9	M_A = 2800 Nm acc. Table NA.A.2					$M_{A,MKV}$ = 2100 Nm + ϑ_{MKV} = 60°				
Factory provided	10%	385,9	583,2	197,3	13,93	30%	485,9	619,3	133,4	7,84
Gleitmo WSP 5040	100%	530,3	594,4	64,1	4,46	100%	571,4	613,0	41,6	2,28
Molykote 1000 spray	90%	478,0	671,1	193,1	10,02	100%	555,2	665,4	110,2	5,77
Microgleit HV-paste LP440	0%	368,4	465,2	96,8	7,52	50%	471,2	558,4	87,2	5,46

M24 8.8: $F_{p,C}$* = 158,1 kN M24 10.9: $F_{p,C}$* = 222.4 kN M36 8.8: $F_{p,C}$* = 366,0 kN M36 10.9: $F_{p,C}$* = 514,7 kN

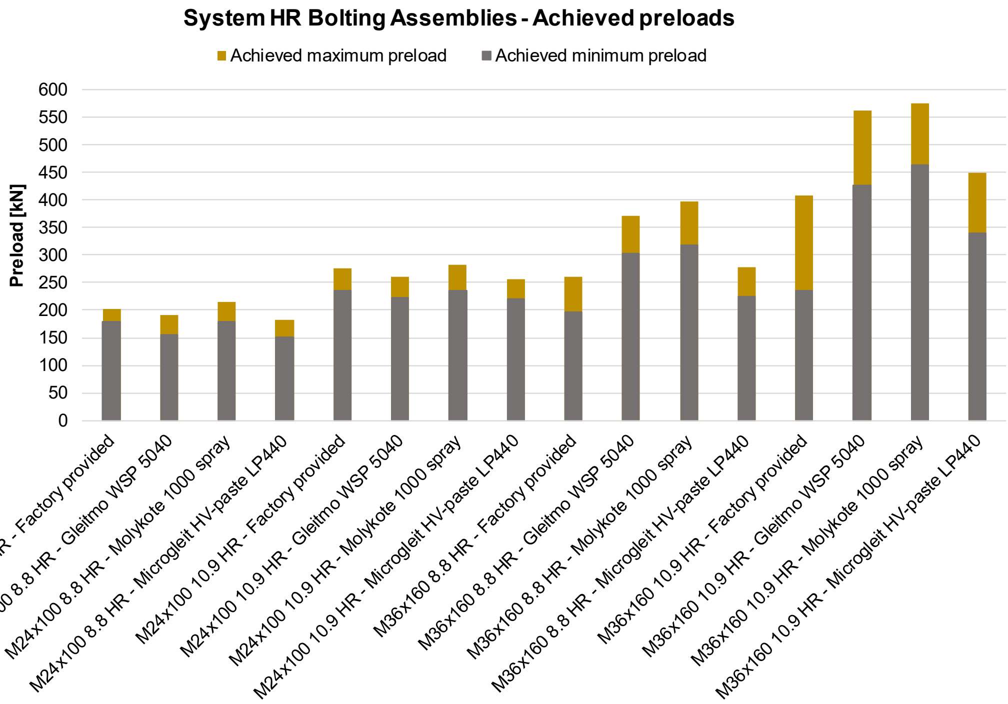


Figure 47 Achieved preloads of HR bolting assemblies in property class 8.8 and 10.9 when using the modified combined method acc. DIN EN 1993-1-8/NA

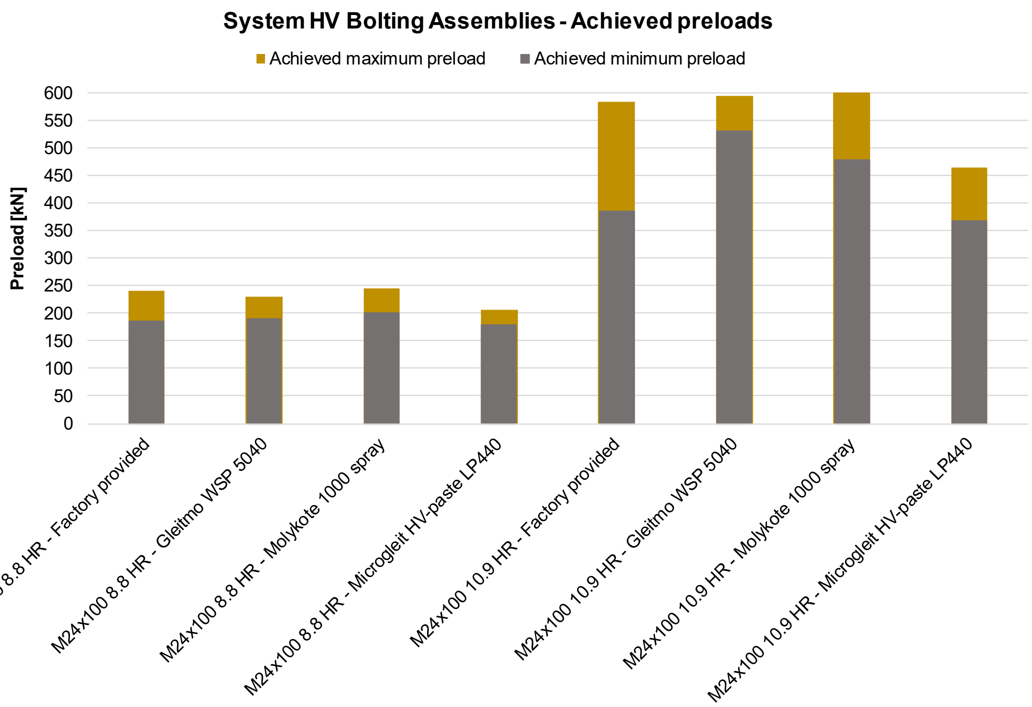


Figure 48 Achieved preloads of HV bolting assemblies in property class 10.9 when using the modified combined method acc. DIN EN 1993-1-8/NA

Additionally, a detailed summary of tightening torques at specified preload levels $F_{p,C}$*, $F_{p,C}$ and at maximum individual bolt force $F_{bi,max}$ is presented in Table 43.

Table 43 Summary of tightening torque at different preloading levels for all tested carbon steel HR/HV bolting assemblies

Tested series	M_i ($F_{p,C}$*) in [Nm]				M_i ($F_{p,C}$) in [Nm]				M_i ($F_{bi,max}$) in [Nm]			
	min	max	range	Vk [%]	min	max	range	Vk [%]	min	max	range	Vk [%]
System HR: M24x100 8.8												
Factory provided	486.9	532.3	45.4	**2.41**	590.1	653.2	63.1	**2.79**	692.5	792.8	100.3	**3.42**
Gleitmo WSP 5040	512.8	605.8	93.0	**4.76**	618.4	732.4	114.0	**4.50**	702.4	855.5	153.1	**6.06**
Molykote 1000 spray	444.7	541.4	96.7	**5.18**	551.9	649.1	97.2	**4.63**	715.3	803.4	88.1	**3.45**
Microgleit HV-paste LP440	526.0	626.8	100.8	**5.55**	641.2	777.6	136.4	**5.74**	900.5	1114.7	214.2	**6.85**
System HR: M24x100 10.9												
Factory provided	659.3	757.9	98.6	**5.44**	724.9	837.5	112.6	**5.34**	957.0	1120.9	163.9	**5.24**
Gleitmo WSP 5040	692.7	799.6	106.9	**4.37**	759.0	877.4	118.4	**4.34**	912.6	1019.7	107.1	**3.40**
Molykote 1000 spray	645.4	750.5	105.1	**4.41**	709.3	830.6	121.3	**4.45**	960.1	1076.3	116.2	**3.72**
Microgleit HV-paste LP440	690.5	806.1	115.6	**5.09**	770.8	899.1	128.3	**5.16**	1043.6	1257.3	213.7	**4.77**
System HR: M36x160 8.8												
Factory provided	2958.5	4160.9	1202.4	**10.74**	3939.8	5734.3	1794.5	**14.68**	4673.7	6371.3	1697.6	**9.58**
Gleitmo WSP 5040	2079.3	2443.8	364.5	**5.36**	2477.6	3007.6	530.0	**6.68**	3027.0	3813.8	786.8	**9.00**
Molykote 1000 spray	1963.7	2358.2	394.5	**6.22**	2349.6	2872.0	522.4	**6.68**	2900.2	4183.8	1283.6	**10.10**
Microgleit HV-paste LP440	2814.6	3283.3	468.7	**6.23**	3455.4	4121.2	665.8	**6.89**	4632.4	5839.8	1207.4	**7.05**
System HR: M36x160 10.9												
Factory provided	3906.4	6505.9	2599.5	**16.35**	4620.7	7634.2	3013.5	**15.63**	6087.1	7578.1	1491.0	**6.30**
Gleitmo WSP 5040	2596.9	3402.5	805.6	**8.46**	2840.1	3849.6	1009.5	**9.92**	3894.2	6920.4	3026.2	**19.83**
Molykote 1000 spray	2506.3	3100.2	593.9	**6.81**	2782.3	3416.8	634.5	**6.83**	3739.7	5022.9	1283.2	**10.21**
Microgleit HV-paste LP440	3234.0	4160.7	926.7	**9.21**	3577.2	4623.6	1046.4	**9.45**	4785.4	6651.3	1865.9	**9.02**
System HV: M24x100 10.9												
Factory provided	541.6	694.3	152.7	**8.55**	816.9	1027.7	210.8	**8.48**	1052.2	1369.3	317.1	**7.57**
Gleitmo WSP 5040	605.0	699.6	94.6	**4.30**	844.8	971.1	126.3	**4.17**	1061.4	1257.0	195.6	**5.00**
Molykote 1000 spray	532.3	619.8	87.5	**5.39**	810.9	961.4	150.5	**5.66**	983.1	1266.0	282.9	**7.99**
Microgleit HV-paste LP440	614.5	714.6	100.1	**5.44**	945.5	1228.7	283.2	**8.55**	1340.0	1686.3	346.3	**7.47**
System HV: M36x160 10.9												
Factory provided	887.2	1247.4	360.2	**8.96**	2754.8	4568.9	1814.1	**12.54**	4223.0	6968.6	2745.6	**13.47**
Gleitmo WSP 5040	943.0	1029.7	86.7	**3.51**	2740.4	2997.8	257.4	**3.51**	3553.1	4938.2	1385.1	**11.71**
Molykote 1000 spray	821.1	959.5	138.4	**4.98**	2497.0	3297.7	800.7	**8.73**	3070.3	4247.7	1177.4	**10.64**
Microgleit HV-paste LP440	969.0	1249.1	280.1	**7.18**	3381.1	4538.9	1157.8	**9.58**	5142.6	6280.5	1137.9	**7.00**

When using the modified torque method according to DIN EN 1993-1-8/NA, it can be shown that $F_{p,C}$* is achieved mainly for M24x100 HR bolting assemblies in property class 8.8 and 10.9. However, the required preload level $F_{p,C}$* for M36x160 HR bolting assemblies in property class 8.8 and 10.9 are only partially achieved when using Gleitmo WSP 5040 and Molykote 1000 spray lubricants, and the factory provided and Microgleit HV-paste LP440 tested series failed completely. The modified torque method also shows inhomogeneous test results for HV bolting assemblies, the reduced preload $F_{p,C}$* is also only partially achieved.

The application of the modified combined method is only valid for bolting assemblies in property class 10.9 and all tested series of M24x100 HR 10.9 and M24x100 HV 10.9 HV achieved the required preload $F_{p,C}$*. However, the required preloading level $F_{p,C}$* for M36x160 HR 10.9 and M36x160 HV 10.9 bolting assemblies is again only partially achieved or failed completely, see Table 42. Best results among tested series were achieved when using Gleitmo WSP 5040 and Molykote 1000 spray lubricants.

Further evaluations should be done for each tested series and lubricants to determine the required tightening torques and additional angle of rotations, depending on the chosen modified tightening method. The scattering of tightening parameters must be considered as well as the maximum preload level to avoid overtightening of the bolting assemblies. For this reason, also limiting criteria must be defined to control the achieved level of preload and to avoid plastic deformations when re-use of the bolting assemblies is intended.

4 Conclusions

In some cases, there is a need for reuse of the bolts and/or the nuts. Preloading in the elastic range would offer the possibility for reusability of the assemblies or parts of them – implied that the bolts/nuts are not damaged due to the previous use.

For this reason, in this task existing preloading procedures (torque and combined method) were experimentally tested with the aim to specify specific parameters (lubrication, tightening steps etc.) in order to be able to achieve guaranteed preload levels in the elastic range with sufficient reliability. Thus, tightening tests acc. to EN ISO 16047 resp. EN 14399-2 were performed for HV and HR bolts, grade 10.9 and 8.8 of two bolt dimensions each: M24 and M36. Due to the fact that the main influencing parameter in the tightening process is the lubrication of the nut, various lubrication types were tested: Factory provided lubrication, Fuchs Lubritech Gleitmo WSP 5040, DOW Corning Molykote 1000 spray and Microgleit HV-paste LP440.

Considering the evaluation results acc. to EN 14399-3 (System HR) and EN 14399-4 (System HV), comparison between various lubrications leads to the following conclusions: In terms of HV bolting assemblies, best results were achieved with Gleitmo WSP 5040 and Molykote 1000 spray. The k-values at $F_{p,C}$ stand out due to low scatterings (0.12–0.16) and low coefficients of variation V_k. In terms of HR bolting assemblies, a distinction must be made between bolt dimension M24 and M36:

- For bolt dimension M24, every tested lubrication showed satisfactory test results, in addition to the factory provided bolting assemblies. k-class K1 and K2 are accomplished in each tested series with low coefficients of variation V_k (2.9–5.8%). Bolt fracture occurred only in one series, and only when turning off the hexagon nut after the end of the test procedure.
- For bolt dimension M36, k-class K2 failed in each tested series, while k-class K1 and other criteria acc. EN 14399-3:2015-04 were only partially accomplished. Bolt fracture occurred in nearly all tested HR M36 series. In this context, better tightening test results were achieved by using Molykote 1000 spray lubrication.

Additionally, the evaluation of the tightening tests for preloading procedures to achieve a reduced preload level in the elastic range of the bolt material with sufficient reliability are based on the German modified torque method and modified combined method according to DIN EN 1993-18/NA. The target level of preload for these tightening methods is $F_{p,C}^* = 0.7\, f_{yb}\, A_s$ and based on the 0.2 % remaining strain level of the bolt material instead of the ultimate stress level.

In case of the application of the modified torque method according to DIN EN 1993-1-8/NA, it can be seen that $F_{p,C}^*$ is achieved mainly for M24x100 HR bolting assemblies in property class 8.8 and 10.9. However, the required preload level $F_{p,C}^*$ for M36x160 HR bolting assemblies in property class 8.8 and 10.9 are only partially achieved when using Gleitmo WSP 5040 and Molykote 1000 spray lubricants, and the factory provided and Microgleit HV-paste LP440 tested series failed completely. The modified torque method also shows inhomogeneous test results for HV bolting assemblies, the reduced preload $F_{p,C}^*$ is also only partially achieved.

The application of the modified combined method is only valid for bolting assemblies in property class 10.9 and all tested series of M24x100 HR 10.9 and M24x100 HV 10.9 HV achieved the required preload $F_{p,C}^*$. Again, the required preload level $F_{p,C}^*$ for M36x160 HR 10.9 and M36x160 HV 10.9 bolting assemblies has been only partially achieved or failed completely, see Table 42. The best results were achieved when using Gleitmo WSP 5040 and Molykote 1000 spray lubricants.

Further evaluations should be done for each tested series and lubricants to determine the required tightening torques and additional angle of rotations, depending on the chosen modified tightening method. The scattering of tightening parameters must be considered as well as the maximum preload level to avoid overtightening of the bolting assemblies. For this reason, also limiting criteria must be defined to control the achieved level of preload and to avoid plastic deformations when re-use of the bolting assemblies is intended.

However, it must be highlighted that numerical investigations at the Institute for Metal and Lightweight Structures indicate local plasticizing already at specified preload $F_{p,C}$*, so it is particularly important to assess potential damages of pre-used bolting assemblies.

Essen, 30.03.2018

Univ.-Prof. Dr.-Ing. habil. Natalie Stranghöner

Christoph Abraham, B.Sc.

Dominik Jungbluth, M.Sc.

5 References

[1] EN 1090-2:2008+A1:2011, Execution of steel structures and aluminium structures - Part 2: Technical requirements for steel structures.

[2] EN ISO 16047:2013-01, Fasteners — Torque/clamp force testing (ISO 16047:2005 + Amd 1:2012).

[3] EN 14399-2:2015, High-strength structural bolting assemblies for preloading — Part 2: Suitability for preloading.

[4] DIN EN 1993-1-8/NA:2010-12, National Annex – Nationally determined parameters – Eurocode 3: Design of steel structures – Part 1-8: Design of joints.

[5] EN 15048-1:2007, Non-preloaded structural bolting assemblies - Part 1: General requirements

[6] EN 14399-1:2015, High-strength structural bolting assemblies for preloading - Part 1: General requirements

[7] EN 1993-1-8:2010-12, Eurocode 3: Design of steel structures — Part 1-8: Design of joints (EN 1993-1-8:2005 + AC:2009).

[8] EN 14399-3:2015, High-strength structural bolting assemblies for preloading – Part 3: System HR – Hexagon bolt and nut assemblies.

[9] EN 14399-4:2015, High-strength structural bolting assemblies for preloading – Part 4: System HV – Hexagon bolt and nut assemblies.

[10] EN ISO 4014:2011, Hexagon head bolts — Product grades A and B (ISO 4014:2011).

[11] EN ISO 4017:2014, Fasteners – Hexagon head screws — Product grades A and B (ISO 4017:2014).

[12] Schmidt, H.; Stranghöner, N. Ausführung geschraubter Verbindungen nach DIN EN 1090-2. In (Kuhlmann, U. Ed.): Stahlbau-Kalender 2011. Eurocode 3 - Grundnorm, Verbindungen. Ernst & Sohn GmbH & Co. KG, Berlin, 2011; pp. 283–340.

[13] Kindmann, R.; Vette, J. Merkblatt 322. Geschraubte Verbindungen im Stahlbau, 2012.

[14] EN ISO 898-1:2013, Mechanical properties of fasteners made of carbon steel and alloy steel – Part 1: Bolts, screws and studs with specified property classes – Coarse thread and fie pitch thread (ISO 898-1:2013).

[15] DIN EN 1993-1-8/NA:2010-12, National Annex – Nationally determined parameters – Eurocode 3: Design of steel structures – Part 1-8: Design of joints.

[16] bauforumstahl e.V. Arbeitshilfe 5.3. Ausführung von Stahlbauten - Geschraubte Verbindungen - Planmäßiges Vorspannen, 2013.

[17] Thomala, W.; Kloos, K.-H. Schraubenverbindungen. Grundlagen, Berechnung, Eigenschaften, Handhabung. Springer-Verlag, Berlin, Heidelberg, 2007.

[18] Abraham, Chr., Tightening behaviour of stainless steel bolting assemblies with regard to suitability as high strength structural bolting assemblies for preloading, Bachelor-Thesis, Institute for Metal and Lightweight Structures, University of Duisburg-Essen, 2016.

[19] VDI 2230:2015-11, Systematic calculation of highly stressed bolted joints Joints with one cylindrical bolt.

[20] Stranghöner, N.; Lorenz, C. Numerische Simulation des Anzieh-verhaltens von Schraubenverbindungen unter Berücksichtigung des plastischen Materialverhaltens: 20. DASt-Forschungskolloquium; pp. 101–106.

6 Annex A: Test protocols of HR 8.8/10.9 bolting assemblies

Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

M24 HR 8.8 - Test protocol

SIROCO - Tightening tests of HR bolting assemblies

Client / Customer	:	SIROCO
Date of reception	:	-
Date of testing	:	05.04.2016 M24x100 HR 8.8
Project	:	RFCS SIROCO WP 1 Task 1.5
Specification	:	According EN 14399-2 and EN ISO 16047
Operator	:	Christoph Abraham B.Sc., Dominik Jungbluth, M.Sc.
Number of assemblies tested	:	40
Designation of bolt	:	M24x100 HR 8.8
Marking of bolt	:	NF HR 8.8 H+15G GFD
Designation of nut	:	Hexagon nut HR M24
Marking of nut	:	HR 10 Z NF GFD
Designation of washer	:	Washer M24 HR
Marking of washer	:	NF H AP GFD
Coating / Surface finish	:	M24x100 - tZn
Ambient temperature	:	22,5 °C
Ambient relative humidity	:	39,0 %
Rotated component	:	Hexagon nut
Special testing conditions	:	Different lubrications used: Si_24_8_1-10: Factory provided lubrication Si_24_8_11-20: Gleitmo WSP 5040 Si_24_8_21-30: Molykote 1000 spray Si_24_8_31-40: Microgleit HV-paste LP440 Bolt fracture occured only in Microgleit HV-paste LP440 series with intended HR-bolting assemblies failure mode: Si_24_8_31: Partial rupture (threaded shank) Si_24_8_33: Total rupture (threaded shank) Si_24_8_37: Partial rupture (threaded shank) Si_24_8_38: Total rupture of bolt (threaded shank)

Test series: M24x100 HR 8.8 - Factory provided

Connecting element	:	M24x100 HR 8.8
Coating / Surface finish	:	M24x100 - tZn
Clamp length Σt	:	67,0 mm
Speed of tightening	:	2,0 1/min
Sensor F - T_{th}	:	SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ	:	SNo. 1024283 - 5000 Nm

Specific thread data:

Thread	Thread data	:	M 24 HV - IML	
d	Nominal diameter	:	24	mm
P	Pitch	:	3	mm
d_2	Pitch diameter	:	22,05	mm
d_o	Outer bearing surface diameter	:	38	mm
d_i	Inner bearing surface diameter	:	27,5	mm
D_b Calc	Bearing surface diameter	:	32,75	mm

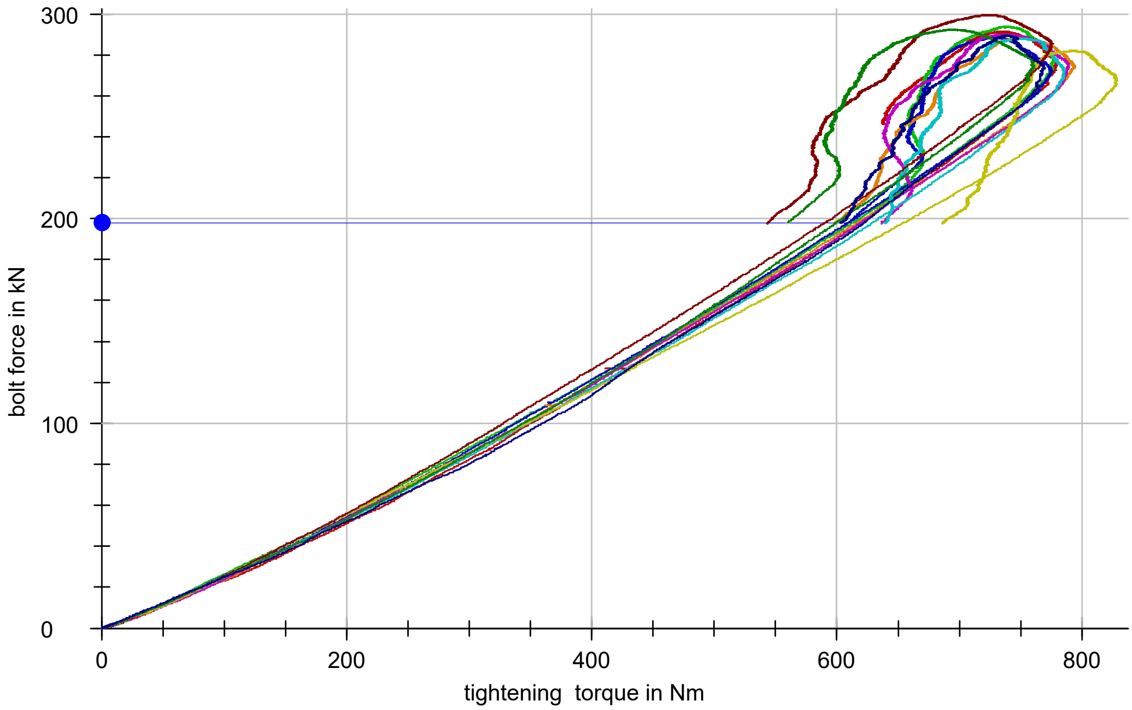
Results table: M24x100 HR 8.8 - Factory provided

Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		197,7	254,2						120	240	0,10	
	Si_24_HR_8.8-01	197,7	291,5	780,5	190	392	849	246,3	201	659	0,13	0,091
	Si_24_HR_8.8-02		293,9	778,1	185	395	967	197,7	209	782	0,13	0,090
	Si_24_HR_8.8-03		288,4	776,0	192	391	950	197,6	200	758	0,13	0,089
	Si_24_HR_8.8-04		288,4	794,5	169	368	1052	197,7	199	883	0,13	0,091
	Si_24_HR_8.8-05		290,0	789,9	164	379	1004	197,5	214	839	0,13	0,091
	Si_24_HR_8.8-06		287,9	786,5	174	376	1053	197,6	202	879	0,13	0,093
	Si_24_HR_8.8-07		282,2	829,1	190	393	997	197,7	203	807	0,14	0,097
	Si_24_HR_8.8-08		299,6	776,5	167	368	1074	197,6	201	907	0,12	0,086
	Si_24_HR_8.8-09		292,4	761,6	167	378	977	197,6	211	810	0,13	0,088
	Si_24_HR_8.8-10		289,5	769,6	235	434	1106	197,8	199	871	0,13	0,092

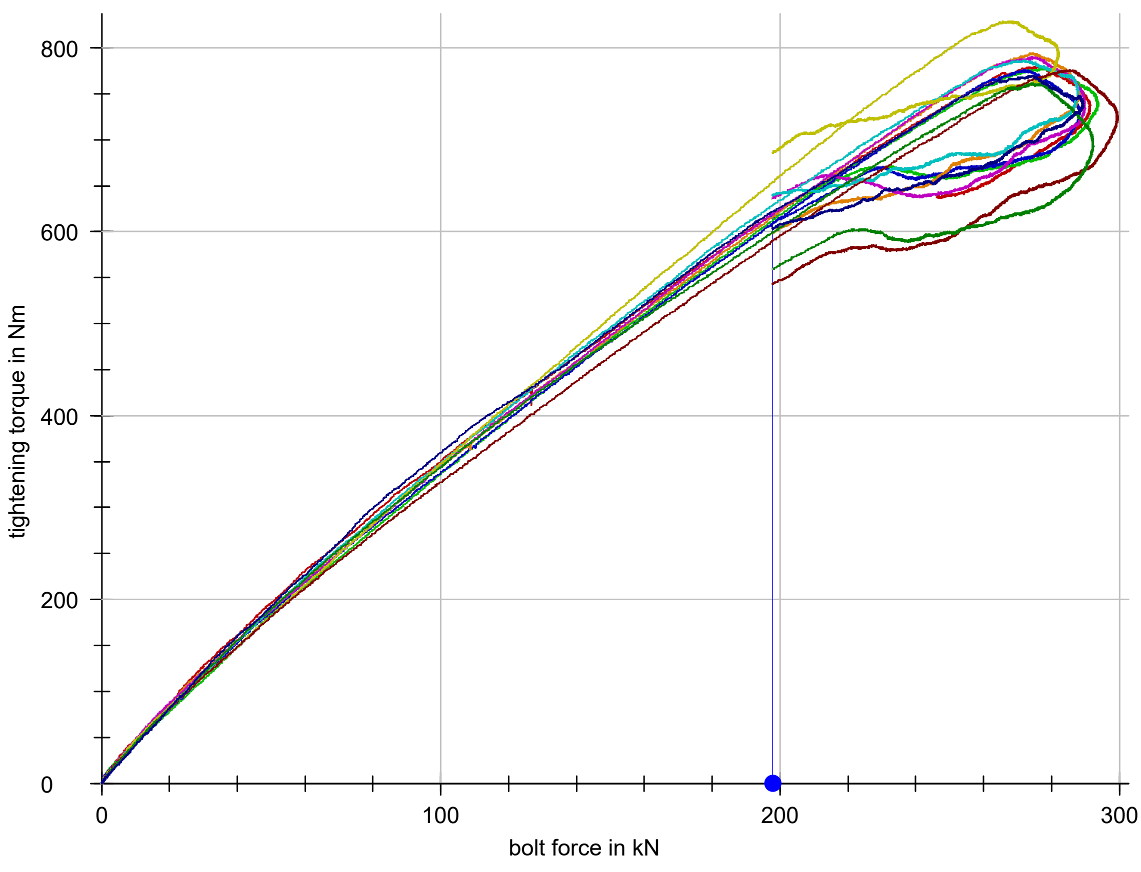
Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			158,1	0,095			
	0,096	0,087	158,1	0,136	618,0	514,3	737,6
	0,097	0,085		0,133	611,3	505,1	738,6
	0,104	0,078		0,133	607,6	502,8	731,8
	0,094	0,088		0,134	615,2	508,1	751,8
	0,096	0,088		0,134	618,9	510,1	734,3
	0,114	0,076		0,137	628,3	519,6	753,8
	0,119	0,080		0,140	653,2	532,3	792,8
	0,089	0,084		0,128	590,1	486,9	723,3
	0,091	0,085		0,132	598,1	499,8	692,5
	0,108	0,079		0,136	621,5	515,7	739,1

ANNEX A

bolt force-tightening torque-curves: M24x100 HR 8.8 - Factory provided

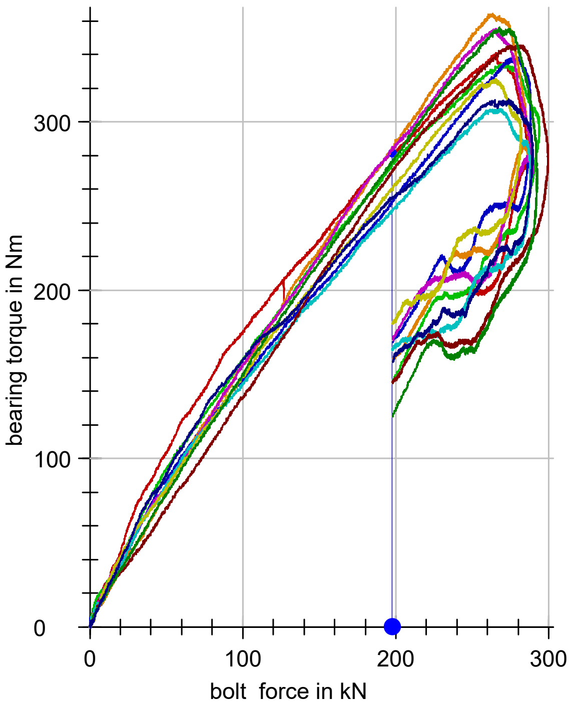


tightening torque-bolt force-curves: M24x100 HR 8.8 - Factory provided

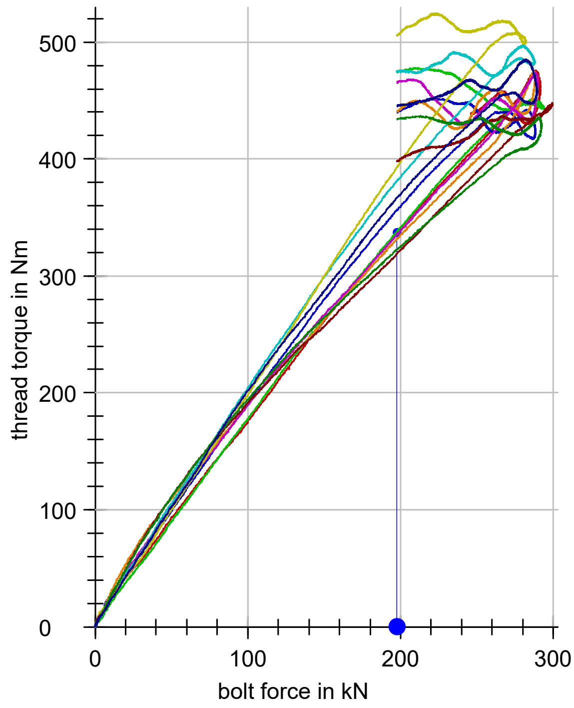


ANNEX A

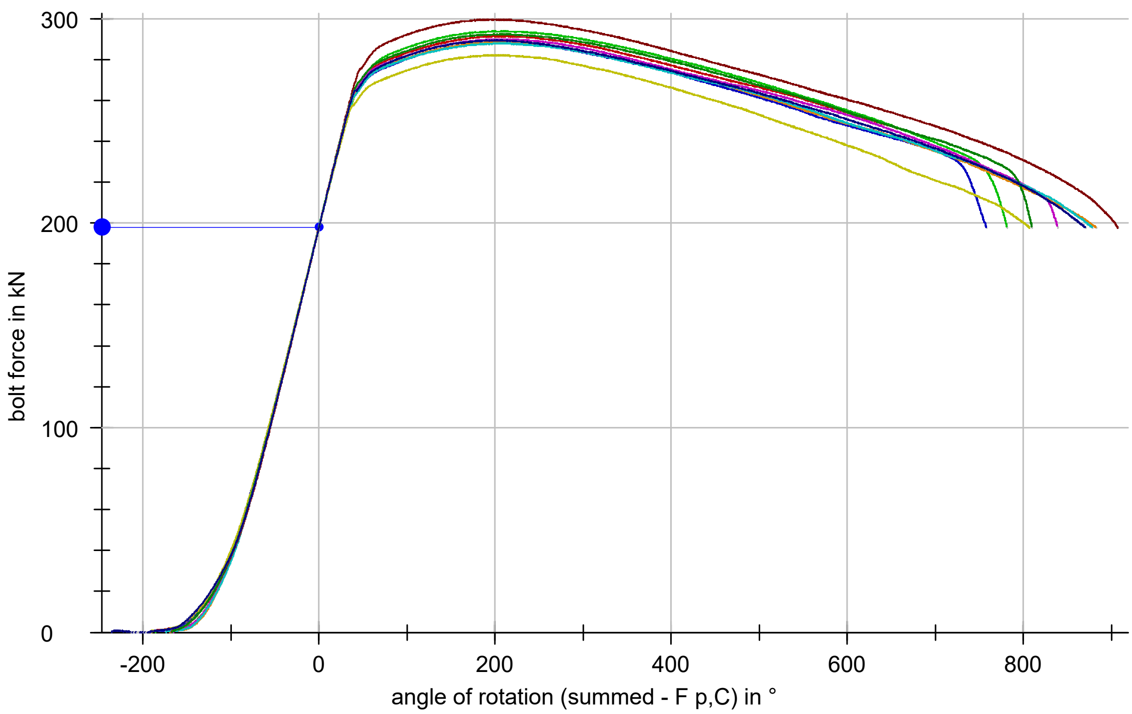
bearing torque-bolt force-curves: M24x100 HR 8.8 - Factory provided



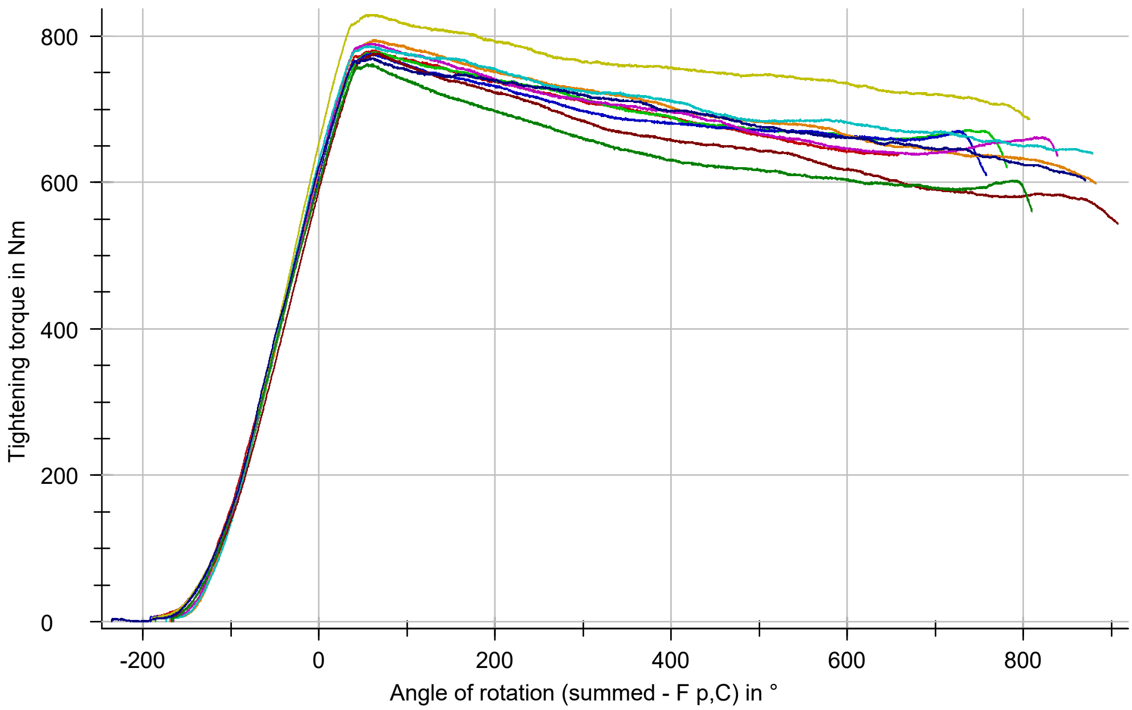
thread torque-bolt force-curves: M24x100 HR 8.8 - Factory provided



bolt force-angle of rotation-curves: M24x100 HR 8.8 - Factory provided



tightening torque-angle of rotation-curves: M24x100 HR 8.8 - Factory provided



ANNEX A

Test series: M24x100 HR 8.8 - Gleitmo WSP 5040

Connecting element	:	M24x100 HR 8.8
Coating / Surface finish	:	M24x100 - tZn
Clamp length Σt	:	67,0 mm
Speed of tightening	:	2,0 1/min
Sensor F - T_{th}	:	SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ	:	SNo. 1024283 - 5000 Nm

Specific thread data:

Thread	Thread data	:	M 24 HV - IML	
d	Nominal diameter	:	24	mm
P	Pitch	:	3	mm
d_2	Pitch diameter	:	22,05	mm
d_o	Outer bearing surface diameter	:	38	mm
d_i	Inner bearing surface diameter	:	27,5	mm
D_b Calc	Bearing surface diameter	:	32,75	mm

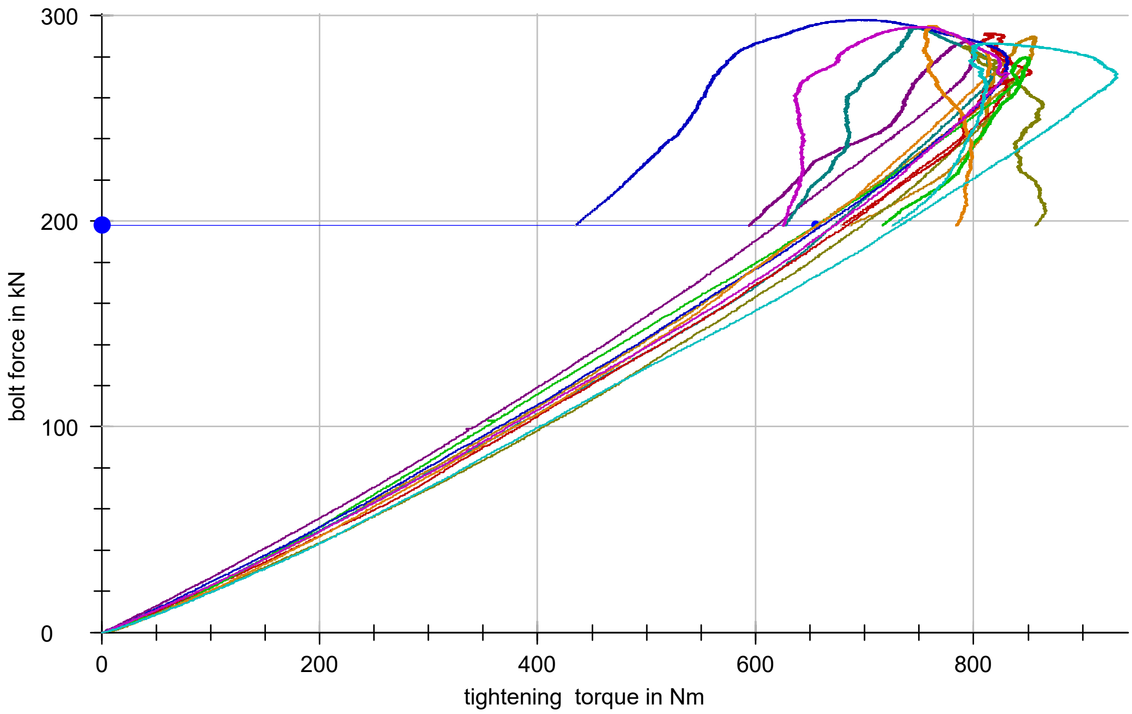
Results table: M24x100 HR 8.8 - Gleitmo WSP 5040

Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		197,7	254,2						120	240	0,10	
	Si_24_HR_8.8-11	197,7	289,7	858,2	178	353	780	197,6	174	602	0,14	0,097
	Si_24_HR_8.8-12		287,2	802,9	217	411	1103	197,6	194	885	0,13	0,091
	Si_24_HR_8.8-13		294,0	817,8	154	358	1012	197,7	203	858	0,14	0,100
	Si_24_HR_8.8-14		285,2	867,0	160	355	1005	197,7	195	844	0,15	0,105
	Si_24_HR_8.8-15		291,3	853,4	219	421	942	197,5	202	723	0,14	0,102
	Si_24_HR_8.8-16		279,7	851,9	216	389	931	197,6	173	715	0,14	0,098
	Si_24_HR_8.8-17		298,0	832,4	173	376	1057	197,7	203	884	0,14	0,098
	Si_24_HR_8.8-18		294,9	816,5	159	355	930	197,8	195	770	0,14	0,098
	Si_24_HR_8.8-19		294,6	832,9	160	354	1029	197,7	195	869	0,14	0,100
	Si_24_HR_8.8-20		286,6	932,2	180	375	678	197,5	196	498	0,15	0,111

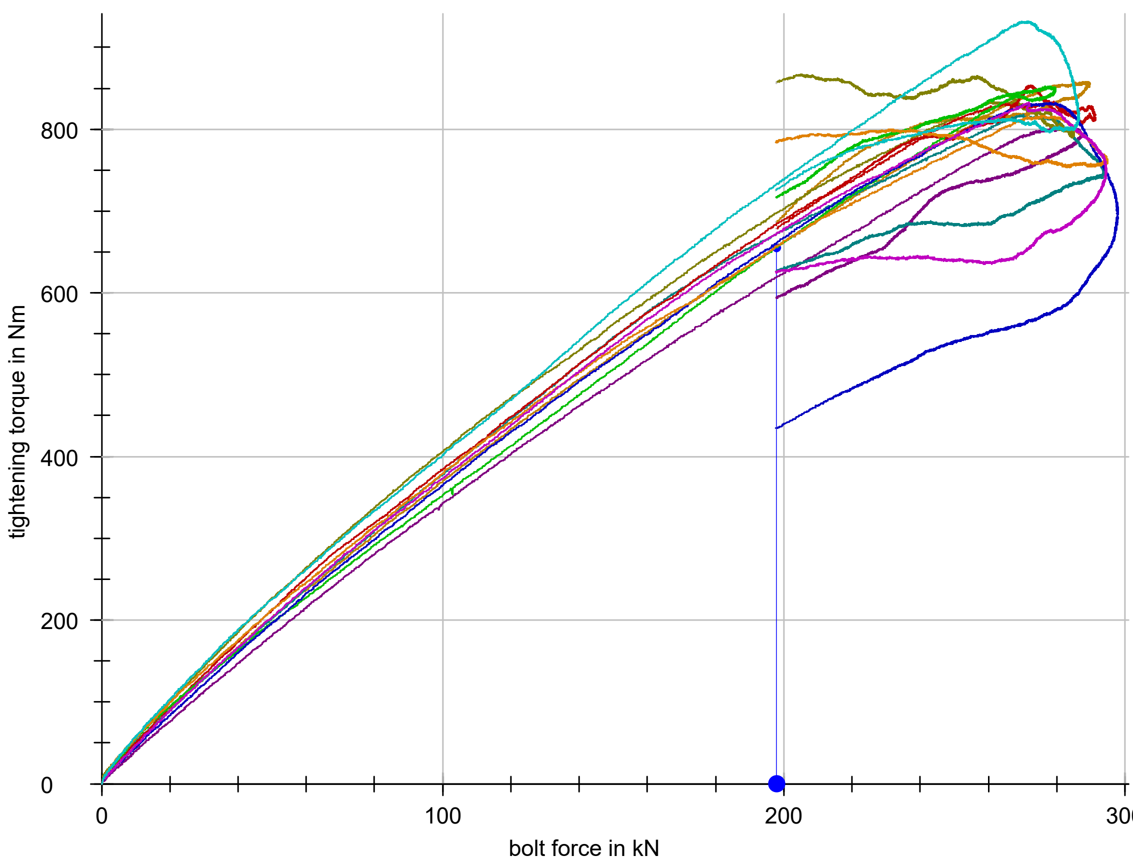
Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			158,1	0,095			
	0,118	0,081	158,1	0,144	655,0	547,4	855,5
	0,097	0,087		0,135	618,4	512,8	794,6
	0,111	0,092		0,150	671,4	569,4	749,2
	0,109	0,101		0,154	697,5	584,5	792,1
	0,111	0,095		0,150	682,8	570,1	813,1
	0,107	0,090		0,140	655,8	532,1	848,0
	0,100	0,097		0,143	659,9	543,3	702,4
	0,111	0,087		0,146	657,0	553,3	761,7
	0,109	0,094		0,148	671,2	560,9	752,6
	0,106	0,115		0,160	732,4	605,8	819,0

ANNEX A

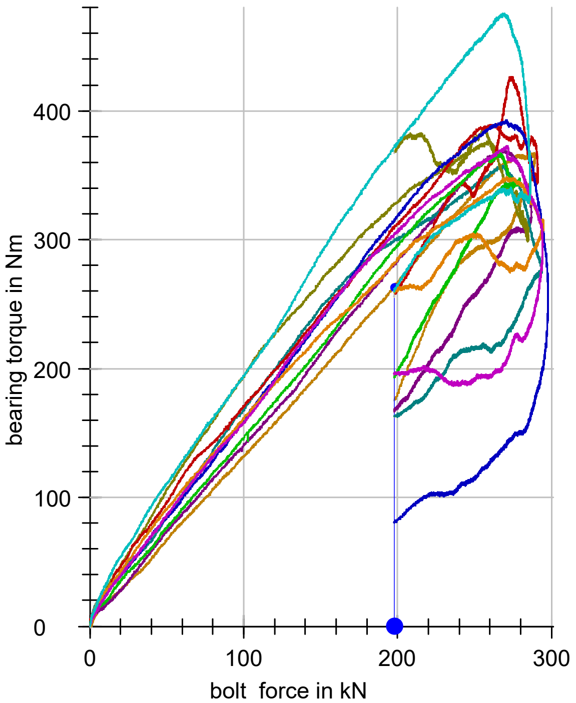
bolt force-tightening torque-curves: M24x100 HR 8.8 - Gleitmo WSP 5040



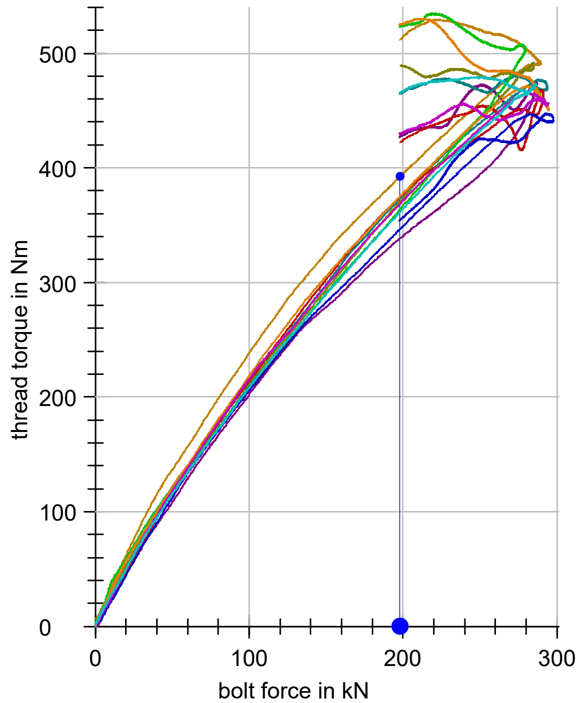
tightening torque-bolt force-curves: M24x100 HR 8.8 - Gleitmo WSP 5040



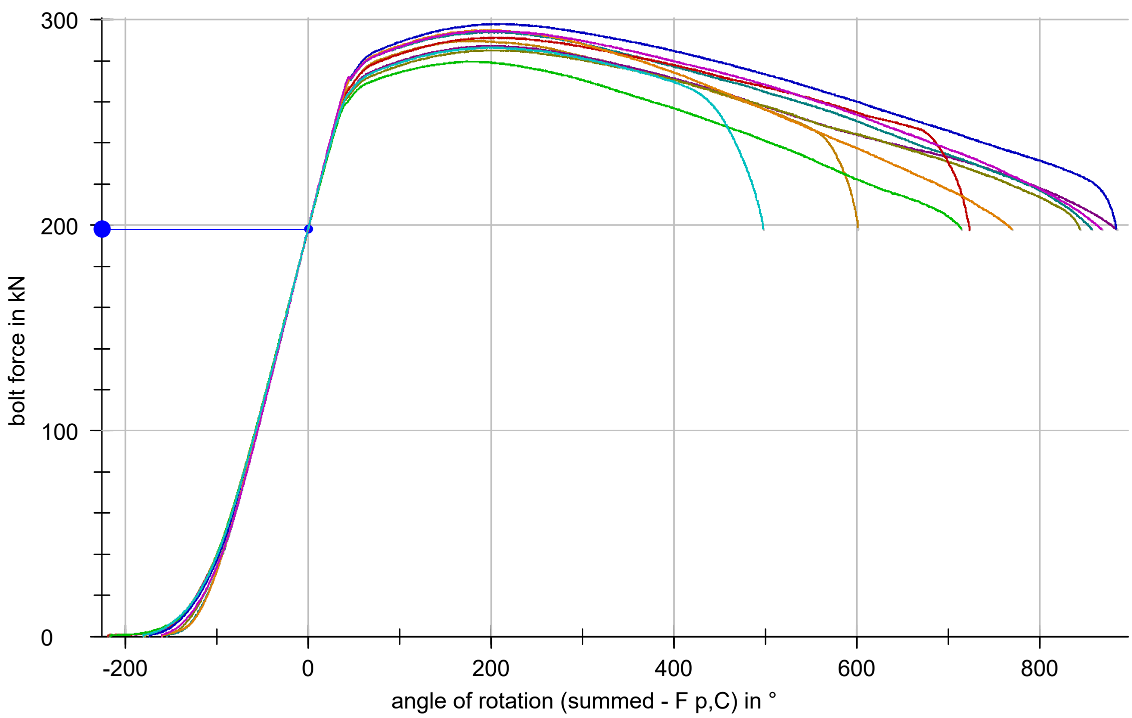
bearing torque-bolt force-curves: M24x100 HR 8.8 - Gleitmo WSP 5040



thread torque-bolt force-curves: M24x100 HR 8.8 - Gleitmo WSP 5040

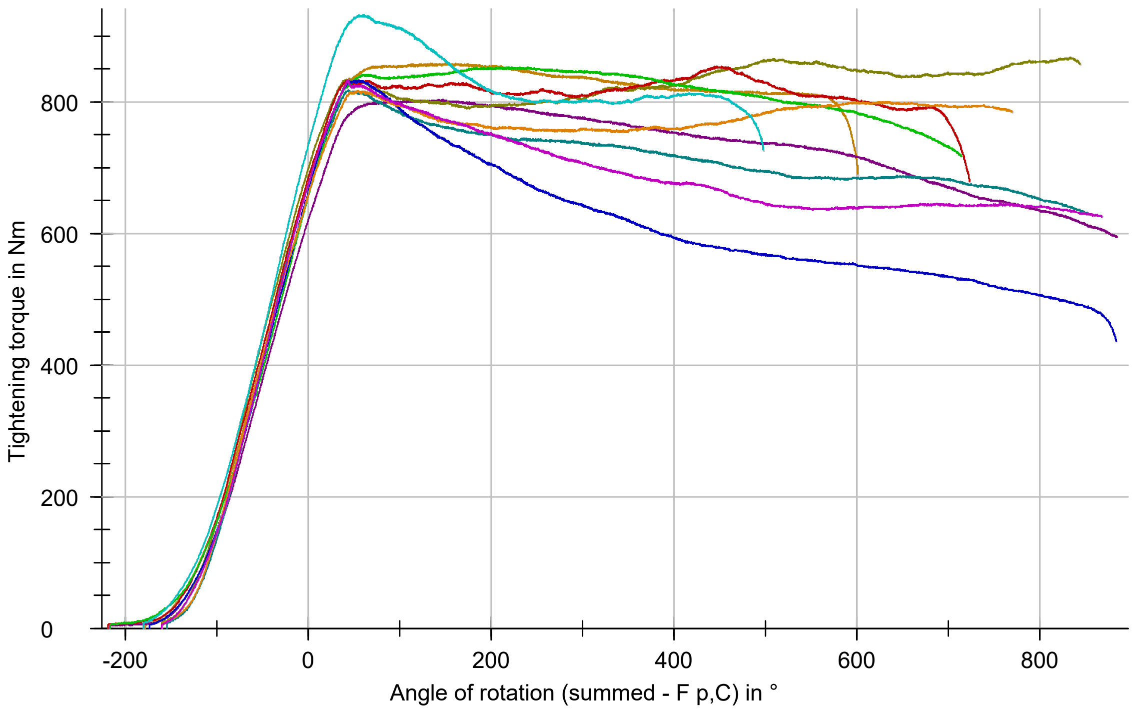


bolt force-angle of rotation-curves: M24x100 HR 8.8 - Gleitmo WSP 5040



Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

tightening torque-angle of rotation-curves: M24x100 HR 8.8 - Gleitmo WSP 5040



Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

Test series: M24x100 HR 8.8 - Molykote 1000 spray

Connecting element	:	M24x100 HR 8.8
Coating / Surface finish	:	M24x100 - tZn
Clamp length Σt	:	67,0 mm
Speed of tightening	:	2,0 1/min
Sensor F - T_{th}	:	SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ	:	SNo. 1024283 - 5000 Nm

Specific thread data:

Thread	Thread data	:	M 24 HV - IML	
d	Nominal diameter	:	24	mm
P	Pitch	:	3	mm
d_2	Pitch diameter	:	22,05	mm
d_o	Outer bearing surface diameter	:	38	mm
d_i	Inner bearing surface diameter	:	27,5	mm
D_b Calc	Bearing surface diameter	:	32,75	mm

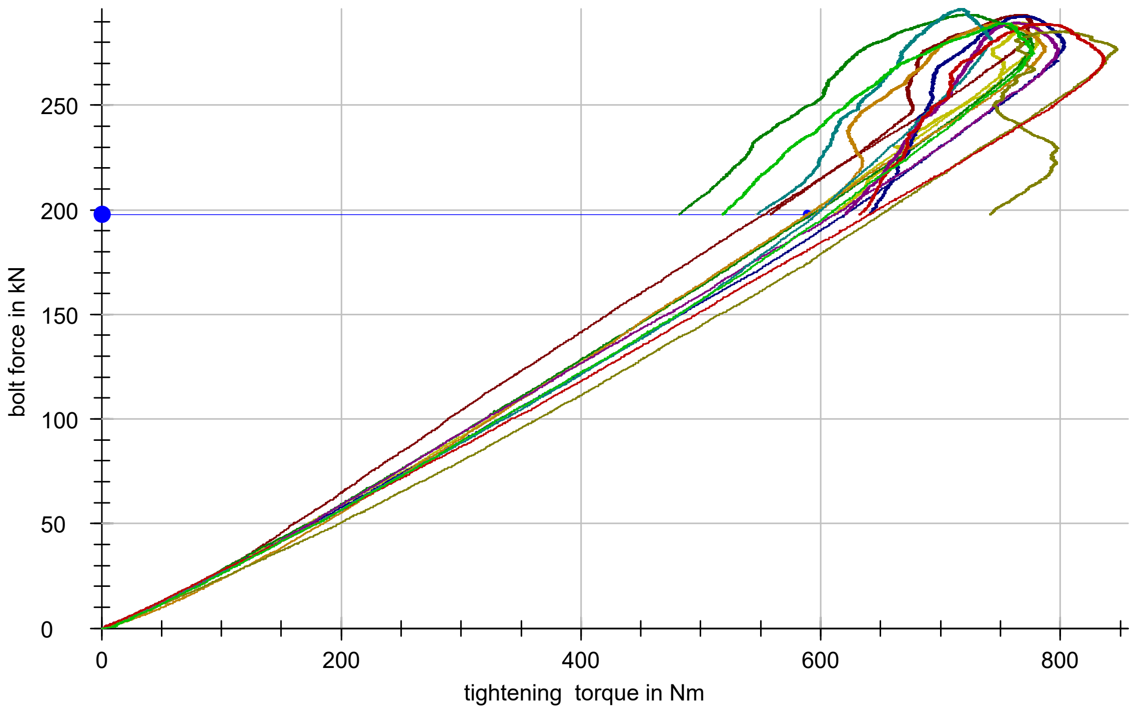
Results table: M24x100 HR 8.8 - Molykote 1000 spray

Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		197,7	254,2						120	240	0,10	
	Si_24_HR_8.8-21	197,7	289,5	783,4	217	416	1170	197,8	199	953	0,12	0,086
	Si_24_HR_8.8-22		293,3	777,0	171	379	842	197,5	208	670	0,12	0,080
	Si_24_HR_8.8-23		293,5	778,0	226	421	1117	197,6	195	891	0,12	0,087
	Si_24_HR_8.8-24		292,6	804,3	159	357	1048	197,8	197	889	0,13	0,091
	Si_24_HR_8.8-25		289,3	788,2	195	388	997	197,5	193	802	0,12	0,086
	Si_24_HR_8.8-26		289,5	799,2	214	405	1086	197,7	191	872	0,13	0,090
	Si_24_HR_8.8-27		296,0	743,1	233	438	1120	197,6	205	887	0,13	0,087
	Si_24_HR_8.8-28		285,6	847,8	170	372	1089	197,7	202	919	0,14	0,096
	Si_24_HR_8.8-29		289,0	837,5	235	440	1012	197,5	205	777	0,13	0,095
	Si_24_HR_8.8-30		289,4	778,5	208	401	1133	197,7	193	925	0,13	0,089

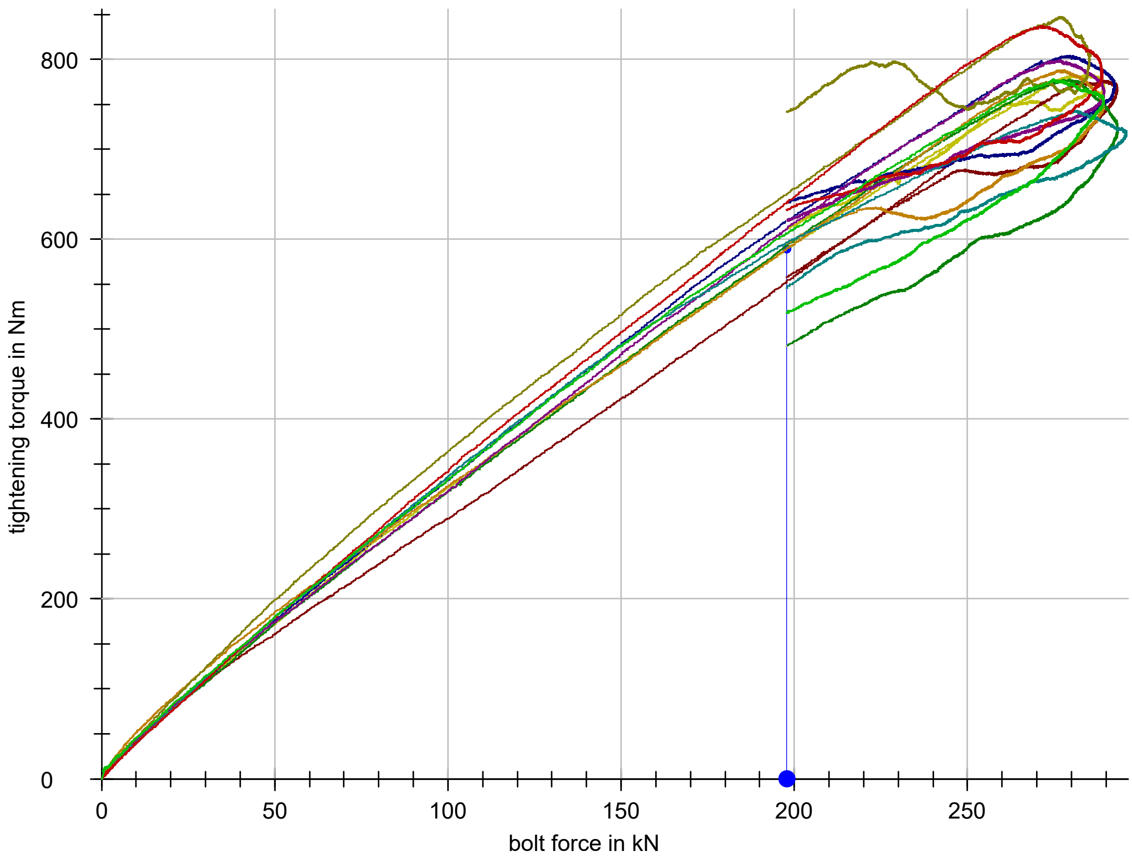
Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			158,1	0,095			
	0,083	0,088	158,1	0,128	588,4	484,5	768,5
	0,085	0,075		0,117	551,9	444,7	765,1
	0,091	0,083		0,128	592,6	485,2	722,6
	0,096	0,088		0,134	620,4	507,7	771,2
	0,092	0,081		0,127	588,6	482,1	748,5
	0,099	0,082		0,131	611,6	496,7	766,0
	0,100	0,078		0,132	596,2	502,6	715,3
	0,104	0,090		0,143	649,1	541,4	803,4
	0,103	0,089		0,137	640,0	520,6	781,9
	0,104	0,077		0,133	606,0	503,3	754,1

ANNEX A

bolt force-tightening torque-curves: M24x100 HR 8.8 - Molykote 1000 spray

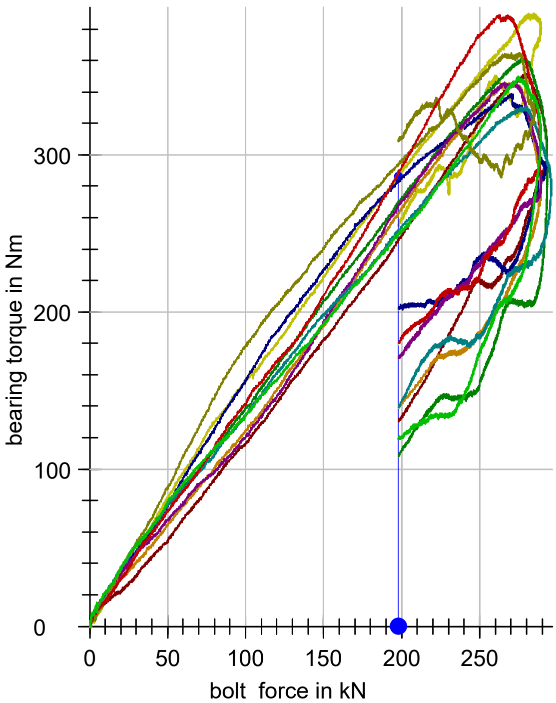


tightening torque-bolt force-curves: M24x100 HR 8.8 - Molykote 1000 spray

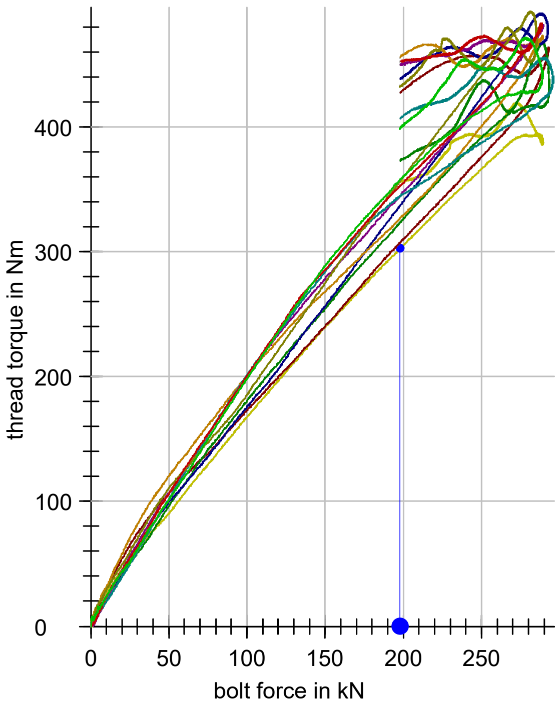


ANNEX A

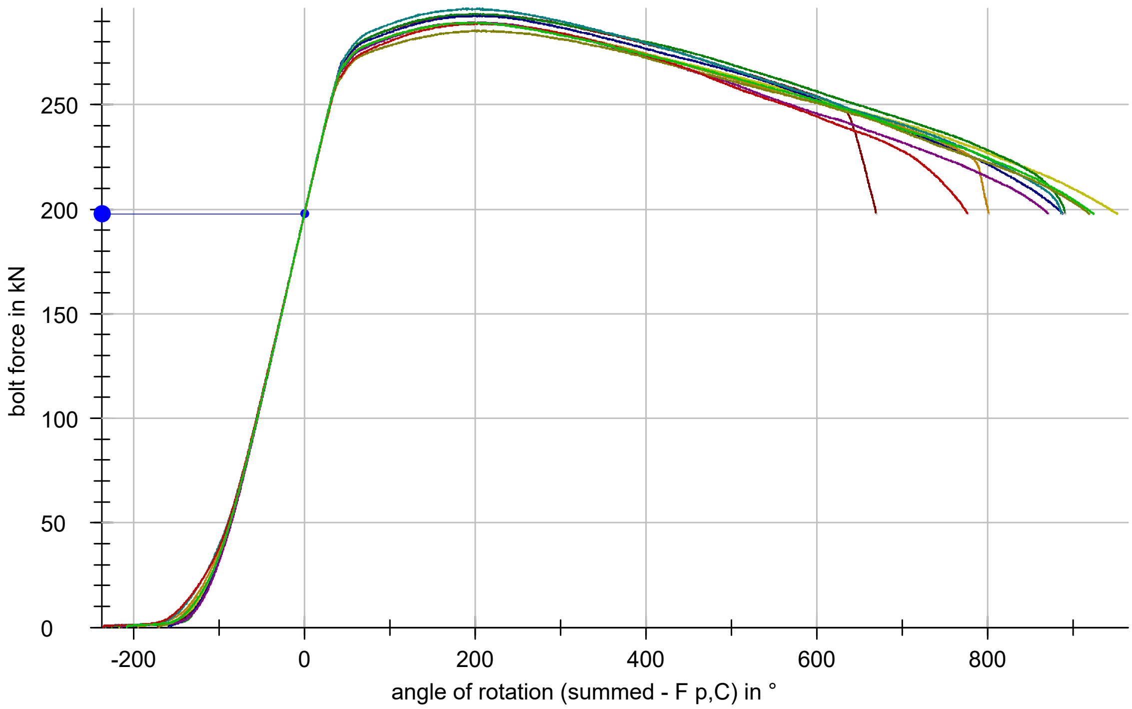
bearing torque-bolt force-curves: M24x100 HR 8.8 - Molykote 1000 spray



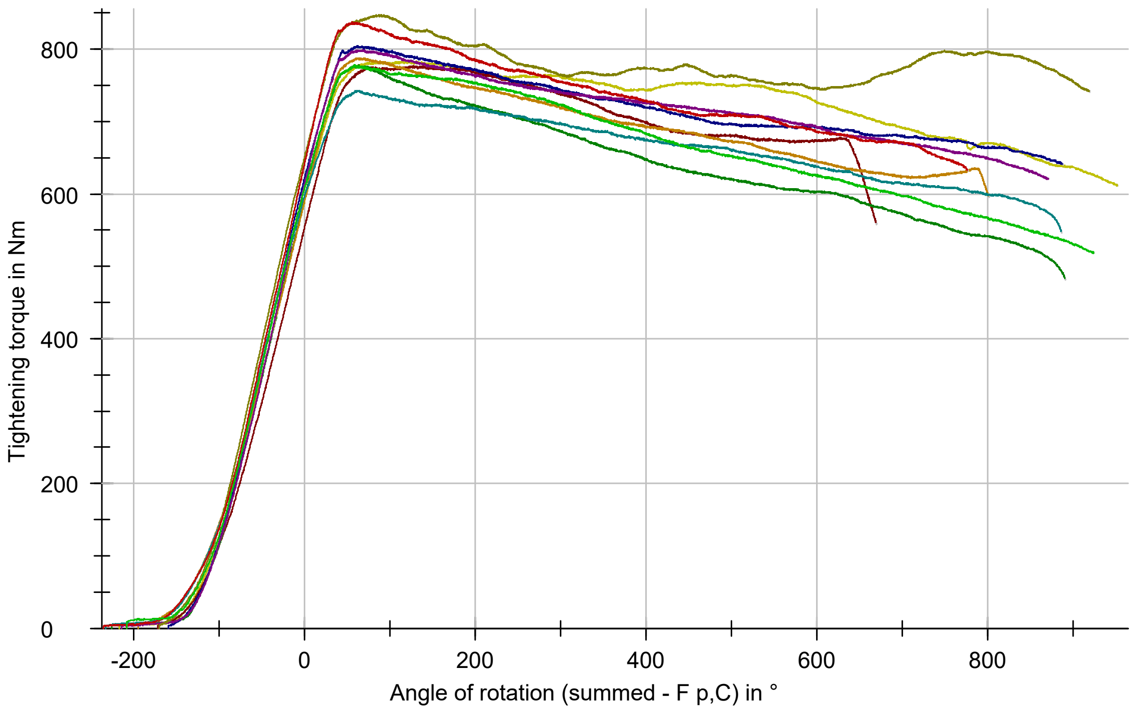
thread torque-bolt force-curves: M24x100 HR 8.8 - Molykote 1000 spray



bolt force-angle of rotation-curves: M24x100 HR 8.8 - Molykote 1000 spray



tightening torque-angle of rotation-curves: M24x100 HR 8.8 - Molykote 1000 spray



Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

Test series: M24x100 HR 8.8 - Microgleit HV-paste LP440

Connecting element	:	M24x100 HR 8.8
Coating / Surface finish	:	M24x100 - tZn
Clamp length Σt	:	67,0 mm
Speed of tightening	:	2,0 1/min
Sensor F - T_{th}	:	SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ	:	SNo. 1024283 - 5000 Nm

Specific thread data:

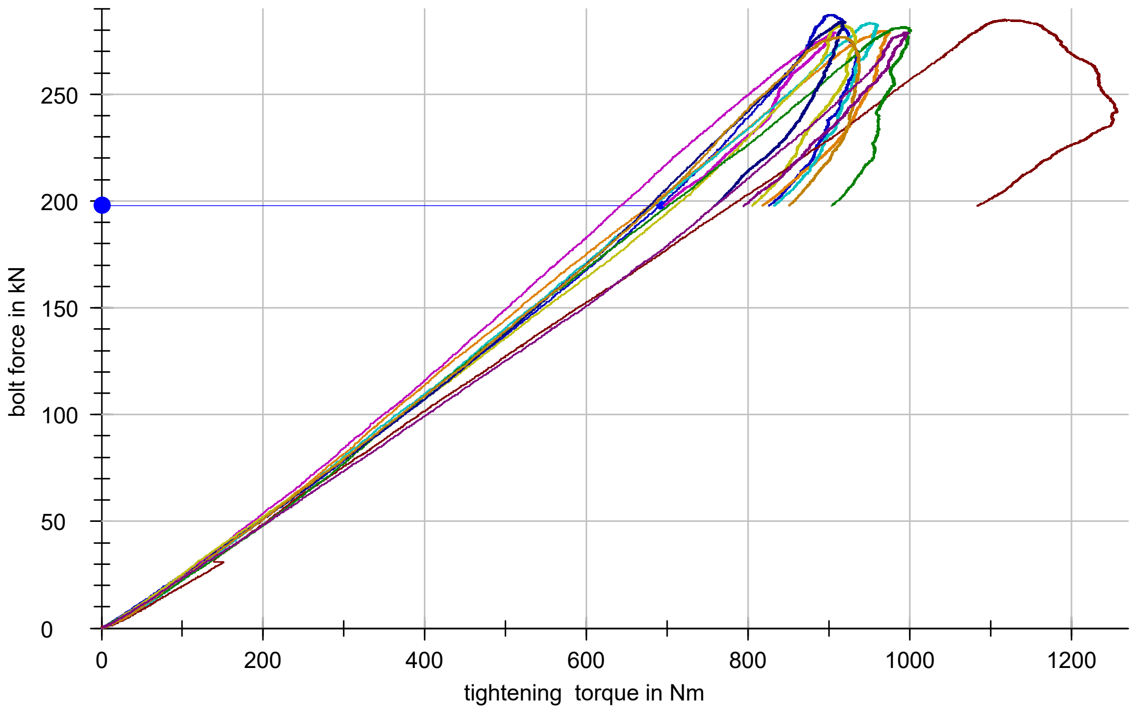
Thread	Thread data	:	M 24 HV - IML	
d	Nominal diameter	:	24	mm
P	Pitch	:	3	mm
d_2	Pitch diameter	:	22,05	mm
d_o	Outer bearing surface diameter	:	38	mm
d_i	Inner bearing surface diameter	:	27,5	mm
D_b Calc	Bearing surface diameter	:	32,75	mm

Results table: M24x100 HR 8.8 - Microgleit HV-paste LP440

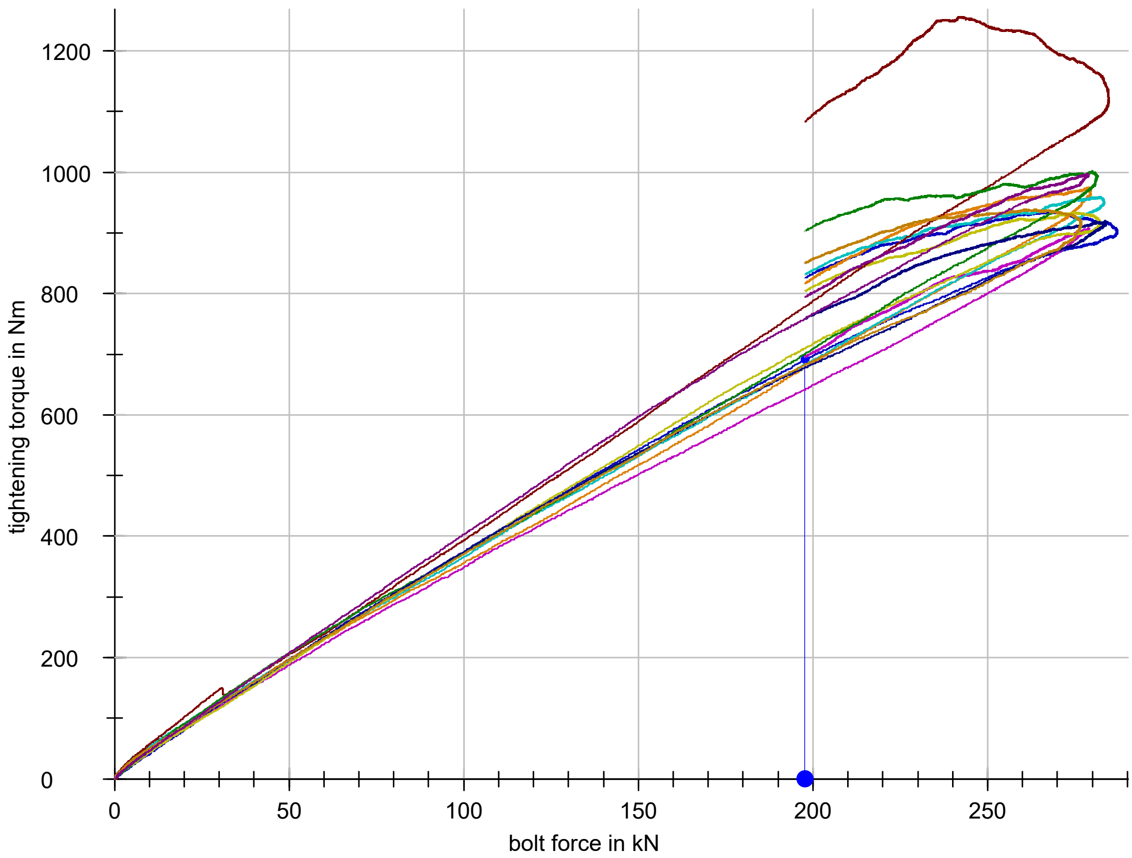
Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		197,7	254,2						120	240	0,10	
(blue)	Si_24_HR_8.8-31	197,7	287,3	935,4	179	345	931	197,7	166	753	0,15	0,104
(orange)	Si_24_HR_8.8-32		279,7	974,9	196	365	923	197,7	169	727	0,14	0,102
(magenta)	Si_24_HR_8.8-33		279,1	908,1	172	342	936	197,7	170	765	0,14	0,095
(cyan)	Si_24_HR_8.8-34		283,5	960,3	291	454	1034	197,8	162	742	0,14	0,102
(yellow)	Si_24_HR_8.8-35		282,3	933,7	172	337	869	197,6	164	697	0,15	0,107
(dark red)	Si_24_HR_8.8-36		284,8	1256,7	156	306	863	197,6	150	707	0,16	0,119
(green)	Si_24_HR_8.8-37		281,6	1001,5	176	334	858	197,6	159	682	0,15	0,105
(navy)	Si_24_HR_8.8-38		284,2	919,8	173	354	944	197,6	181	770	0,14	0,101
(ochre)	Si_24_HR_8.8-39		276,8	938,3	395	551	1079	197,7	156	684	0,14	0,102
(purple)	Si_24_HR_8.8-40		278,9	998,3	164	322	909	197,7	158	744	0,16	0,115

Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			158,1	0,095			
(blue)	0,108	0,100	158,1	0,150	691,0	568,7	900,5
(orange)	0,111	0,094		0,143	678,8	543,1	970,3
(magenta)	0,117	0,078		0,139	641,2	526,0	907,3
(cyan)	0,114	0,094		0,147	683,0	558,0	950,3
(yellow)	0,113	0,102		0,152	709,4	578,2	914,9
(dark red)	0,119	0,119		>0,164	777,6	622,9	1114,7
(green)	0,120	0,094		0,149	699,5	564,3	992,7
(navy)	0,120	0,087		0,148	677,8	560,9	917,3
(ochre)	0,110	0,097		0,148	683,5	562,6	912,7
(purple)	0,131	0,103		>0,165	758,0	626,8	993,7

bolt force-tightening torque-curves: M24x100 HR 8.8 - Microgleit HV-paste LP440

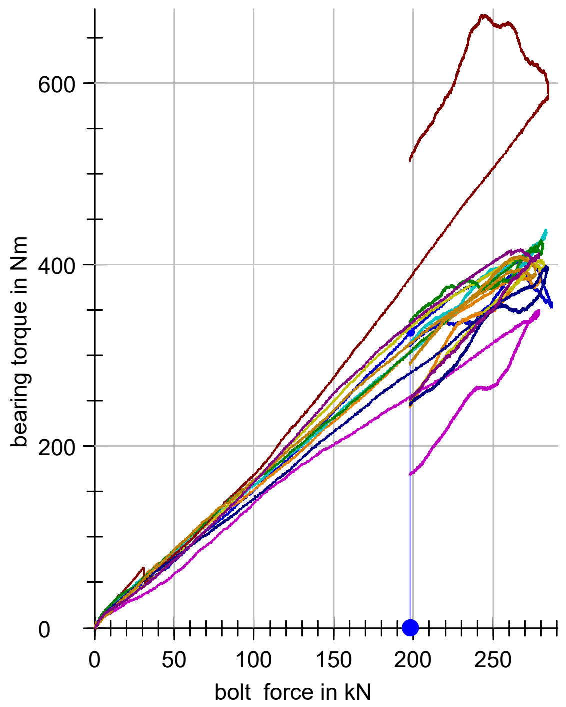


tightening torque-bolt force-curves: M24x100 HR 8.8 - Microgleit HV-paste LP440

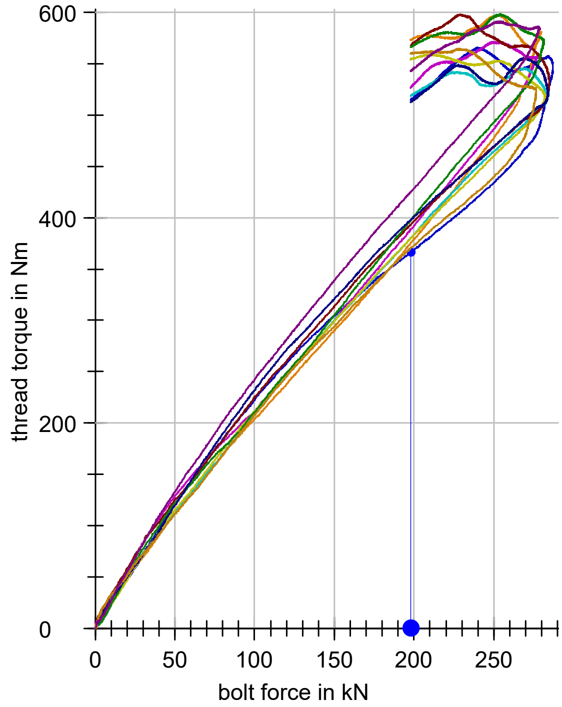


ANNEX A

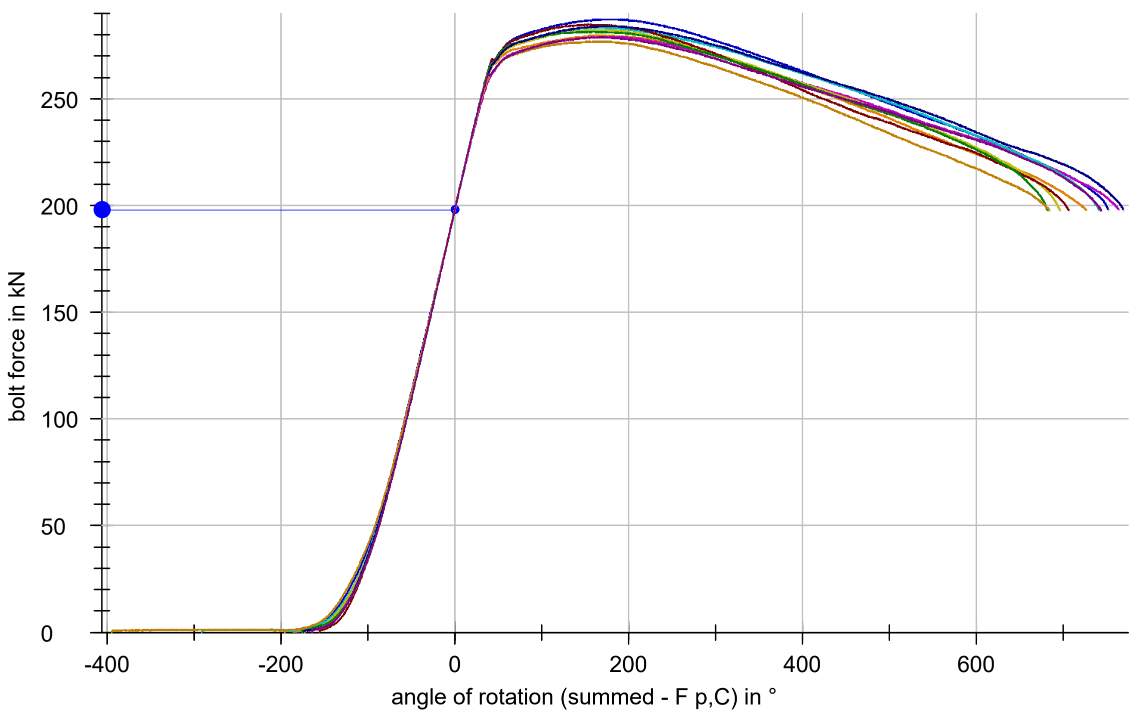
bearing torque-bolt force-curves: M24x100 HR 8.8 - Microgleit HV-paste LP440



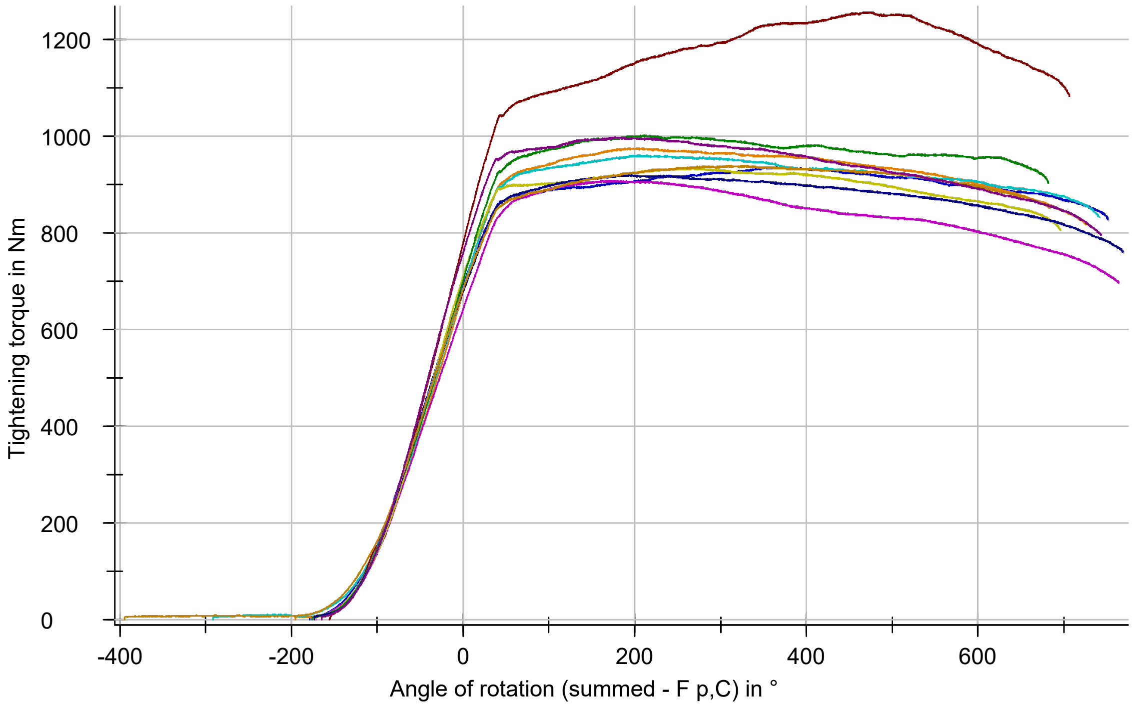
thread torque-bolt force-curves: M24x100 HR 8.8 - Microgleit HV-paste LP440



bolt force-angle of rotation-curves: M24x100 HR 8.8 - Microgleit HV-paste LP440



tightening torque-angle of rotation-curves: M24x100 HR 8.8 - Microgleit HV-paste LP440



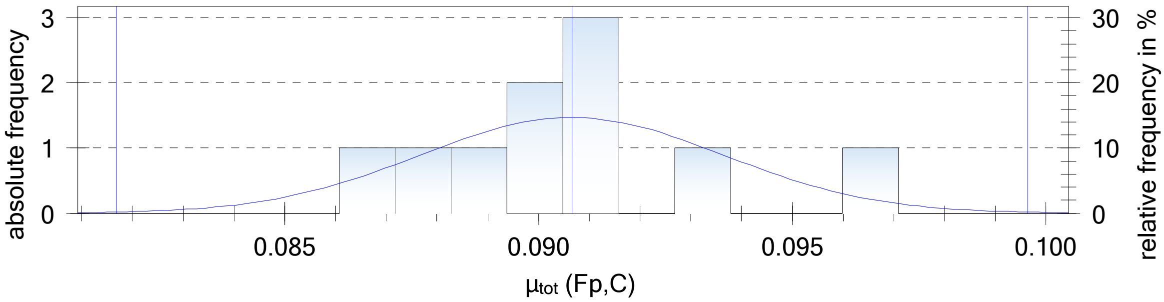
Statistical evaluation: M24x100 HR 8.8 - Factory provided

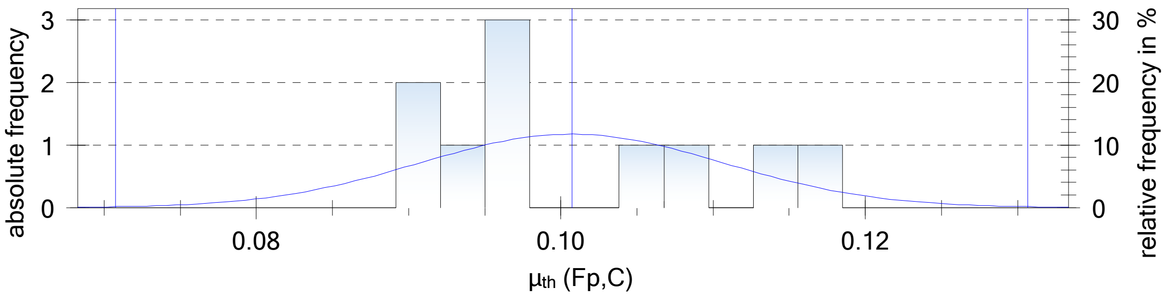
M24x100 HR 8.8 - Factory provided n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	299,6	829,1	235	434	1106	246,3	214	907	0,097
min	282,2	761,6	164	368	849	197,5	199	659	0,086
R	17,4	67,5	71	66	257	48,8	15	248	0,011
$\bar{x}$	290,4	784,2	183	387	1003	202,5	204	820	0,091
s	4,5	18,4	21	19	74	15,4	5	74	0,003
ν	1,56	2,35	11,55	4,97	7,36	7,60	2,65	9,05	3,28

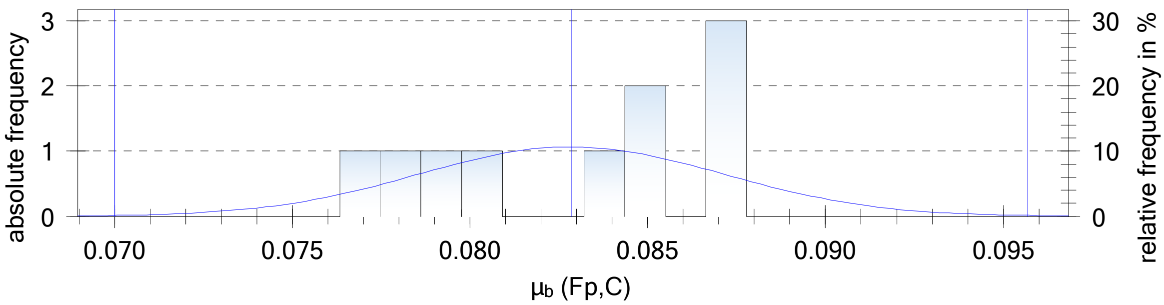
M24x100 HR 8.8 - Factory provided n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C*}$)	M ($F_{bi,max}$) Nm
max	0,119	0,088	653,2	0,14	532,3	0,140	792,8
min	0,089	0,076	590,1	0,12	486,9	0,128	692,5
R	0,030	0,012	63,1	0,02	45,4	0,012	100,3
$\bar{x}$	0,101	0,083	616,2	0,13	509,5	0,134	739,6
s	0,010	0,004	17,2	0,00	12,3	0,003	25,3
ν	9,97	5,30	2,79	3,63	2,41	2,41	3,42

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M24x100 HR 8.8 - Factory provided







Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

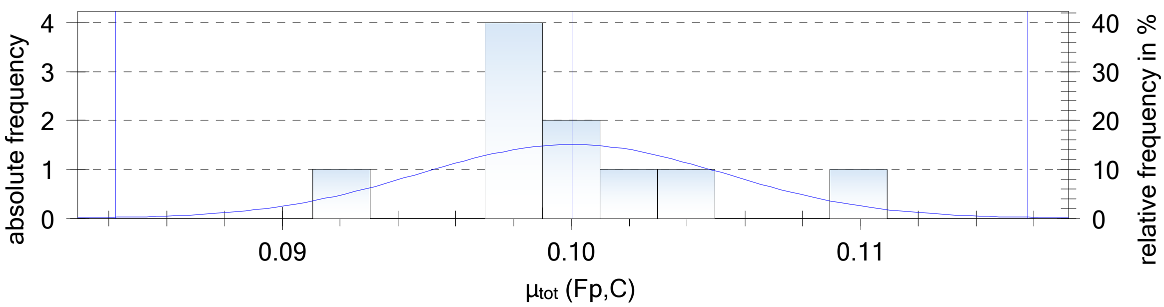
Statistical evaluation: M24x100 HR 8.8 - Gleitmo WSP 5040

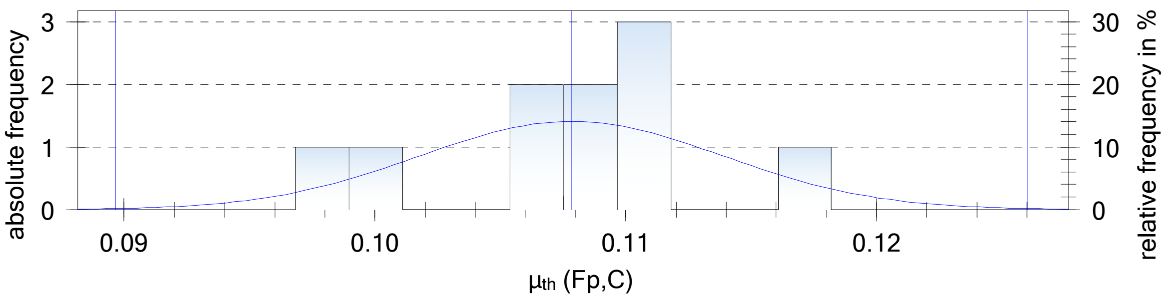
M24x100 HR 8.8 - Gleitmo WSP 5040 n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	298,0	932,2	219	421	1103	197,8	203	885	0,111
min	279,7	802,9	154	353	678	197,5	173	498	0,091
R	18,3	129,3	65	68	425	0,3	30	387	0,020
$\bar{x}$	290,1	846,5	182	375	947	197,6	193	765	0,100
s	5,5	36,5	26	25	130	0,1	11	132	0,005
ν	1,91	4,31	14,37	6,67	13,71	0,05	5,63	17,24	5,29

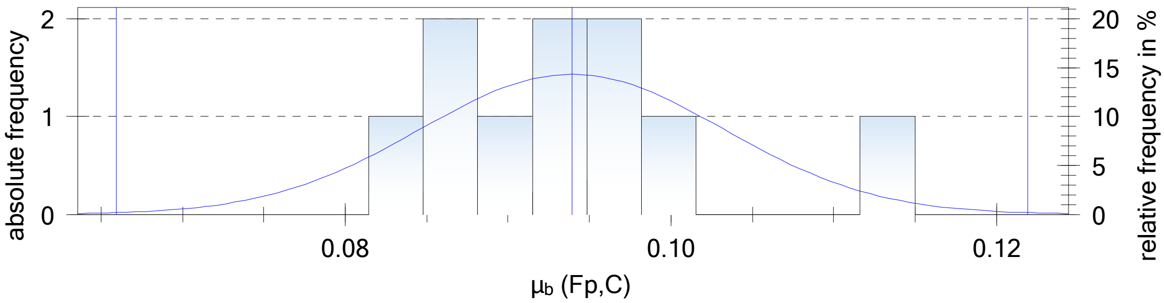
M24x100 HR 8.8 - Gleitmo WSP 5040 n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C*}$)	M ($F_{bi,max}$) Nm
max	0,118	0,115	732,4	0,15	605,8	0,160	855,5
min	0,097	0,081	618,4	0,13	512,8	0,135	702,4
R	0,021	0,034	114,0	0,02	93,0	0,025	153,1
$\bar{x}$	0,108	0,094	670,1	0,14	558,0	0,147	788,8
s	0,006	0,009	30,1	0,01	26,5	0,007	47,8
ν	5,52	9,96	4,50	4,03	4,76	4,84	6,06

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M24x100 HR 8.8 - Gleitmo WSP 5040







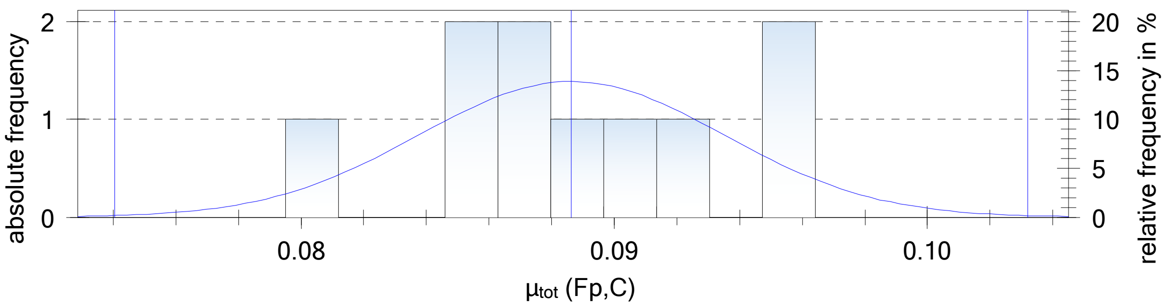
Statistical evaluation: M24x100 HR 8.8 - Molykote 1000 spray

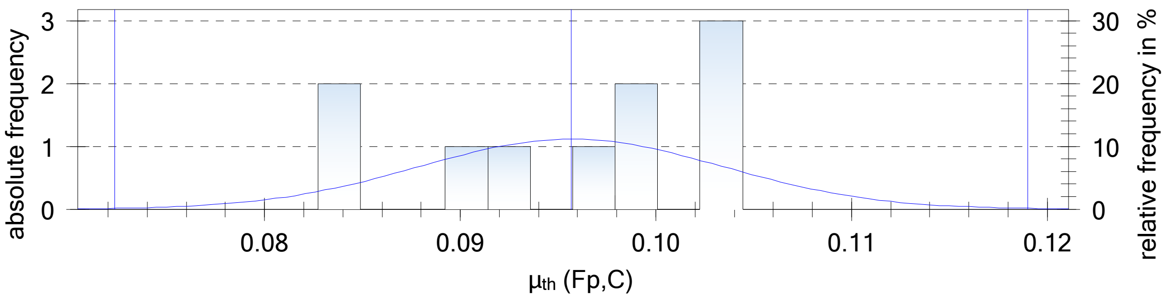
M24x100 HR 8.8 - Molykote 1000 spray n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	296,0	847,8	235	440	1170	197,8	208	953	0,096
min	285,6	743,1	159	357	842	197,5	191	670	0,080
R	10,4	104,7	76	83	328	0,3	17	283	0,016
$\bar{x}$	290,8	793,7	203	402	1061	197,6	199	859	0,089
s	3,0	30,6	28	28	94	0,1	6	85	0,005
ν	1,04	3,86	13,66	6,92	8,87	0,06	2,99	9,93	5,26

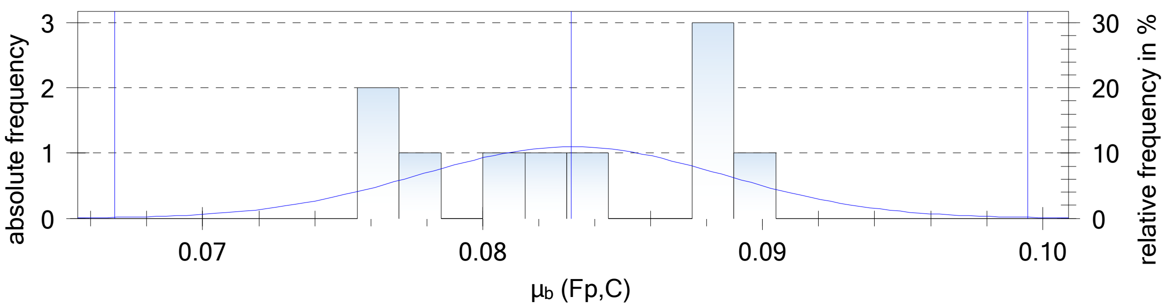
M24x100 HR 8.8 - Molykote 1000 spray n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C}$*)	M ($F_{bi,max}$) Nm
max	0,104	0,090	649,1	0,14	541,4	0,143	803,4
min	0,083	0,075	551,9	0,12	444,7	0,117	715,3
R	0,021	0,015	97,2	0,02	96,7	0,026	88,1
$\bar{x}$	0,096	0,083	604,5	0,13	496,9	0,131	759,7
s	0,008	0,005	28,0	0,01	25,7	0,007	26,2
ν	8,03	6,53	4,63	5,31	5,18	5,24	3,45

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M24x100 HR 8.8 - Molykote 1000 spray







Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

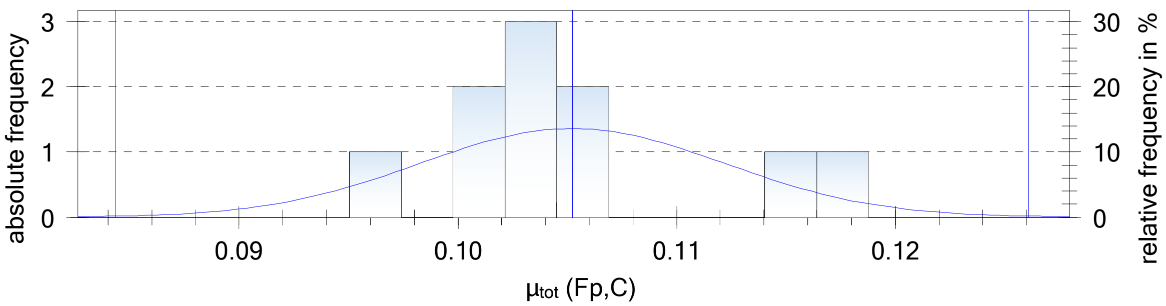
Statistical evaluation: M24x100 HR 8.8 - Microgleit HV-paste LP440

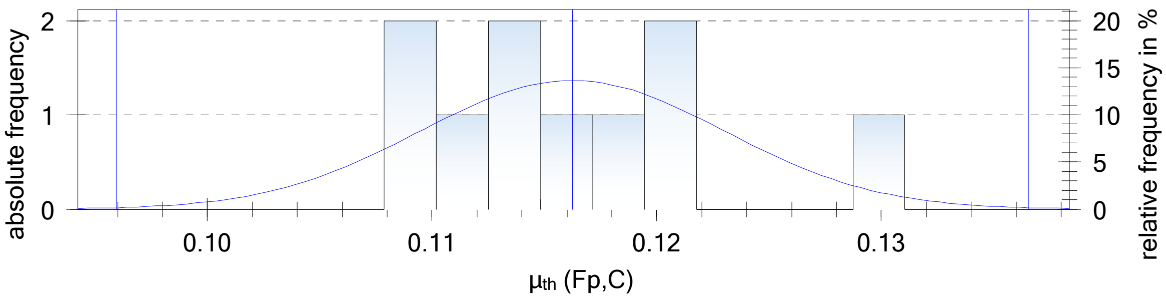
M24x100 HR 8.8 - Microgleit HV-paste LP440 n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	287,3	1256,7	395	551	1079	197,8	181	770	0,119
min	276,8	908,1	156	306	858	197,6	150	682	0,095
R	10,5	348,6	239	245	221	0,2	31	88	0,024
$\bar{x}$	281,8	982,7	207	371	935	197,7	164	727	0,105
s	3,2	101,3	76	75	72	0,1	9	33	0,007
ν	1,14	10,31	36,76	20,15	7,73	0,03	5,30	4,51	6,67

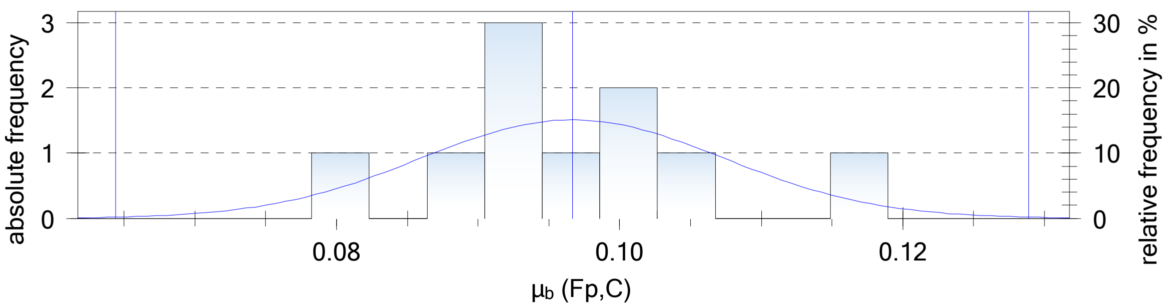
M24x100 HR 8.8 - Microgleit HV-paste LP440 n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C*}$)	M ($F_{bi,max}$) Nm
max	0,131	0,119	777,6	0,16	626,8	0,165	1114,7
min	0,108	0,078	641,2	0,14	526,0	0,139	900,5
R	0,023	0,041	136,4	0,02	100,8	0,026	214,2
$\bar{x}$	0,116	0,097	700,0	0,15	571,2	0,151	957,4
s	0,007	0,011	40,2	0,01	31,7	0,008	65,6
ν	5,76	11,11	5,74	5,60	5,55	5,47	6,85

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M24x100 HR 8.8 - Microgleit HV-paste LP440







ANNEX A

M24 HR 10.9 - Test protocol

SIROCO - Tightening tests of HR bolting assemblies

Client / Customer	:	SIROCO
Date of reception	:	-
Date of testing	:	06.04.2016 M24x100 HR 10.9
Project	:	RFCS SIROCO WP 1 Task 1.5
Specification	:	According EN 14399-2 and EN ISO 16047
Operator	:	Christoph Abraham B.Sc., Dominik Jungbluth M.Sc.
Number of assemblies tested	:	40
Designation of bolt	:	M24x100 HR 10.9
Marking of bolt	:	NF HR 10.9 H+1CJ GFD
Designation of nut	:	Hexagon nut HR M24
Marking of nut	:	HR 10 Z NF GFD F
Designation of washer	:	Washer M24 HR
Marking of washer	:	NF H AP GFD
Coating / Surface finish	:	M24x100 - tZn
Ambient temperature	:	23,6 °C
Ambient relative humidity	:	25,8 %
Rotated component	:	Hexagon nut
Special testing conditions	:	Different lubrications used: Si_24_10_1-10: Factory provided lubrication Si_24_10_11-20: Gleitmo WSP 5040 Si_24_10_21-30: Molykote 1000 spray Si_24_10_31-40: Microgleit HV-paste LP440 No bolt fracture in all tested series.

Test specimens identification

Si_xx_yy_zz

Si: RFCS SIROCO
xx: thread
yy: strength class
zz: sequential number of bolt

Test series: M24x100 HR 10.9 - Factory provided

Connecting element	:	M24x100 HR 10.9
Coating / Surface finish	:	M24x100 - tZn
Clamp length Σt	:	67,0 mm
Speed of tightening	:	2,0 1/min
Sensor F - T_{th}	:	SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ	:	SNo. 1024283 - 5000 Nm

Specific thread data:

Thread	Thread data	:	M 24 HV - IML	
d	Nominal diameter	:	24	mm
P	Pitch	:	3	mm
d_2	Pitch diameter	:	22,05	mm
d_o	Outer bearing surface diameter	:	38	mm
d_i	Inner bearing surface diameter	:	27,5	mm
D_b Calc	Bearing surface diameter	:	32,75	mm

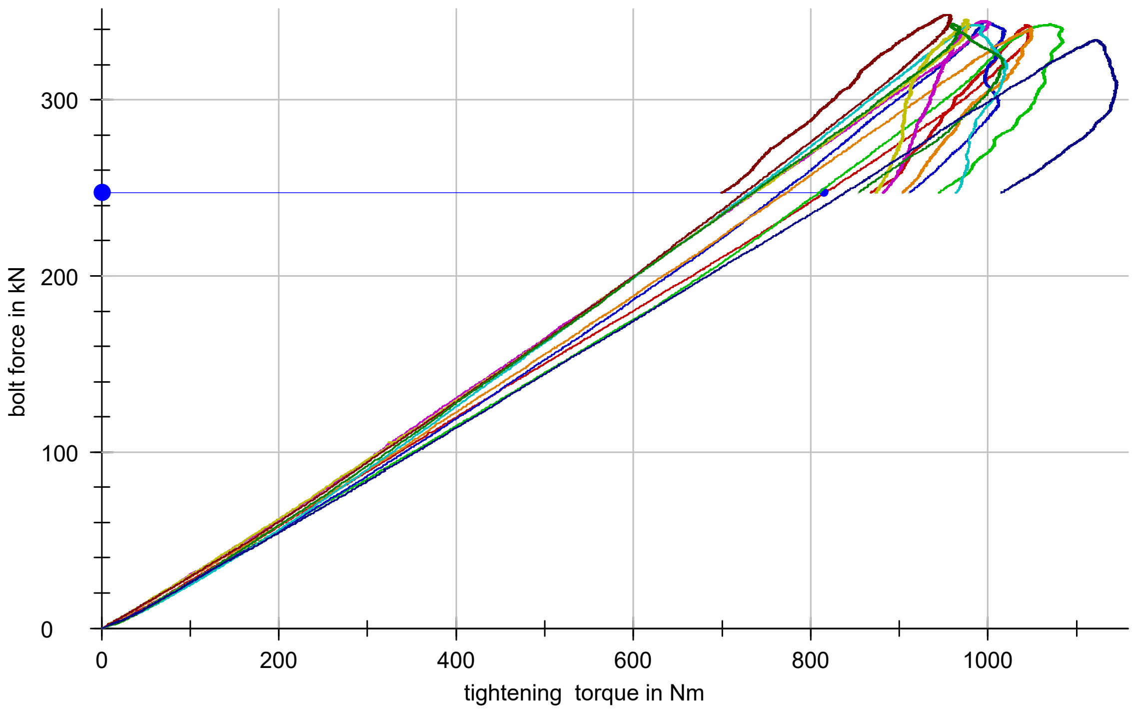
Results table: M24x100 HR 10.9 - Factory provided

Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		247,1	317,7						120	240	0,10	
	Si_24_HR_10.9-01	247,1	342,7	1049,0	176	351	893	247,1	175	718	0,14	0,097
	Si_24_HR_10.9-02		343,0	1085,3	186	341	844	247,0	155	658	0,14	0,096
	Si_24_HR_10.9-03		344,5	1019,7	180	357	716	247,1	177	536	0,13	0,090
	Si_24_HR_10.9-04		340,6	1051,2	213	384	925	247,0	171	712	0,13	0,091
	Si_24_HR_10.9-05		344,8	1003,1	209	393	924	247,0	184	715	0,12	0,086
	Si_24_HR_10.9-06		342,8	1021,9	177	334	568	246,9	156	391	0,12	0,085
	Si_24_HR_10.9-07		345,7	979,4	205	379	909	247,0	174	704	0,12	0,086
	Si_24_HR_10.9-08		348,4	959,4	196	373	1032	247,0	177	836	0,12	0,084
	Si_24_HR_10.9-09		343,3	1018,5	169	333	541	246,9	164	373	0,12	0,086
	Si_24_HR_10.9-10		334,0	1146,3	218	365	784	247,0	148	566	0,14	0,100

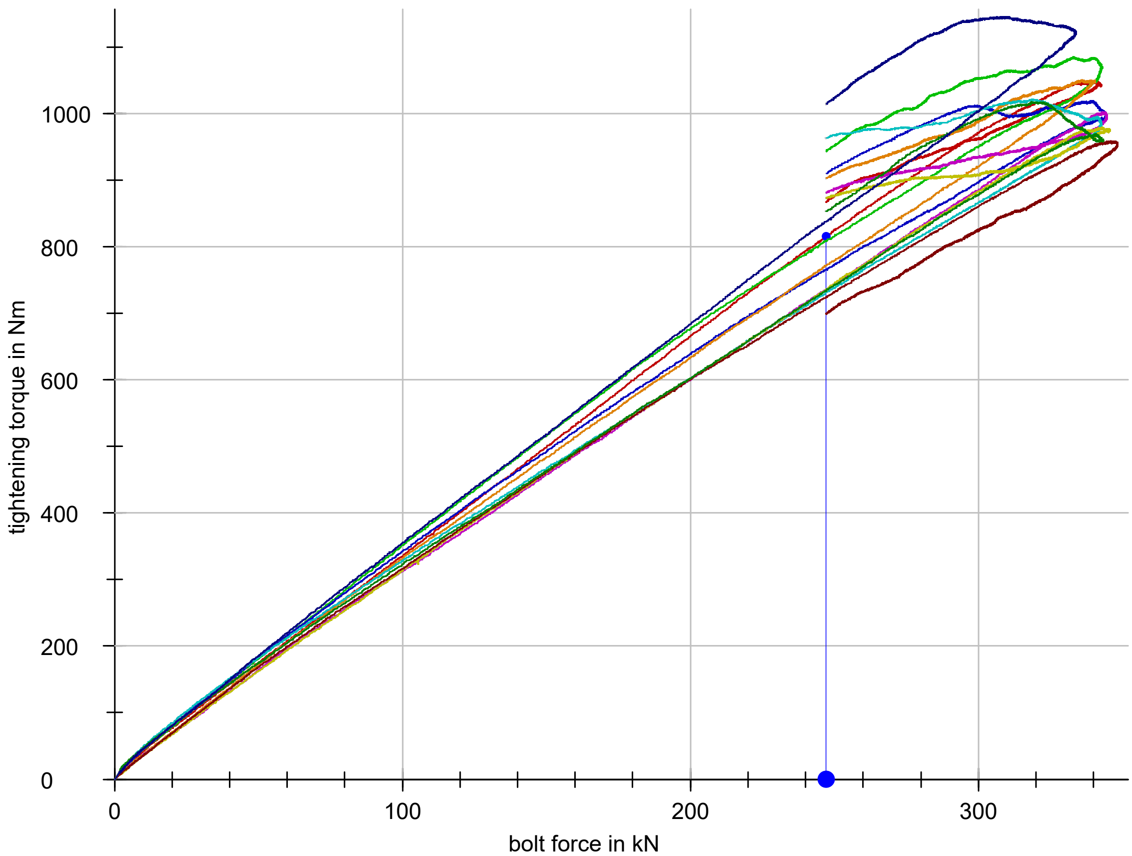
Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			222,4	0,095			
	0,112	0,085	222,4	0,138	815,0	738,3	1042,4
	0,107	0,088		0,139	808,8	742,0	1068,7
	0,103	0,080		0,132	765,8	703,0	999,2
	0,109	0,077		0,131	772,3	699,1	1049,0
	0,099	0,076		0,125	736,6	665,1	995,5
	0,101	0,073		0,125	731,3	665,4	983,8
	0,109	0,068		0,125	736,1	665,0	975,3
	0,098	0,074		0,124	724,9	659,3	957,0
	0,100	0,074		0,125	733,6	665,9	960,6
	0,129	0,077		0,142	837,5	757,9	1120,9

ANNEX A

bolt force-tightening torque-curves: M24x100 HR 10.9 - Factory provided



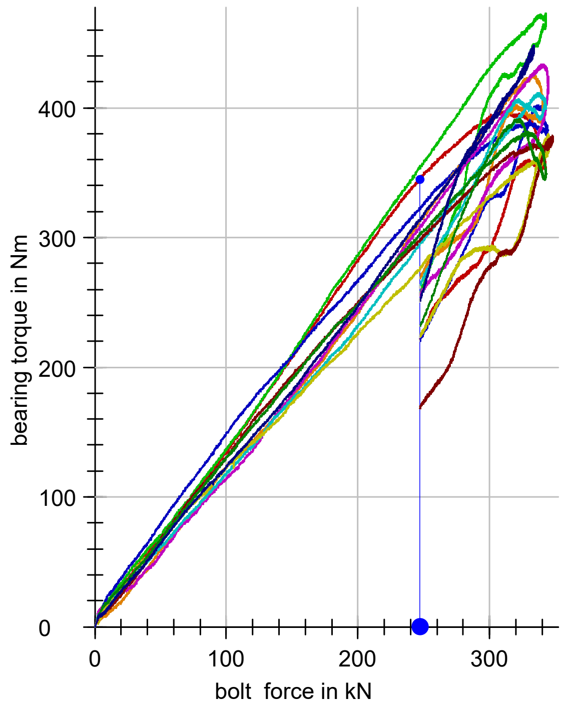
tightening torque-bolt force-curves: M24x100 HR 10.9 - Factory provided



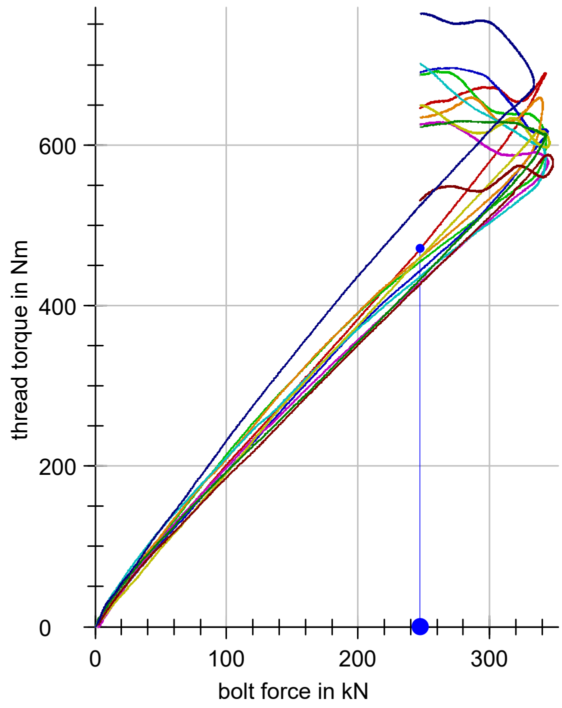
Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

ANNEX A

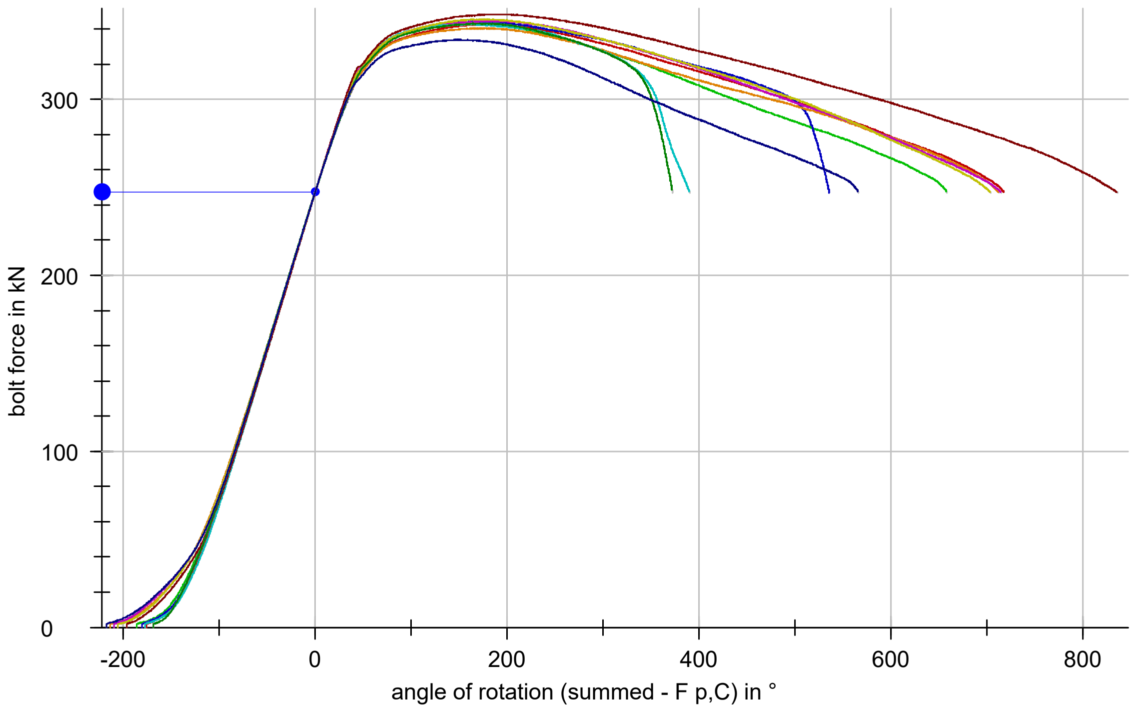
bearing torque-bolt force-curves: M24x100 HR 10.9 - Factory provided



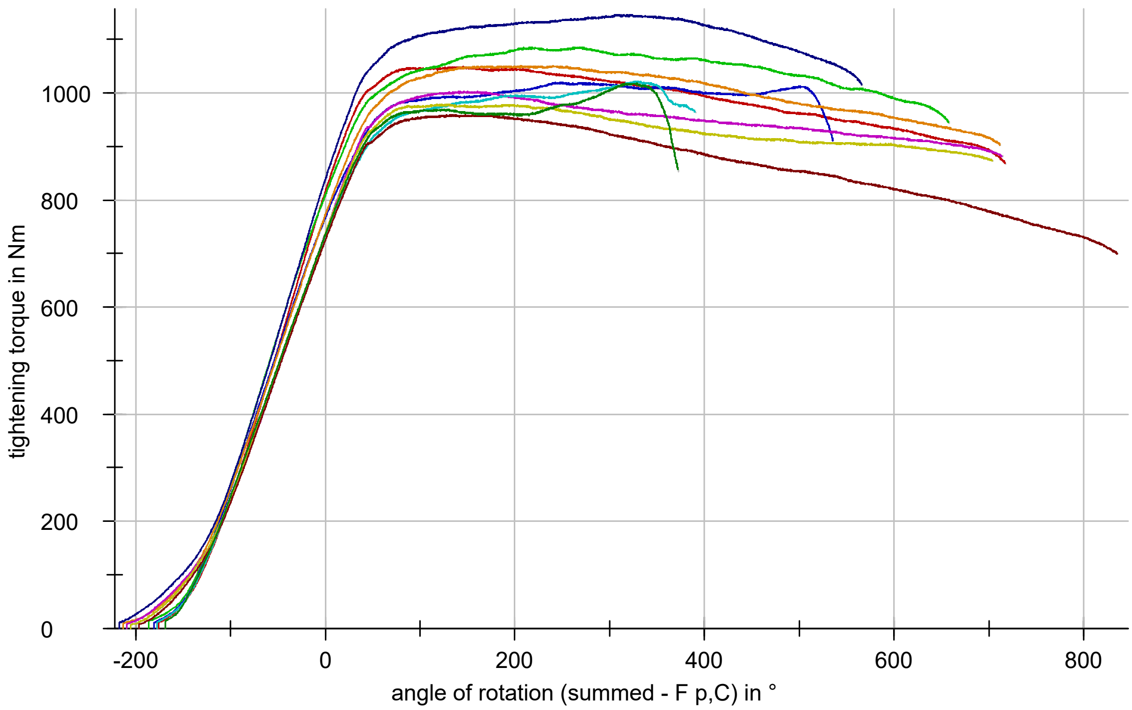
thread torque-bolt force-curves: M24x100 HR 10.9 - Factory provided



bolt force-angle of rotation-curves: M24x100 HR 10.9 - Factory provided



tightening torque-angle of rotation-curves: M24x100 HR 10.9 - Factory provided



Test series: M24x100 HR 10.9 - Gleitmo WSP 5040

Connecting element	:	M24x100 HR 10.9
Coating / Surface finish	:	M24x100 - tZn
Clamp length Σt	:	67,0 mm
Speed of tightening	:	2,0 1/min
Sensor F - T_{th}	:	SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ	:	SNo. 1024283 - 5000 Nm

Specific thread data:

Thread	Thread data	:	M 24 HV - IML	
d	Nominal diameter	:	24	mm
P	Pitch	:	3	mm
d_2	Pitch diameter	:	22,05	mm
d_o	Outer bearing surface diameter	:	38	mm
d_i	Inner bearing surface diameter	:	27,5	mm
D_b Calc	Bearing surface diameter	:	32,75	mm

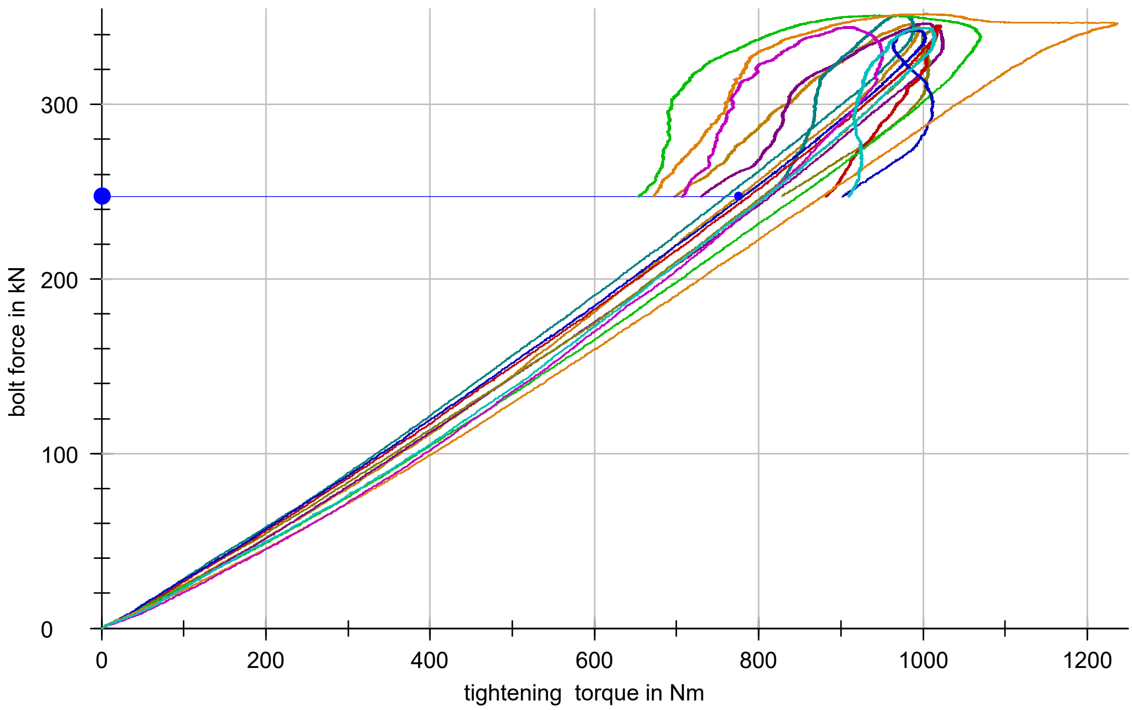
Results table: M24x100 HR 10.9 - Gleitmo WSP 5040

Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		247,1	317,7						120	240	0,10	
	Si_24_HR_10.9-11	247,1	346,1	998,2	168	355	996	246,9	186	828	0,13	0,091
	Si_24_HR_10.9-12		346,7	1025,3	184	382	987	247,0	197	802	0,14	0,097
	Si_24_HR_10.9-13		351,4	990,2	202	390	953	247,0	188	751	0,13	0,089
	Si_24_HR_10.9-14		342,9	1017,2	212	387	664	247,1	175	451	0,14	0,095
	Si_24_HR_10.9-15		345,4	1022,1	202	365	899	247,1	163	697	0,13	0,093
	Si_24_HR_10.9-16		351,1	1070,9	166	368	964	247,1	203	799	0,14	0,101
	Si_24_HR_10.9-17		342,6	1012,8	203	389	654	247,0	185	451	0,13	0,092
	Si_24_HR_10.9-18		352,0	1236,8	194	388	969	247,0	193	774	0,15	0,106
	Si_24_HR_10.9-19		344,4	951,4	182	352	966	247,0	171	784	0,14	0,096
	Si_24_HR_10.9-20		343,9	1015,3	209	386	894	246,9	176	685	0,14	0,096

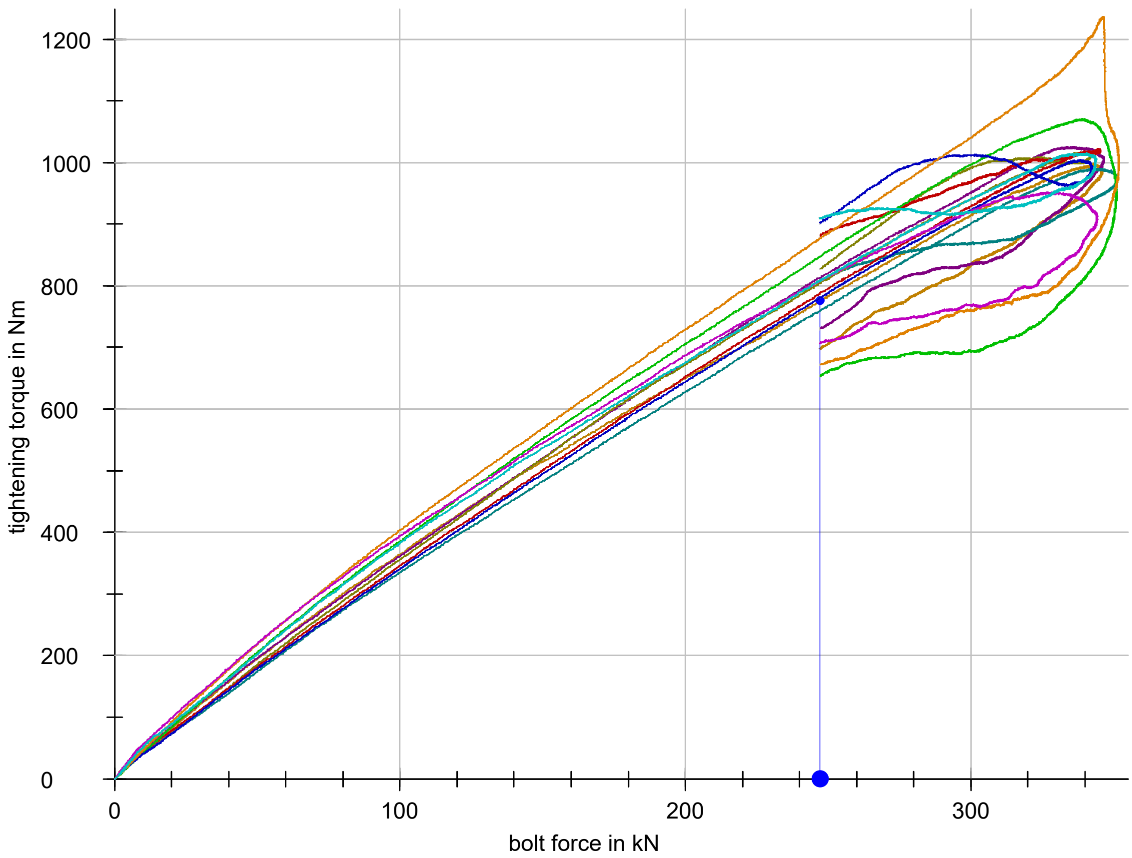
Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k (F_{p,C^*})	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			222,4	0,095			
	0,099	0,085	222,4	0,133	774,9	707,4	985,0
	0,118	0,080		0,139	813,6	743,0	1004,5
	0,095	0,084		0,130	759,0	692,7	973,6
	0,106	0,088		0,138	804,5	735,9	1013,6
	0,108	0,082		0,134	787,5	717,1	1019,7
	0,095	0,107		0,145	846,9	772,7	947,5
	0,106	0,081		0,133	780,8	709,3	993,1
	0,103	0,107		0,150	877,4	799,6	1006,0
	0,104	0,090		0,140	807,9	745,7	912,6
	0,101	0,092		0,138	807,4	738,3	1005,8

ANNEX A

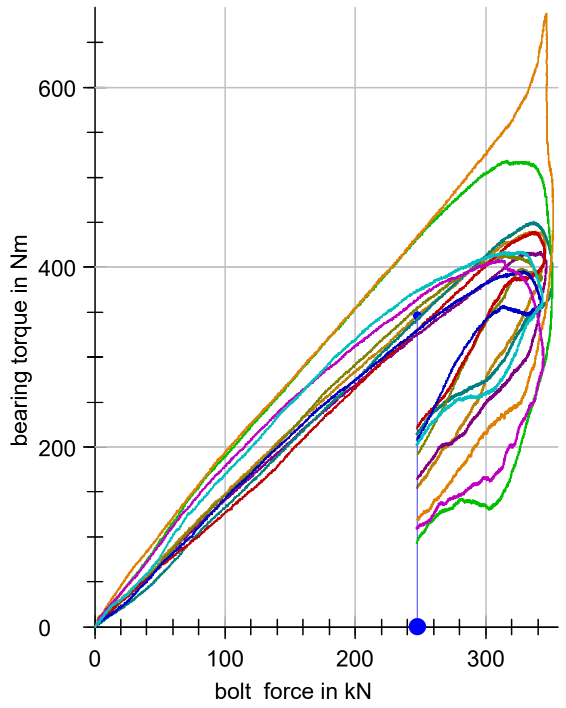
bolt force-tightening torque-curves: M24x100 HR 10.9 - Gleitmo WSP 5040



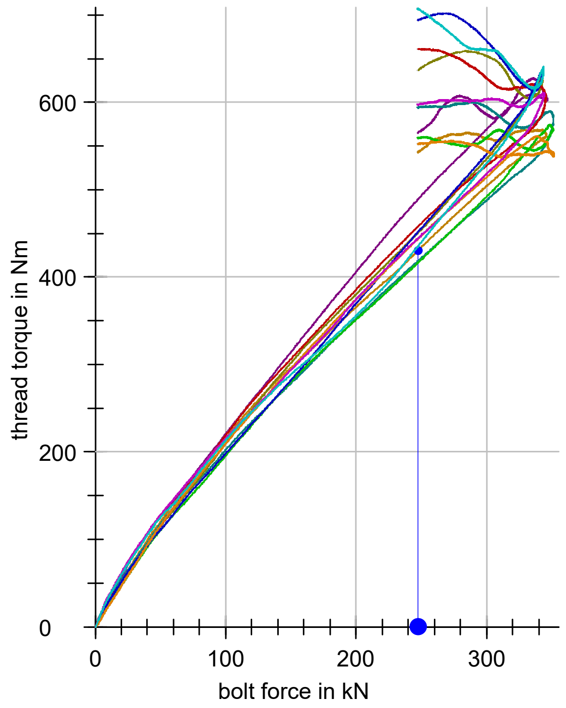
tightening torque-bolt force-curves: M24x100 HR 10.9 - Gleitmo WSP 5040



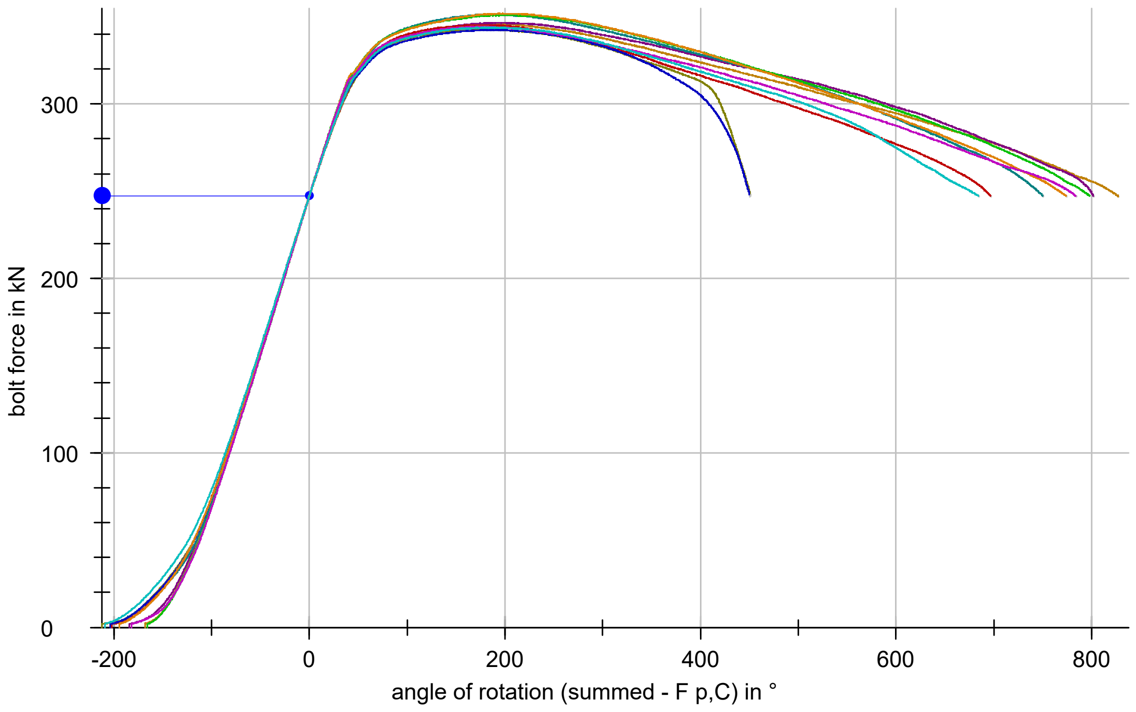
bearing torque-bolt force-curves: M24x100 HR 10.9 - Gleitmo WSP 5040



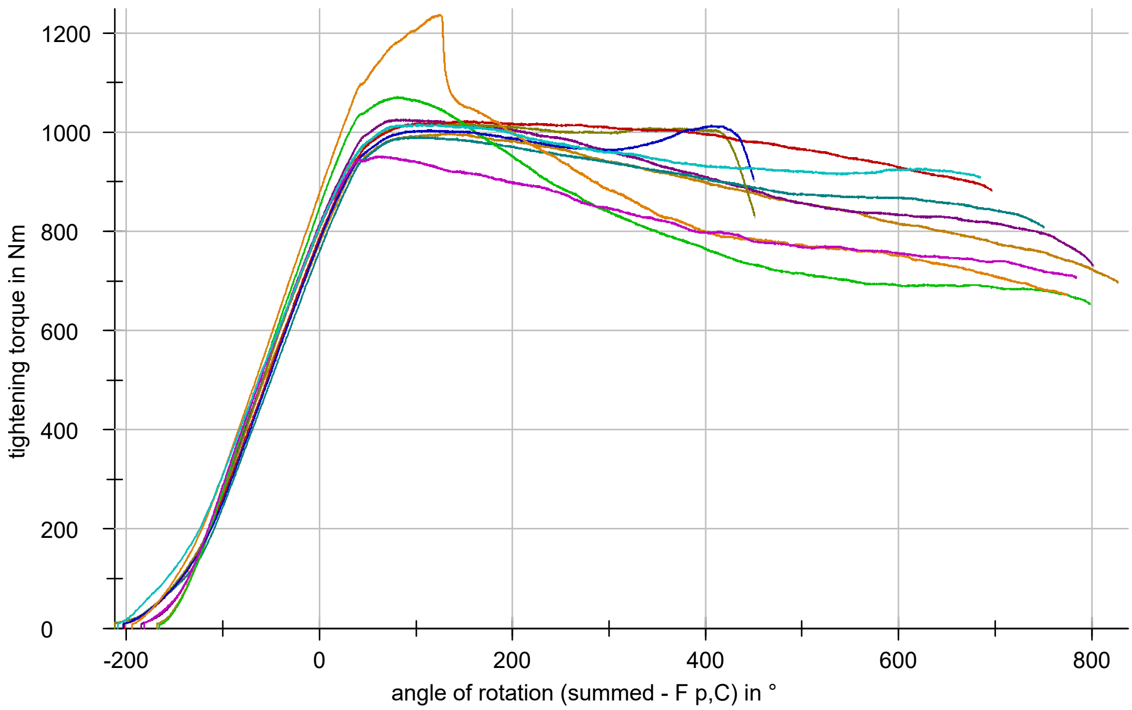
thread torque-bolt force-curves: M24x100 HR 10.9 - Gleitmo WSP 5040



bolt force-angle of rotation-curves: M24x100 HR 10.9 - Gleitmo WSP 5040



tightening torque-angle of rotation-curves: M24x100 HR 10.9 - Gleitmo WSP 5040



Test series: M24x100 HR 10.9 - Molykote 1000 spray

Connecting element	:	M24x100 HR 10.9
Coating / Surface finish	:	M24x100 - tZn
Clamp length Σt	:	67,0 mm
Speed of tightening	:	2,0 1/min
Sensor F - T_{th}	:	SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ	:	SNo. 1024283 - 5000 Nm

Specific thread data:

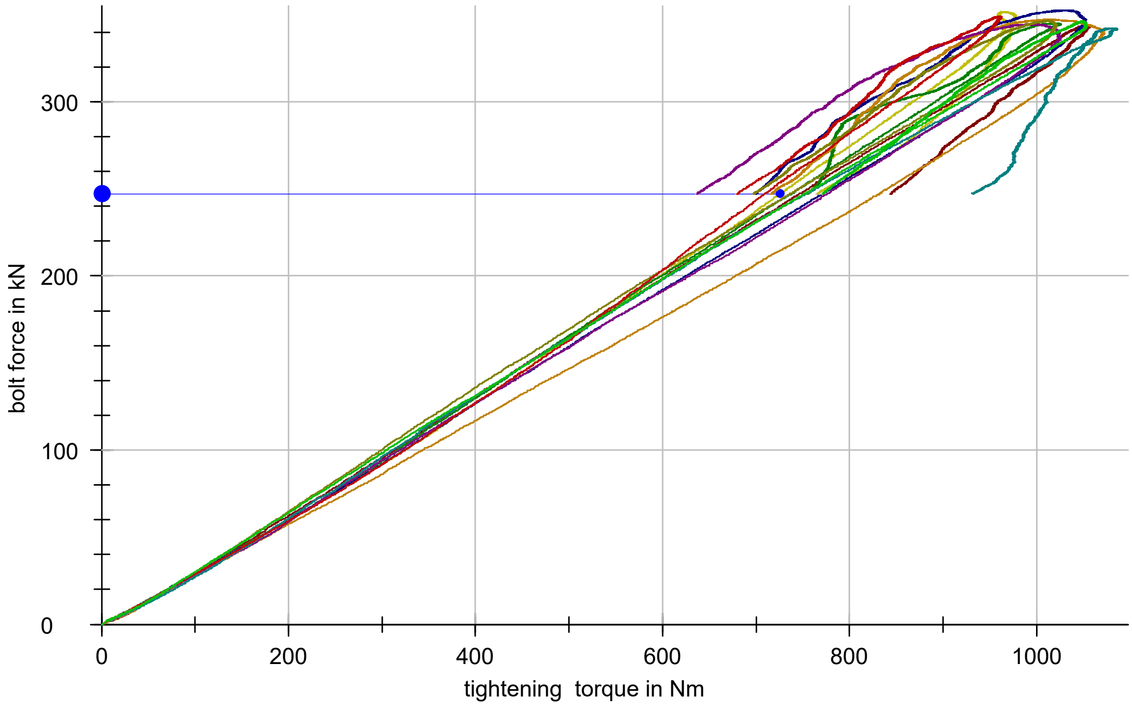
Thread	Thread data	:	M 24 HV - IML	
d	Nominal diameter	:	24	mm
P	Pitch	:	3	mm
d_2	Pitch diameter	:	22,05	mm
d_o	Outer bearing surface diameter	:	38	mm
d_i	Inner bearing surface diameter	:	27,5	mm
D_b Calc	Bearing surface diameter	:	32,75	mm

Results table: M24x100 HR 10.9 - Molykote 1000 spray

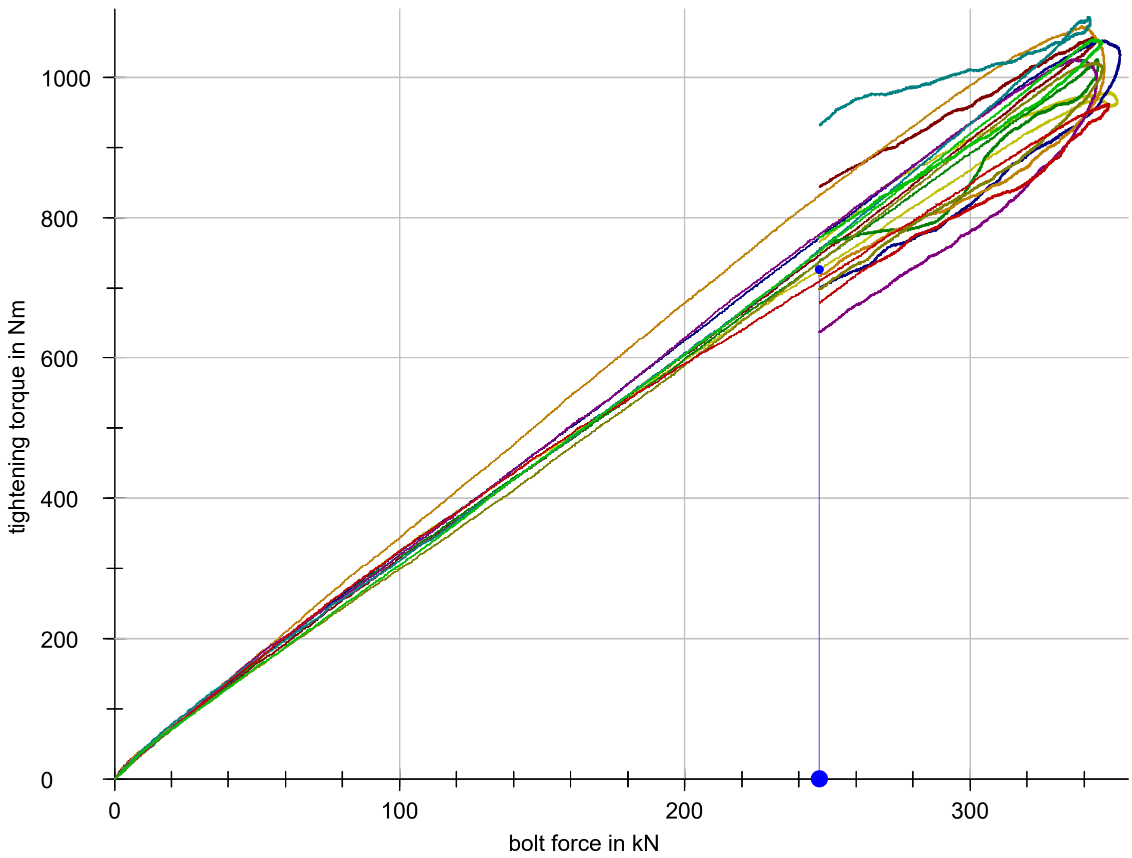
Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		247,1	317,7						120	240	0,10	
	Si_24_HR_10.9-21	247,1	351,8	978,4	211	376	626	247,0	165	414	0,12	0,084
	Si_24_HR_10.9-22		343,7	1057,3	228	409	988	247,0	180	760	0,13	0,087
	Si_24_HR_10.9-23		345,0	1026,3	214	386	1051	247,0	173	837	0,12	0,086
	Si_24_HR_10.9-24		352,7	1053,1	226	409	1062	247,0	183	836	0,13	0,091
	Si_24_HR_10.9-25		347,3	1073,1	177	373	984	247,1	196	808	0,14	0,099
	Si_24_HR_10.9-26		344,7	1026,0	178	363	994	247,0	186	816	0,13	0,091
	Si_24_HR_10.9-27		342,3	1086,5	177	370	952	247,1	193	775	0,13	0,089
	Si_24_HR_10.9-28		346,7	1021,6	174	348	985	247,0	173	810	0,12	0,086
	Si_24_HR_10.9-29		348,9	962,6	175	353	969	247,0	178	794	0,12	0,082
	Si_24_HR_10.9-30		346,3	1053,8	228	398	985	246,9	170	757	0,13	0,088

Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			222,4	0,095			
	0,091	0,079	222,4	0,123	725,7	659,0	963,3
	0,106	0,073		0,125	745,7	669,5	1052,6
	0,096	0,078		0,125	736,1	666,9	1021,4
	0,094	0,088		0,130	771,0	695,6	1032,6
	0,090	0,106		0,141	830,6	750,5	1010,2
	0,085	0,096		0,131	775,6	700,8	992,1
	0,087	0,090		0,126	754,6	672,3	1076,3
	0,088	0,085		0,123	736,2	659,0	1012,8
	0,085	0,080		0,121	709,3	645,4	960,1
	0,098	0,080		0,126	751,2	675,1	1049,2

bolt force-tightening torque-curves: M24x100 HR 10.9 - Molykote 1000 spray

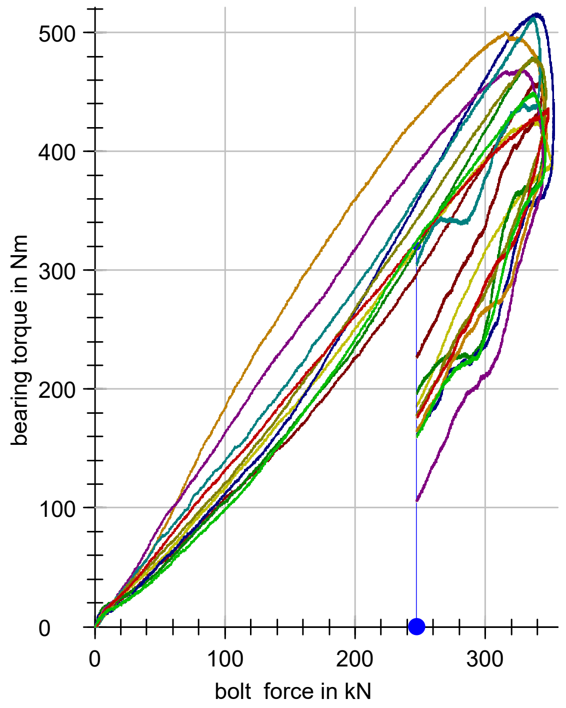


tightening torque-bolt force-curves: M24x100 HR 10.9 - Molykote 1000 spray

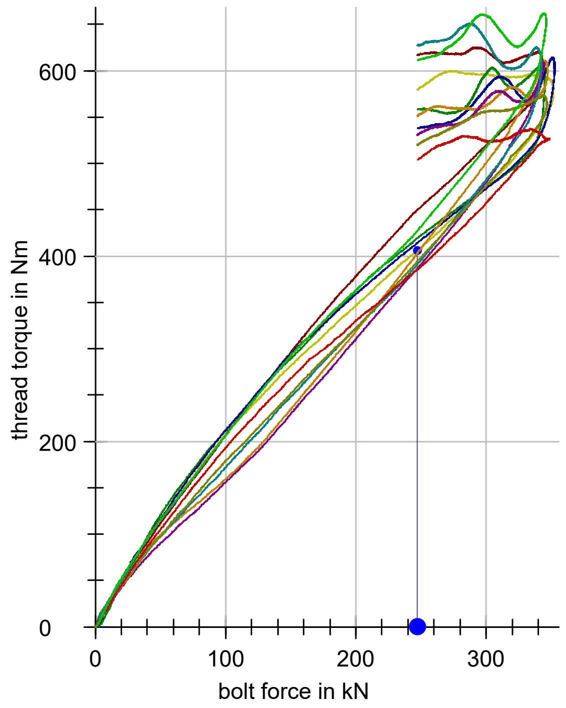


ANNEX A

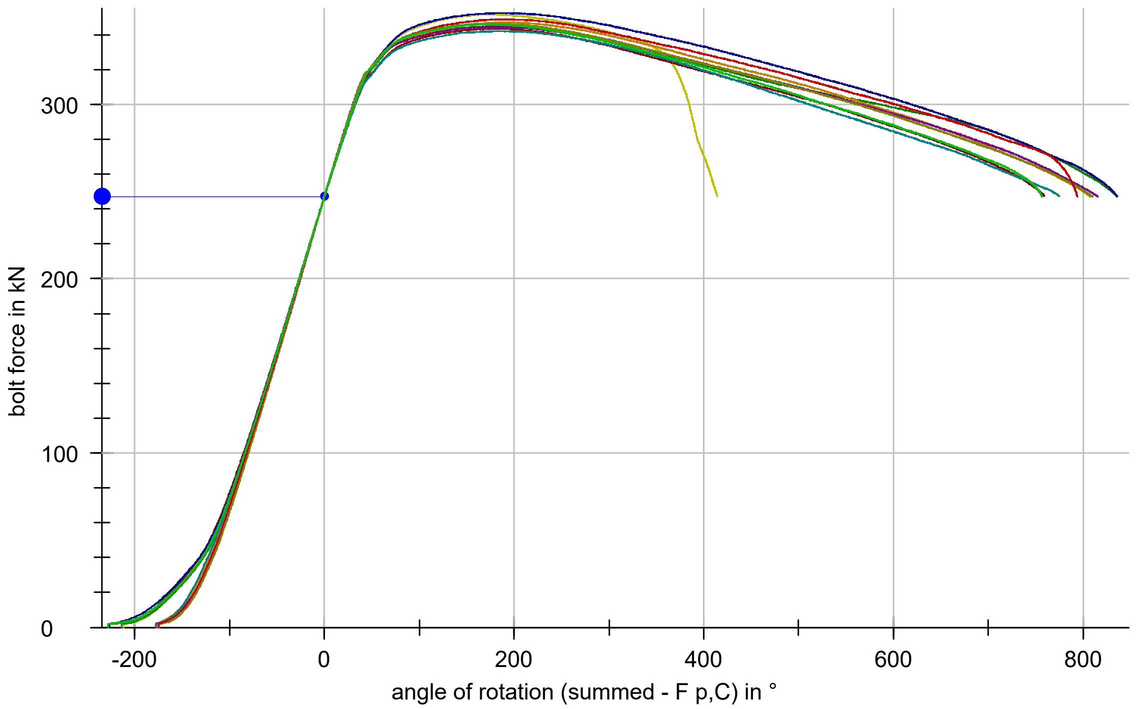
bearing torque-bolt force-curves: M24x100 HR 10.9 - Molykote 1000 spray



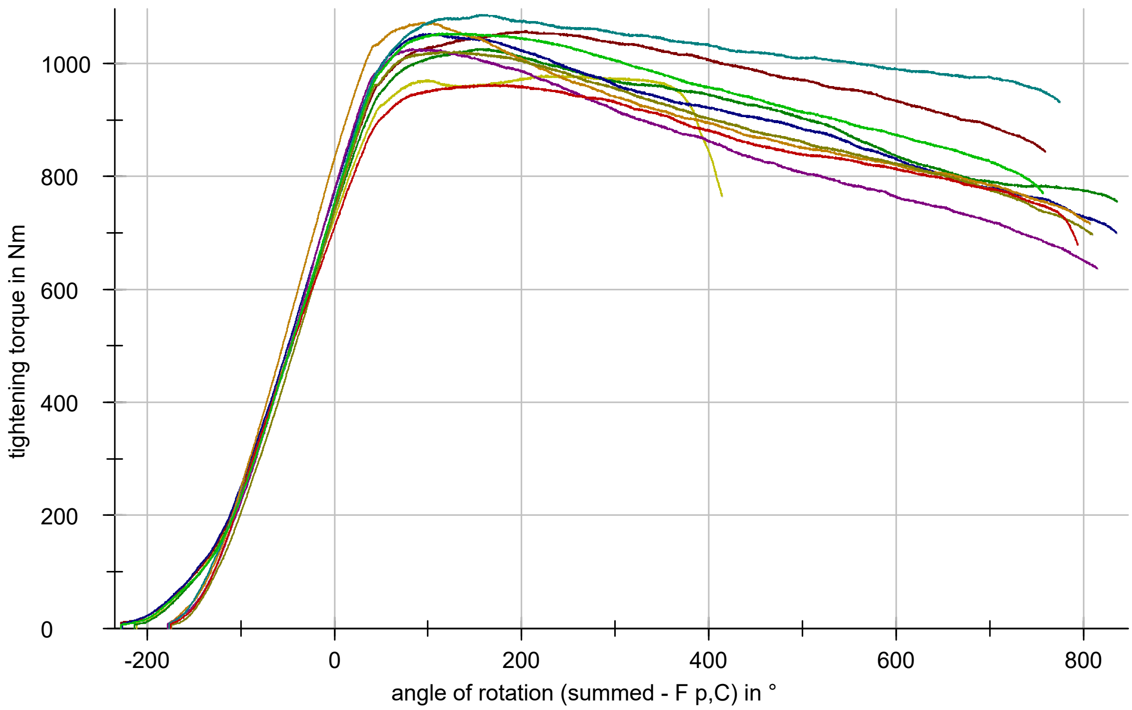
thread torque-bolt force-curves: M24x100 HR 10.9 - Molykote 1000 spray



bolt force-angle of rotation-curves: M24x100 HR 10.9 - Molykote 1000 spray



tightening torque-angle of rotation-curves: M24x100 HR 10.9 - Molykote 1000 spray



Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

Test series: M24x100 HR 10.9 - Microgleit HV-paste LP440

Connecting element	:	M24x100 HR 10.9
Coating / Surface finish	:	M24x100 - tZn
Clamp length Σt	:	67,0 mm
Speed of tightening	:	2,0 1/min
Sensor F - T_{th}	:	SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ	:	SNo. 1024283 - 5000 Nm

Specific thread data:

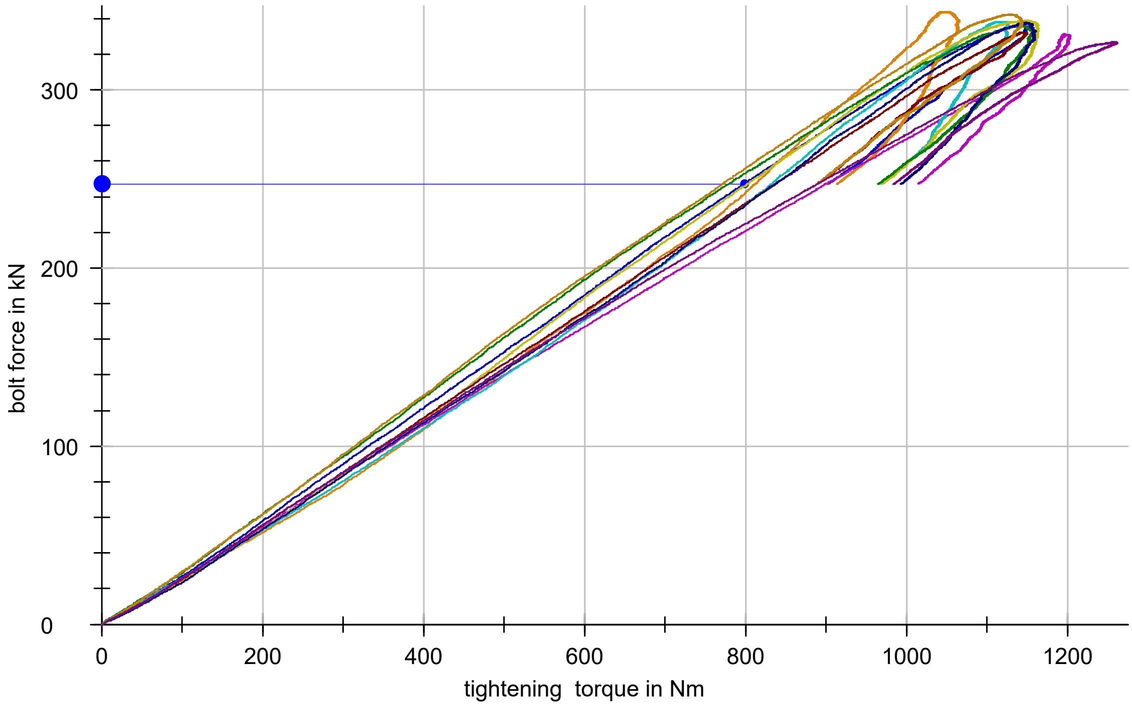
Thread	Thread data	:	M 24 HV - IML	
d	Nominal diameter	:	24	mm
P	Pitch	:	3	mm
d_2	Pitch diameter	:	22,05	mm
d_o	Outer bearing surface diameter	:	38	mm
d_i	Inner bearing surface diameter	:	27,5	mm
D_b Calc	Bearing surface diameter	:	32,75	mm

Results table: M24x100 HR 10.9 - Microgleit HV-paste LP440

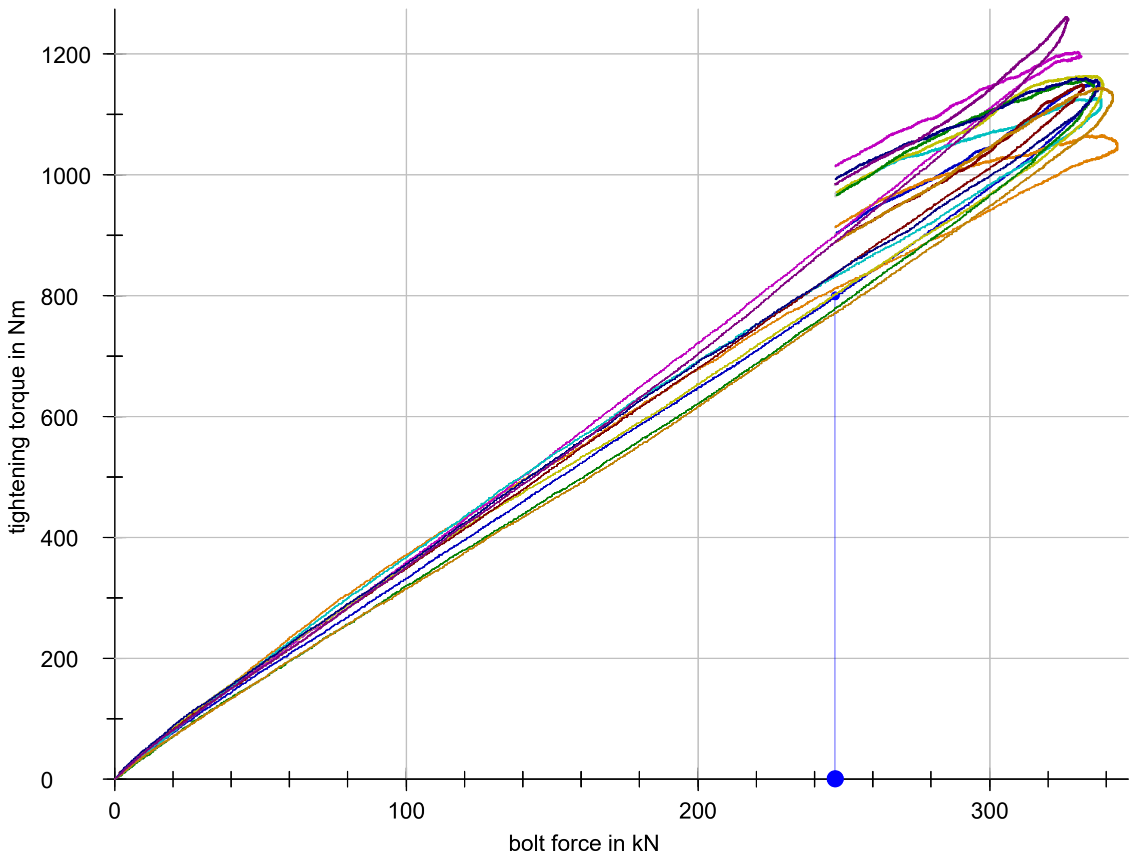
Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		247,1	317,7						120	240	0,10	
	Si_24_HR_10.9-31	247,1	337,8	1156,8	176	329	865	247,0	154	689	0,13	0,095
	Si_24_HR_10.9-32		343,9	1065,8	178	338	926	246,9	160	748	0,14	0,096
	Si_24_HR_10.9-33		331,4	1203,4	179	352	882	247,1	173	702	0,15	0,109
	Si_24_HR_10.9-34		338,4	1127,0	207	354	891	247,1	146	684	0,14	0,099
	Si_24_HR_10.9-35		339,0	1164,1	174	325	844	247,0	151	670	0,14	0,095
	Si_24_HR_10.9-36		332,4	1150,0	173	322	918	247,0	149	745	0,14	0,100
	Si_24_HR_10.9-37		336,0	1157,8	204	351	913	247,0	147	709	0,13	0,092
	Si_24_HR_10.9-38		337,7	1160,2	178	342	905	247,0	164	727	0,14	0,100
	Si_24_HR_10.9-39		342,3	1144,1	207	354	953	247,0	147	746	0,13	0,091
	Si_24_HR_10.9-40		327,0	1262,0	162	296	817	246,8	134	655	0,15	0,107

Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			222,4	0,095			
	0,104	0,087	222,4	0,134	798,1	716,1	1149,0
	0,107	0,088		0,140	812,0	746,6	1043,6
	0,120	0,100		0,151	899,1	806,1	1195,6
	0,116	0,086		0,142	830,6	758,4	1113,4
	0,103	0,089		0,136	803,1	724,9	1146,8
	0,118	0,086		0,141	836,4	755,1	1140,0
	0,106	0,081		0,130	778,2	694,4	1138,3
	0,107	0,094		0,142	836,6	759,8	1147,5
	0,101	0,083		0,129	770,8	690,5	1125,6
	0,118	0,099		0,148	888,8	789,0	1257,3

bolt force-tightening torque-curves: M24x100 HR 10.9 - Microgleit HV-paste LP440

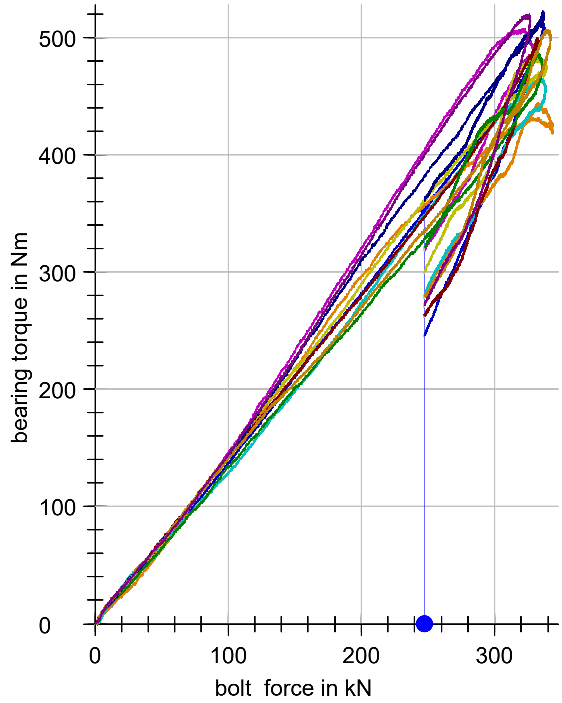


tightening torque-bolt force-curves: M24x100 HR 10.9 - Microgleit HV-paste LP440

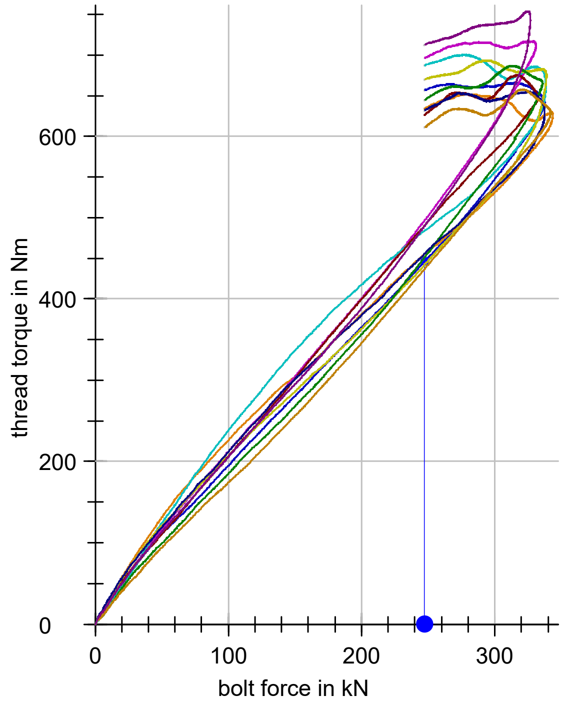


ANNEX A

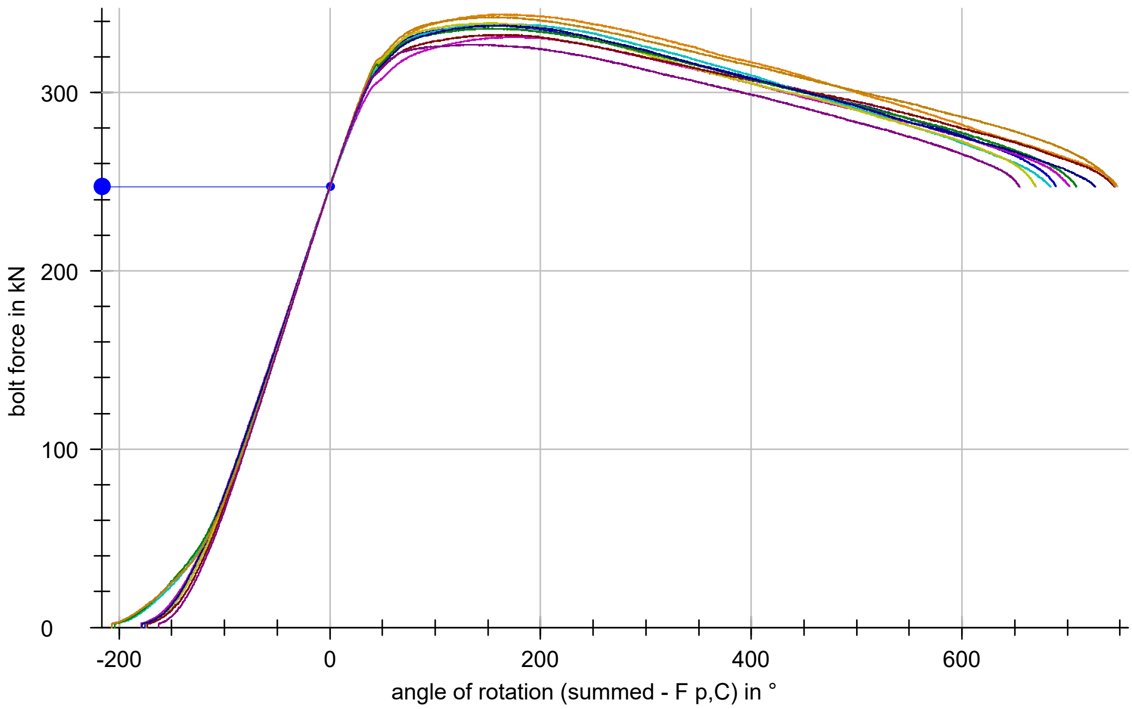
bearing torque-bolt force-curves: M24x100 HR 10.9 - Microgleit HV-paste LP440



thread torque-bolt force-curves: M24x100 HR 10.9 - Microgleit HV-paste LP440

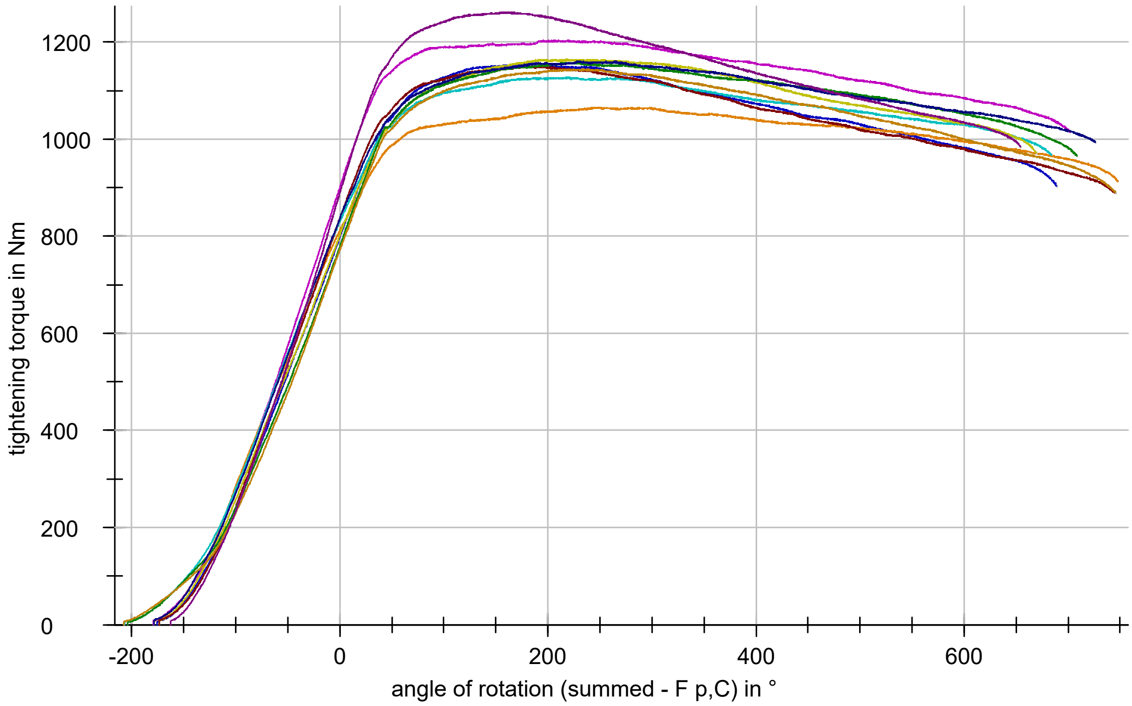


bolt force-angle of rotation-curves: M24x100 HR 10.9 - Microgleit HV-paste LP440



ANNEX A

tightening torque-angle of rotation-curves: M24x100 HR 10.9 - Microgleit HV-paste LP440



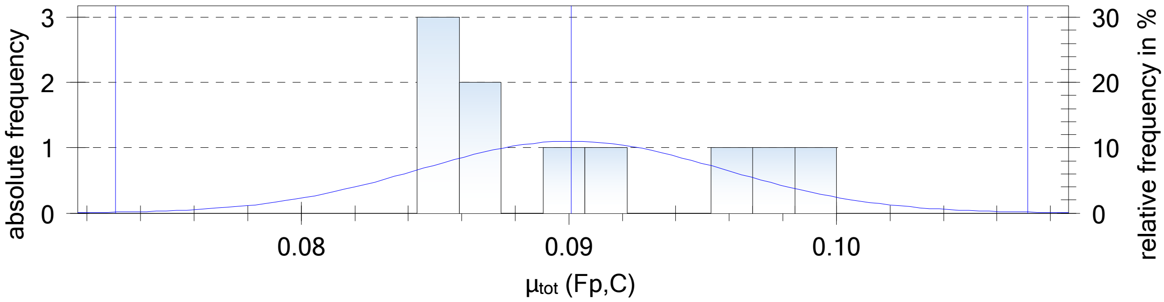
Statistical evaluation: M24x100 HR 10.9 - Factory provided

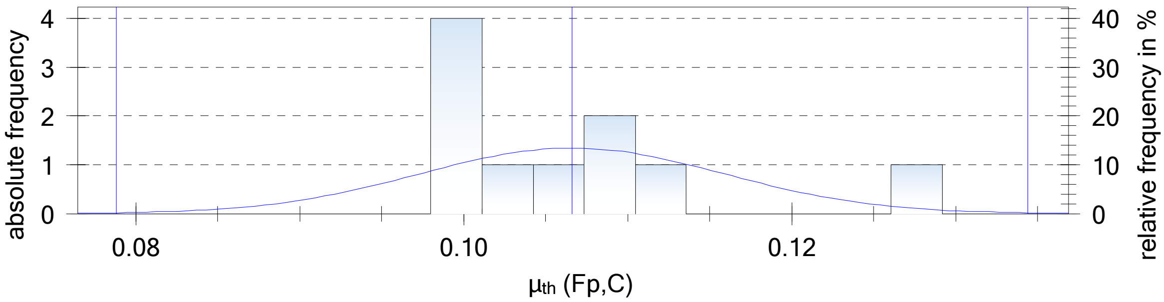
M24x100 HR 10.9 - Factory provided n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	348,4	1146,3	218	393	1032	247,1	184	836	0,100
min	334,0	959,4	169	333	541	246,9	148	373	0,084
R	14,4	186,9	49	60	491	0,2	36	463	0,016
$\bar{x}$	343,0	1033,4	193	361	814	247,0	168	621	0,090
s	3,8	53,6	18	21	161	0,1	12	151	0,006
ν	1,10	5,19	9,10	5,89	19,80	0,03	6,99	24,35	6,35

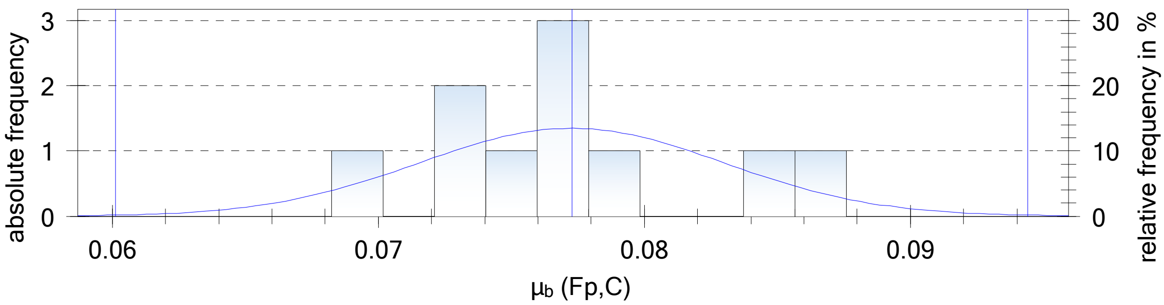
M24x100 HR 10.9 - Factory provided n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C*}$)	M ($F_{bi,max}$) Nm
max	0,129	0,088	837,5	0,14	757,9	0,142	1120,9
min	0,098	0,068	724,9	0,12	659,3	0,124	957,0
R	0,031	0,020	112,6	0,02	98,6	0,018	163,9
$\bar{x}$	0,107	0,077	766,2	0,13	696,1	0,131	1015,2
s	0,009	0,006	40,9	0,01	37,9	0,007	53,2
ν	8,62	7,60	5,34	7,18	5,44	5,27	5,24

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M24x100 HR 10.9 - Factory provided







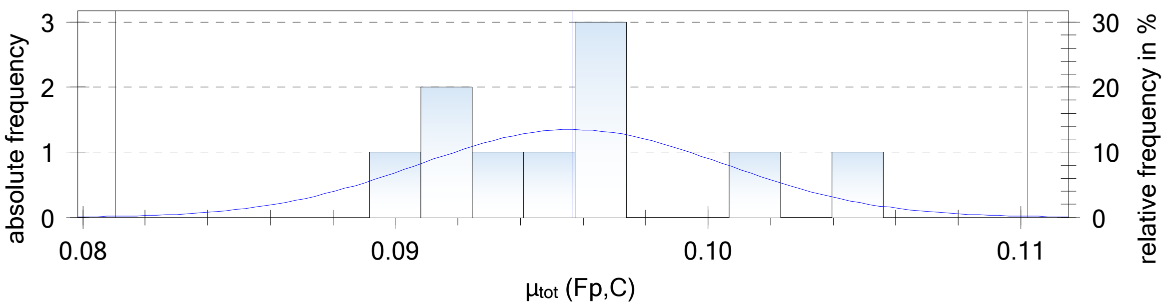
Statistical evaluation: M24x100 HR 10.9 - Gleitmo WSP 5040

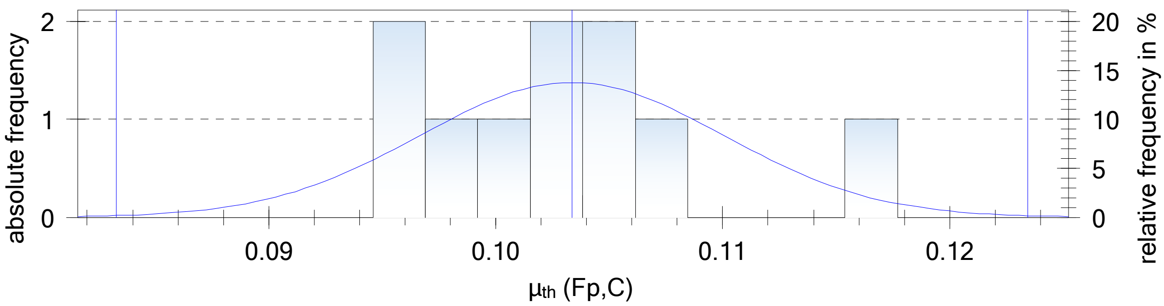
M24x100 HR 10.9 - Gleitmo WSP 5040 n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	352,0	1236,8	212	390	996	247,1	203	828	0,106
min	342,6	951,4	166	352	654	246,9	163	451	0,089
R	9,4	285,4	46	38	342	0,2	40	377	0,017
$\bar{x}$	346,7	1034,0	192	376	895	247,0	184	702	0,096
s	3,6	77,3	16	15	129	0,1	12	140	0,005
ν	1,04	7,48	8,55	3,93	14,37	0,03	6,76	19,91	5,22

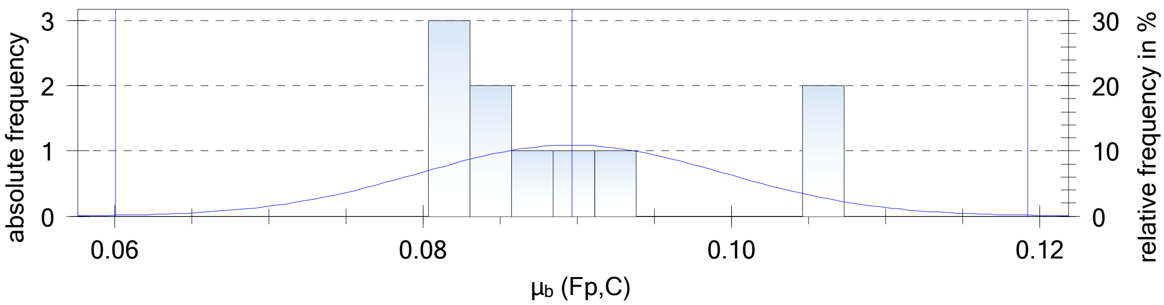
M24x100 HR 10.9 - Gleitmo WSP 5040 n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C*}$) Nm	k ($F_{p,C*}$)	M ($F_{bi,max}$) Nm
max	0,118	0,107	877,4	0,15	799,6	0,150	1019,7
min	0,095	0,080	759,0	0,13	692,7	0,130	912,6
R	0,023	0,027	118,4	0,02	106,9	0,020	107,1
$\bar{x}$	0,104	0,090	806,0	0,14	736,2	0,138	986,1
s	0,007	0,010	34,9	0,01	32,2	0,006	33,5
ν	6,56	11,10	4,34	4,93	4,37	4,37	3,40

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M24x100 HR 10.9 - Gleitmo WSP 5040







Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

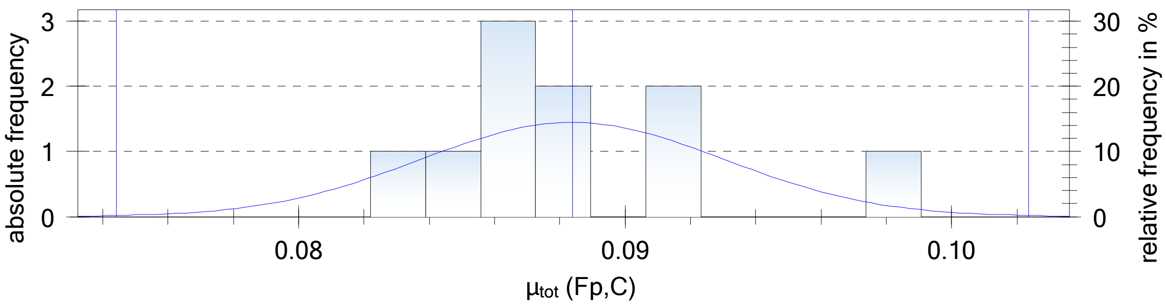
Statistical evaluation: M24x100 HR 10.9 - Molykote 1000 spray

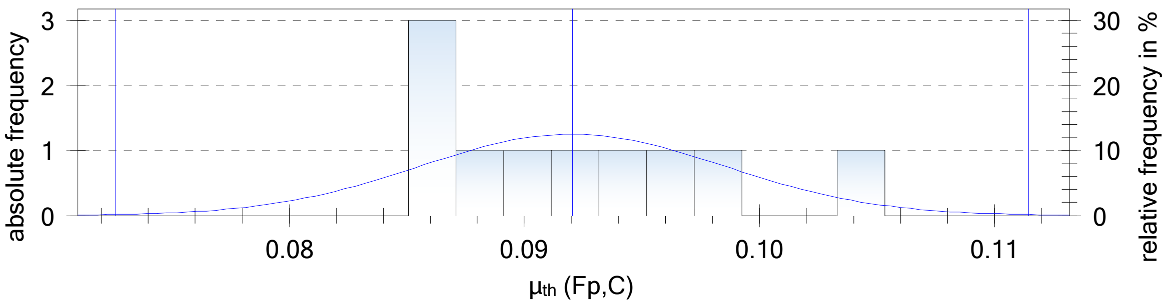
M24x100 HR 10.9 - Molykote 1000 spray n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	352,7	1086,5	228	409	1062	247,1	196	837	0,099
min	342,3	962,6	174	348	626	246,9	165	414	0,082
R	10,4	123,9	54	61	436	0,2	31	423	0,017
$\bar{x}$	346,9	1033,9	199	379	960	247,0	180	761	0,088
s	3,4	39,5	24	22	122	0,1	10	125	0,005
ν	0,97	3,82	12,31	5,73	12,72	0,02	5,55	16,44	5,34

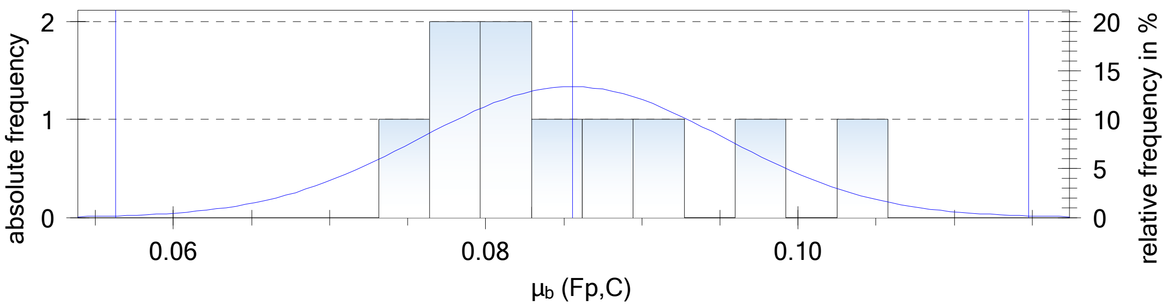
M24x100 HR 10.9 - Molykote 1000 spray n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C}$*)	M ($F_{bi,max}$) Nm
max	0,106	0,106	830,6	0,14	750,5	0,141	1076,3
min	0,085	0,073	709,3	0,12	645,4	0,121	960,1
R	0,021	0,033	121,3	0,02	105,1	0,020	116,2
$\bar{x}$	0,092	0,086	753,6	0,13	679,4	0,127	1017,1
s	0,007	0,010	33,6	0,01	30,0	0,006	37,8
ν	7,21	11,52	4,45	5,31	4,41	4,53	3,72

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M24x100 HR 10.9 - Molykote 1000 spray







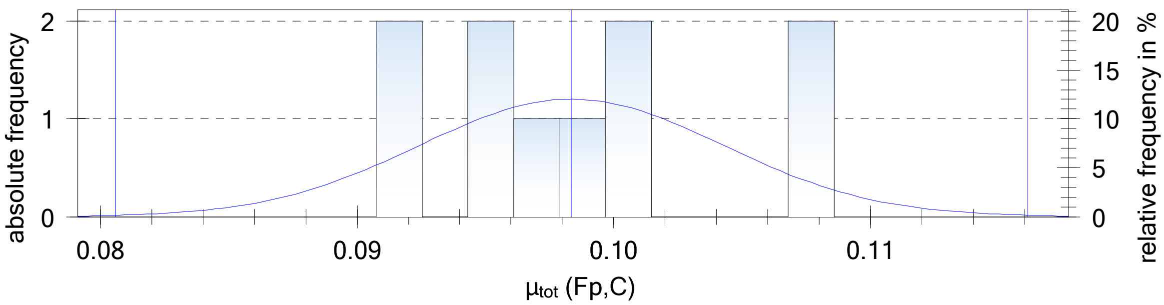
Statistical evaluation: M24x100 HR 10.9 - Microgleit HV-paste LP440

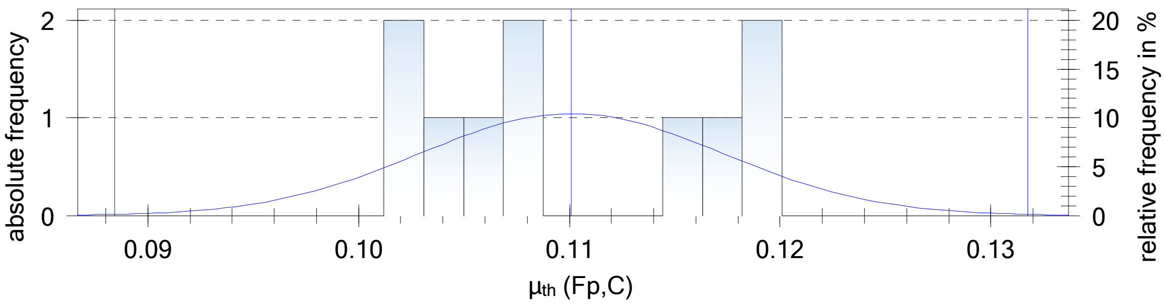
M24x100 HR 10.9 - Microgleit HV-paste LP440 n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	343,9	1262,0	207	354	953	247,1	173	748	0,109
min	327,0	1065,8	162	296	817	246,8	134	655	0,091
R	16,9	196,2	45	58	136	0,3	39	93	0,018
$\bar{x}$	336,6	1159,1	184	336	891	247,0	153	708	0,098
s	5,1	50,1	16	19	41	0,1	11	33	0,006
ν	1,52	4,33	8,74	5,55	4,57	0,04	7,15	4,71	6,03

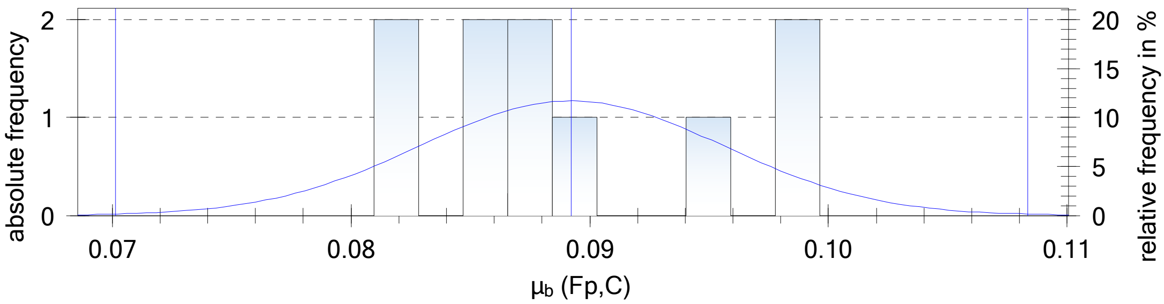
M24x100 HR 10.9 - Microgleit HV-paste LP440 n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C*}$)	M ($F_{bi,max}$) Nm
max	0,120	0,100	899,1	0,15	806,1	0,151	1257,3
min	0,101	0,081	770,8	0,13	690,5	0,129	1043,6
R	0,019	0,019	128,3	0,02	115,6	0,022	213,7
$\bar{x}$	0,110	0,089	825,4	0,14	744,1	0,139	1145,7
s	0,007	0,006	42,6	0,01	37,9	0,007	54,7
ν	6,53	7,16	5,16	5,31	5,09	5,14	4,77

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M24x100 HR 10.9 - Microgleit HV-paste LP440







Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

ANNEX A

M36 HR 8.8 - Test protocol

SIROCO - Tightening tests of HR bolting assemblies

Client / Customer	:	SIROCO
Date of reception	:	-
Date of testing	:	08.04.2016 M36x160 HR 8.8
Project	:	RFCS SIROCO WP 1 Task 1.5
Specification	:	According EN 14399-2 and EN ISO 16047
Operator	:	Christoph Abraham B.Sc., Dominik Jungbluth M.Sc.
Number of assemblies tested	:	40
Designation of bolt	:	M36x160 HR 8.8
Marking of bolt	:	M36 FAST 8.8 HR
Designation of nut	:	Hexagon nut HR M36
Marking of nut	:	FAST 10HR
Designation of washer	:	Washer M36 HR
Marking of washer	:	H FAST
Coating / Surface finish	:	M36x160 - tZn
Ambient temperature	:	23,4 °C
Ambient relative humidity	:	24,2 %
Rotated component	:	Hexagon nut
Special testing conditions	:	Different lubrications used: Si_36_8_1-10: Factory provided lubrication Si_36_8_11-20: Gleitmo WSP 5040 Si_36_8_21-30: Molykote 1000 spray Si_36_8_31-40: Microgleit HV-paste LP440 Bolt fracture occured in tested specimens: Si_36_8_2: Total rupture (threaded shank) / Fp,C not achieved Si_36_8_4: Total rupture (threaded shank) / Fp,C not achieved Si_36_8_5: Partial rupture (threaded shank) when turning off the nut Si_36_8_16: Partial rupture (threaded shank) Si_36_8_18: Total rupture (threaded shank) Si_36_8_20: Total rupture (threaded shank) Si_36_8_33: Partial rupture (threaded shank) when turning off the nut Si_36_8_34: Partial rupture (threaded shank) when turning off the nut Si_36_8_36: Partial rupture (threaded shank) when turning off the nut Si_36_8_37: Partial rupture (threaded shank) when turning off the nut Si_36_8_39: Total rupture (threaded shank) when turning off the nut

Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

ANNEX A

Test specimens identification

Si_xx_yy_zz

Si: RFCS SIROCO
xx: thread
yy: strength class
zz: sequential number of bolt

Test series: M36x160 HR 8.8 - Factory provided

Connecting element	:	M36x160 HR 8.8
Coating / Surface finish	:	M36x160 - tZn
Clamp length Σt	:	123,5 mm
Speed of tightening	:	2,0 1/min
Sensor F - T_{th}	:	SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ	:	SNo. 1016241 - 15000 Nm

Specific thread data:

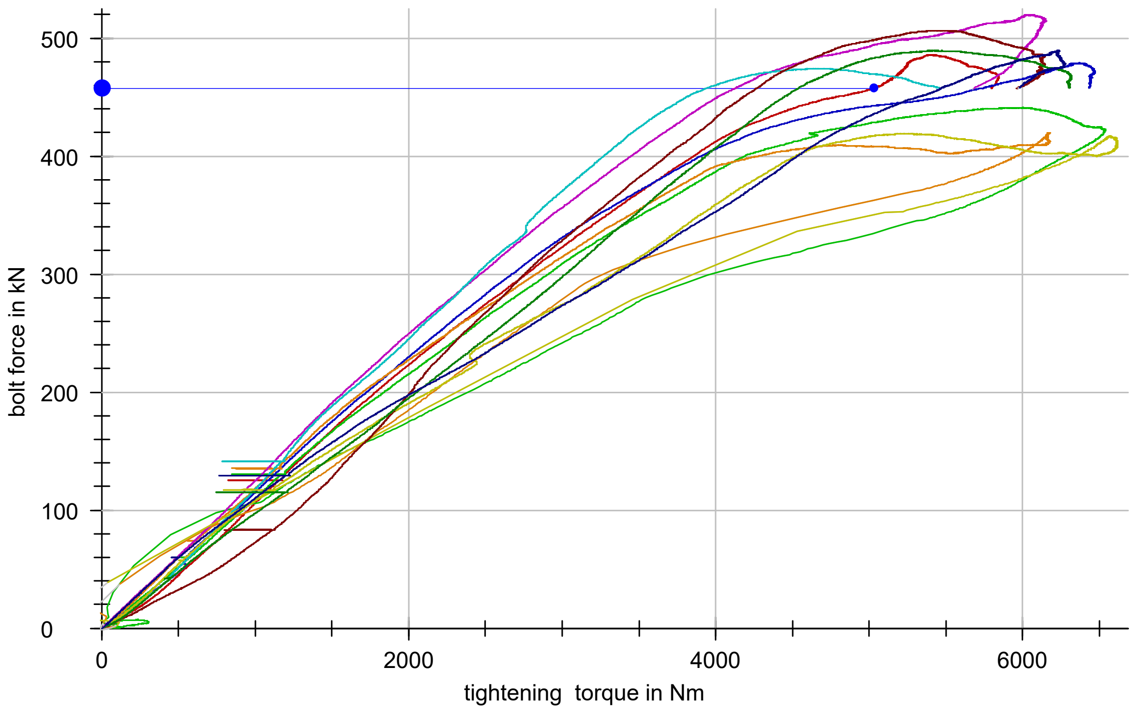
Thread	Thread data	:	M 36/4.00 HV - IML	
d	Nominal diameter	:	36	mm
P	Pitch	:	4	mm
d_2	Pitch diameter	:	33,4	mm
d_o	Outer bearing surface diameter	:	55,9	mm
d_i	Inner bearing surface diameter	:	42	mm
D_b Calc	Bearing surface diameter	:	48,95	mm

Results table: M36x160 HR 8.8 - Factory provided

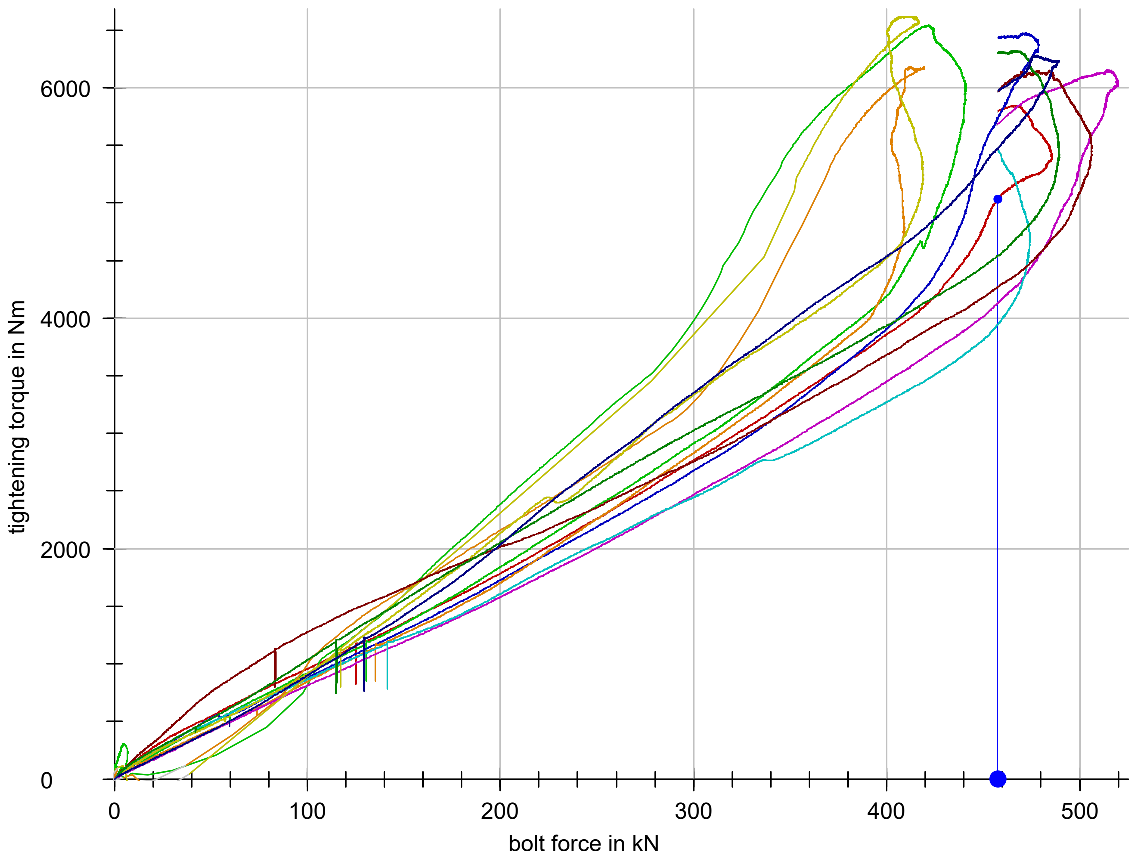
Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		457,5	588,2						120	240	0,10	
	Si_36_HR_8.8-01	457,5	<485,7	5842,9	319	402	525	457,3	<83	<207	>0,31	0,237
	Si_36_HR_8.8-02		<441,1	6540,9	-	327	-	-	-	-	-	-
	Si_36_HR_8.8-03		<478,9	6470,7	286	393	487	457,5	<108	<201	>0,35	0,272
	Si_36_HR_8.8-04		<419,7	6179,7	-	465	-	-	-	-	-	-
	Si_36_HR_8.8-05		<519,9	6154,5	234	492	632	457,0	258	398	>0,25	0,191
	Si_36_HR_8.8-06		<474,4	5472,1	248	284	331	457,3	<35	<82	>0,24	0,182
	Si_36_HR_8.8-07		<419,1	6618,4	-	240	-	-	-	-	-	-
	Si_36_HR_8.8-08		<506,3	6147,4	255	339	622	457,5	<84	367	>0,26	0,198
	Si_36_HR_8.8-09		<489,5	6320,2	223	269	432	457,4	<45	<209	>0,28	0,212
	Si_36_HR_8.8-10		<489,4	6278,4	264	426	608	457,4	162	345	>0,33	0,259

Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			366	0,095			
	0,268	0,212	366	>0,263	5030,2	3463,7	5391,1
	-	-		>0,283	-	3728,6	5999,9
	0,259	0,282		>0,261	5734,3	3443,1	6371,3
	-	-		>0,277	-	3644,2	6166,3
	0,196	0,188		>0,235	4122,2	3098,5	6030,6
	0,177	0,186		>0,225	3939,8	2958,5	4673,7
	-	-		>0,310	-	4081,2	5243,3
	0,123	0,258		>0,254	4263,1	3351,4	5412,2
	0,139	0,270		>0,274	4541,0	3614,1	5394,8
	0,232	0,280		>0,316	5467,4	4160,9	6225,6

bolt force-tightening torque-curves: M36x160 HR 8.8 - Factory provided



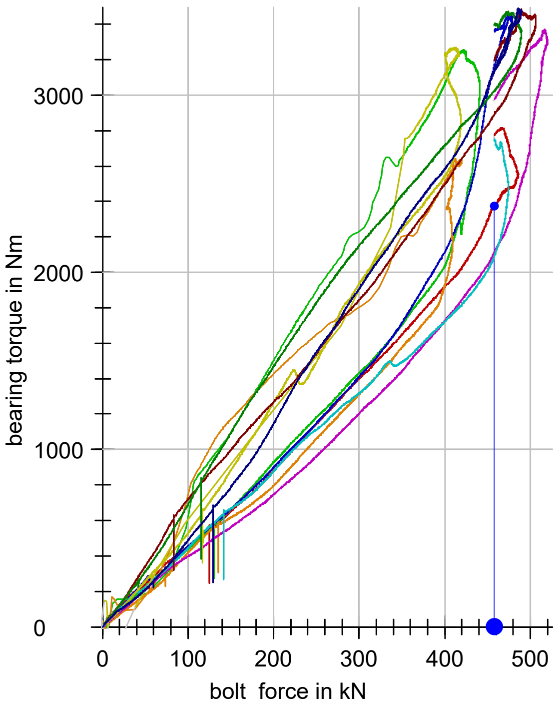
tightening torque-bolt force-curves: M36x160 HR 8.8 - Factory provided



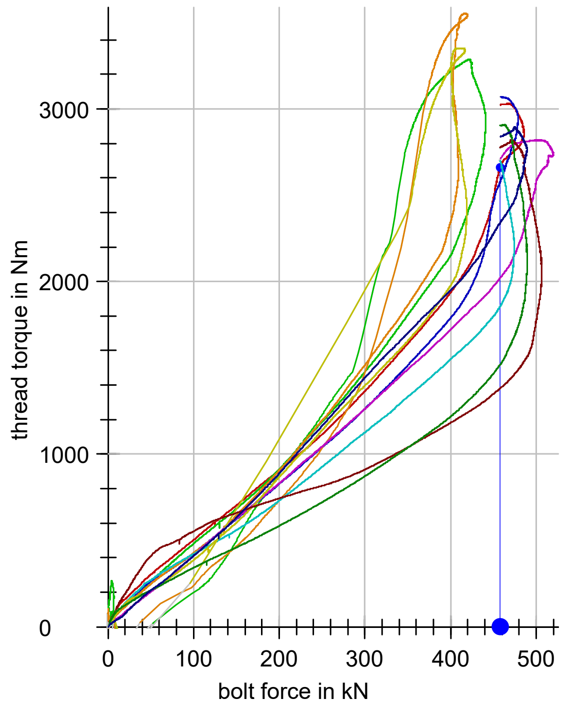
Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

ANNEX A

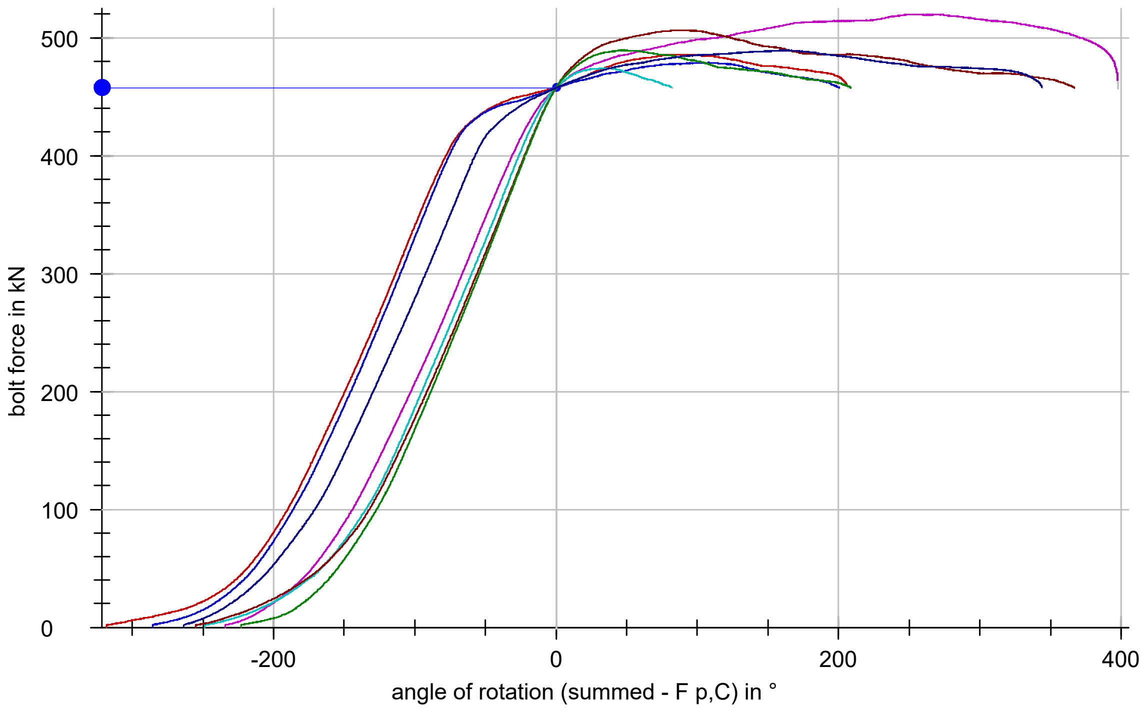
bearing torque-bolt force-curves: M36x160 HR 8.8 - Factory provided



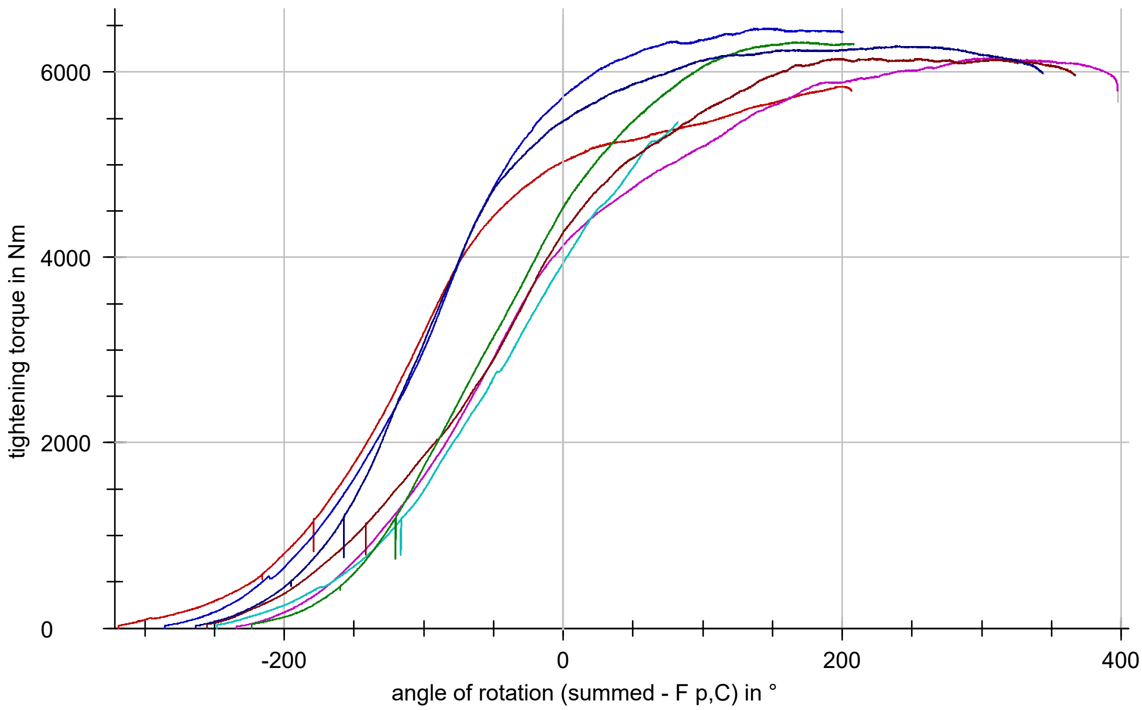
thread torque-bolt force-curves: M36x160 HR 8.8 - Factory provided



bolt force-angle of rotation-curves: M36x160 HR 8.8 - Factory provided



tightening torque-angle of rotation-curves: M36x160 HR 8.8 - Factory provided



Test series: M36x160 HR 8.8 - Gleitmo WSP 5040

Connecting element	:	M36x160 HR 8.8
Coating / Surface finish	:	M36x160 - tZn
Clamp length Σt	:	123,5 mm
Speed of tightening	:	2,0 1/min
Sensor F - T_{th}	:	SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ	:	SNo. 1016241 - 15000 Nm

Specific thread data:

Thread	Thread data	:	M 36/4.00 HV - IML	
d	Nominal diameter	:	36	mm
P	Pitch	:	4	mm
d_2	Pitch diameter	:	33,4	mm
d_o	Outer bearing surface diameter	:	55,9	mm
d_i	Inner bearing surface diameter	:	42	mm
D_b Calc	Bearing surface diameter	:	48,95	mm

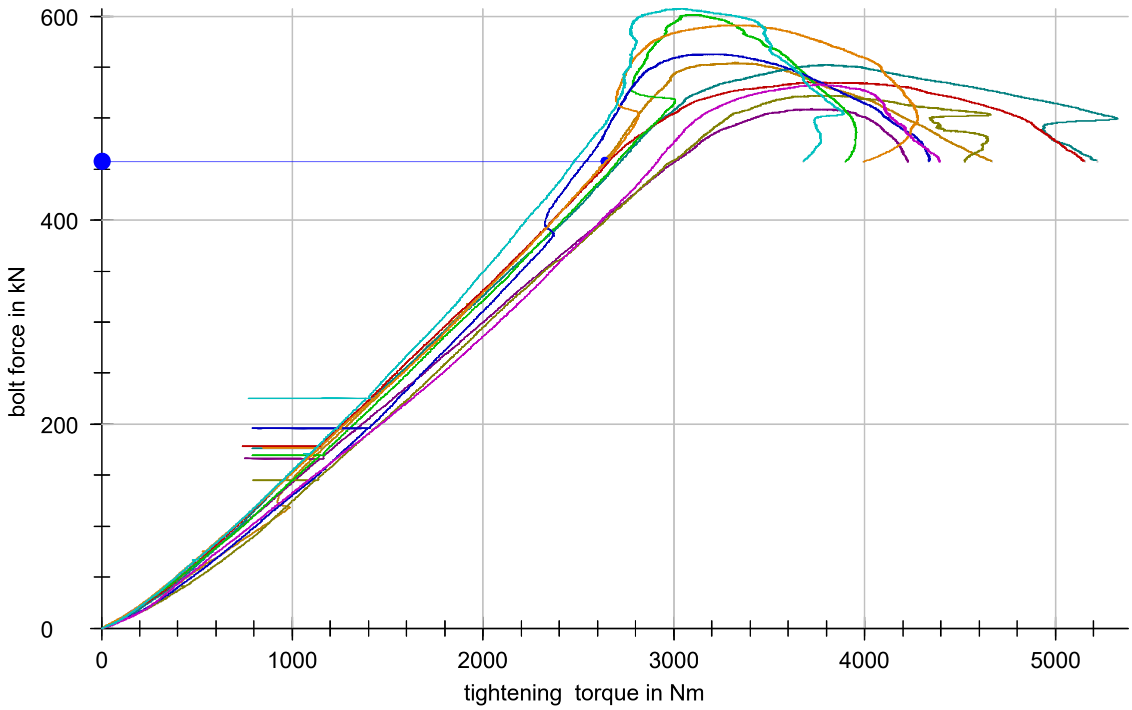
Results table: M36x160 HR 8.8 - Gleitmo WSP 5040

Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		457,5	588,2						120	240	0,10	
	Si_36_HR_8.8-11	457,5	<554,3	4676,7	219	376	603	457,5	158	384	0,16	0,117
	Si_36_HR_8.8-12		<509,0	4231,0	223	321	447	457,5	<98	<224	>0,18	0,136
	Si_36_HR_8.8-13		<552,4	5326,7	236	442	638	457,3	206	402	>0,17	0,121
	Si_36_HR_8.8-14		<522,0	4660,9	228	367	674	457,3	140	447	>0,18	0,135
	Si_36_HR_8.8-15		<535,7	5161,0	232	357	515	457,3	125	282	0,16	0,118
	Si_36_HR_8.8-16		601,5	3960,5	210	452	701	457,4	242	490	>0,16	0,120
	Si_36_HR_8.8-17		<563,0	4342,4	225	372	552	457,4	146	327	0,15	0,112
	Si_36_HR_8.8-18		591,1	4281,7	233	430	700	457,1	197	467	0,16	0,118
	Si_36_HR_8.8-19		<533,0	4399,2	259	370	526	457,4	<111	267	>0,18	0,131
	Si_36_HR_8.8-20		607,4	3894,2	229	472	811	457,3	242	582	0,15	0,109

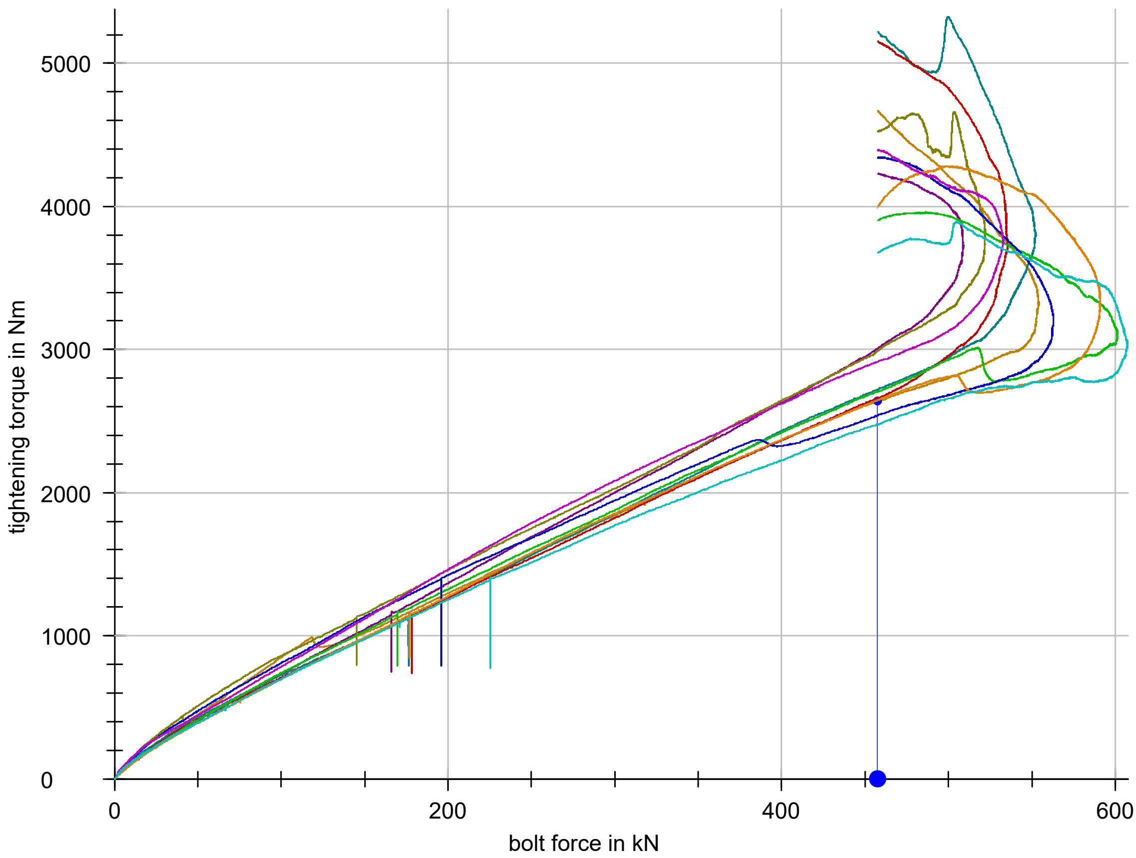
Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k (F_{p,C^*})	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			366	0,095			
	0,125	0,111	366	>0,167	2638,2	2200,7	3331,0
	0,161	0,116		>0,183	3007,6	2407,4	3719,9
	0,137	0,109		>0,170	2719,5	2234,6	3801,2
	0,163	0,112		>0,185	2987,1	2439,7	3813,8
	0,131	0,109		>0,166	2660,1	2189,7	3701,8
	0,114	0,126		>0,170	2703,3	2234,7	3098,0
	0,126	0,101		>0,173	2538,5	2279,7	3188,8
	0,116	0,119		>0,167	2644,1	2197,6	3345,0
	0,151	0,115		>0,185	2914,2	2443,8	3770,3
	0,102	0,115		0,158	2477,6	2079,3	3027,0

ANNEX A

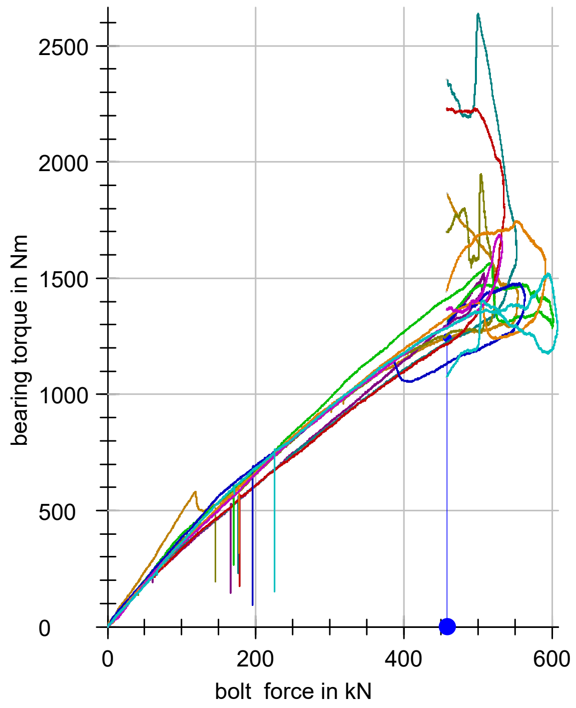
bolt force-tightening torque-curves: M36x160 HR 8.8 - Gleitmo WSP 5040



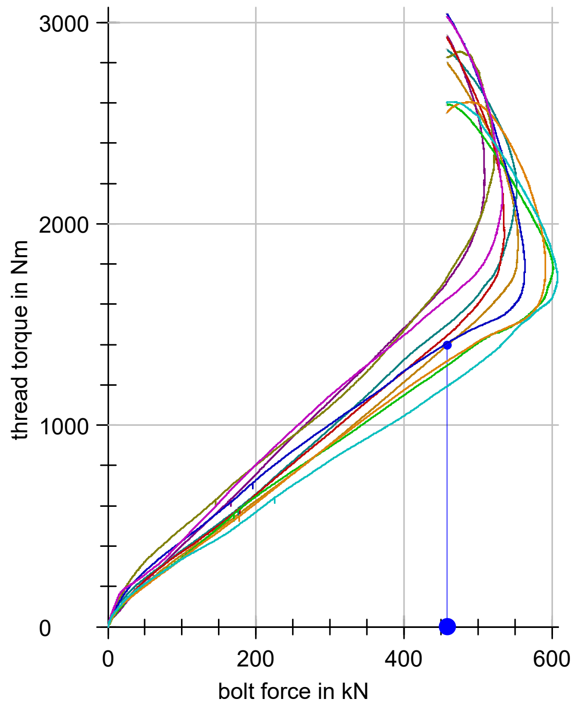
tightening torque-bolt force-curves: M36x160 HR 8.8 - Gleitmo WSP 5040



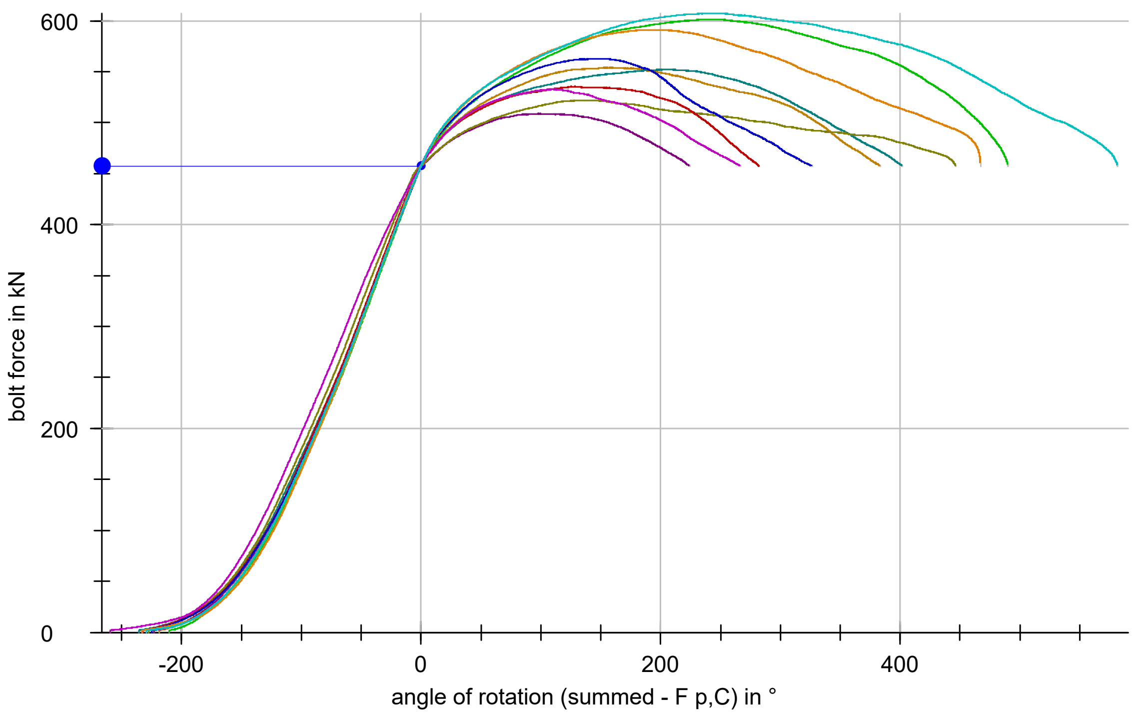
bearing torque-bolt force-curves: M36x160 HR 8.8 - Gleitmo WSP 5040



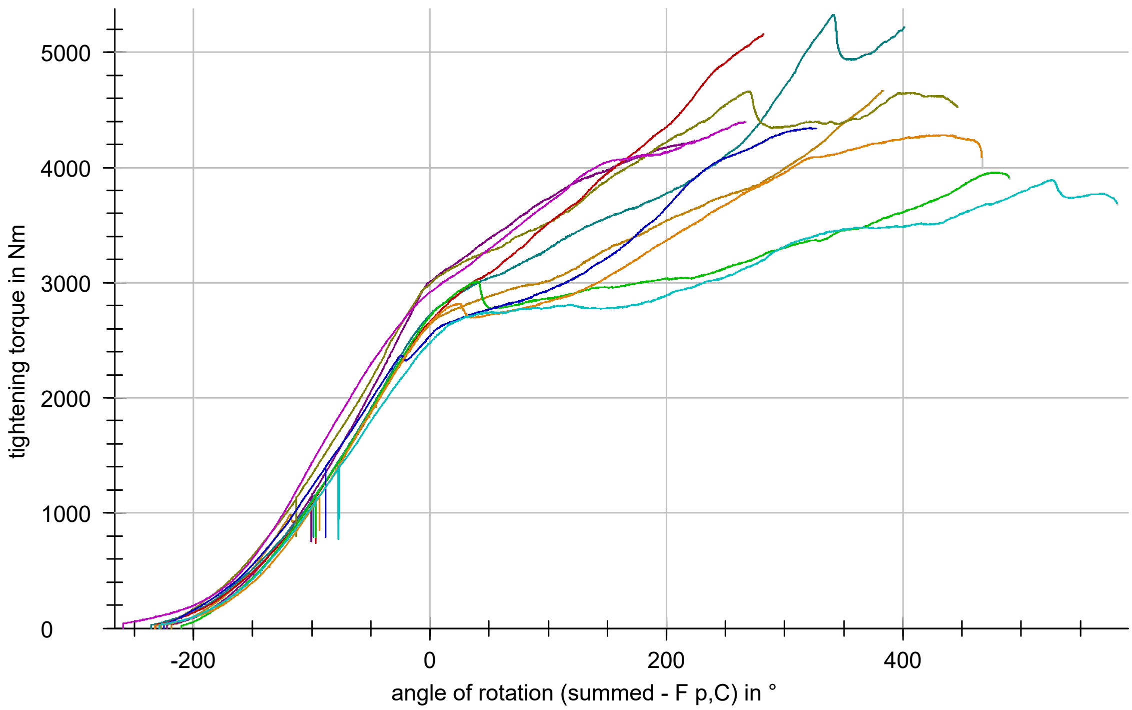
thread torque-bolt force-curves: M36x160 HR 8.8 - Gleitmo WSP 5040



bolt force-angle of rotation-curves: M36x160 HR 8.8 - Gleitmo WSP 5040



tightening torque-angle of rotation-curves: M36x160 HR 8.8 - Gleitmo WSP 5040



Test series: M36x160 HR 8.8 - Molykote 1000 spray

Connecting element	:	M36x160 HR 8.8
Coating / Surface finish	:	M36x160 - tZn
Clamp length Σt	:	75,0 mm
Speed of tightening	:	2,0 1/min
Sensor F - T_{th}	:	SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ	:	SNo. 1016241 - 15000 Nm

Specific thread data:

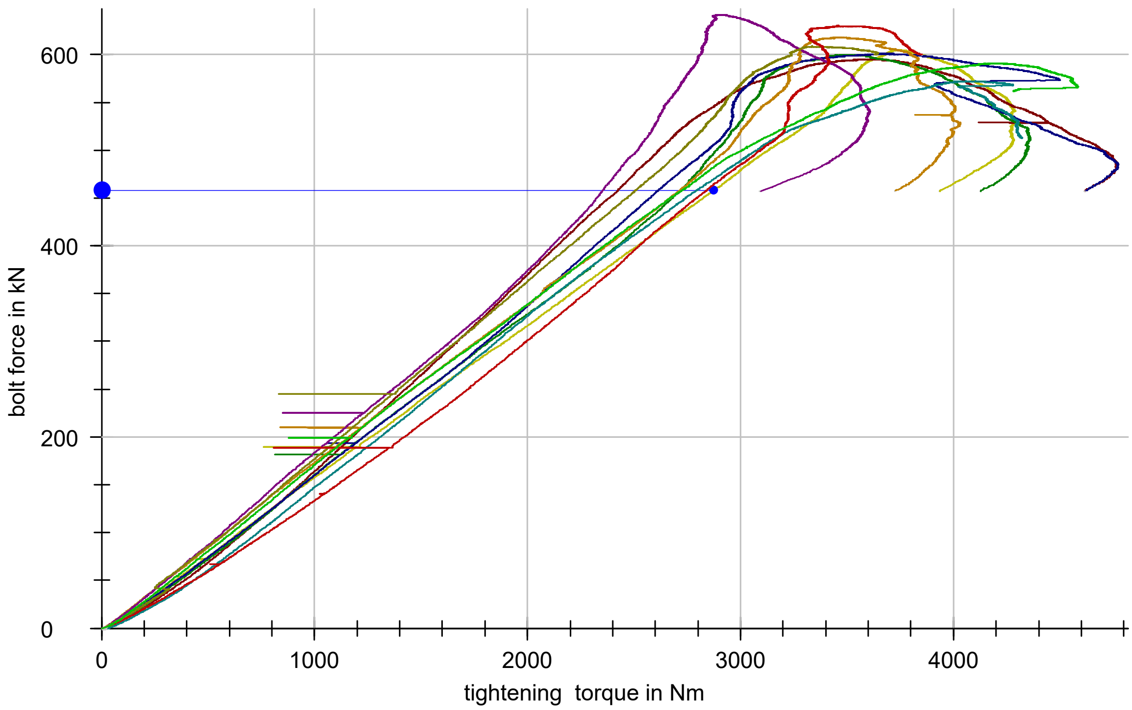
Thread	Thread data	:	M 36/4.00 HV - IML	
d	Nominal diameter	:	36	mm
P	Pitch	:	4	mm
d_2	Pitch diameter	:	33,4	mm
d_o	Outer bearing surface diameter	:	55,9	mm
d_i	Inner bearing surface diameter	:	42	mm
D_b Calc	Bearing surface diameter	:	48,95	mm

Results table: M36x160 HR 8.8 - Molykote 1000 spray

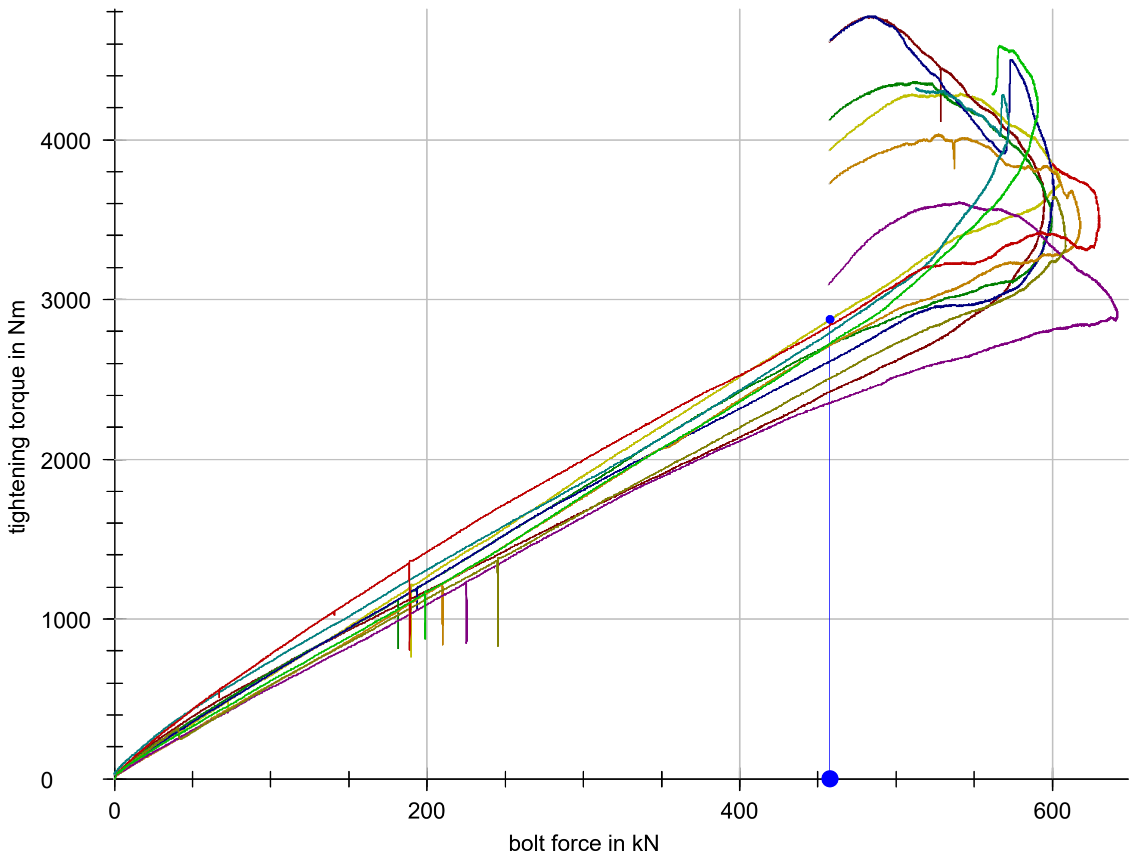
Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		457,5	588,2						120	240	0,10	
	Si_36_HR_8.8-21	457,5	605,1	4290,3	225	467	831	457,1	242	606	>0,17	0,129
	Si_36_HR_8.8-22		595,2	4770,7	215	431	751	457,1	216	537	0,15	0,106
	Si_36_HR_8.8-23		599,6	4362,9	218	486	859	457,2	267	641	>0,17	0,121
	Si_36_HR_8.8-24		600,9	4773,9	210	427	731	457,3	216	520	0,16	0,116
	Si_36_HR_8.8-25		618,0	4033,9	223	500	914	457,2	278	691	>0,16	0,121
	Si_36_HR_8.8-26		641,8	3608,6	211	499	895	456,8	289	684	0,14	0,103
	Si_36_HR_8.8-27		<572,3	4322,6	264	464	666	512,8	200	401	>0,17	0,125
	Si_36_HR_8.8-28		608,6	3644,9	208	499	611	600,3	291	403	0,15	0,110
	Si_36_HR_8.8-29		630,0	3855,6	245	528	648	599,9	282	403	>0,17	0,127
	Si_36_HR_8.8-30		590,9	4586,9	216	459	618	561,4	244	402	>0,17	0,121

Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			366	0,095			
	0,111	0,143	366	>0,175	2872,0	2306,9	3727,0
	0,104	0,108		0,150	2422,5	1978,9	3622,0
	0,113	0,128		>0,169	2720,6	2227,2	3491,9
	0,103	0,126		0,163	2613,0	2148,3	3648,9
	0,092	0,144		0,163	2712,4	2149,9	3453,2
	0,085	0,117		0,149	2349,6	1963,7	2900,2
	0,105	0,141		>0,169	2791,7	2227,2	4056,0
	0,099	0,119		0,153	2503,3	2017,3	3332,5
	0,106	0,144		>0,179	2837,2	2358,2	3454,8
	0,106	0,134		0,164	2723,2	2159,2	4183,8

bolt force-tightening torque-curves: M36x160 HR 8.8 - Molykote 1000 spray

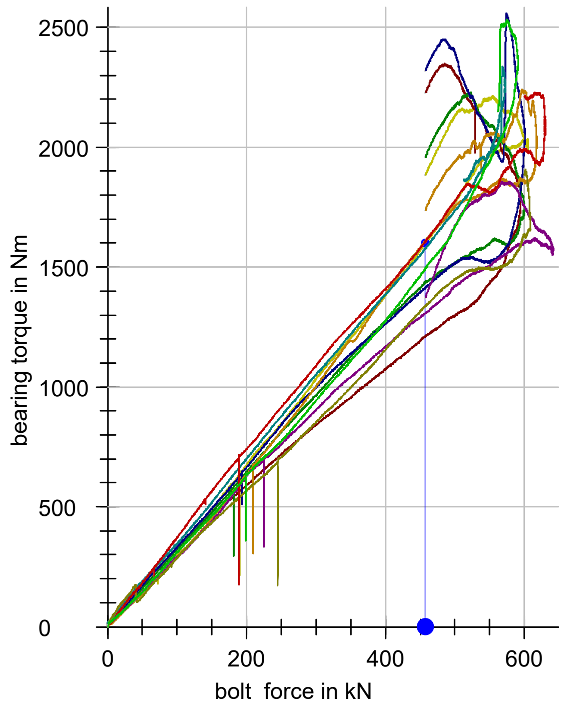


tightening torque-bolt force-curves: M36x160 HR 8.8 - Molykote 1000 spray

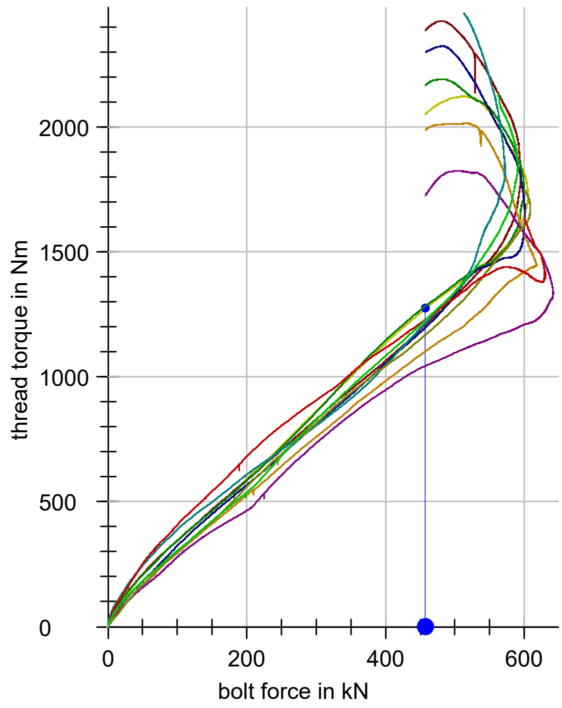


Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

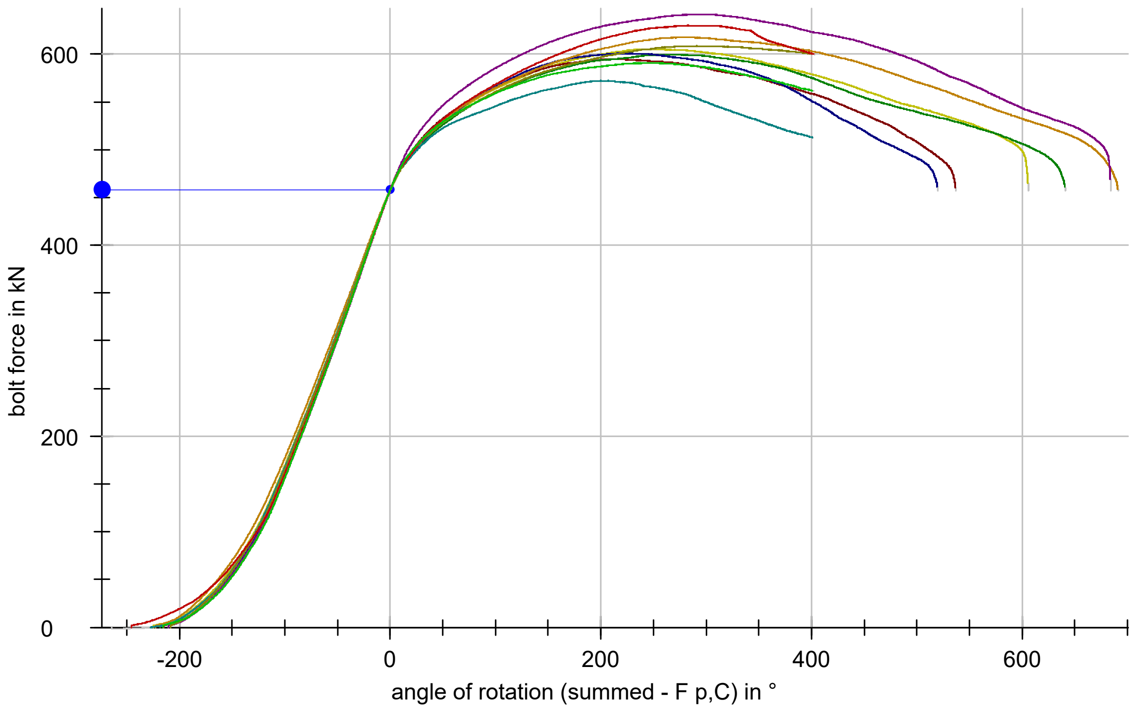
bearing torque-bolt force-curves: M36x160 HR 8.8 - Molykote 1000 spray



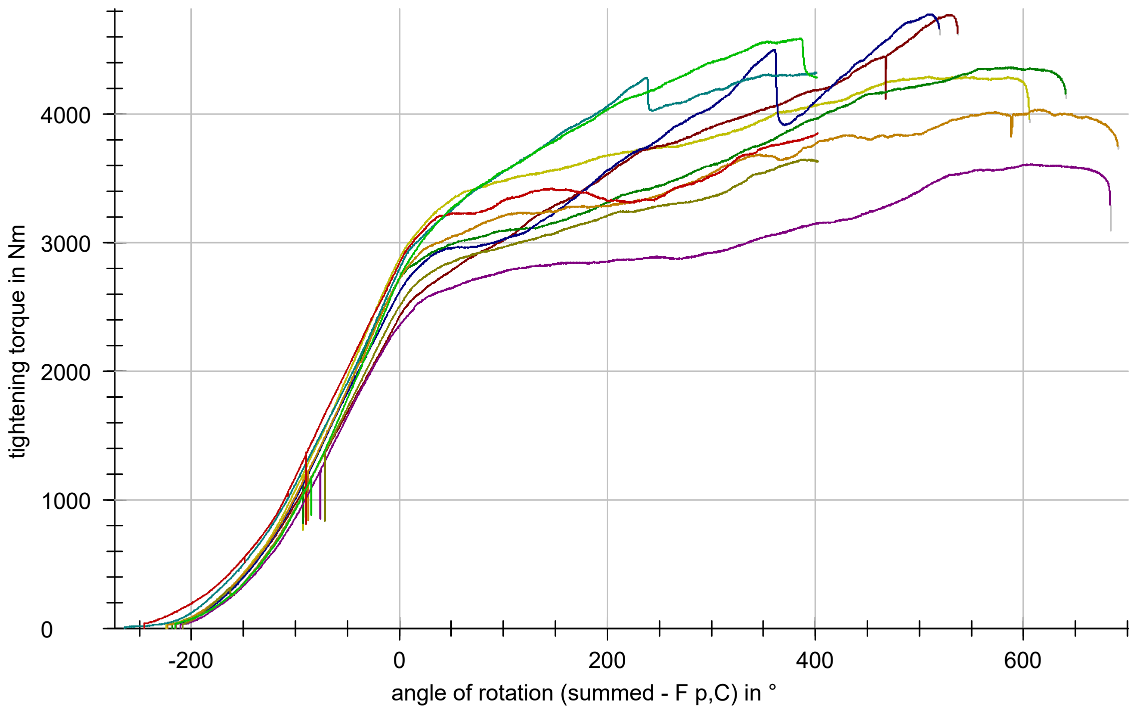
thread torque-bolt force-curves: M36x160 HR 8.8 - Molykote 1000 spray



bolt force-angle of rotation-curves: M36x160 HR 8.8 - Molykote 1000 spray



tightening torque-angle of rotation-curves: M36x160 HR 8.8 - Molykote 1000 spray



Test series: M36x160 HR 8.8 - Microgleit HV-paste LP440

Connecting element	:	M36x160 HR 8.8
Coating / Surface finish	:	M36x160 - tZn
Clamp length Σt	:	75,0 mm
Speed of tightening	:	2,0 1/min
Sensor F - T_{th}	:	SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ	:	SNo. 1016241 - 15000 Nm

Specific thread data:

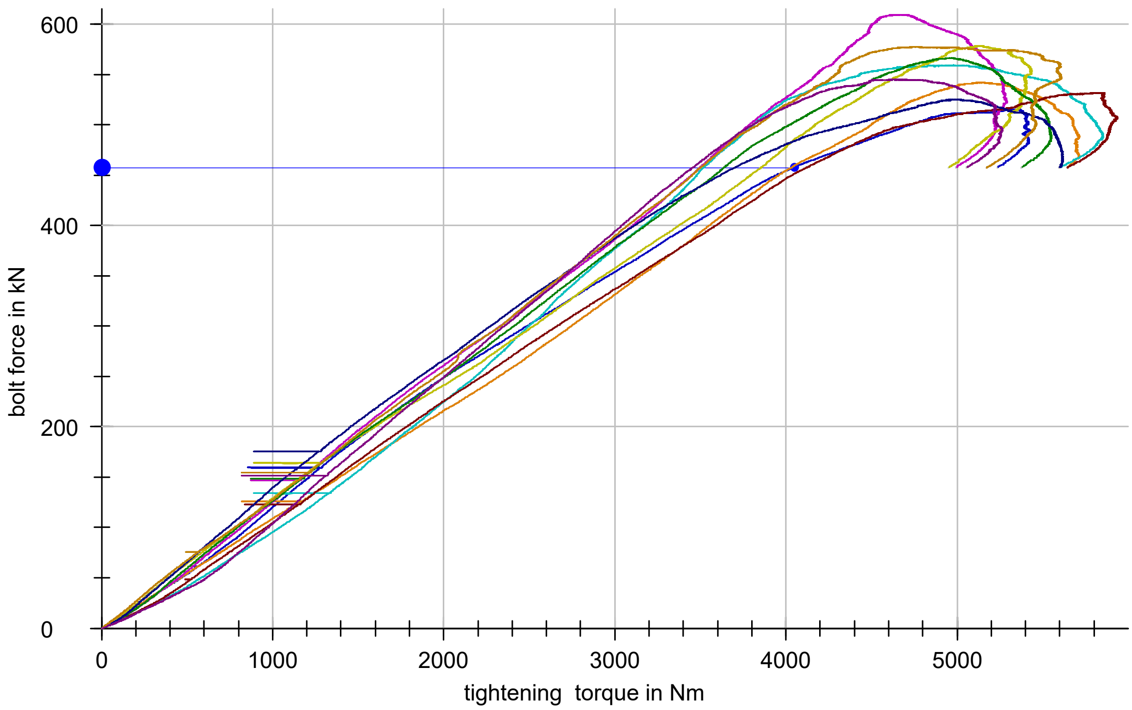
Thread	Thread data	:	M 36/4.00 HV - IML	
d	Nominal diameter	:	36	mm
P	Pitch	:	4	mm
d_2	Pitch diameter	:	33,4	mm
d_o	Outer bearing surface diameter	:	55,9	mm
d_i	Inner bearing surface diameter	:	42	mm
D_b Calc	Bearing surface diameter	:	48,95	mm

Results table: M36x160 HR 8.8 - Microgleit HV-paste LP440

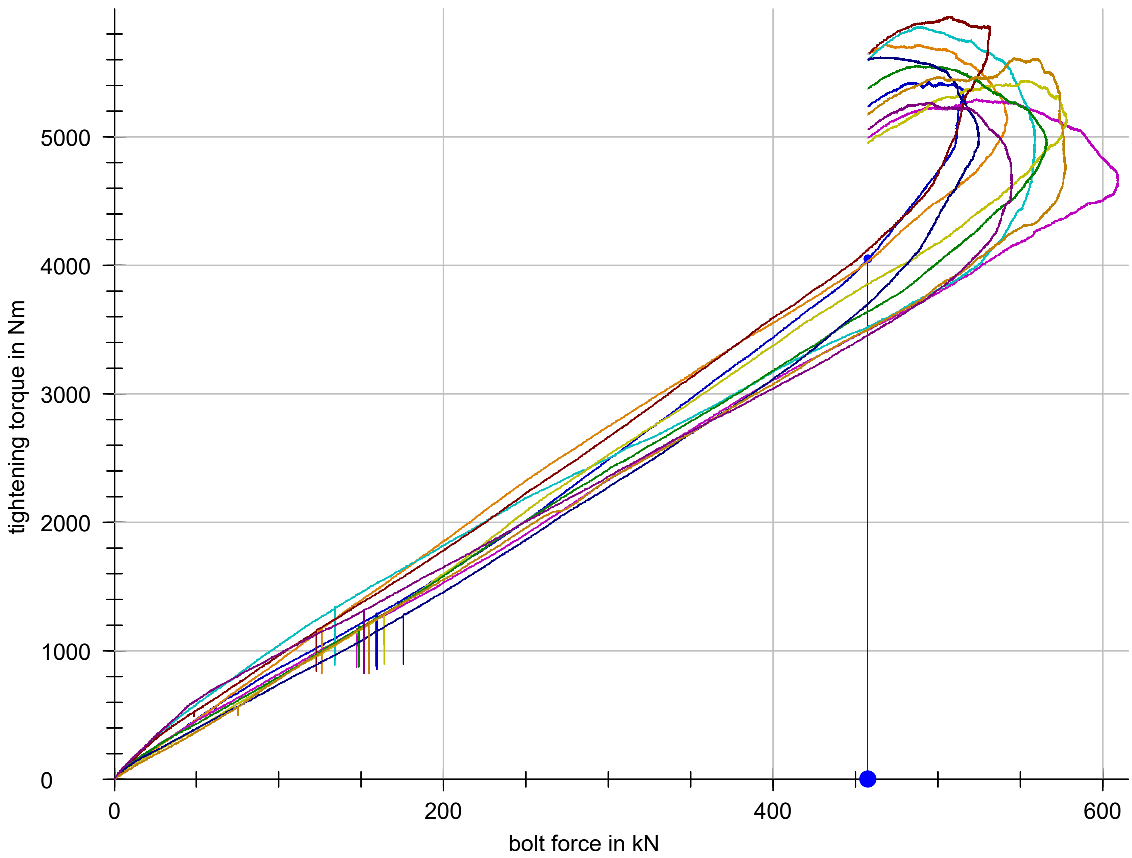
Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		457,5	588,2						120	240	0,10	
	Si_36_HR_8.8-31	457,5	<515,5	5437,8	231	429	711	457,2	198	480	>0,25	0,188
	Si_36_HR_8.8-32		<542,1	5719,2	219	392	660	457,4	173	441	>0,24	0,187
	Si_36_HR_8.8-33		609,3	5293,5	234	503	889	457,3	269	655	>0,21	0,160
	Si_36_HR_8.8-34		<559,1	5855,6	246	436	700	457,2	190	454	>0,21	0,161
	Si_36_HR_8.8-35		<578,4	5437,6	230	491	914	457,3	261	684	>0,23	0,178
	Si_36_HR_8.8-36		<531,9	5938,4	246	502	690	457,3	256	444	>0,25	0,191
	Si_36_HR_8.8-37		<566,1	5554,3	229	399	611	457,3	170	382	>0,22	0,167
	Si_36_HR_8.8-38		<524,9	5621,3	229	398	653	457,5	169	424	>0,22	0,170
	Si_36_HR_8.8-39		<577,5	5611,1	218	418	881	457,2	199	663	>0,21	0,160
	Si_36_HR_8.8-40		<545,1	5265,7	267	428	703	457,4	161	436	>0,21	0,158

Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			366	0,095			
	0,166	0,205	366	>0,237	4047,1	3123,3	5310,1
	0,157	0,210		>0,249	4026,7	3283,3	5149,3
	0,113	0,197		>0,216	3494,7	2845,0	4666,0
	0,151	0,169		>0,222	3518,1	2921,9	4981,8
	0,139	0,209		>0,233	3852,4	3071,7	5114,3
	0,169	0,209		>0,249	4121,2	3275,2	5839,8
	0,127	0,199		>0,220	3638,1	2903,7	4938,4
	0,161	0,177		>0,214	3700,4	2822,5	4978,6
	0,125	0,188		>0,214	3497,7	2823,3	4755,4
	0,144	0,169		>0,214	3455,4	2814,6	4632,4

bolt force-tightening torque-curves: M36x160 HR 8.8 - Microgleit HV-paste LP440

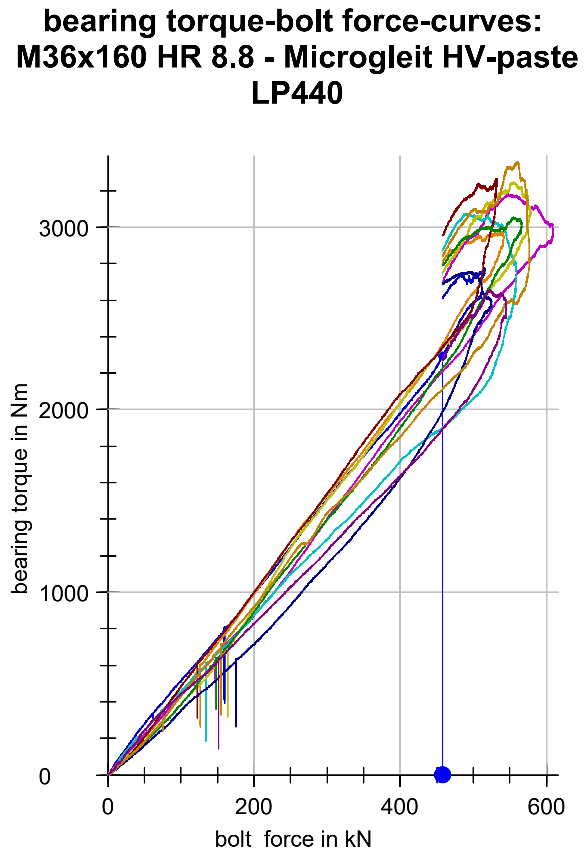


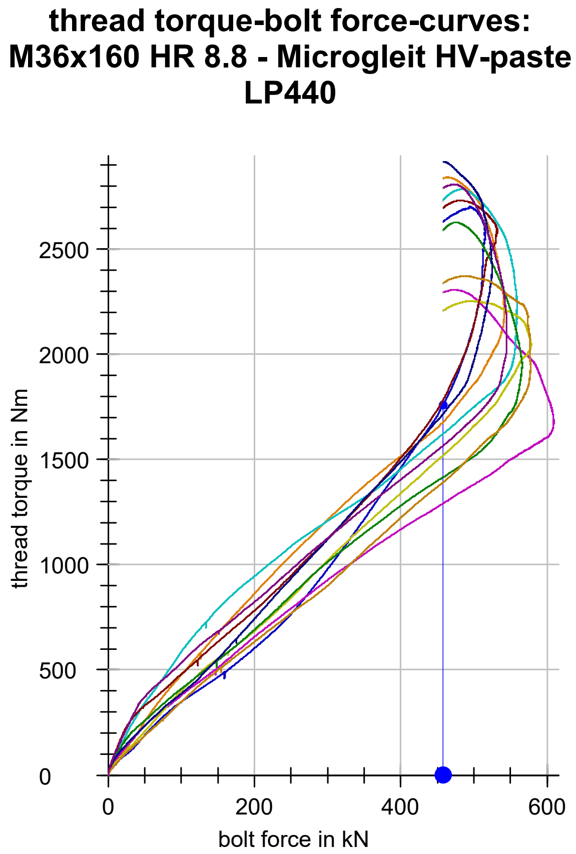
tightening torque-bolt force-curves: M36x160 HR 8.8 - Microgleit HV-paste LP440

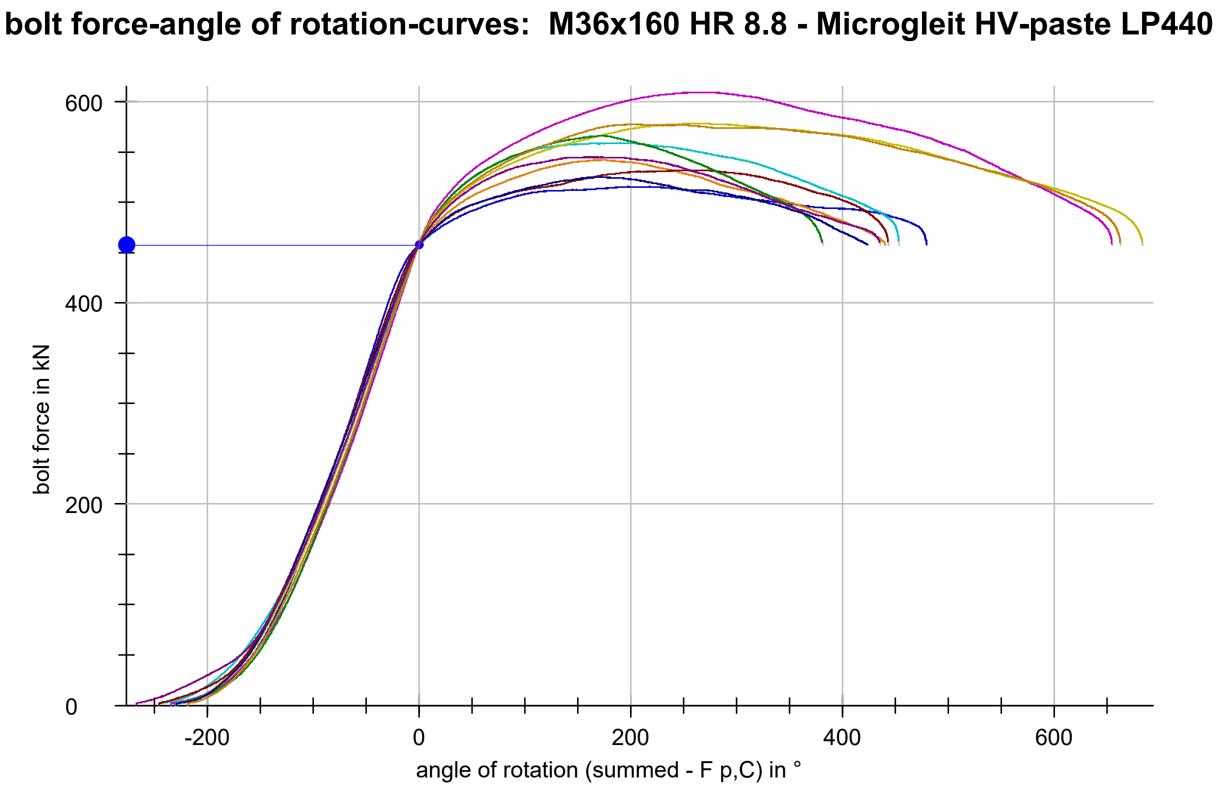


Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

ANNEX A

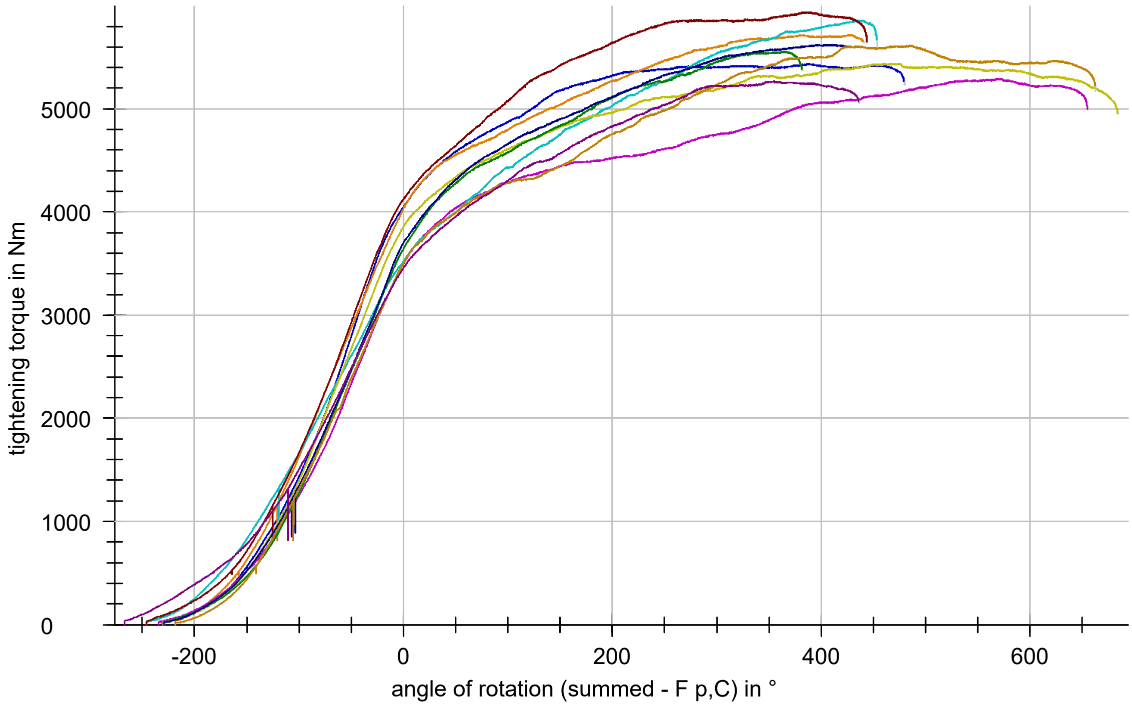






Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

tightening torque-angle of rotation-curves: M36x160 HR 8.8 - Microgleit HV-paste LP440



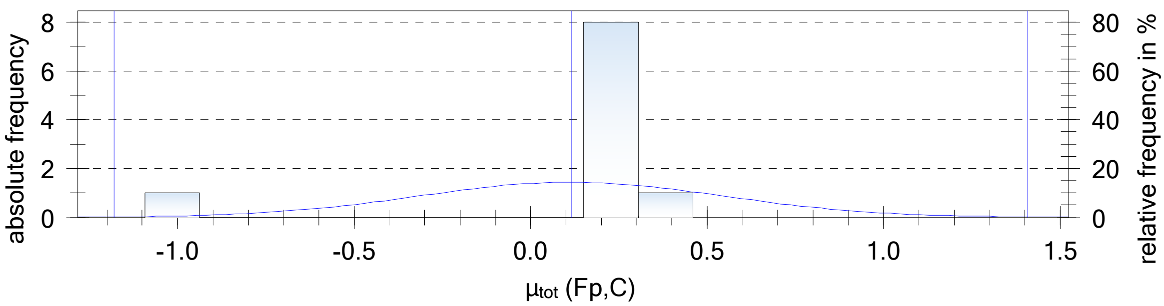
Statistical evaluation: M36x160 HR 8.8 - Factory provided

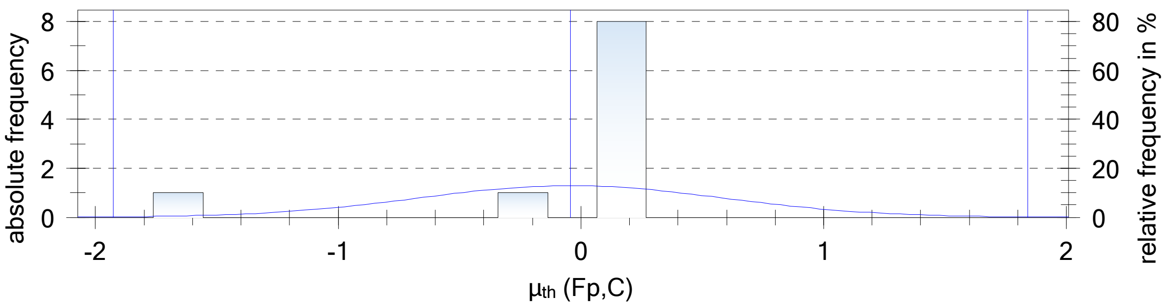
M36x160 HR 8.8 - Factory provided n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	519,9	6618,4	319	492	632	457,5	258	398	0,272
min	419,1	5472,1	223	240	331	457,0	35	82	0,182
R	100,8	1146,3	96	252	301	0,5	223	316	0,090
$\bar{x}$	472,4	6202,5	261	364	520	457,3	111	258	0,222
s	34,7	341,2	33	85	112	0,2	77	114	0,035
ν	7,34	5,50	12,48	23,46	21,56	0,04	69,83	44,20	15,77

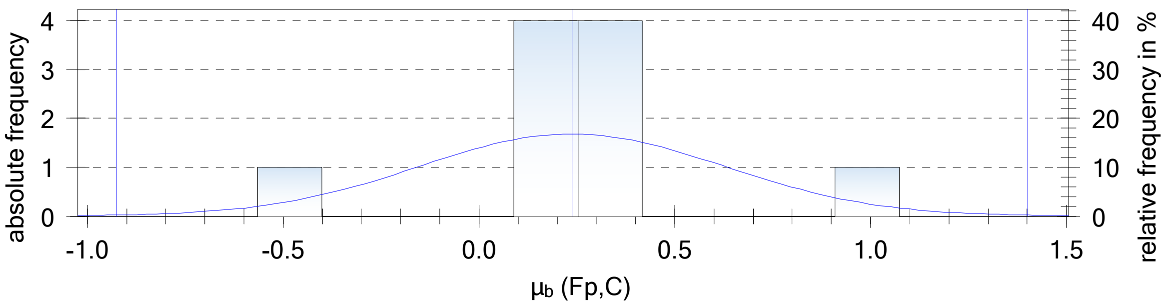
M36x160 HR 8.8 - Factory provided n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C*}$)	M ($F_{bi,max}$) Nm
max	0,268	0,282	5734,3	0,35	4160,9	0,316	6371,3
min	0,123	0,186	3939,8	0,24	2958,5	0,225	4673,7
R	0,145	0,096	1794,5	0,11	1202,4	0,091	1697,6
$\bar{x}$	0,199	0,239	4728,3	0,29	3554,4	0,270	5690,9
s	0,057	0,043	694,0	0,04	381,8	0,029	545,3
ν	28,49	17,87	14,68	14,62	10,74	10,76	9,58

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M36x160 HR 8.8 - Factory provided







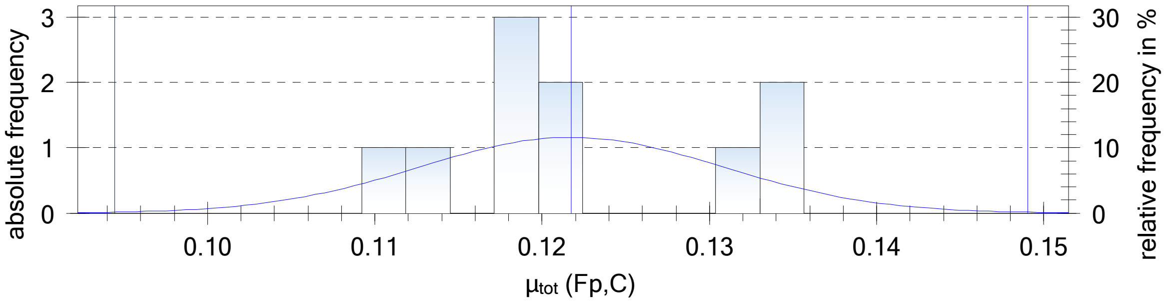
Statistical evaluation: M36x160 HR 8.8 - Gleitmo WSP 5040

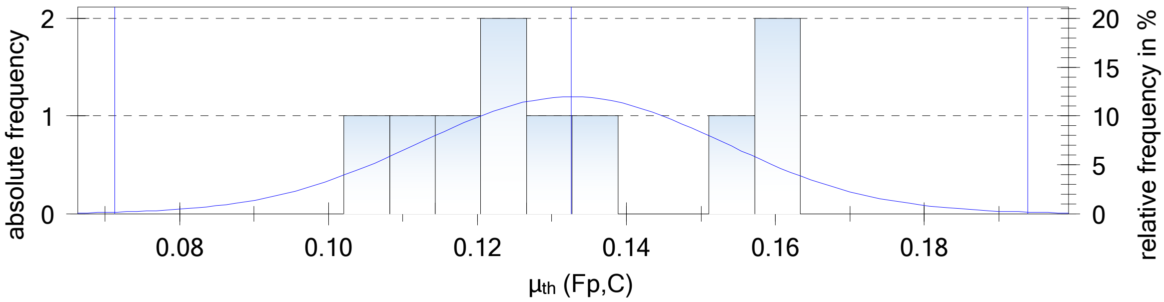
M36x160 HR 8.8 - Gleitmo WSP 5040 n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	607,4	5326,7	259	472	811	457,5	242	582	0,136
min	509,0	3894,2	210	321	447	457,1	98	224	0,109
R	98,4	1432,5	49	151	364	0,4	144	358	0,027
$\bar{x}$	556,9	4493,4	229	396	617	457,4	167	387	0,122
s	33,8	470,2	13	49	109	0,1	52	113	0,009
ν	6,08	10,46	5,60	12,44	17,70	0,03	31,39	29,13	7,63

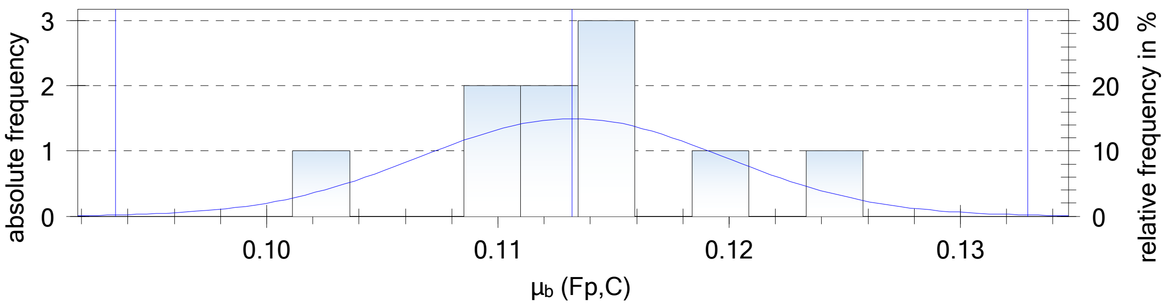
M36x160 HR 8.8 - Gleitmo WSP 5040 n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k (F_{p,C^*})	M ($F_{bi,max}$) Nm
max	0,163	0,126	3007,6	0,18	2443,8	0,185	3813,8
min	0,102	0,101	2477,6	0,15	2079,3	0,158	3027,0
R	0,061	0,025	530,0	0,03	364,5	0,027	786,8
$\bar{x}$	0,133	0,113	2729,0	0,17	2270,7	0,172	3479,7
s	0,020	0,007	182,3	0,01	121,7	0,009	313,0
ν	15,39	5,90	6,68	7,14	5,36	5,29	9,00

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M36x160 HR 8.8 - Gleitmo WSP 5040







Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

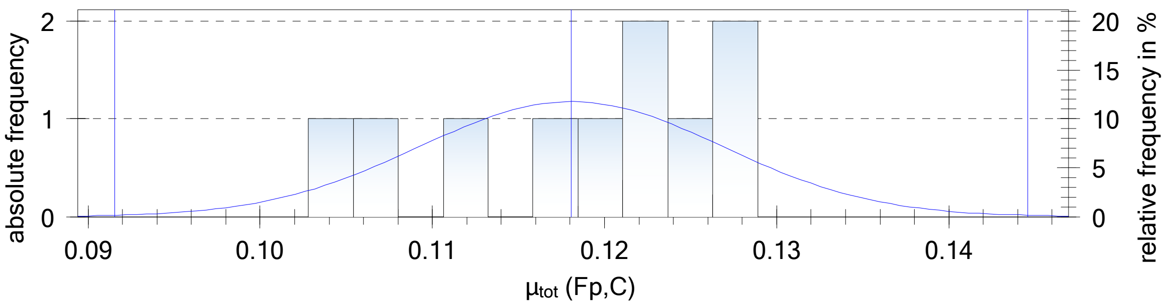
Statistical evaluation: M36x160 HR 8.8 - Molykote 1000 spray

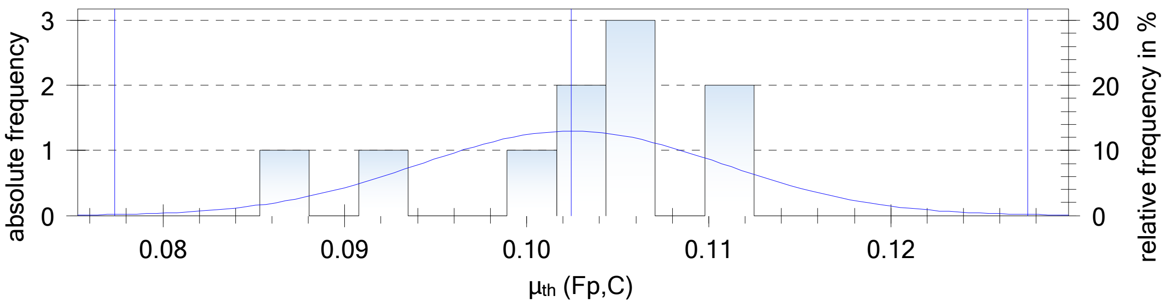
M36x160 HR 8.8 - Molykote 1000 spray n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	641,8	4773,9	264	528	914	600,3	291	691	0,129
min	572,3	3608,6	208	427	611	456,8	200	401	0,103
R	69,5	1165,3	56	101	303	143,5	91	290	0,026
$\bar{x}$	606,2	4225,0	224	476	752	501,7	253	529	0,118
s	19,9	428,5	18	32	116	62,3	34	122	0,009
ν	3,28	10,14	7,95	6,78	15,40	12,43	13,30	23,00	7,56

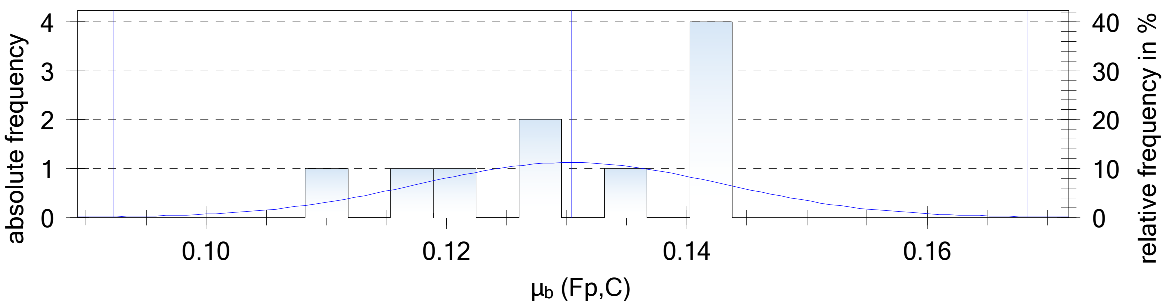
M36x160 HR 8.8 - Molykote 1000 spray n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C*}$)	M ($F_{bi,max}$) Nm
max	0,113	0,144	2872,0	0,17	2358,2	0,179	4183,8
min	0,085	0,108	2349,6	0,14	1963,7	0,149	2900,2
R	0,028	0,036	522,4	0,03	394,5	0,030	1283,6
$\bar{x}$	0,102	0,130	2654,6	0,16	2153,7	0,163	3587,0
s	0,008	0,013	177,4	0,01	133,9	0,010	362,3
ν	8,26	9,87	6,68	6,84	6,22	6,24	10,10

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M36x160 HR 8.8 - Molykote 1000 spray







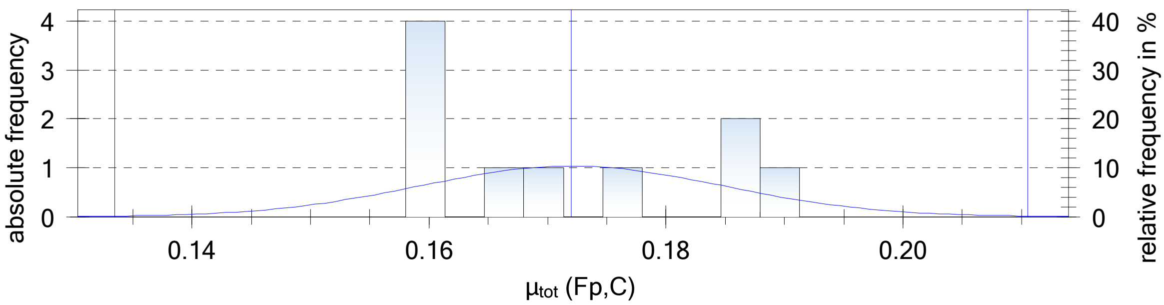
Statistical evaluation: M36x160 HR 8.8 - Microgleit HV-paste LP440

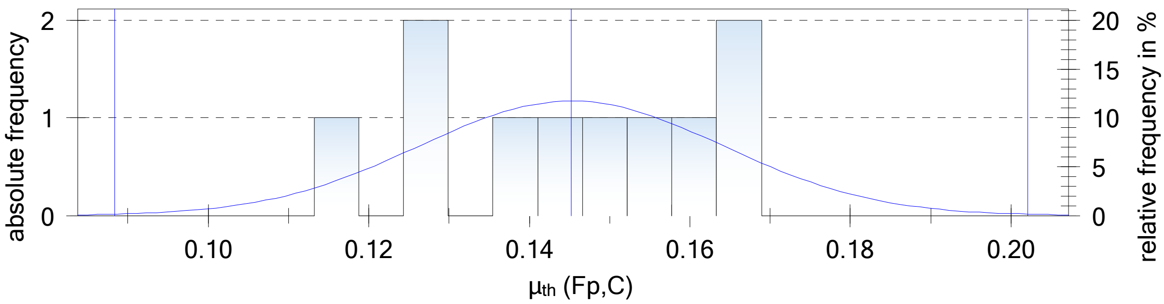
M36x160 HR 8.8 - Microgleit HV-paste LP440 n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	609,3	5938,4	267	503	914	457,5	269	684	0,191
min	515,5	5265,7	218	392	611	457,2	161	382	0,158
R	93,8	672,7	49	111	303	0,3	108	302	0,033
$\bar{x}$	555,0	5573,5	235	440	741	457,3	205	506	0,172
s	28,7	223,1	15	43	110	0,1	42	114	0,013
ν	5,17	4,00	6,23	9,87	14,87	0,02	20,36	22,52	7,54

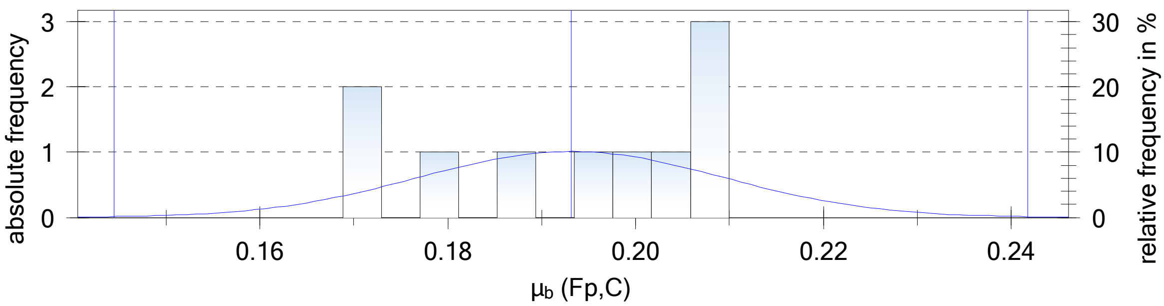
M36x160 HR 8.8 - Microgleit HV-paste LP440 n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C*}$)	M ($F_{bi,max}$) Nm
max	0,169	0,210	4121,2	0,25	3283,3	0,249	5839,8
min	0,113	0,169	3455,4	0,21	2814,6	0,214	4632,4
R	0,056	0,041	665,8	0,04	468,7	0,035	1207,4
$\bar{x}$	0,145	0,193	3735,2	0,23	2988,5	0,227	5036,6
s	0,019	0,016	257,2	0,02	186,0	0,014	355,0
ν	13,06	8,50	6,89	7,33	6,23	6,25	7,05

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M36x160 HR 8.8 - Microgleit HV-paste LP440







Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

M36 HR 10.9 - Test protocol

SIROCO - Tightening tests of HR bolting assemblies

Client / Customer	:	SIROCO
Date of reception	:	-
Date of testing	:	07.04.2016 and 13.04.2016 M36x160 HR 10.9
Project	:	RFCS SIROCO WP 1 Task 1.5
Specification	:	According EN 14399-2 and EN ISO 16047
Operator	:	Christoph Abraham B.Sc., Dominik Jungbluth M.Sc.
Number of assemblies tested	:	40
Designation of bolt	:	M36x160 HR 10.9
Marking of bolt	:	M36 FAST 10.9 HR
Designation of nut	:	Hexagon nut HR M36
Marking of nut	:	FAST 10HR
Designation of washer	:	Washer M36 HR
Marking of washer	:	FAST H
Coating / Surface finish	:	M36x160 - tZn
Ambient temperature	:	23,6 °C
Ambient relative humidity	:	25,8 %
Rotated component	:	Hexagon nut
Special testing conditions	:	Different lubrications used: Si_36_10_1-10: Factory provided lubrication Si_36_10_11-20: Gleitmo WSP 5040 Si_36_10_21-30: Molykote 1000 spray Si_36_10_31-40: Microgleit HV-paste LP440 Total bolt fracture occured: Si_36_10_1 Si_36_10_8 Si_36_10_11 Si_36_10_12 Si_36_10_21 Si_36_10_31 Si_36_10_32 Si_36_10_33 Si_36_10_34 Si_36_10_35 Annotations: Changed test procedure because of bolt fractures and heavy vibrations of IML tightening testing machine. New stop criteria for testing: Bolt force dropped to 660 kN or angle of rotation Delta-Tetha2i = 400° * Tested with regular stop criteria (bolt force dropped to Fp,C) ** Invalid. Old lubrication used.

Test specimens identification

Si_xx_yy_zz

Si: RFCS SIROCO
xx: thread
yy: strength class
zz: sequential number of bolt

ANNEX A

Test series: M36x160 HR 10.9 - Factory provided

Connecting element	:	M36x160 HR 10.9
Coating / Surface finish	:	M36x160 - tZn
Clamp length Σt	:	123,5 mm
Speed of tightening	:	2,0 1/min
Sensor F - T_{th}	:	SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ	:	SNo. 1016241 - 15000 Nm

Specific thread data:

Thread	Thread data	:	M 36/4.00 HV - IML	
d	Nominal diameter	:	36	mm
P	Pitch	:	4	mm
d_2	Pitch diameter	:	33,4	mm
d_o	Outer bearing surface diameter	:	55,9	mm
d_i	Inner bearing surface diameter	:	42	mm
D_b Calc	Bearing surface diameter	:	48,95	mm

Results table: M36x160 HR 10.9 - Factory provided

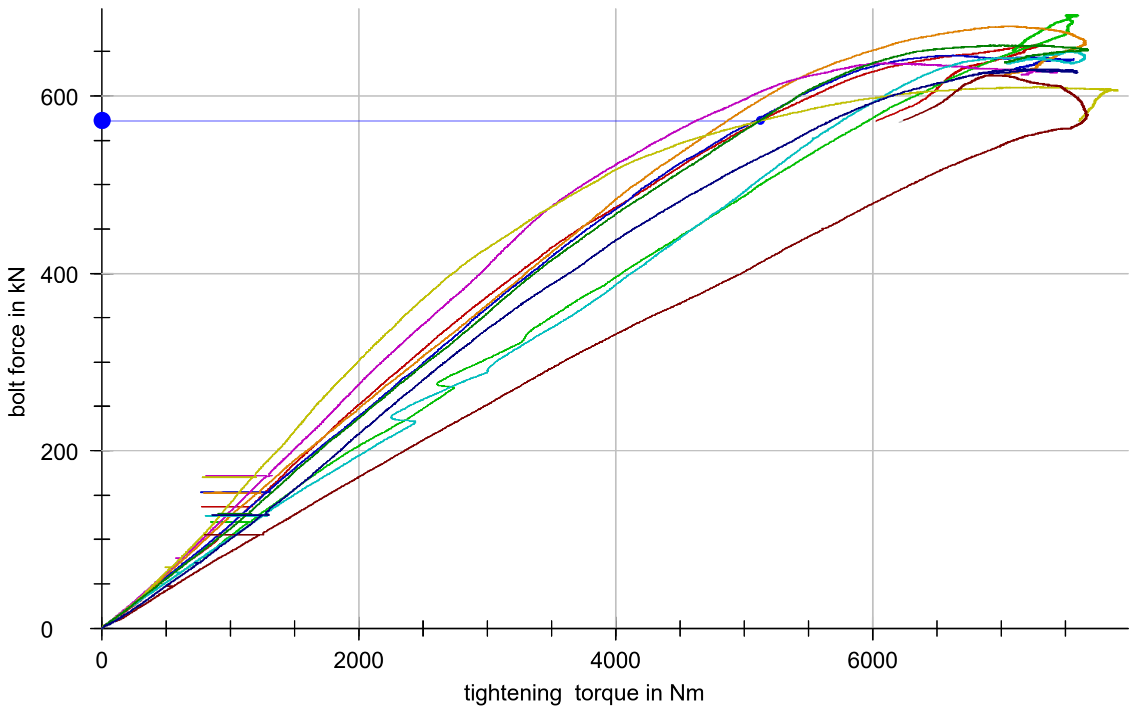
Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		571,9	735,3						120	240	0,10	
	Si_36_HR_10.9-01	571,9	<659,0	7318,1	242	457	739	571,1	215	498	>0,25	0,190
	Si_36_HR_10.9-02		<691,7	7600,2	284	493	685	651,0	210	401	>0,29	0,224
	Si_36_HR_10.9-03		<645,7	7565,5	248	321	649	631,1	<74	401	>0,25	0,189
	Si_36_HR_10.9-04		<678,5	7656,3	291	382	692	623,4	<91	401	>0,24	0,180
	Si_36_HR_10.9-05		<637,2	7433,5	252	326	653	623,7	<75	401	>0,22	0,170
	Si_36_HR_10.9-06		<650,5	7654,0	246	482	647	636,5	236	401	>0,28	0,216
	Si_36_HR_10.9-07		<610,0	7904,4	293	362	567	571,8	<68	273	>0,25	0,190
	Si_36_HR_10.9-08		<623,7	7672,1	349	625	693	570,1	276	343	>0,37	0,291
	Si_36_HR_10.9-09		<656,9	7675,3	268	366	670	637,7	<98	401	>0,25	0,190
	Si_36_HR_10.9-10		<630,3	7591,6	292	386	693	625,3	<94	401	>0,28	0,212

Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			514,7	0,095			
	0,171	0,205	514,7	>0,240	5122,1	4443,4	7301,6
	0,176	0,261		>0,285	5962,3	5289,1	7578,1
	0,161	0,210		>0,238	5081,8	4403,4	6618,1
	0,125	0,223		>0,231	4863,8	4286,4	7088,2
	0,156	0,181		>0,211	4620,7	3906,4	6087,1
	0,155	0,263		>0,281	5758,3	5200,6	7537,0
	0,176	0,202		>0,214	5126,5	3969,6	7258,9
	0,324	0,264		>0,351	7634,2	6505,9	6927,1
	0,171	0,205		>0,243	5121,3	4508,3	6952,3
	0,211	0,213		>0,265	5669,2	4909,9	7171,2

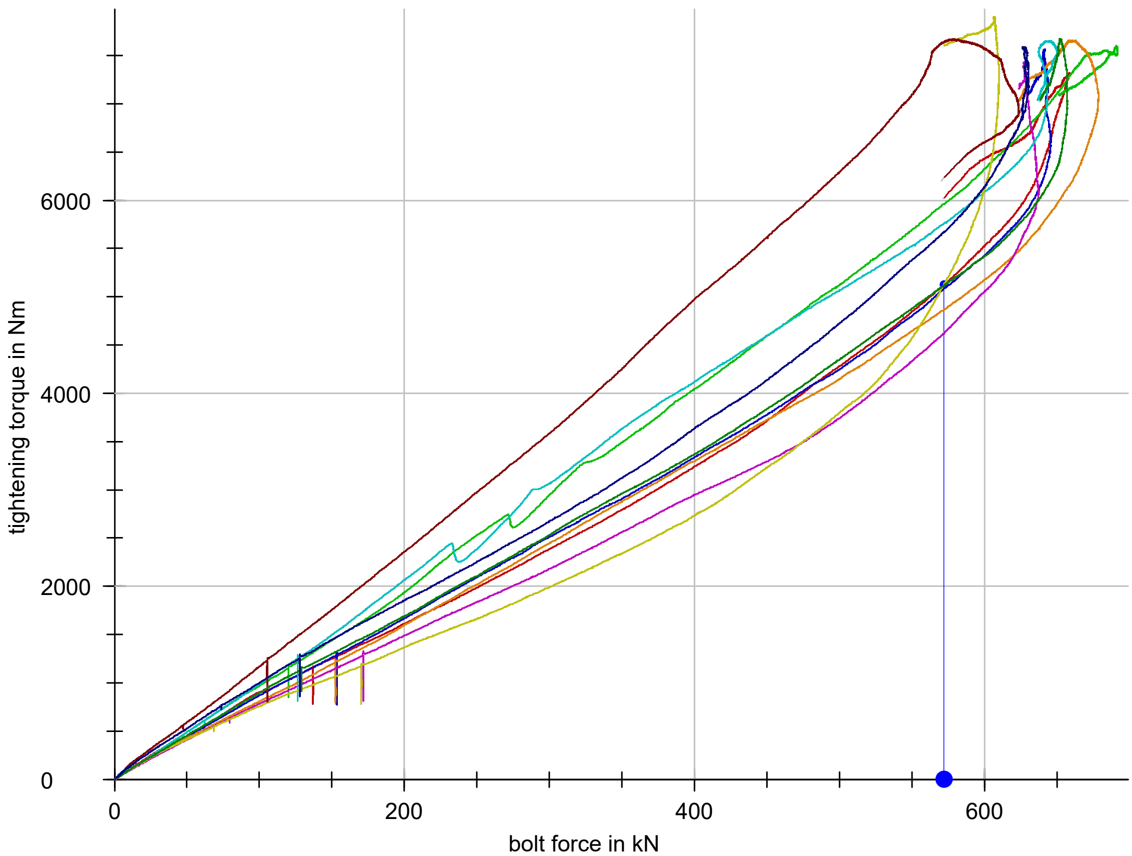
Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

ANNEX A

bolt force-tightening torque-curves: M36x160 HR 10.9 - Factory provided

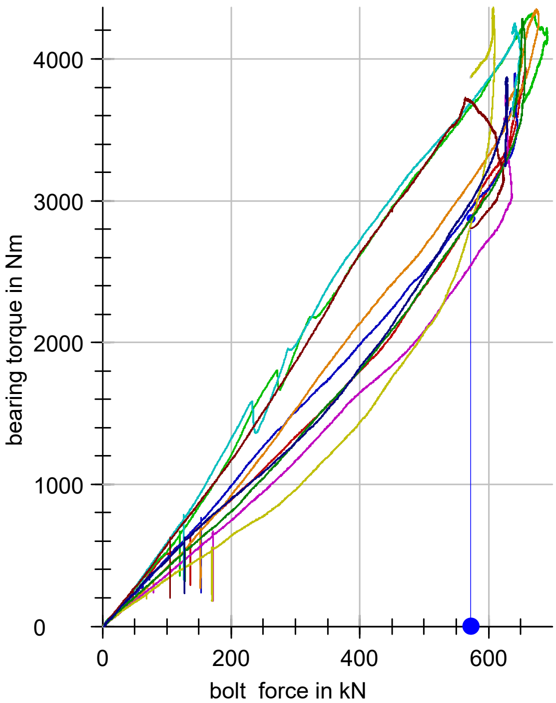


tightening torque-bolt force-curves: M36x160 HR 10.9 - Factory provided

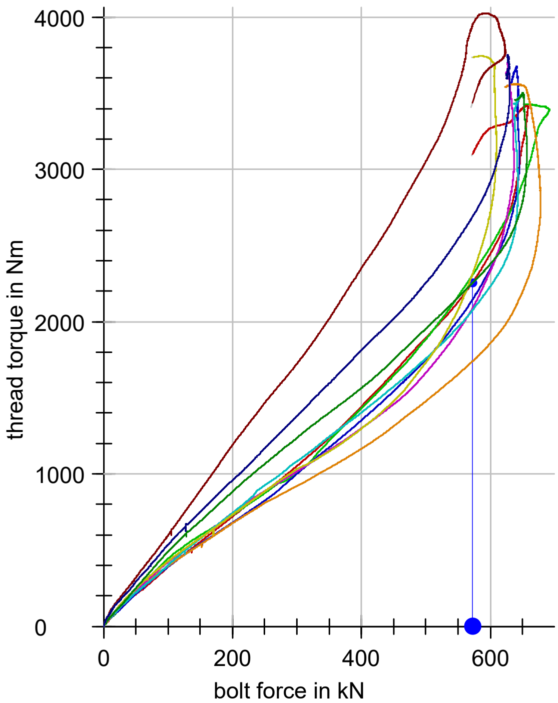


ANNEX A

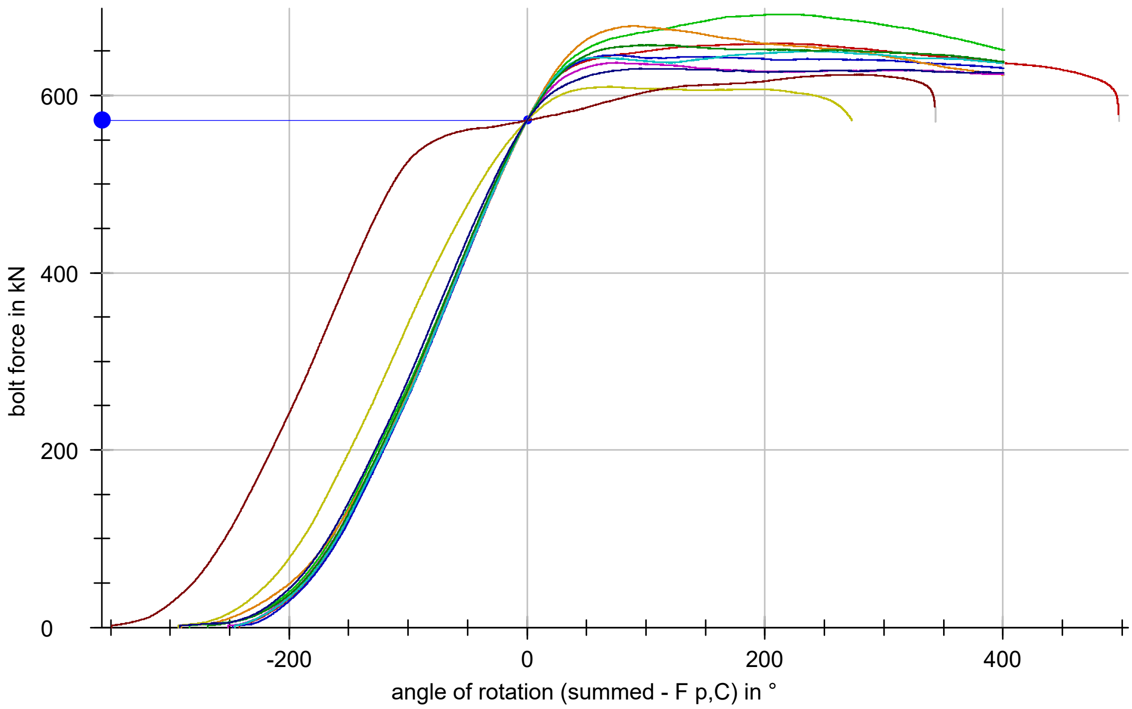
bearing torque-bolt force-curves: M36x160 HR 10.9 - Factory provided



thread torque-bolt force-curves: M36x160 HR 10.9 - Factory provided

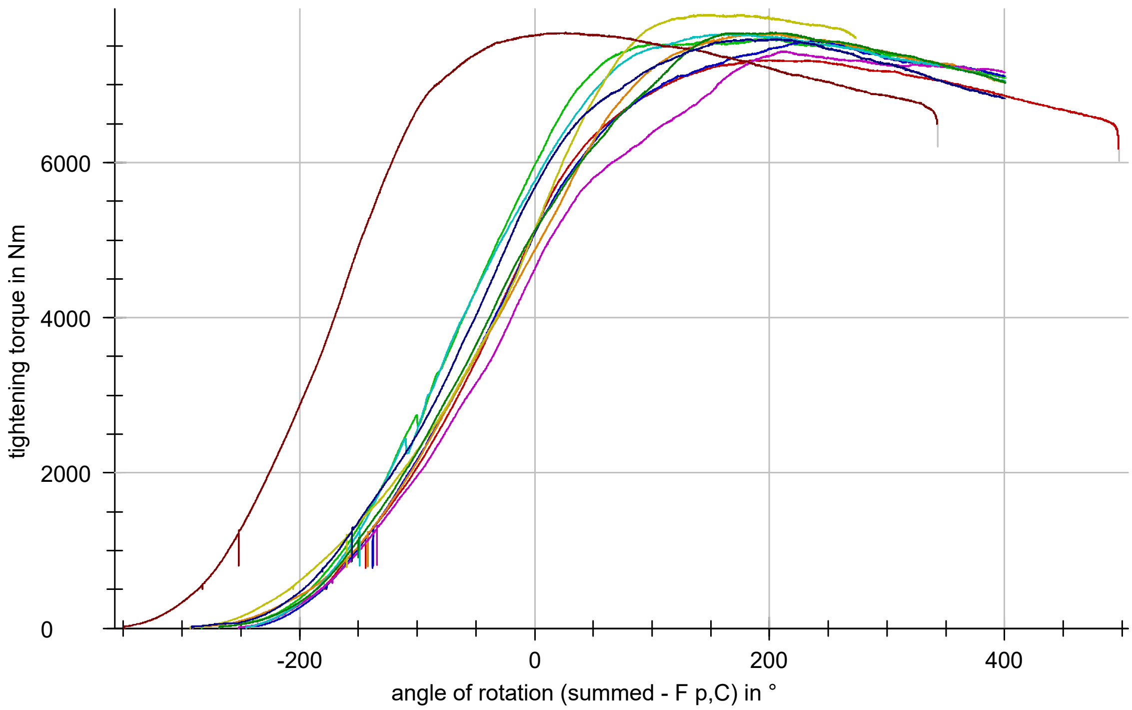


bolt force-angle of rotation-curves: M36x160 HR 10.9 - Factory provided



ANNEX A

tightening torque-angle of rotation-curves: M36x160 HR 10.9 - Factory provided



Test specimens identification

Si_xx_yy_zz

Si: RFCS SIROCO
xx: thread
yy: strength class
zz: sequential number of bolt

Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

Test series: M36x160 HR 10.9 - Gleitmo WSP 5040

Connecting element	:	M36x160 HR 10.9
Coating / Surface finish	:	M36x160 - tZn
Clamp length Σt	:	123,5 mm
Speed of tightening	:	2,0 1/min
Sensor F - T_{th}	:	SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ	:	SNo. 1016241 - 15000 Nm

Specific thread data:

Thread	Thread data	:	M 36/4.00 HV - IML	
d	Nominal diameter	:	36	mm
P	Pitch	:	4	mm
d_2	Pitch diameter	:	33,4	mm
d_o	Outer bearing surface diameter	:	55,9	mm
d_i	Inner bearing surface diameter	:	42	mm
D_b Calc	Bearing surface diameter	:	48,95	mm

Results table: M36x160 HR 10.9 - Gleitmo WSP 5040

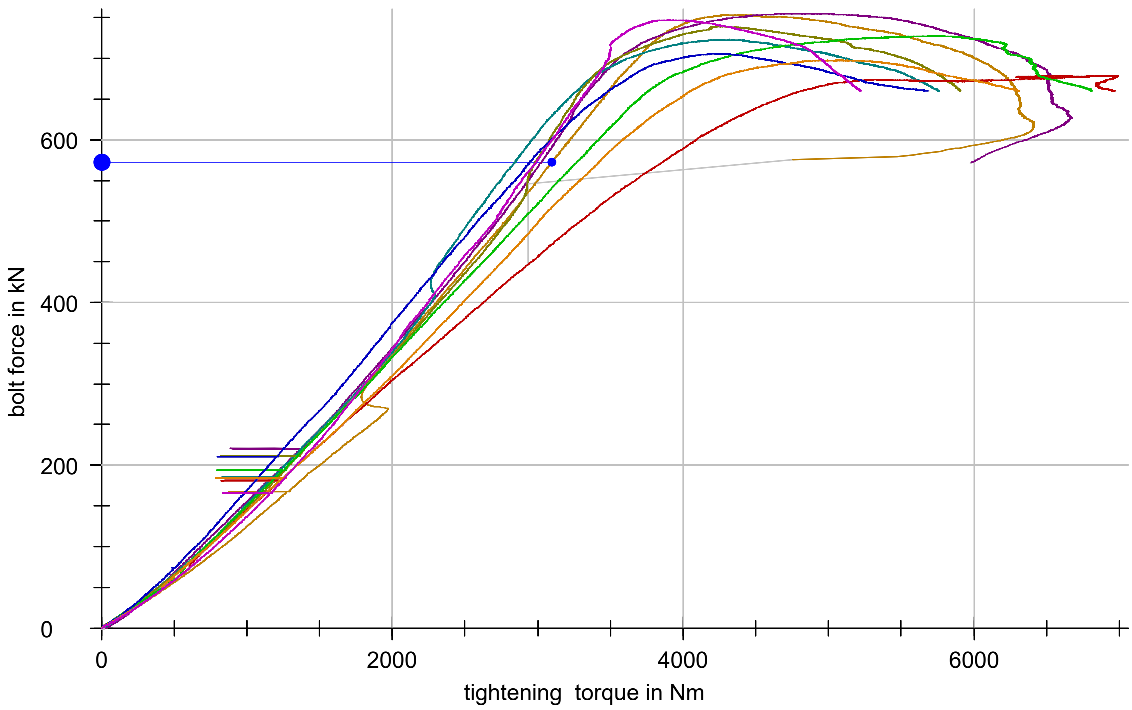
Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		571,9	735,3						120	240	0,10	
	Si_36_HR_10.9-11	571,9	753,6	6414,3	240	367	734	447,1	127	494	0,15	0,109
	Si_36_HR_10.9-12		755,5	6672,2	348	500	892	571,3	152	544	0,15	0,106
	Si_36_HR_10.9-14		<723,1	5767,7	268	377	595	659,9	<109	327	0,14	0,099
	Si_36_HR_10.9-15		739,4	5914,9	255	388	573	660,0	133	318	0,14	0,105
	Si_36_HR_10.9-16		<679,3	6989,7	248	488	594	659,8	240	345	>0,19	0,139
	Si_36_HR_10.9-17		<728,0	6810,7	246	428	632	659,9	182	386	0,16	0,116
	Si_36_HR_10.9-18		<706,3	5697,7	269	375	515	659,9	<106	246	0,14	0,103
	Si_36_HR_10.9-19		<698,1	6314,2	243	357	464	660,0	<114	<220	>0,17	0,122
	Si_36_HR_10.9-20		747,3	5225,1	278	421	592	660,0	143	314	0,14	0,105

Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			514,7	0,095			
	0,106	0,112	514,7	0,154	3097,7	2845,4	4317,5
	0,107	0,106		0,150	3026,4	2785,5	4811,3
	0,086	0,109		0,140	2840,1	2596,9	4318,2
	0,103	0,106		0,154	2981,7	2855,2	4248,2
	0,176	0,110		>0,184	3849,6	3402,5	6920,4
	0,122	0,111		0,160	3264,9	2962,3	5766,1
	0,111	0,097		0,144	2943,5	2661,1	4250,6
	0,127	0,118		>0,167	3414,5	3086,7	5093,1
	0,107	0,103		0,149	2984,9	2757,4	3894,2

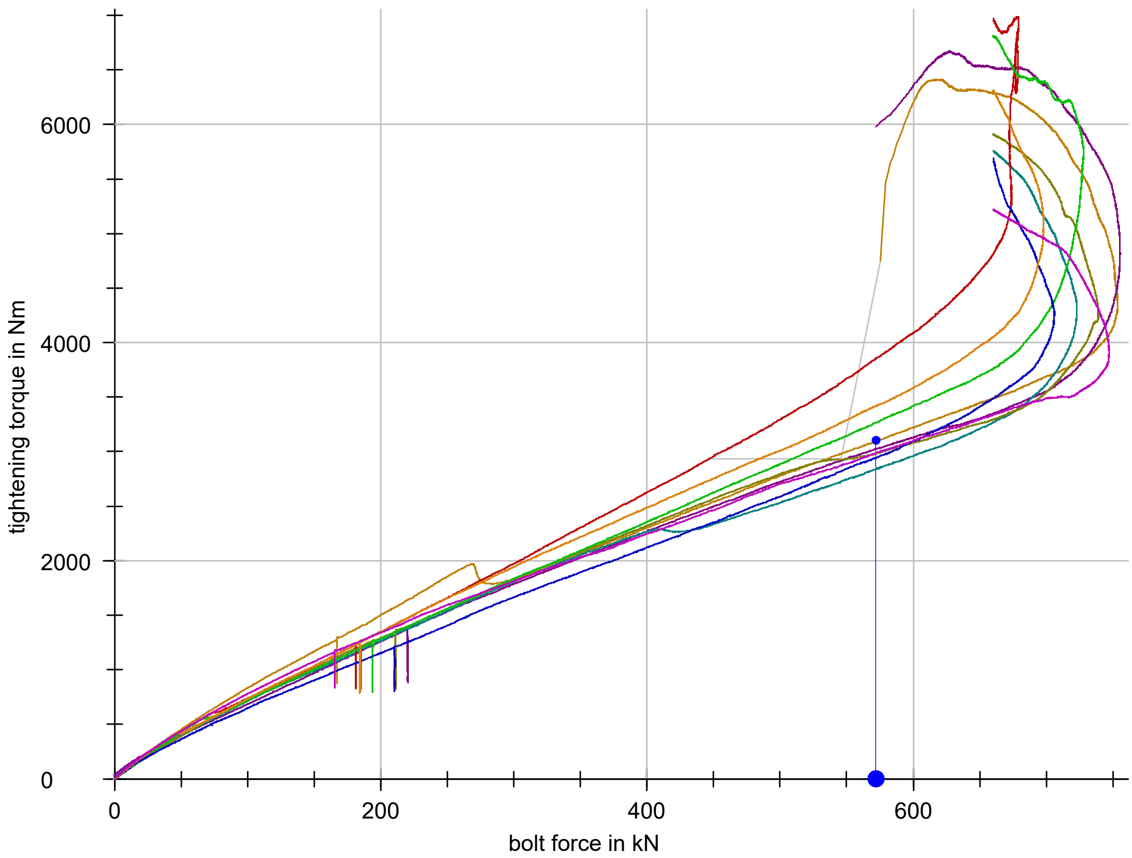
Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

ANNEX A

bolt force-tightening torque-curves: M36x160 HR 10.9 - Gleitmo WSP 5040

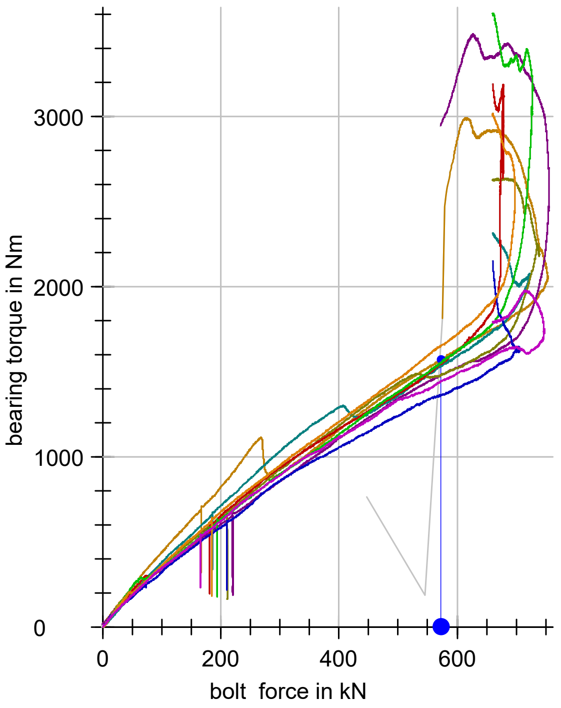


tightening torque-bolt force-curves: M36x160 HR 10.9 - Gleitmo WSP 5040

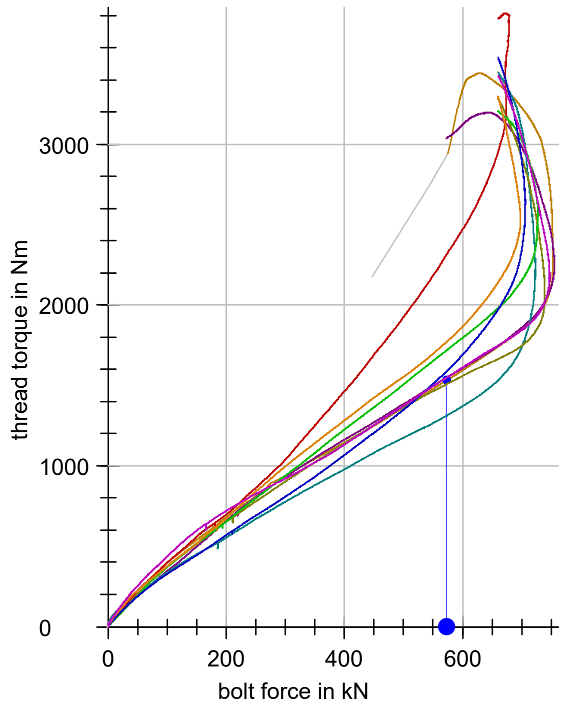


ANNEX A

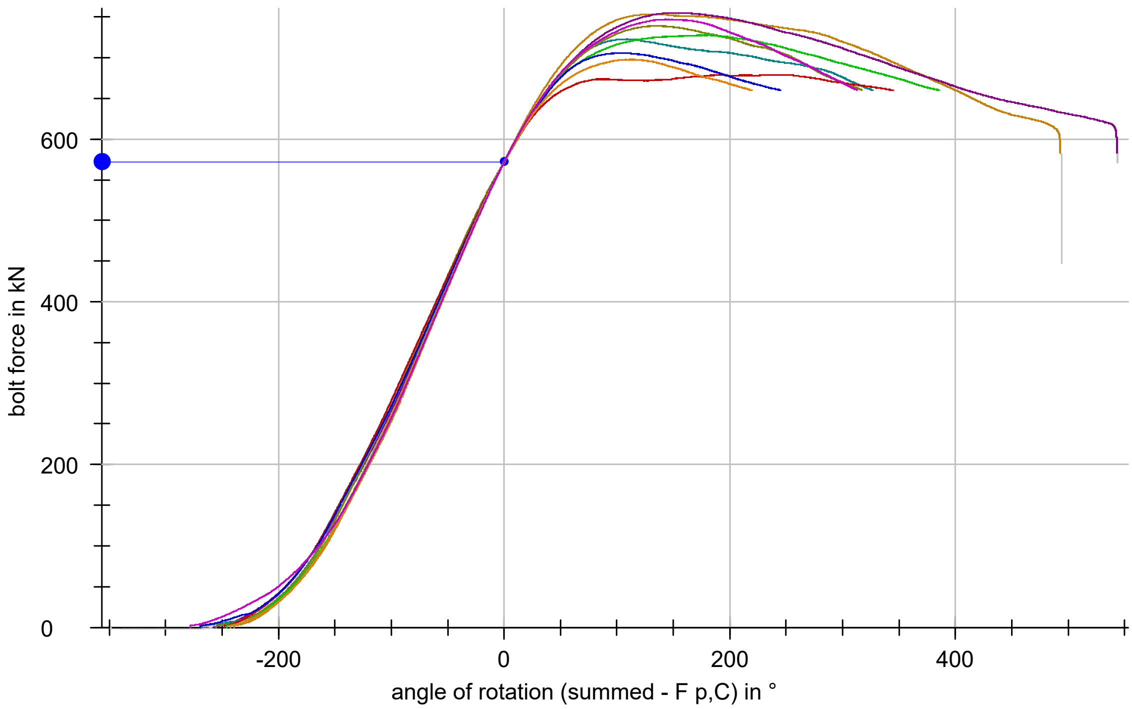
bearing torque-bolt force-curves: M36x160 HR 10.9 - Gleitmo WSP 5040



thread torque-bolt force-curves: M36x160 HR 10.9 - Gleitmo WSP 5040

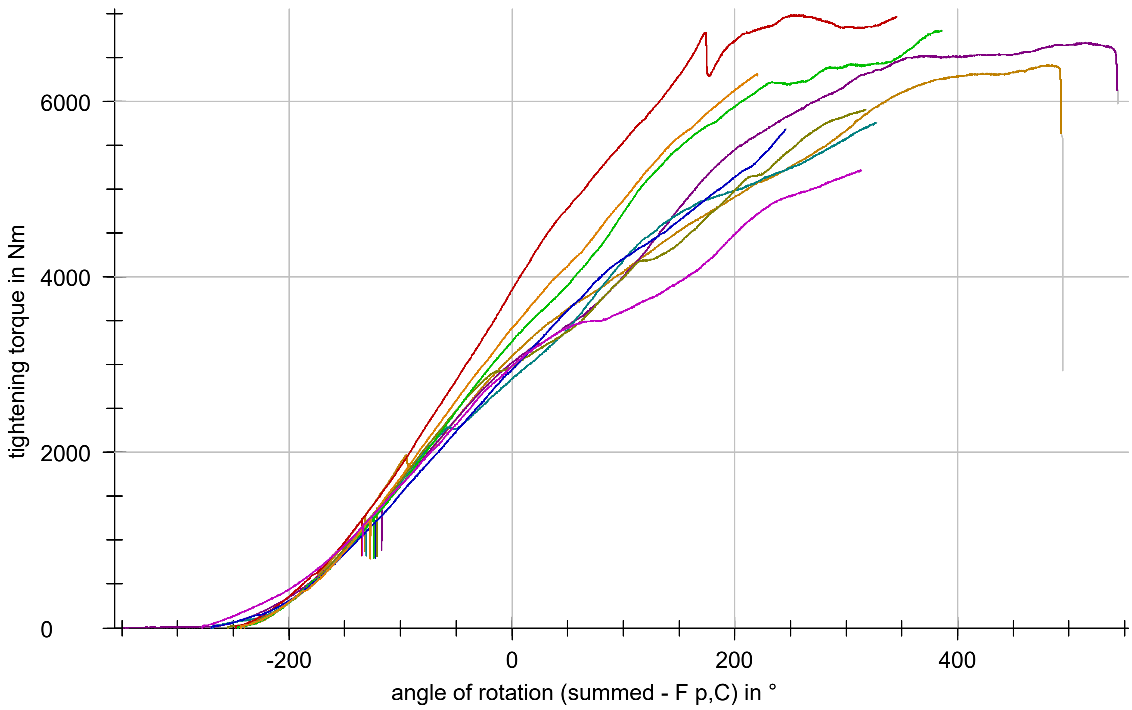


bolt force-angle of rotation-curves: M36x160 HR 10.9 - Gleitmo WSP 5040



ANNEX A

tightening torque-angle of rotation-curves: M36x160 HR 10.9 - Gleitmo WSP 5040



ANNEX A

Test series: M36x160 HR 10.9 - Molykote 1000 spray

Connecting element : M36x160 HR 10.9
Coating / Surface finish : M36x160 - tZn
Clamp length Σt : 123,5 mm

Speed of tightening : 2,0 1/min
Sensor F - T_{th} : SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ : SNo. 1016241 - 15000 Nm

Specific thread data:

Thread	Thread data	:	M 36/4.00 HV - IML	
d	Nominal diameter	:	36	mm
P	Pitch	:	4	mm
d_2	Pitch diameter	:	33,4	mm
d_o	Outer bearing surface diameter	:	55,9	mm
d_i	Inner bearing surface diameter	:	42	mm
D_b Calc	Bearing surface diameter	:	48,95	mm

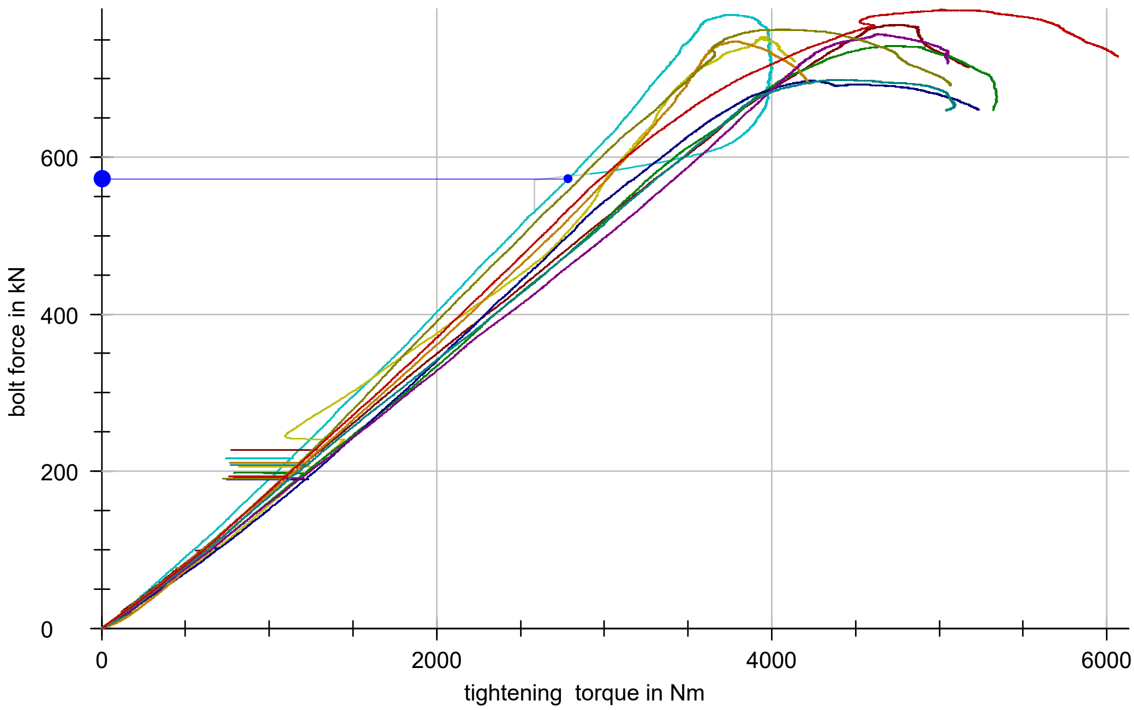
Results table: M36x160 HR 10.9 - Molykote 1000 spray

Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		571,9	735,3						120	240	0,10	
	Si_36_HR_10.9-21	571,9	781,8	4003,9	261	486	915	527,6	225	654	0,14	0,097
	Si_36_HR_10.9-22		753,7	4145,6	244	472	646	722,3	228	403	0,15	0,106
	Si_36_HR_10.9-23		769,1	5184,6	256	491	658	714,0	235	403	0,16	0,117
	Si_36_HR_10.9-24		742,3	5343,7	266	424	571	659,8	159	305	0,16	0,116
	Si_36_HR_10.9-25		<697,6	5239,5	249	384	570	659,9	135	321	0,15	0,112
	Si_36_HR_10.9-26		747,7	4237,1	263	478	665	693,3	215	402	0,15	0,106
	Si_36_HR_10.9-27		756,9	5057,3	260	488	663	719,9	228	403	>0,17	0,122
	Si_36_HR_10.9-28		<698,8	5094,7	242	361	583	660,0	<119	341	0,16	0,118
	Si_36_HR_10.9-29		763,0	5071,8	245	452	647	691,9	207	402	0,14	0,099
	Si_36_HR_10.9-30		787,9	6067,6	247	469	650	728,7	223	403	0,14	0,104

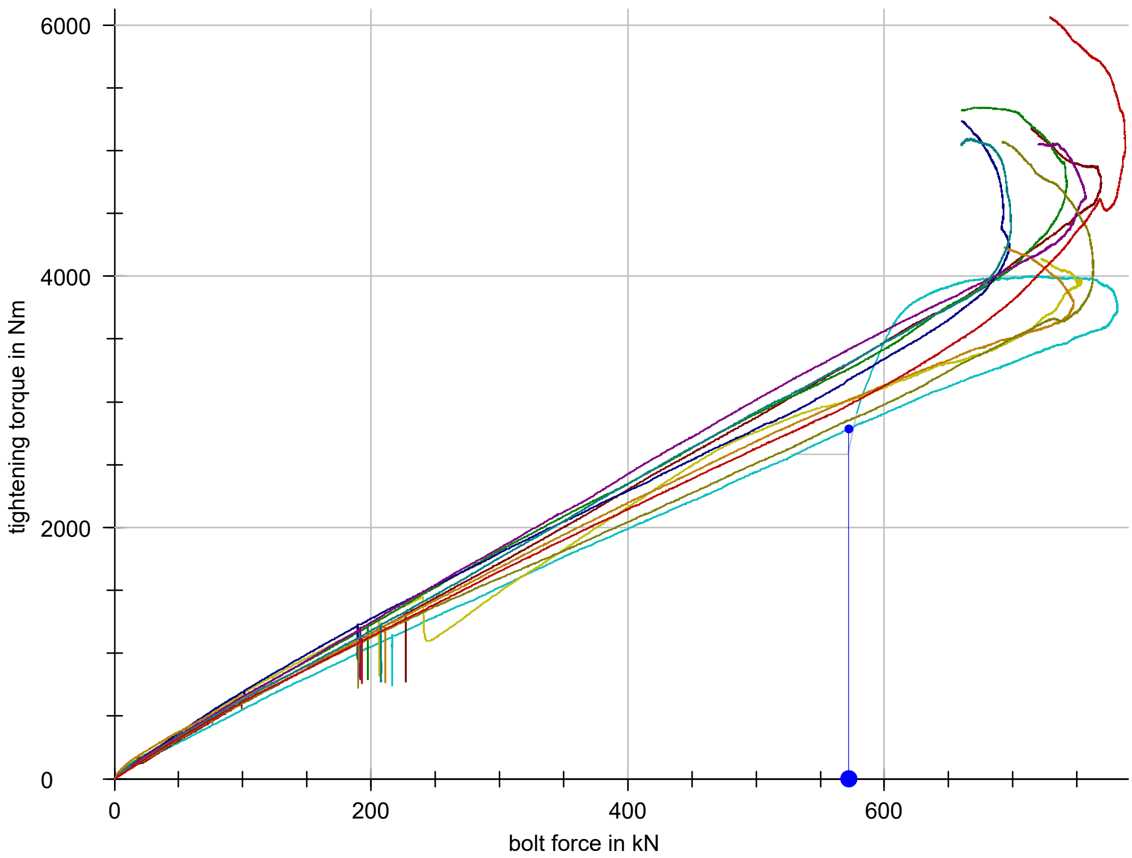
Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			514,7	0,095			
	0,103	0,091	514,7	0,135	2782,3	2506,3	3739,7
	0,113	0,100		0,152	3008,0	2824,2	3969,0
	0,094	0,136		0,160	3299,9	2961,8	4742,2
	0,123	0,110		0,161	3259,3	2981,7	4716,0
	0,124	0,103		0,154	3176,6	2849,7	4231,5
	0,127	0,089		0,149	3015,9	2758,9	3788,4
	0,104	0,136		>0,167	3416,8	3100,2	4626,9
	0,125	0,112		0,162	3305,9	2998,4	4398,6
	0,090	0,107		0,139	2852,7	2576,9	4043,7
	0,100	0,108		0,146	2974,8	2698,5	5022,9

ANNEX A

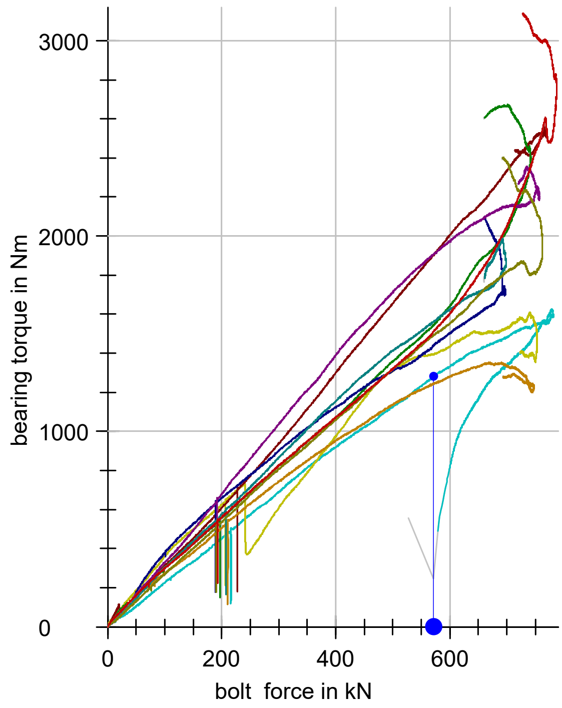
bolt force-tightening torque-curves: M36x160 HR 10.9 - Molykote 1000 spray



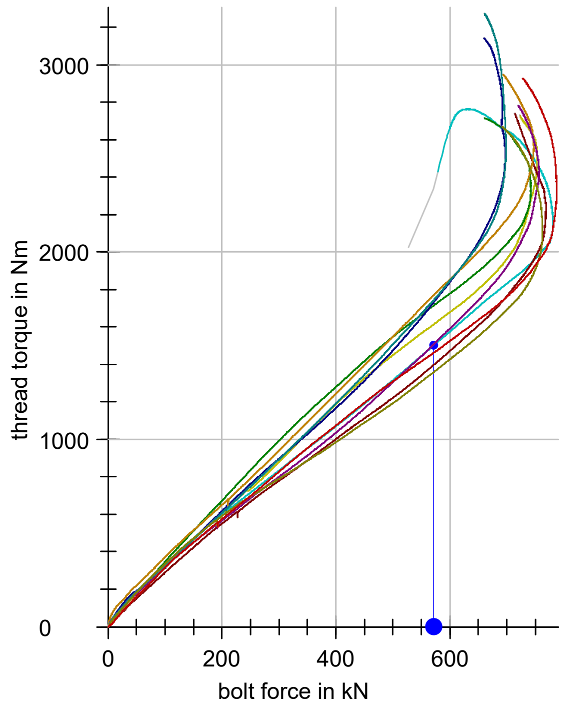
tightening torque-bolt force-curves: M36x160 HR 10.9 - Molykote 1000 spray



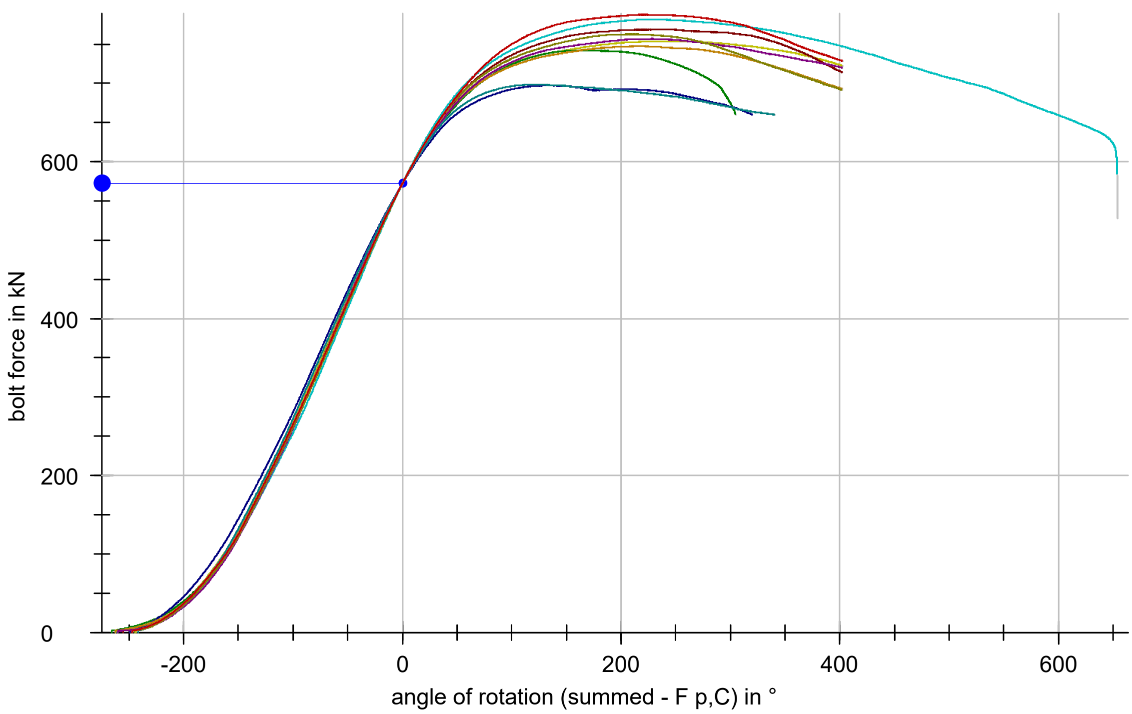
bearing torque-bolt force-curves: M36x160 HR 10.9 - Molykote 1000 spray



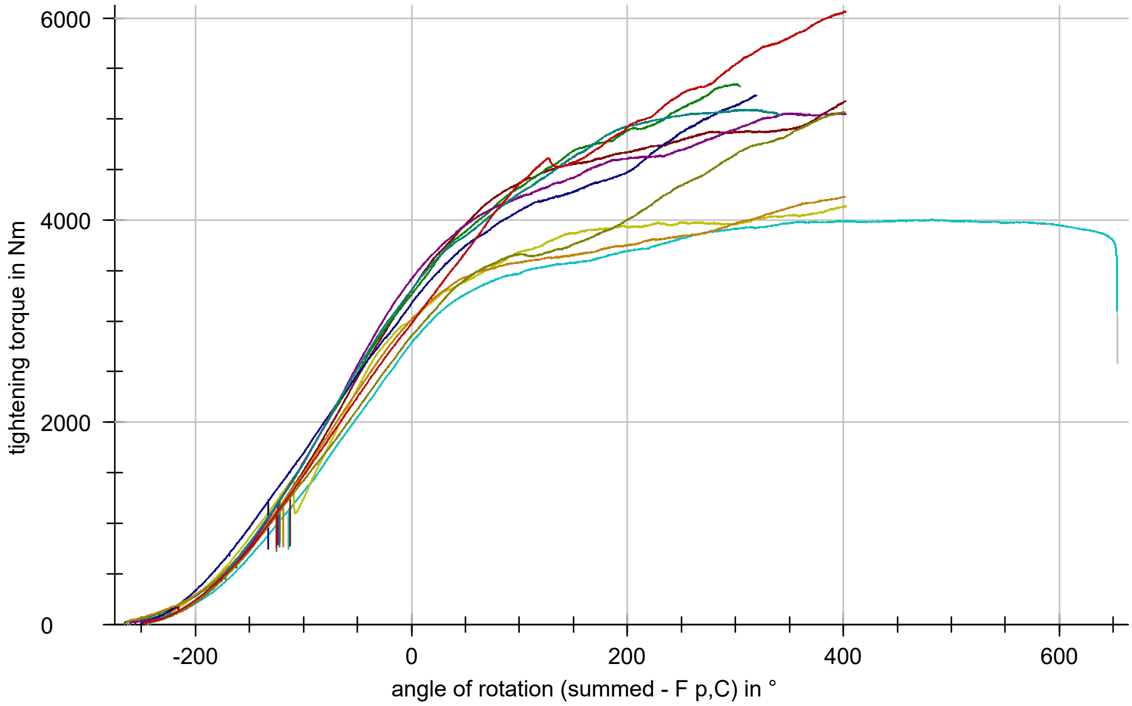
thread torque-bolt force-curves: M36x160 HR 10.9 - Molykote 1000 spray



bolt force-angle of rotation-curves: M36x160 HR 10.9 - Molykote 1000 spray



tightening torque-angle of rotation-curves: M36x160 HR 10.9 - Molykote 1000 spray



Test series: M36x160 HR 10.9 - Microgleit HV-paste LP440

Connecting element	:	M36x160 HR 10.9
Coating / Surface finish	:	M36x160 - tZn
Clamp length Σt	:	123,5 mm
Speed of tightening	:	2,0 1/min
Sensor F - T_{th}	:	SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ	:	SNo. 1016241 - 15000 Nm

Specific thread data:

Thread	Thread data	:	M 36/4.00 HV - IML	
d	Nominal diameter	:	36	mm
P	Pitch	:	4	mm
d_2	Pitch diameter	:	33,4	mm
d_o	Outer bearing surface diameter	:	55,9	mm
d_i	Inner bearing surface diameter	:	42	mm
D_b Calc	Bearing surface diameter	:	48,95	mm

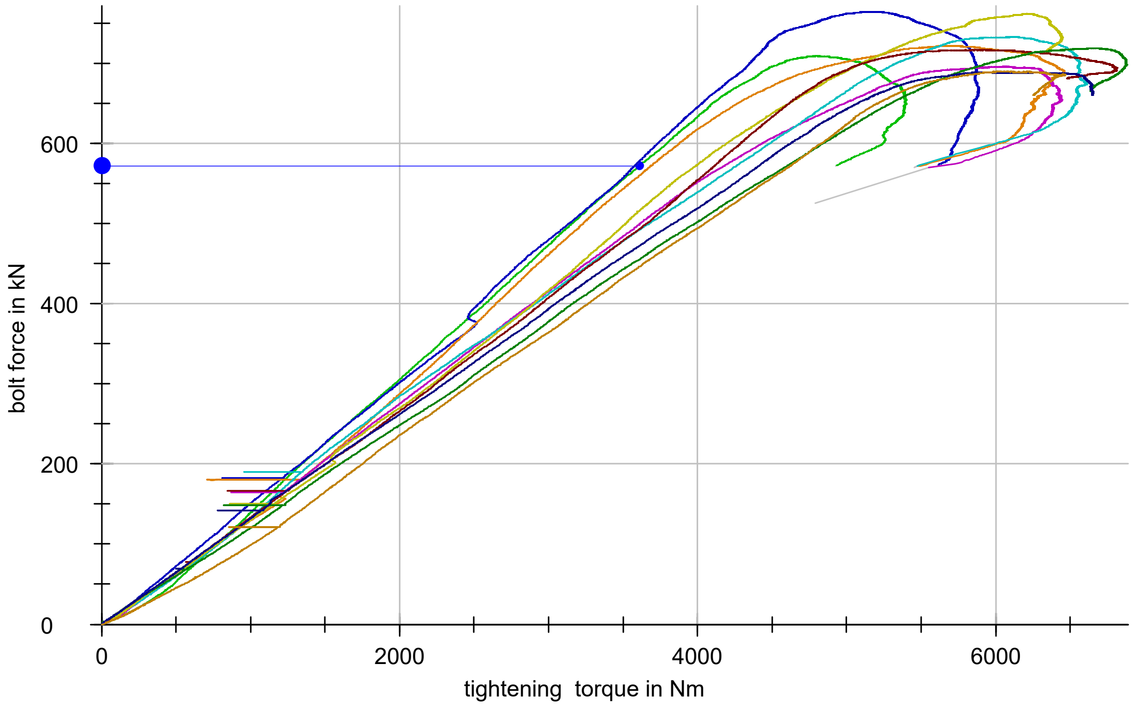
Results table: M36x160 HR 10.9 - Microgleit HV-paste LP440

Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		571,9	735,3						120	240	0,10	
	Si_36_HR_10.9-31	571,9	<708,8	5402,1	294	437	762	571,6	143	467	>0,18	0,130
	Si_36_HR_10.9-32		764,1	5891,0	243	471	821	571,8	228	578	>0,17	0,128
	Si_36_HR_10.9-33		<721,5	6462,1	257	419	842	570,1	163	585	>0,18	0,133
	Si_36_HR_10.9-34		<695,5	6448,6	275	432	840	525,6	157	565	>0,20	0,152
	Si_36_HR_10.9-35		<733,1	6616,7	274	438	787	570,5	163	513	>0,21	0,156
	Si_36_HR_10.9-36		761,5	6451,3	253	482	656	712,3	229	403	>0,19	0,145
	Si_36_HR_10.9-37		<716,3	6818,8	245	392	647	681,0	146	402	>0,20	0,150
	Si_36_HR_10.9-38		<718,6	6882,1	241	457	643	664,9	215	402	>0,22	0,169
	Si_36_HR_10.9-39		<688,5	6658,4	269	399	580	660,0	130	311	>0,21	0,162
	Si_36_HR_10.9-40		<689,3	6468,7	322	424	591	659,9	<102	269	>0,22	0,170

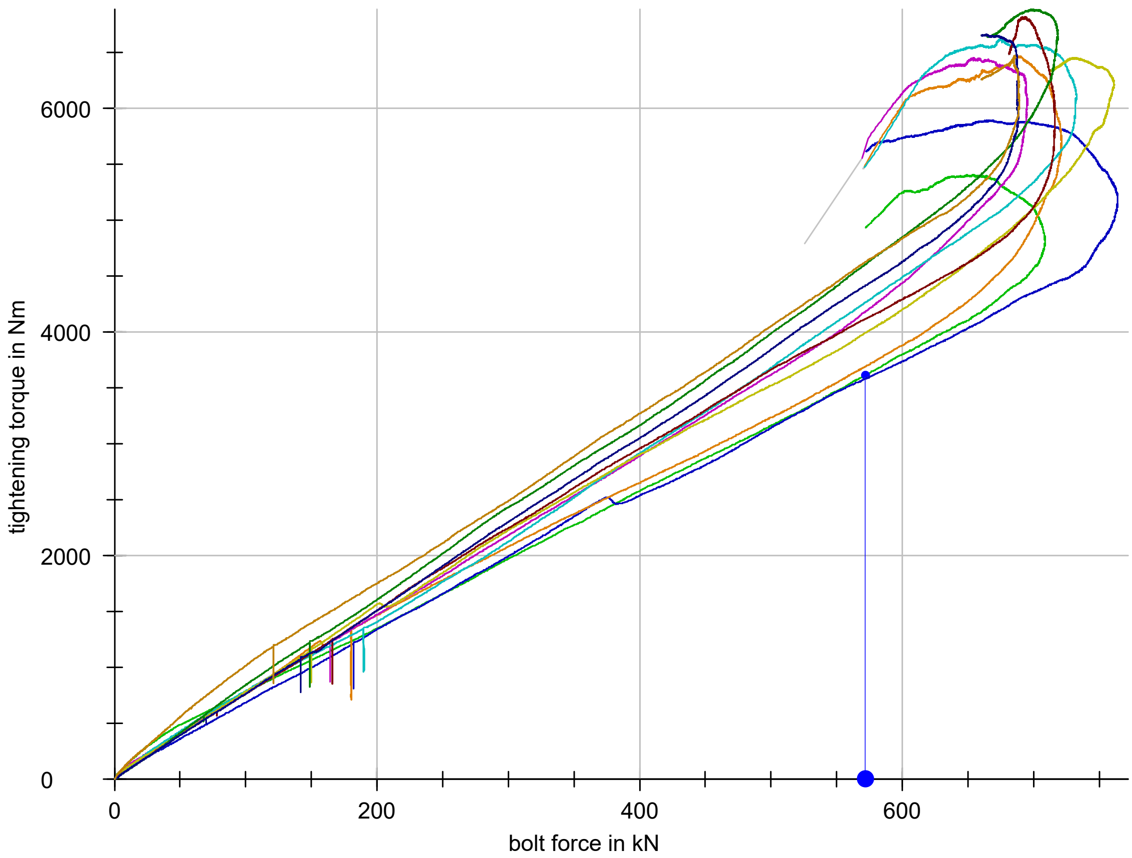
Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			514,7	0,095			
	0,135	0,125	514,7	>0,175	3608,0	3248,9	4785,4
	0,102	0,149		>0,175	3577,2	3234,0	5201,3
	0,118	0,144		>0,179	3685,4	3317,0	5655,1
	0,131	0,169		>0,201	4176,1	3716,9	6049,5
	0,123	0,182		>0,205	4262,0	3798,2	6085,8
	0,123	0,162		>0,194	3991,3	3595,6	6211,0
	0,127	0,168		>0,203	4111,5	3753,6	5826,9
	0,131	0,199		>0,222	4600,9	4108,5	6651,3
	0,128	0,188		>0,214	4413,4	3963,1	5940,7
	0,161	0,177		>0,225	4623,6	4160,7	6024,5

ANNEX A

bolt force-tightening torque-curves: M36x160 HR 10.9 - Microgleit HV-paste LP440



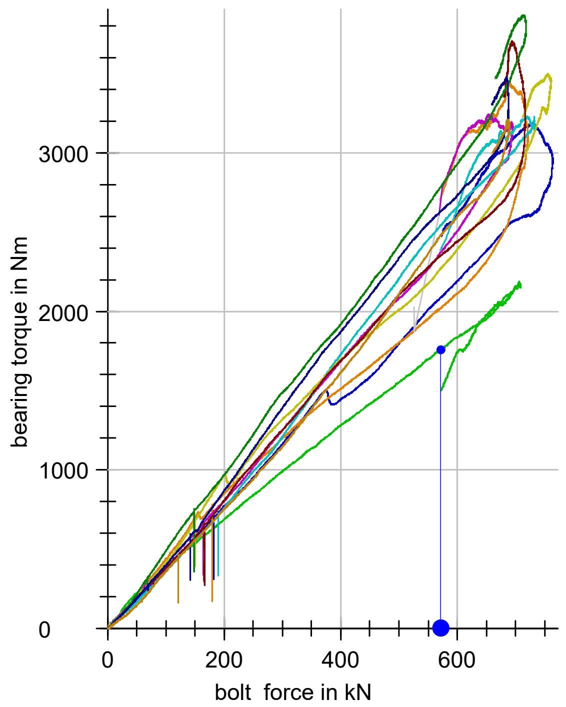
tightening torque-bolt force-curves: M36x160 HR 10.9 - Microgleit HV-paste LP440



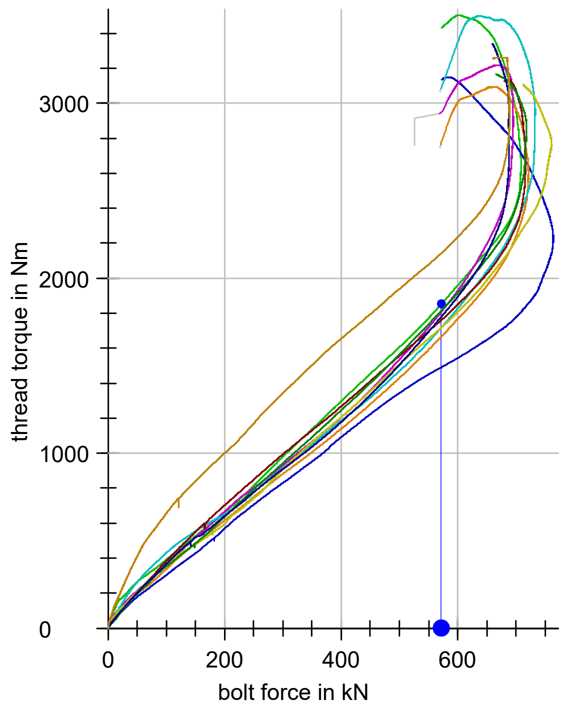
Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

ANNEX A

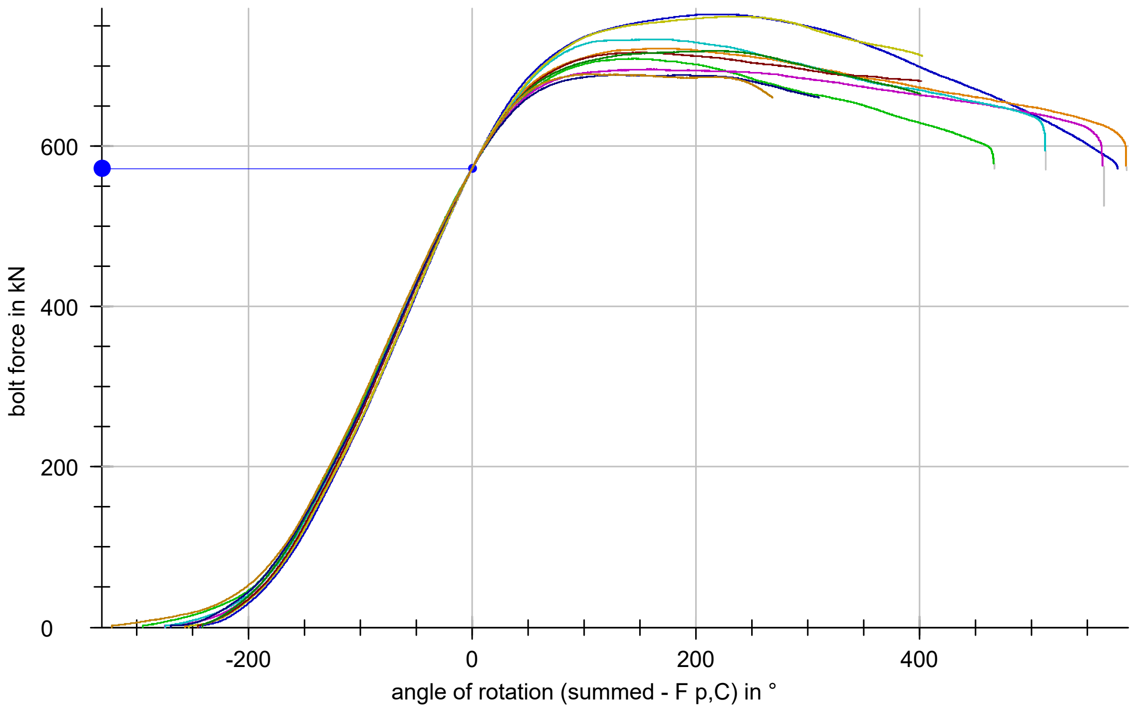
bearing torque-bolt force-curves: M36x160 HR 10.9 - Microgleit HV-paste LP440



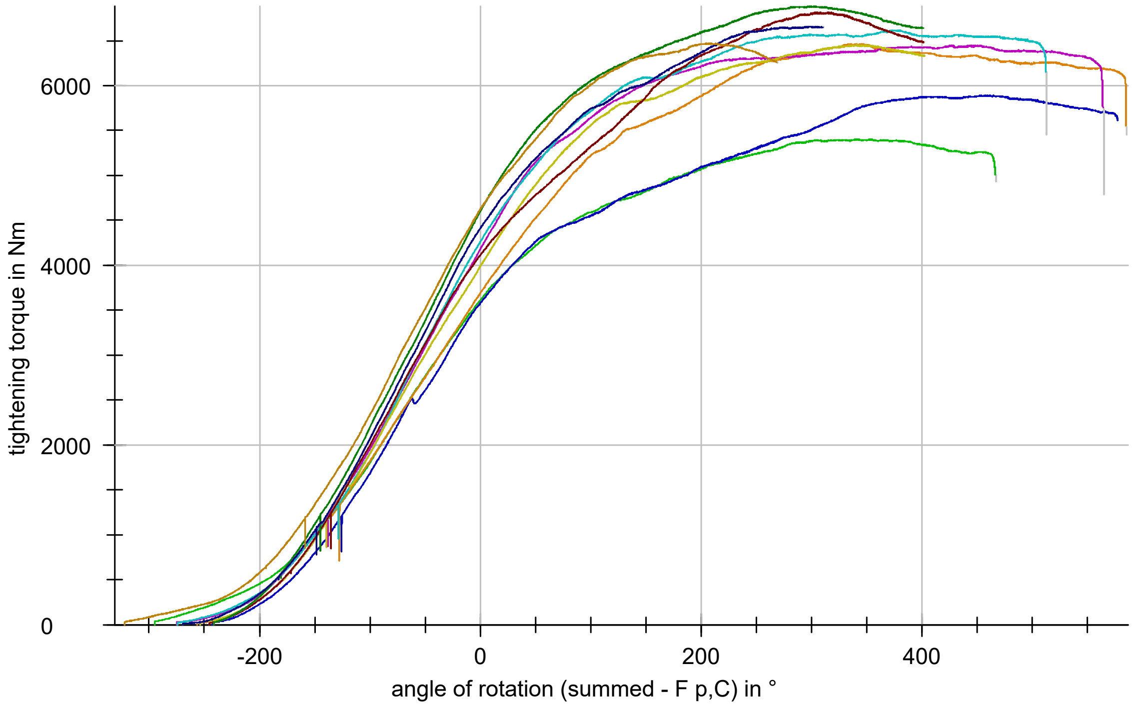
thread torque-bolt force-curves: M36x160 HR 10.9 - Microgleit HV-paste LP440



bolt force-angle of rotation-curves: M36x160 HR 10.9 - Microgleit HV-paste LP440



tightening torque-angle of rotation-curves: M36x160 HR 10.9 - Microgleit HV-paste LP440



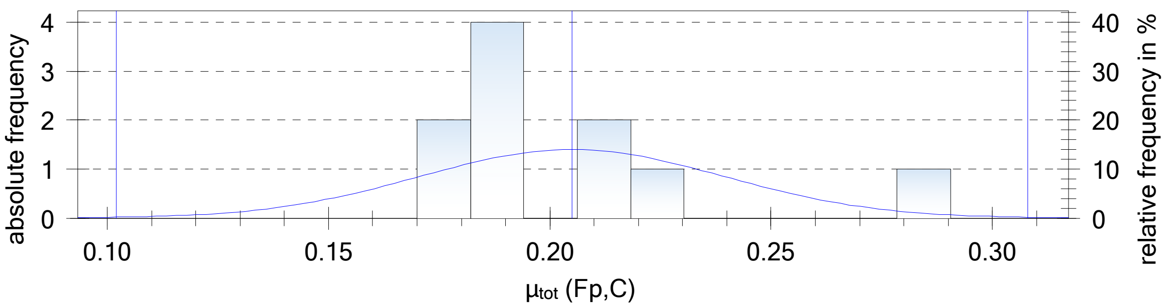
Statistical evaluation: M36x160 HR 10.9 - Factory provided

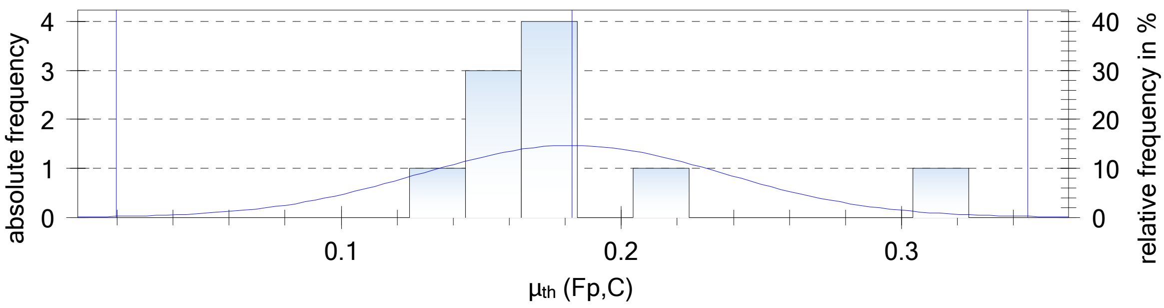
M36x160 HR 10.9 - Factory provided n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	691,7	7904,4	349	625	739	651,0	276	498	0,291
min	610,0	7318,1	242	321	567	570,1	68	273	0,170
R	81,7	586,3	107	304	172	80,9	208	225	0,121
$\bar{x}$	648,4	7607,1	277	420	669	614,2	144	392	0,205
s	24,8	155,5	33	94	45	30,9	80	56	0,034
ν	3,82	2,04	11,84	22,46	6,76	5,03	55,93	14,32	16,81

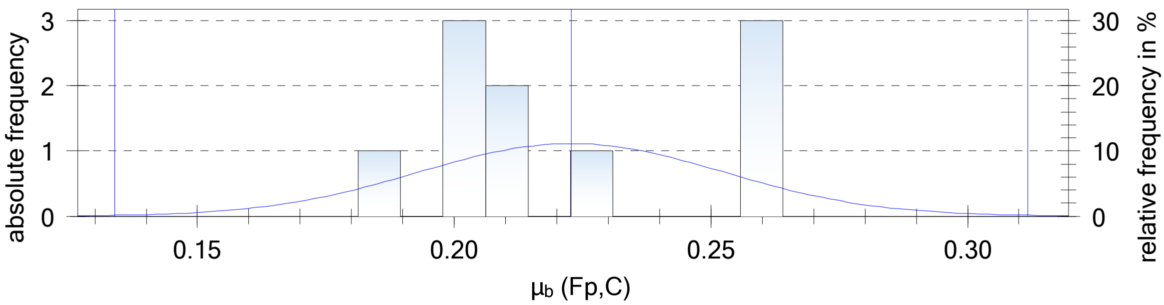
M36x160 HR 10.9 - Factory provided n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C*}$)	M ($F_{bi,max}$) Nm
max	0,324	0,264	7634,2	0,37	6505,9	0,351	7578,1
min	0,125	0,181	4620,7	0,22	3906,4	0,211	6087,1
R	0,199	0,083	3013,5	0,15	2599,5	0,140	1491,0
$\bar{x}$	0,183	0,223	5496,0	0,27	4742,3	0,256	7052,0
s	0,054	0,030	859,1	0,04	775,3	0,042	444,4
ν	29,67	13,26	15,63	15,51	16,35	16,34	6,30

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M36x160 HR 10.9 - Factory provided







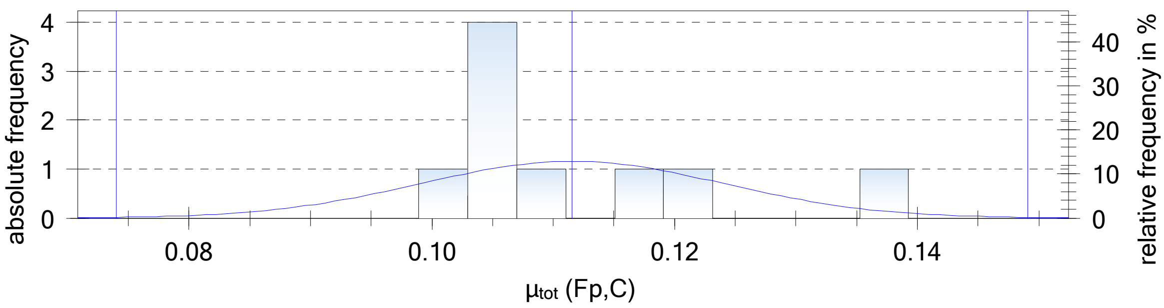
Statistical evaluation: M36x160 HR 10.9 - Gleitmo WSP 5040

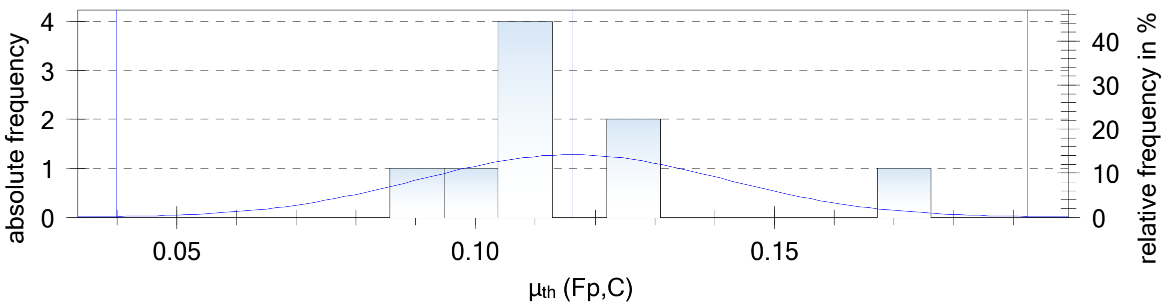
M36x160 HR 10.9 - Gleitmo WSP 5040 n = 9	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	755,5	6989,7	348	500	892	660,0	240	544	0,139
min	679,3	5225,1	240	357	464	447,1	106	220	0,099
R	76,2	1764,6	108	143	428	212,9	134	324	0,040
$\bar{x}$	725,6	6200,7	266	411	621	626,4	145	355	0,112
s	26,5	586,2	33	53	126	73,4	43	106	0,012
ν	3,65	9,45	12,56	12,77	20,26	11,71	29,53	29,89	11,14

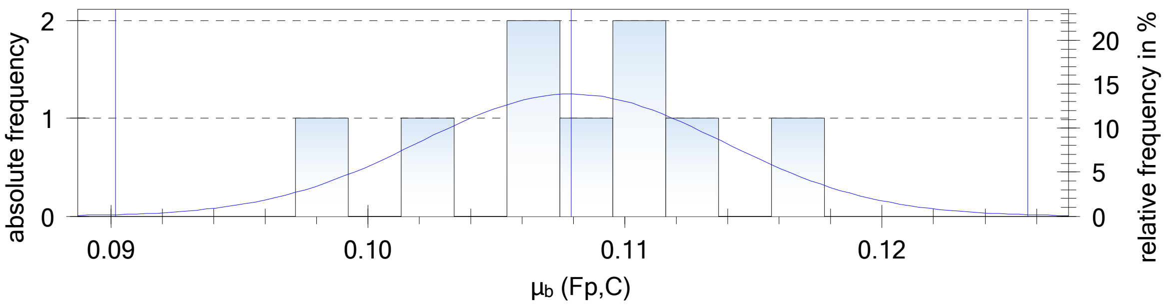
M36x160 HR 10.9 - Gleitmo WSP 5040 n = 9	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C*}$)	M ($F_{bi,max}$) Nm
max	0,176	0,118	3849,6	0,19	3402,5	0,184	6920,4
min	0,086	0,097	2840,1	0,14	2596,9	0,140	3894,2
R	0,090	0,021	1009,5	0,05	805,6	0,044	3026,2
$\bar{x}$	0,116	0,108	3155,9	0,15	2883,7	0,156	4846,6
s	0,025	0,006	313,2	0,02	244,0	0,013	961,0
ν	21,77	5,52	9,92	11,30	8,46	8,53	19,83

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M36x160 HR 10.9 - Gleitmo WSP 5040







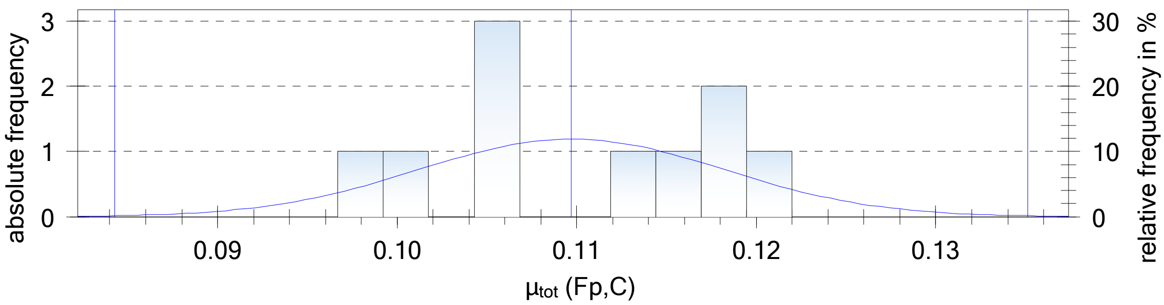
Statistical evaluation: M36x160 HR 10.9 - Molykote 1000 spray

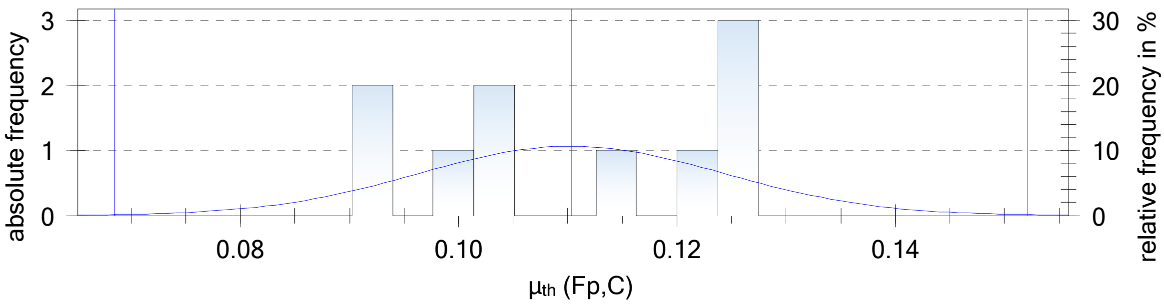
M36x160 HR 10.9 - Molykote 1000 spray n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	787,9	6067,6	266	491	915	728,7	235	654	0,122
min	697,6	4003,9	242	361	570	527,6	119	305	0,097
R	90,3	2063,7	24	130	345	201,1	116	349	0,025
$\bar{x}$	749,9	4944,6	253	451	657	677,7	197	404	0,110
s	30,7	636,0	9	46	99	59,3	43	96	0,009
ν	4,09	12,86	3,50	10,20	15,00	8,74	21,77	23,81	7,77

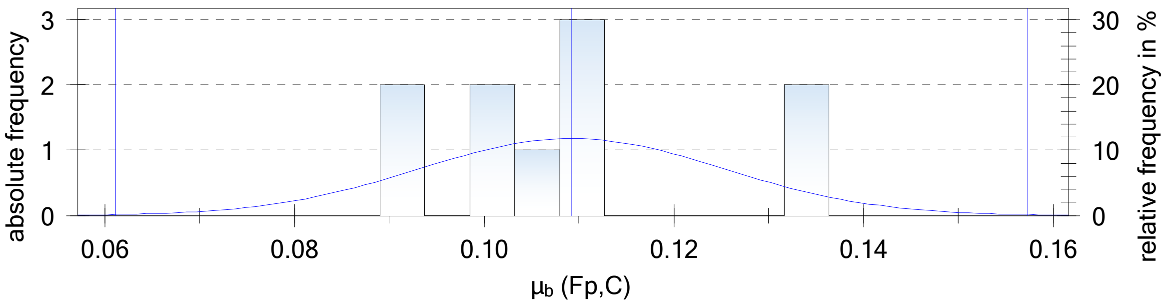
M36x160 HR 10.9 - Molykote 1000 spray n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C}$*)	M ($F_{bi,max}$) Nm
max	0,127	0,136	3416,8	0,17	3100,2	0,167	5022,9
min	0,090	0,089	2782,3	0,14	2506,3	0,135	3739,7
R	0,037	0,047	634,5	0,03	593,9	0,032	1283,2
$\bar{x}$	0,110	0,109	3109,2	0,15	2825,7	0,153	4327,9
s	0,014	0,016	212,5	0,01	192,4	0,010	441,7
ν	12,56	14,68	6,83	6,79	6,81	6,82	10,21

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M36x160 HR 10.9 - Molykote 1000 spray







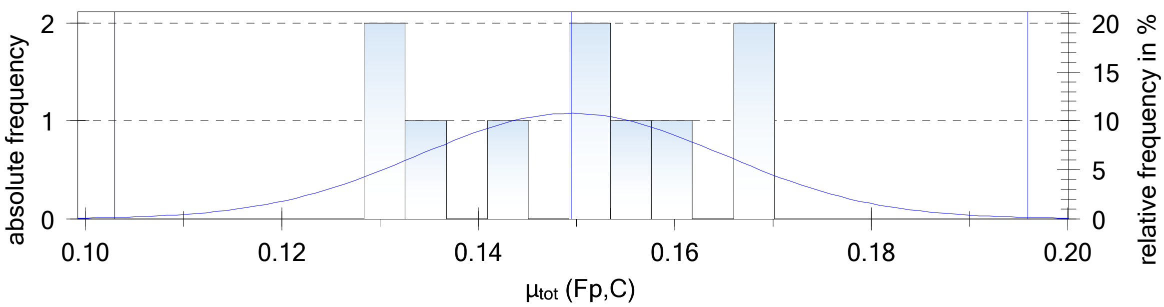
Statistical evaluation: M36x160 HR 10.9 - Microgleit HV-paste LP440

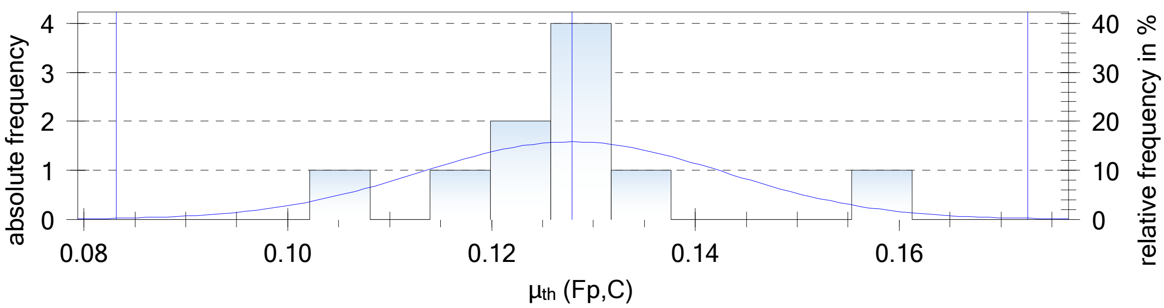
M36x160 HR 10.9 - Microgleit HV-paste LP440 n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	764,1	6882,1	322	482	842	712,3	229	585	0,170
min	688,5	5402,1	241	392	580	525,6	102	269	0,128
R	75,6	1480,0	81	90	262	186,7	127	316	0,042
$\bar{x}$	719,7	6410,0	267	435	717	618,8	168	450	0,150
s	26,9	445,8	26	29	104	63,2	43	111	0,015
ν	3,74	6,96	9,58	6,65	14,50	10,21	25,63	24,71	10,32

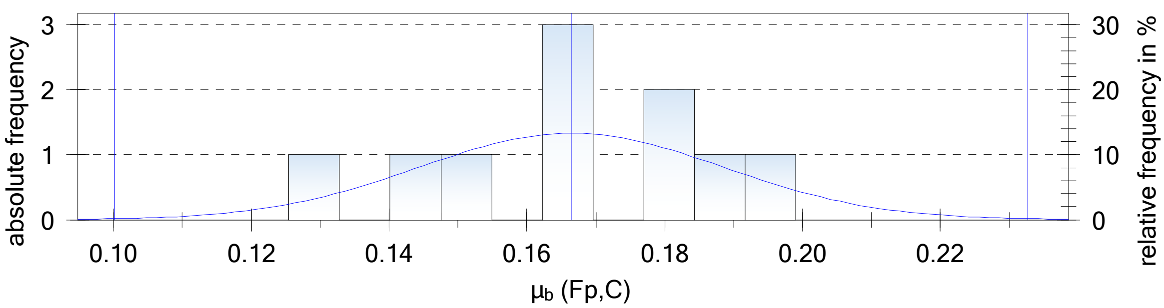
M36x160 HR 10.9 - Microgleit HV-paste LP440 n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C*}$)	M ($F_{bi,max}$) Nm
max	0,161	0,199	4623,6	0,22	4160,7	0,225	6651,3
min	0,102	0,125	3577,2	0,17	3234,0	0,175	4785,4
R	0,059	0,074	1046,4	0,05	926,7	0,050	1865,9
$\bar{x}$	0,128	0,166	4104,9	0,20	3689,7	0,199	5843,2
s	0,015	0,022	387,9	0,02	339,7	0,018	526,9
ν	11,61	13,34	9,45	8,84	9,21	9,26	9,02

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M36x160 HR 10.9 - Microgleit HV-paste LP440







7 Annex B: Test protocols of HV 10.9 bolting assemblies

Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

M24 HV 10.9 - Test protocol

SIROCO - Tightening tests of HV bolting assemblies

Client / Customer	:	SIROCO
Date of reception	:	-
Date of testing	:	20.05.2016 M24x100 HV 10.9
Project	:	RFCS SIROCO WP 1 Task 1.5
Specification	:	According EN 14399-2 and EN ISO 16047
Operator	:	Christoph Abraham B.Sc., Dominik Jungbluth M.Sc.
Number of assemblies tested	:	40
Designation of bolt	:	M24x100 HV 10.9
Marking of bolt	:	-
Designation of nut	:	Hexagon nut HV M24
Marking of nut	:	-
Designation of washer	:	Washer M24 HV
Marking of washer	:	
Coating / Surface finish	:	M24x100 - tZn
Ambient temperature	:	23,6 °C
Ambient relative humidity	:	25,8 %
Rotated component	:	Hexagon nut
Special testing conditions	:	Different lubrications used: - Factory provided lubrication - Gleitmo WSP 5040 - Molykote 1000 spray - Microgleit HV-paste LP440

Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

Test specimens identification

Si_xx_yy_zz

Si: RFCS SIROCO
xx: thread
yy: strength class
zz: sequential number of bolt

Test series: M24x100 HV 10.9 - Factory provided

Connecting element	:	M24x100 HV 10.9
Coating / Surface finish	:	M24x100 - tZn
Clamp length Σt	:	67,0 mm
Speed of tightening	:	2,0 1/min
Sensor F - T_{th}	:	SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ	:	SNo. 1024283 - 5000 Nm

Specific thread data:

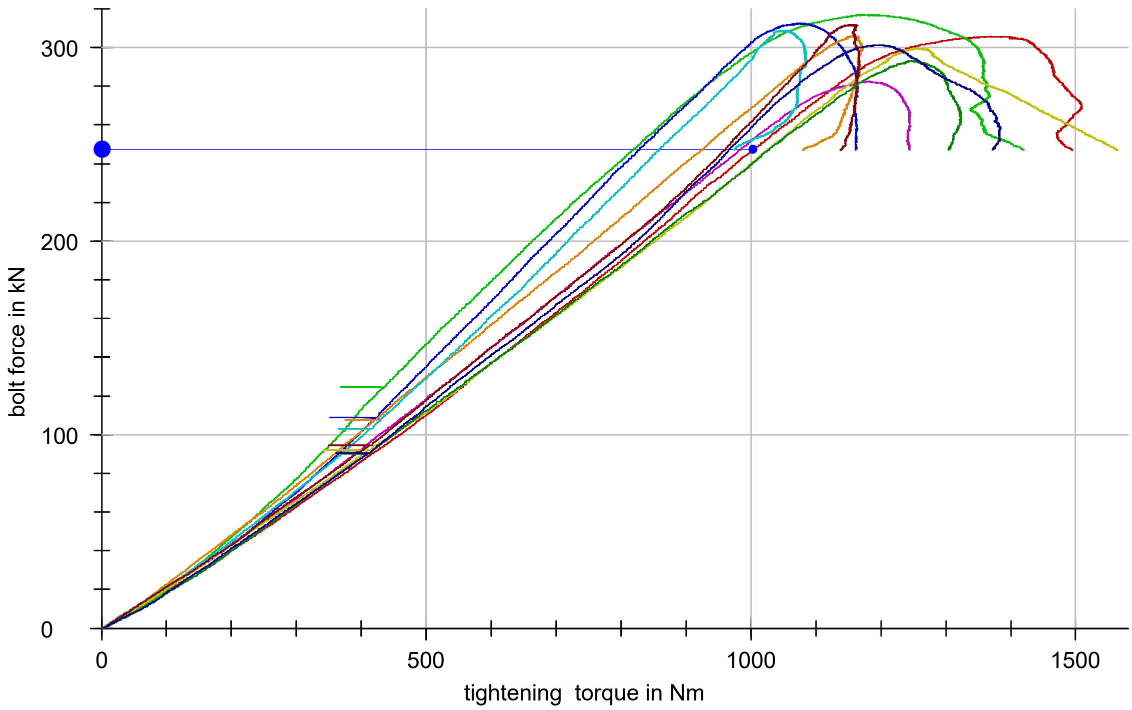
Thread	Thread data	:	M 24 HV - IML	
d	Nominal diameter	:	24	mm
P	Pitch	:	3	mm
d_2	Pitch diameter	:	22,05	mm
d_o	Outer bearing surface diameter	:	38	mm
d_i	Inner bearing surface diameter	:	27,5	mm
D_b Calc	Bearing surface diameter	:	32,75	mm

Results table: M24x100 HV 10.9 - Factory provided

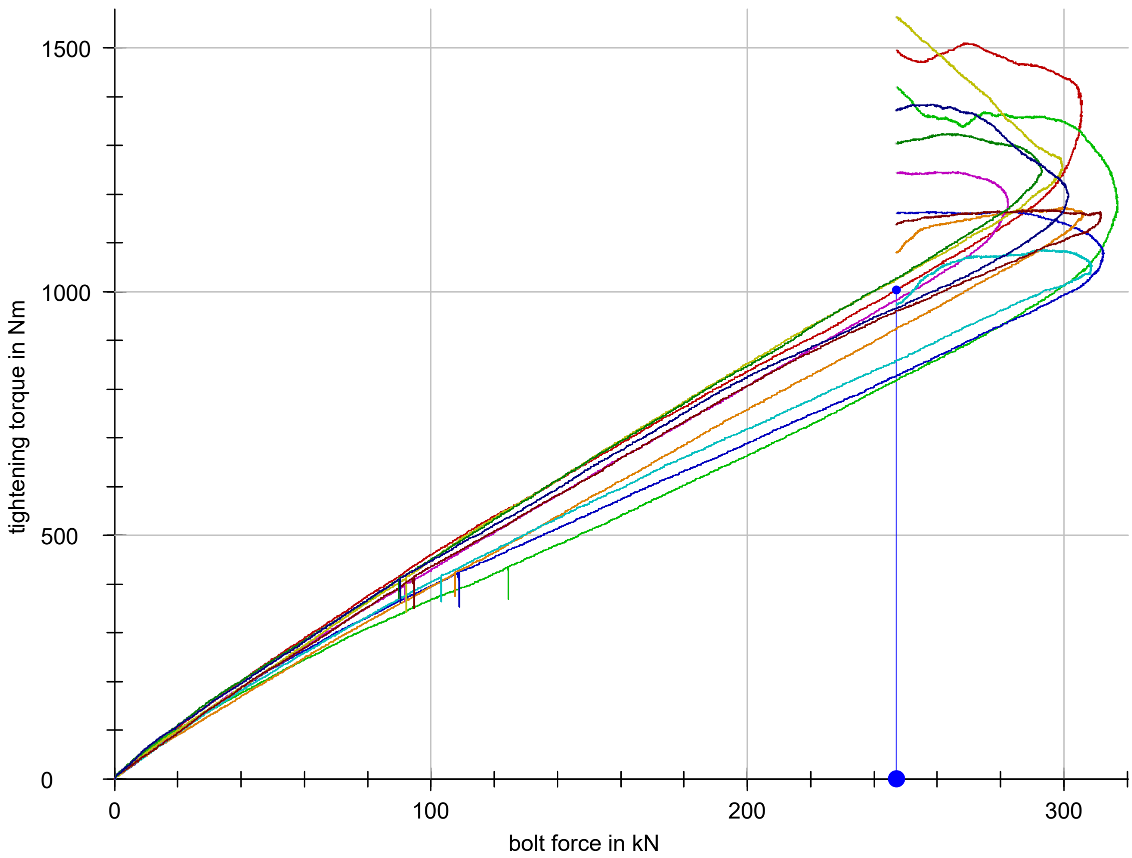
Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	$F_{bi}(\Theta_{2i})$ kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		247,1	317,7						120	210	0,10	
	Si_24_HV_10.9-01	247,1	<305,8	1509,5	211	313	549	247,0	178	414	>0,17	0,123
	Si_24_HV_10.9-02		<317,0	1421,7	180	280	575	246,9	174	469	0,14	0,097
	Si_24_HV_10.9-03		<312,6	1164,2	197	296	472	246,9	175	350	0,14	0,099
	Si_24_HV_10.9-04		<306,3	1172,7	182	285	531	246,9	179	425	0,16	0,112
	Si_24_HV_10.9-05		<282,5	1245,8	176	243	383	247,0	143	283	>0,17	0,120
	Si_24_HV_10.9-06		<308,8	1086,1	192	289	580	246,8	173	464	0,14	0,103
	Si_24_HV_10.9-07		<299,7	1565,2	227	331	539	247,0	180	388	>0,17	0,126
	Si_24_HV_10.9-08		<311,8	1167,7	184	283	533	246,8	174	423	0,16	0,117
	Si_24_HV_10.9-09		<293,0	1324,0	187	262	399	246,8	151	289	>0,17	0,126
	Si_24_HV_10.9-10		<301,4	1384,8	183	269	508	246,9	158	398	0,16	0,118

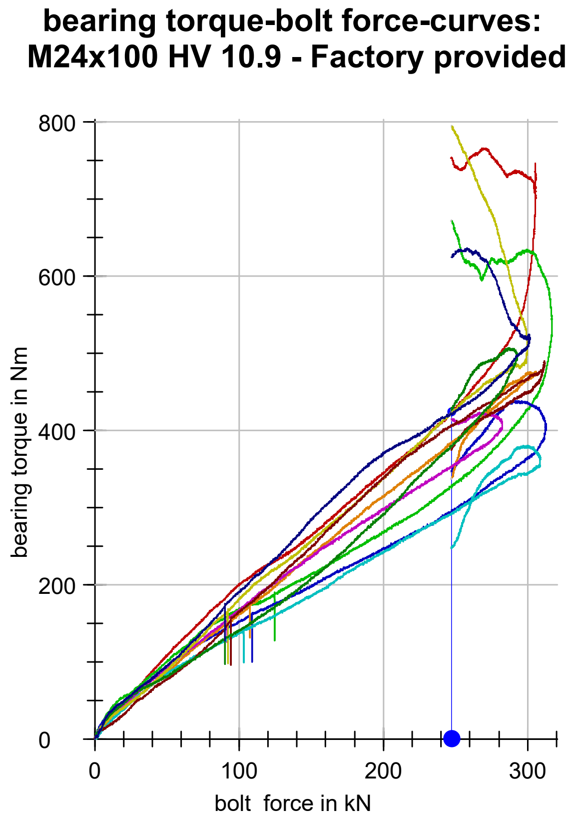
Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			222,4	0,095			
	0,147	0,105	222,4	>0,171	1003,1	912,4	1369,3
	0,119	0,081		0,138	818,6	734,5	1172,0
	0,132	0,073		0,141	827,9	754,7	1078,1
	0,134	0,095		0,157	924,2	836,9	1160,0
	0,163	0,087		>0,167	982,7	890,3	1180,3
	0,142	0,072		0,147	857,9	785,5	1052,2
	0,154	0,104		>0,176	1025,8	939,0	1251,0
	0,138	0,100		>0,166	960,1	883,7	1158,7
	0,168	0,094		>0,175	1027,7	935,9	1244,8
	0,136	0,104		>0,167	965,5	890,8	1195,7

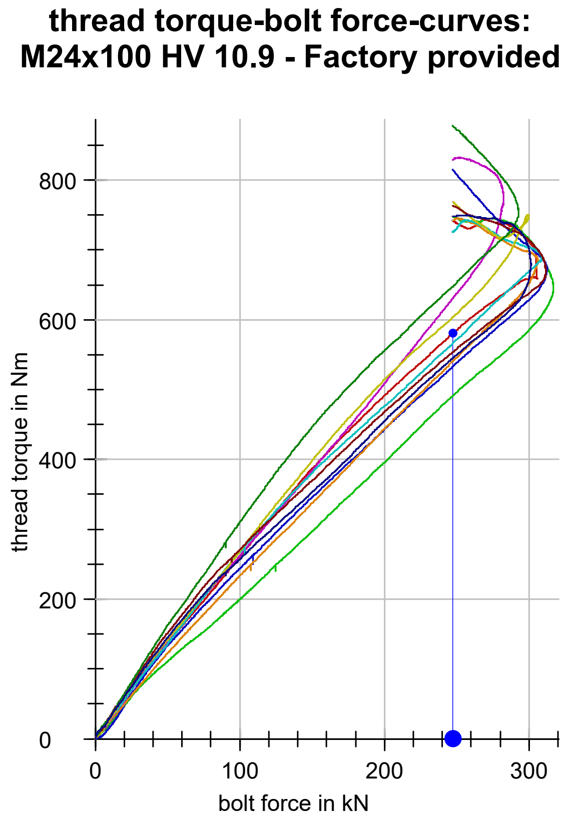
bolt force-tightening torque-curves: M24x100 HV 10.9 - Factory provided

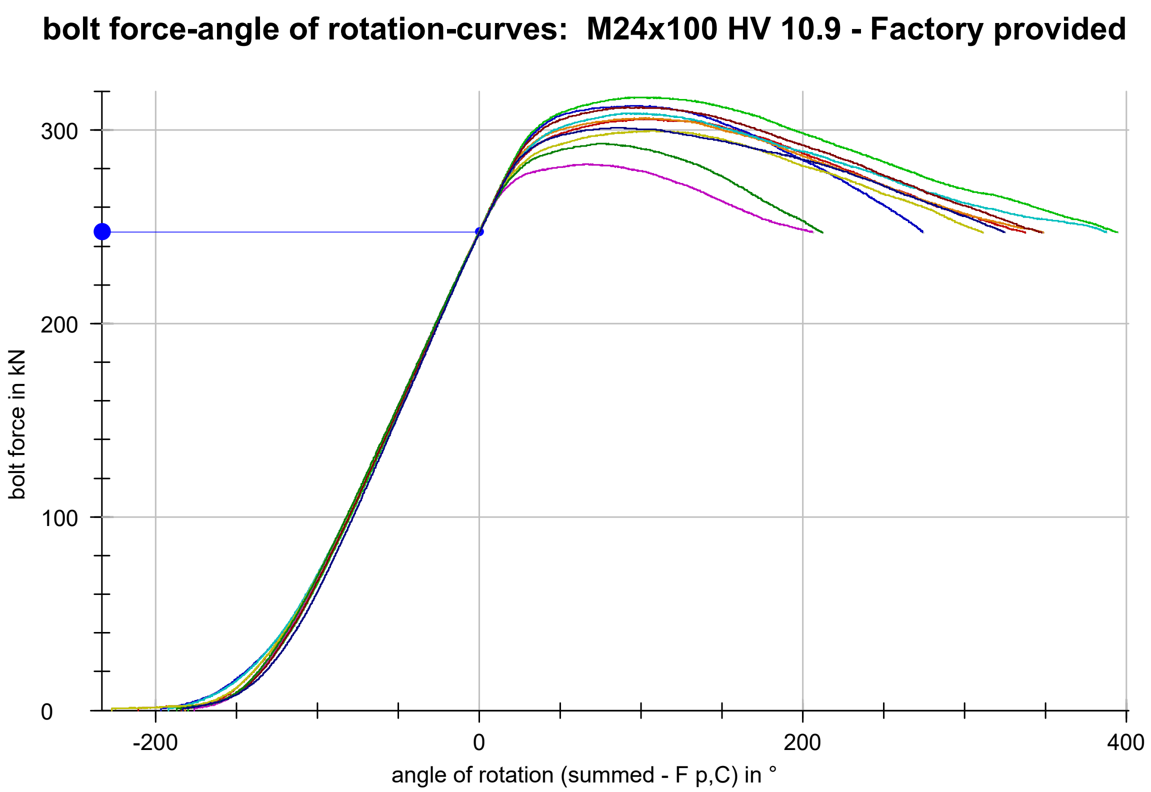


tightening torque-bolt force-curves: M24x100 HV 10.9 - Factory provided

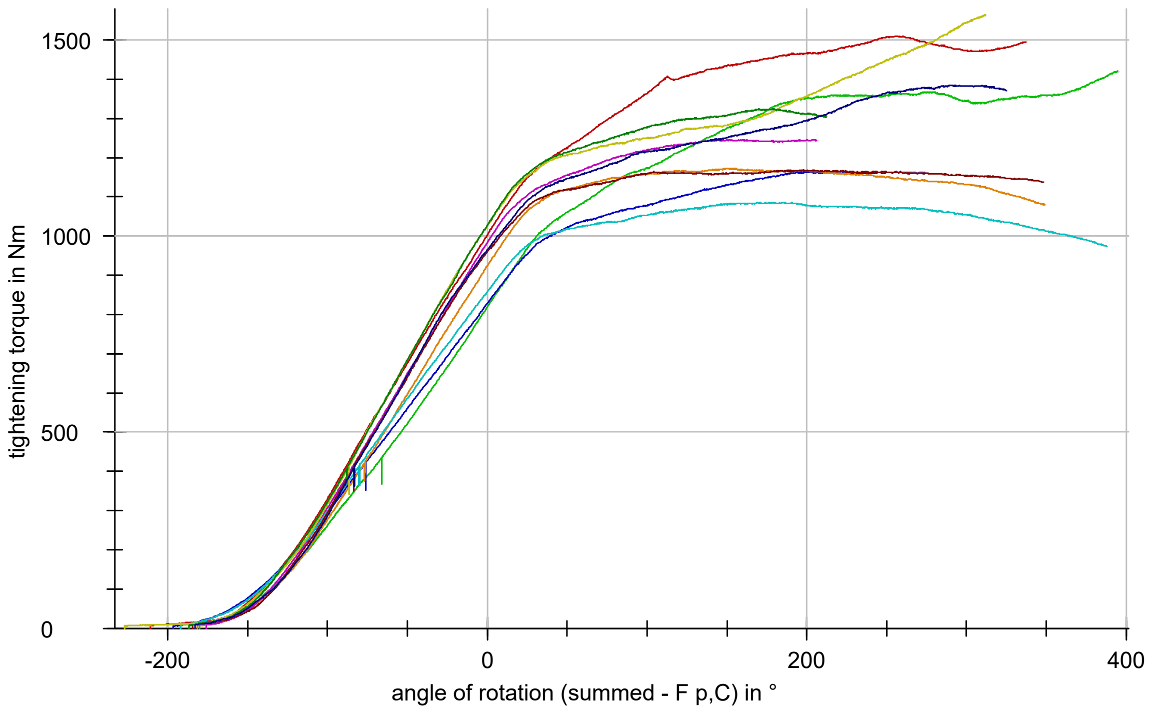



bearing torque-bolt force-curves:
M24x100 HV 10.9 - Factory provided
800
600
400
200
0
0
100
200
300
bolt force in kN
bearing torque in Nm


thread torque-bolt force-curves:
M24x100 HV 10.9 - Factory provided
800
600
400
200
0
0
100
200
300
bolt force in kN
thread torque in Nm


bolt force-angle of rotation-curves: M24x100 HV 10.9 - Factory provided
300
200
100
0
-200
0
200
400
angle of rotation (summed - F p,C) in °
bolt force in kN

tightening torque-angle of rotation-curves: M24x100 HV 10.9 - Factory provided



Test series: M24x100 HV 10.9 - Gleitmo WSP 5040

Connecting element	:	M24x100 HV 10.9
Coating / Surface finish	:	M24x100 - tZn
Clamp length Σt	:	67,0 mm
Speed of tightening	:	2,0 1/min
Sensor F - T_{th}	:	SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ	:	SNo. 1024283 - 5000 Nm

Specific thread data:

Thread	Thread data	:	M 24 HV - IML	
d	Nominal diameter	:	24	mm
P	Pitch	:	3	mm
d_2	Pitch diameter	:	22,05	mm
d_o	Outer bearing surface diameter	:	38	mm
d_i	Inner bearing surface diameter	:	27,5	mm
D_b Calc	Bearing surface diameter	:	32,75	mm

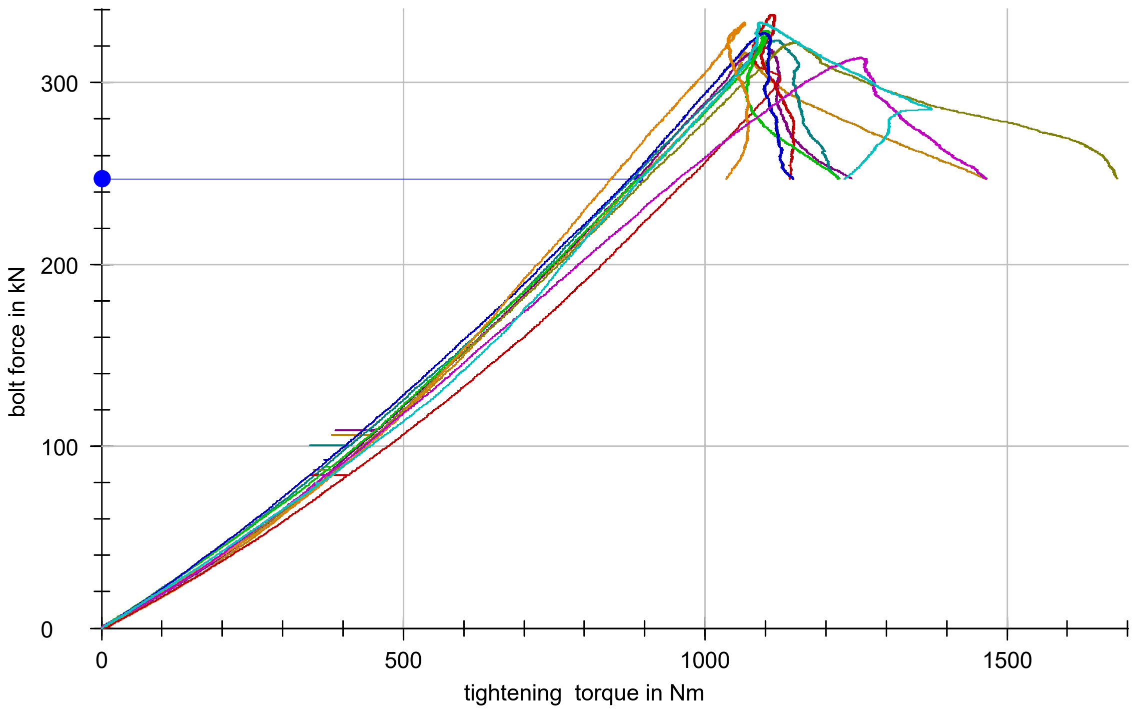
Results table: M24x100 HV 10.9 - Gleitmo WSP 5040

Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		247,1	317,7						120	210	0,10	
	Si_24_HV_10.9-17	247,1	<317,4	1467,5	179	291	560	247,0	185	454	0,15	0,107
	Si_24_HV_10.9-18		319,5	1244,8	189	301	593	247,0	186	478	0,15	0,107
	Si_24_HV_10.9-19		323,2	1221,4	214	319	634	246,9	180	495	0,15	0,106
	Si_24_HV_10.9-20		322,0	1684,2	176	290	592	247,0	188	489	0,15	0,109
	Si_24_HV_10.9-21		337,4	1148,0	219	354	648	246,8	209	503	0,16	0,119
	Si_24_HV_10.9-22		328,3	1223,1	229	349	646	247,0	196	493	0,15	0,107
	Si_24_HV_10.9-23		327,4	1147,0	216	329	678	247,0	185	535	0,15	0,105
	Si_24_HV_10.9-24		332,8	1074,1	230	359	619	247,0	204	465	0,14	0,101
	Si_24_HV_10.9-25		<313,8	1467,8	237	341	618	247,0	181	458	0,16	0,116
	Si_24_HV_10.9-26		333,0	1375,8	198	327	589	246,9	206	467	0,15	0,108

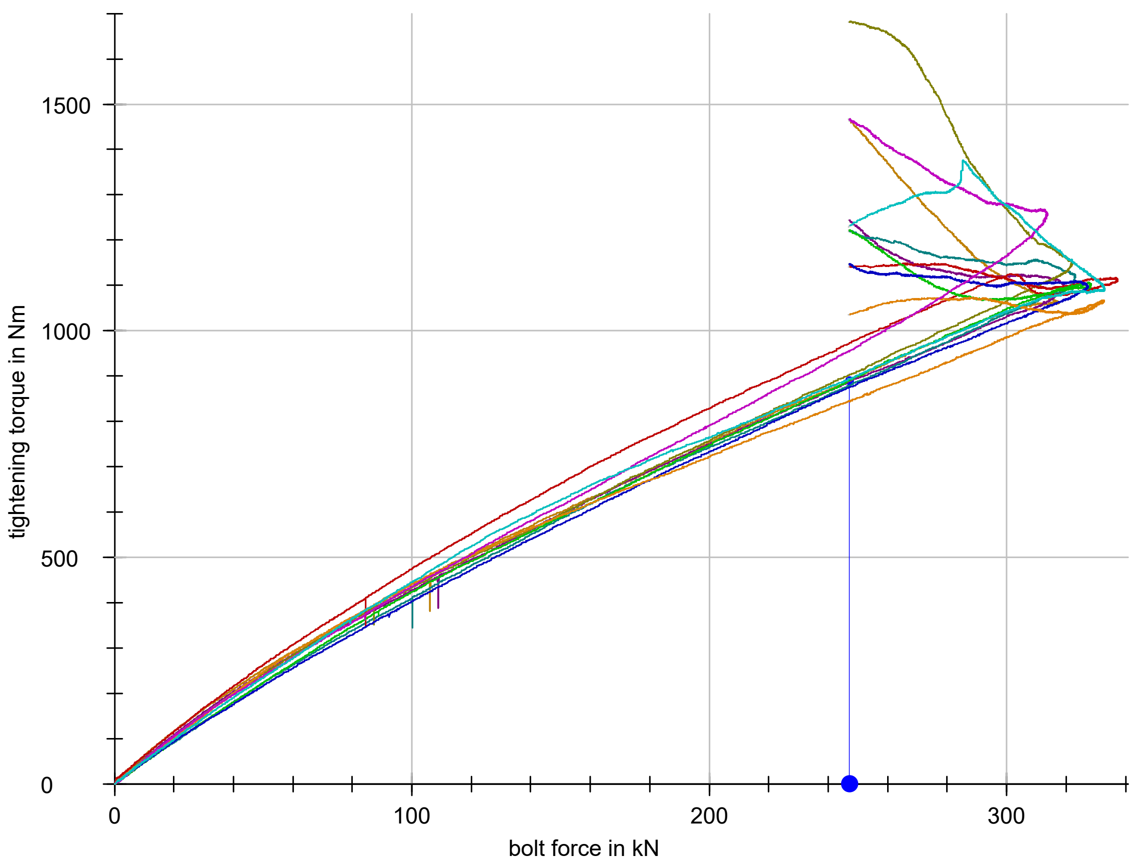
Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			222,4	0,095			
	0,105	0,109	222,4	0,154	889,2	821,7	1061,4
	0,114	0,101		0,152	887,8	813,9	1097,0
	0,109	0,104		0,151	878,9	805,0	1118,7
	0,104	0,113		0,155	904,0	827,7	1146,5
	0,110	0,125		>0,168	971,5	895,7	1114,1
	0,099	0,114		0,153	890,1	815,7	1104,6
	0,100	0,109		0,150	875,5	801,3	1095,3
	0,092	0,108		0,147	844,8	782,1	1064,1
	0,121	0,113		0,163	955,8	867,9	1257,0
	0,105	0,110		0,155	893,1	826,2	1092,8

ANNEX B

bolt force-tightening torque-curves: M24x100 HV 10.9 - Gleitmo WSP 5040

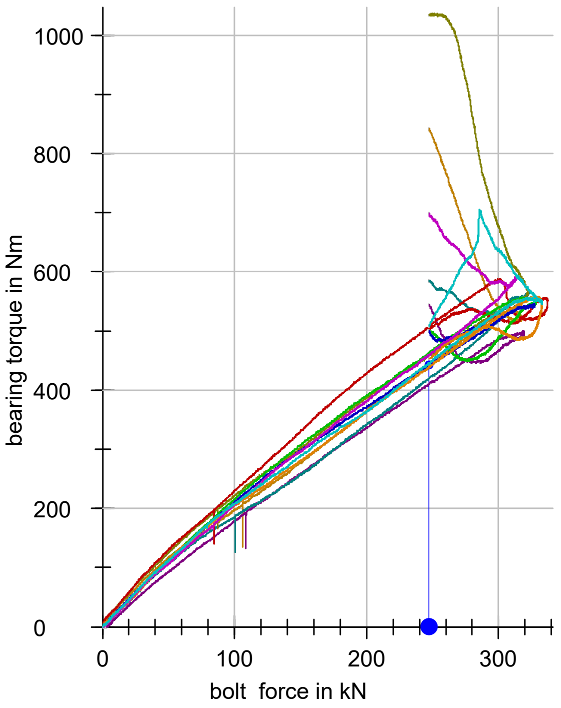


tightening torque-bolt force-curves: M24x100 HV 10.9 - Gleitmo WSP 5040

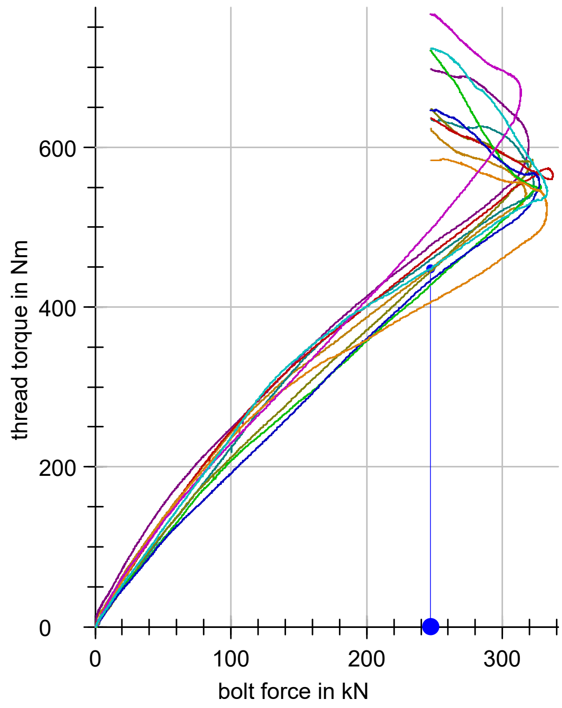


Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

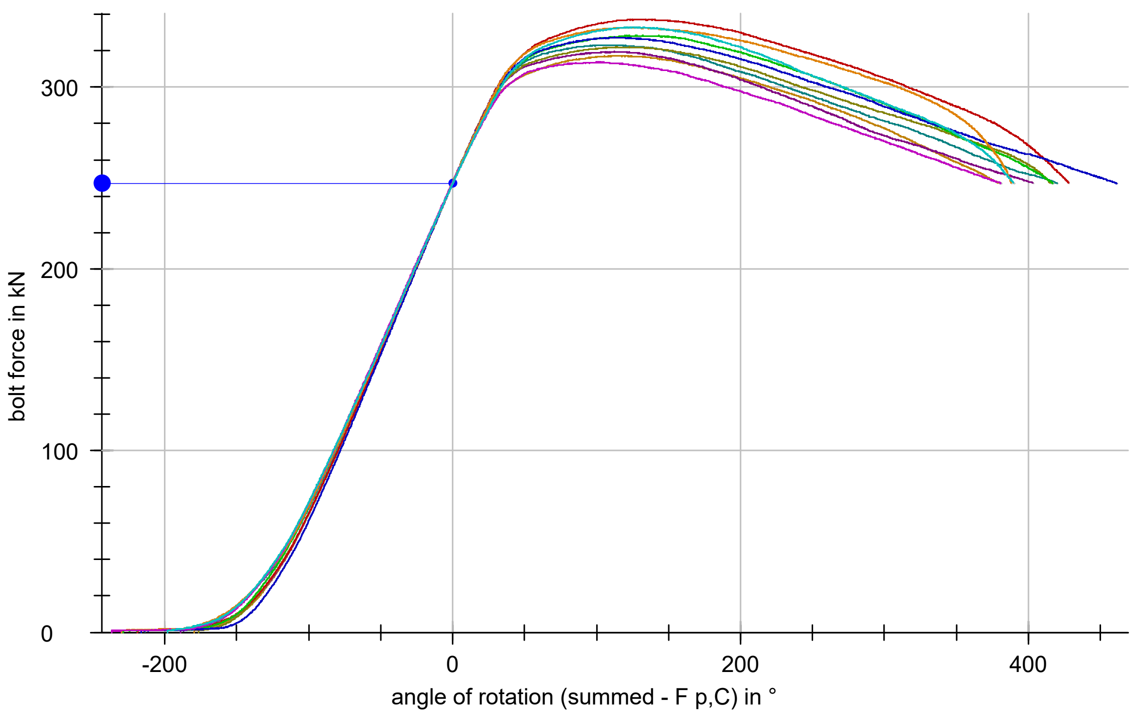
bearing torque-bolt force-curves: M24x100 HV 10.9 - Gleitmo WSP 5040



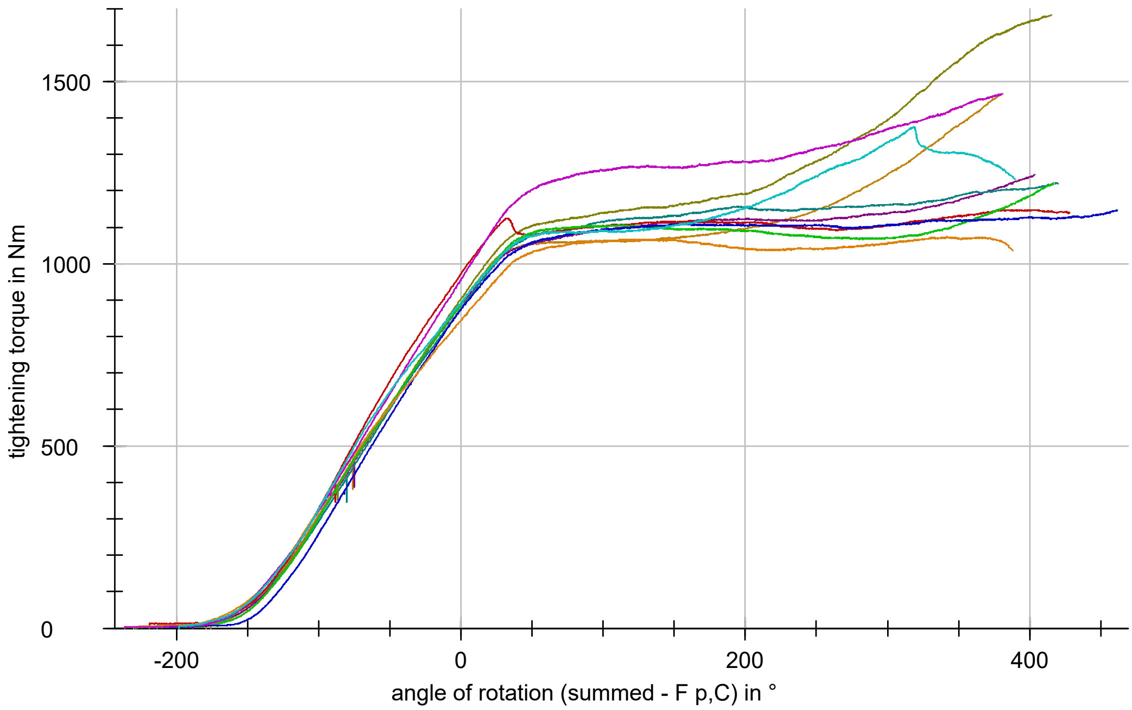
thread torque-bolt force-curves: M24x100 HV 10.9 - Gleitmo WSP 5040



bolt force-angle of rotation-curves: M24x100 HV 10.9 - Gleitmo WSP 5040



tightening torque-angle of rotation-curves: M24x100 HV 10.9 - Gleitmo WSP 5040



Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

Test series: M24x100 HV 10.9 - Molykote 1000 spray

Connecting element	:	M24x100 HV 10.9
Coating / Surface finish	:	M24x100 - tZn
Clamp length Σt	:	67,0 mm
Speed of tightening	:	2,0 1/min
Sensor F - T_{th}	:	SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ	:	SNo. 1024283 - 5000 Nm

Specific thread data:

Thread	Thread data	:	M 24 HV - IML	
d	Nominal diameter	:	24	mm
P	Pitch	:	3	mm
d_2	Pitch diameter	:	22,05	mm
d_o	Outer bearing surface diameter	:	38	mm
d_i	Inner bearing surface diameter	:	27,5	mm
D_b Calc	Bearing surface diameter	:	32,75	mm

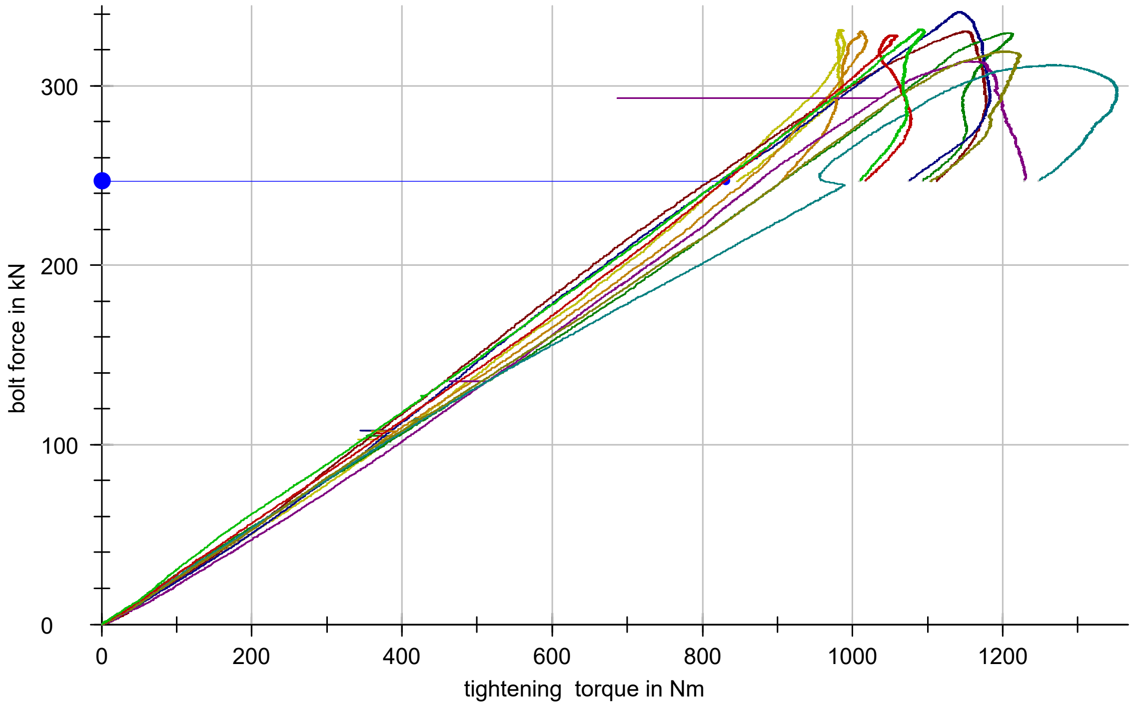
Results table: M24x100 HV 10.9 - Molykote 1000 spray

Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		247,1	317,7						120	210	0,10	
	Si_24_HV_10.9-27	247,1	331,1	990,4	227	360	570	246,9	210	419	0,14	0,099
	Si_24_HV_10.9-28		330,4	1179,0	210	335	584	246,9	198	447	0,14	0,096
	Si_24_HV_10.9-29		329,6	1214,1	221	347	638	247,0	201	493	0,15	0,110
	Si_24_HV_10.9-30		341,4	1183,8	217	363	582	247,0	219	438	0,14	0,098
	Si_24_HV_10.9-31		330,3	1019,9	232	362	598	246,9	206	442	0,14	0,103
	Si_24_HV_10.9-32		<313,8	1231,4	267	375	625	247,0	<108	358	0,15	0,105
	Si_24_HV_10.9-33		<311,7	1352,9	243	349	607	246,8	<106	363	0,16	0,117
	Si_24_HV_10.9-34		319,4	1223,6	244	360	614	246,9	<115	370	0,15	0,110
	Si_24_HV_10.9-35		328,3	1078,7	242	374	590	247,0	133	349	0,14	0,099
	Si_24_HV_10.9-36		331,7	1096,3	222	348	606	247,0	126	384	0,14	0,098

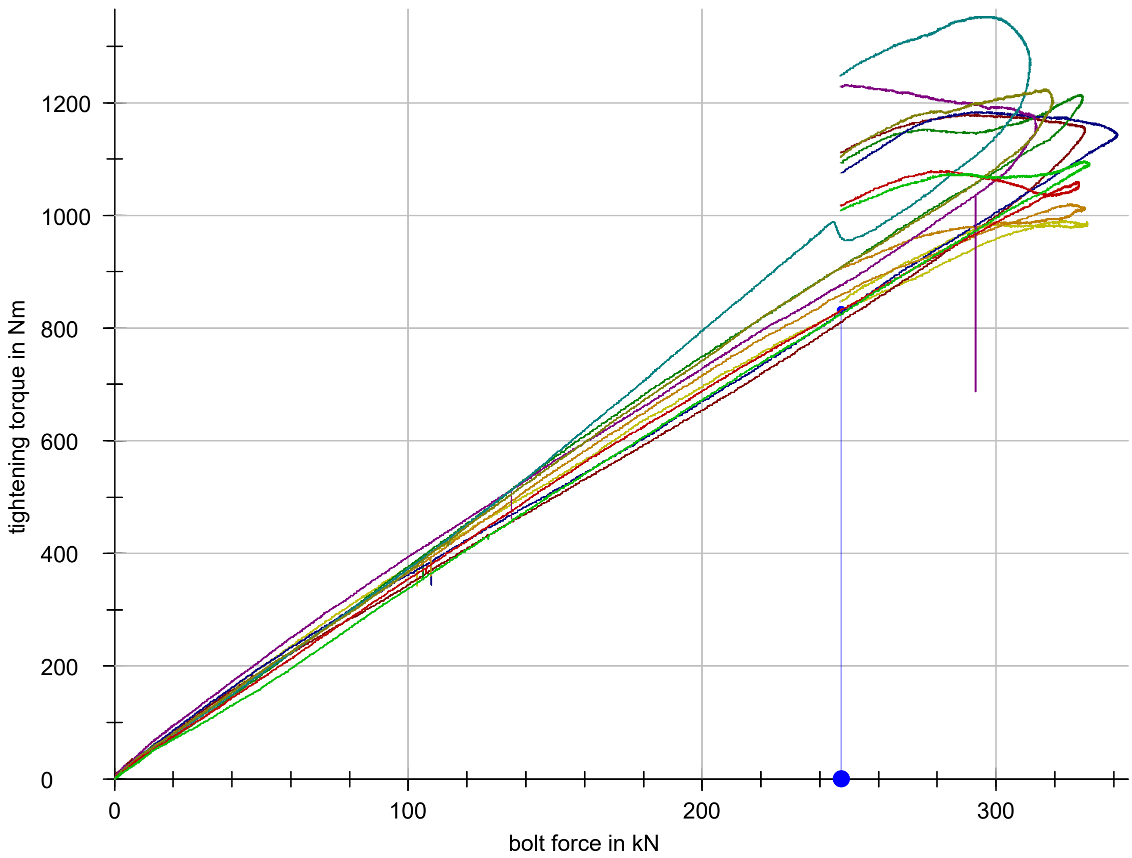
Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			222,4	0,095			
	0,110	0,090	222,4	0,143	830,4	762,3	983,1
	0,084	0,106		0,136	810,9	726,2	1147,7
	0,104	0,114		0,155	907,0	825,6	1206,3
	0,090	0,105		0,139	826,1	741,9	1142,9
	0,126	0,085		0,147	858,0	786,8	1013,6
	0,108	0,103		0,150	876,7	803,0	1153,3
	0,106	0,126		>0,167	961,2	893,8	1266,0
	0,083	0,130		0,155	906,5	825,2	1202,1
	0,071	0,121		0,142	831,1	758,4	1054,5
	0,069	0,121		0,140	824,3	746,9	1089,7

ANNEX B

bolt force-tightening torque-curves: M24x100 HV 10.9 - Molykote 1000 spray



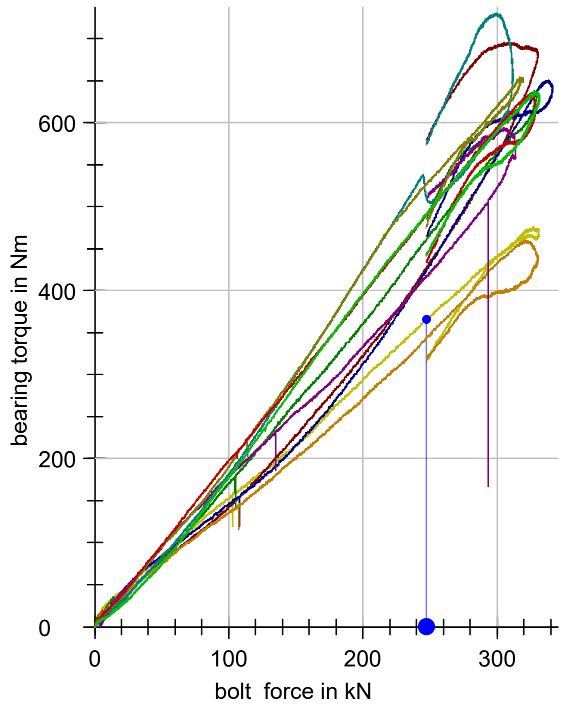
tightening torque-bolt force-curves: M24x100 HV 10.9 - Molykote 1000 spray



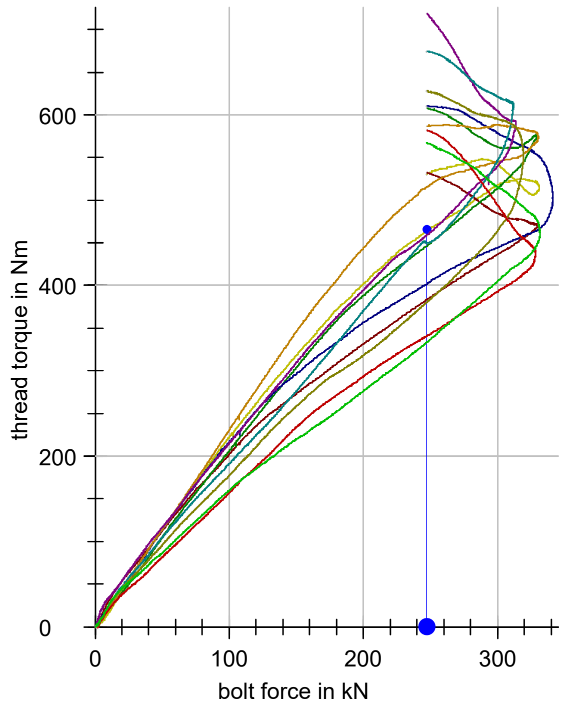
Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

ANNEX B

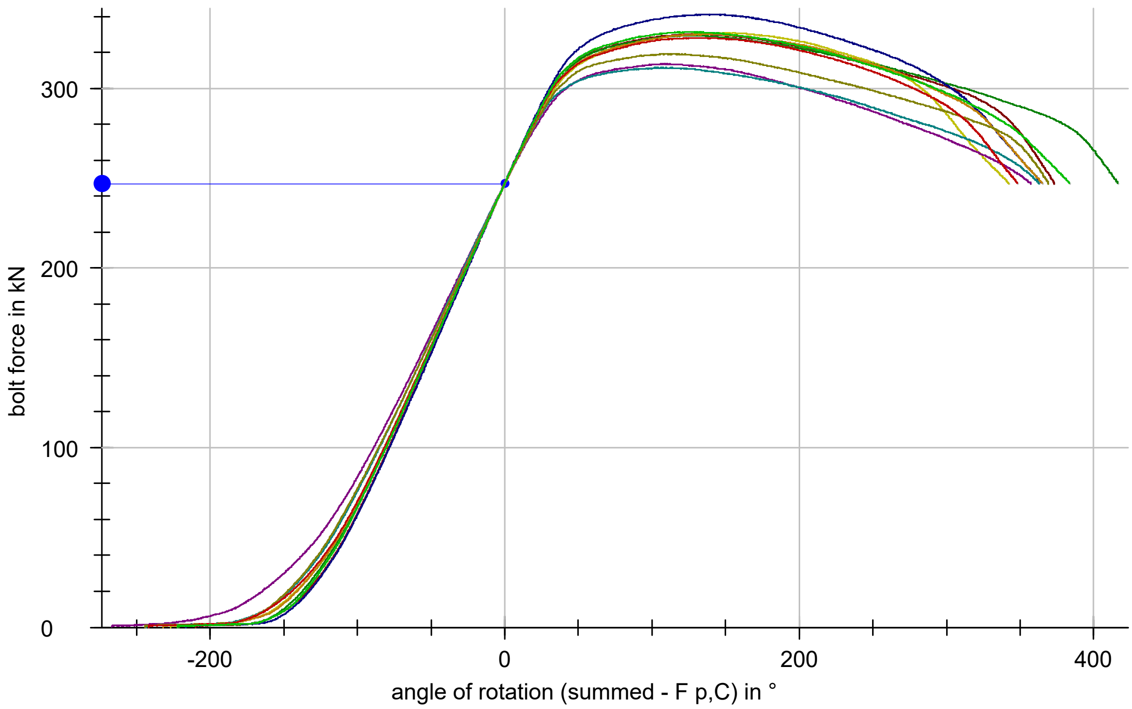
bearing torque-bolt force-curves: M24x100 HV 10.9 - Molykote 1000 spray



thread torque-bolt force-curves: M24x100 HV 10.9 - Molykote 1000 spray

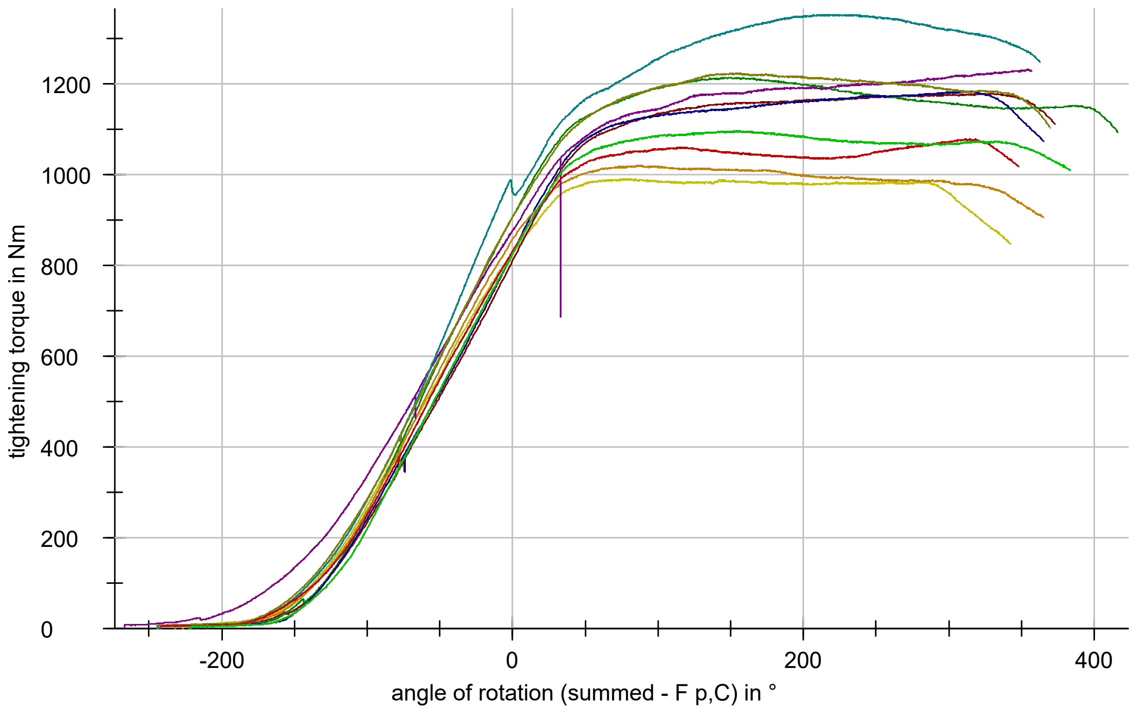


bolt force-angle of rotation-curves: M24x100 HV 10.9 - Molykote 1000 spray



Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

tightening torque-angle of rotation-curves: M24x100 HV 10.9 - Molykote 1000 spray



Test series: M24x100 HV 10.9 - Microgleit HV-paste LP440

Connecting element	:	M24x100 HV 10.9
Coating / Surface finish	:	M24x100 - tZn
Clamp length Σt	:	67,0 mm
Speed of tightening	:	2,0 1/min
Sensor F - T_{th}	:	SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ	:	SNo. 1024283 - 5000 Nm

Specific thread data:

Thread	Thread data	:	M 24 HV - IML	
d	Nominal diameter	:	24	mm
P	Pitch	:	3	mm
d_2	Pitch diameter	:	22,05	mm
d_o	Outer bearing surface diameter	:	38	mm
d_i	Inner bearing surface diameter	:	27,5	mm
D_b Calc	Bearing surface diameter	:	32,75	mm

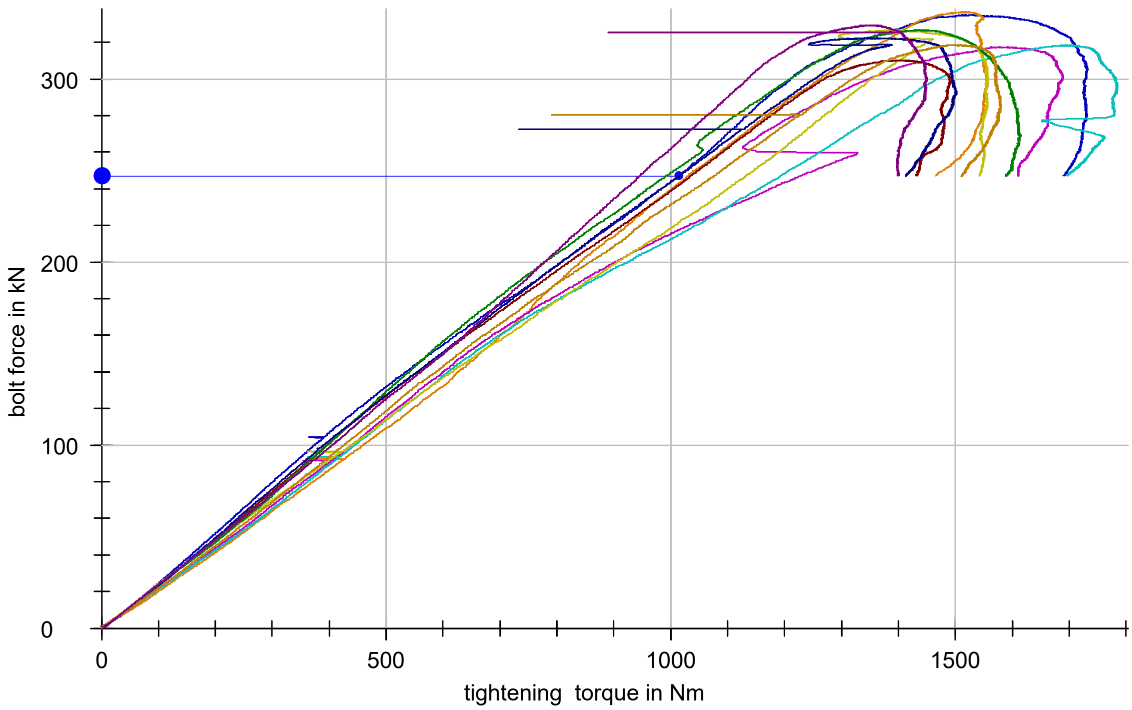
Results table: M24x100 HV 10.9 - Microgleit HV-paste LP440

Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		247,1	317,7						120	210	0,10	
	Si_24_HV_10.9-37	247,1	335,1	1733,1	223	347	626	246,9	201	480	>0,17	0,124
	Si_24_HV_10.9-38		336,5	1557,7	221	346	584	246,9	202	439	>0,17	0,127
	Si_24_HV_10.9-39		<317,5	1690,2	248	358	664	246,9	187	492	>0,21	0,154
	Si_24_HV_10.9-40		318,3	1785,3	212	314	623	246,9	178	487	>0,20	0,150
	Si_24_HV_10.9-41		326,8	1558,0	180	298	557	247,0	194	452	>0,19	0,141
	Si_24_HV_10.9-42		<310,3	1492,7	231	332	629	246,9	179	477	>0,17	0,128
	Si_24_HV_10.9-43		326,6	1615,1	191	299	610	246,9	183	494	>0,17	0,121
	Si_24_HV_10.9-44		322,4	1501,9	227	331	694	247,0	181	543	>0,17	0,125
	Si_24_HV_10.9-45		318,5	1581,2	224	336	653	246,9	191	507	>0,18	0,133
	Si_24_HV_10.9-46		329,3	1450,9	184	295	607	247,0	186	498	0,16	0,115

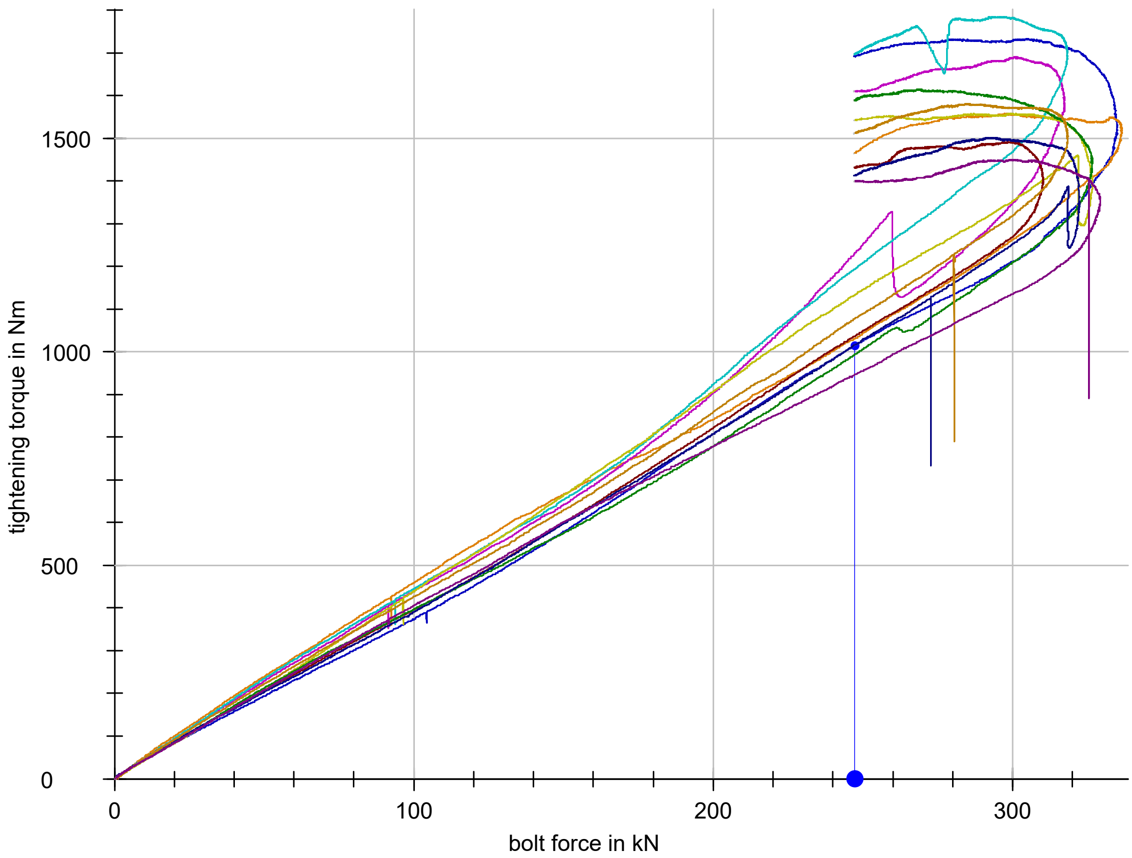
Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			222,4	0,095			
	0,120	0,128	222,4	>0,170	1013,1	908,5	1519,9
	0,127	0,127		>0,175	1030,7	932,1	1517,2
	0,123	0,179		>0,197	1228,7	1049,0	1577,0
	0,137	0,159		>0,199	1193,6	1059,7	1686,3
	0,118	0,159		>0,191	1131,7	1017,5	1390,2
	0,112	0,140		>0,173	1035,5	925,4	1392,9
	0,089	0,147		>0,165	991,4	881,8	1443,6
	0,100	0,145		>0,169	1016,7	904,5	1340,0
	0,122	0,142		>0,179	1076,5	955,3	1505,3
	0,108	0,121		0,160	946,2	856,0	1348,5

ANNEX B

bolt force-tightening torque-curves: M24x100 HV 10.9 - Microgleit HV-paste LP440

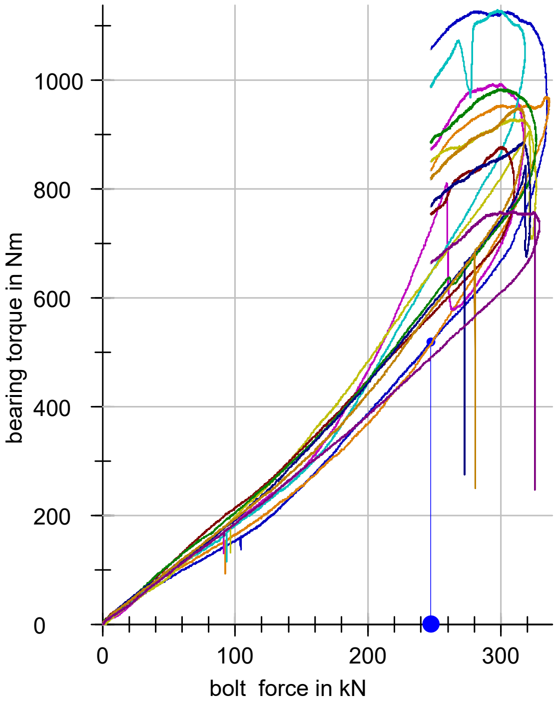


tightening torque-bolt force-curves: M24x100 HV 10.9 - Microgleit HV-paste LP440

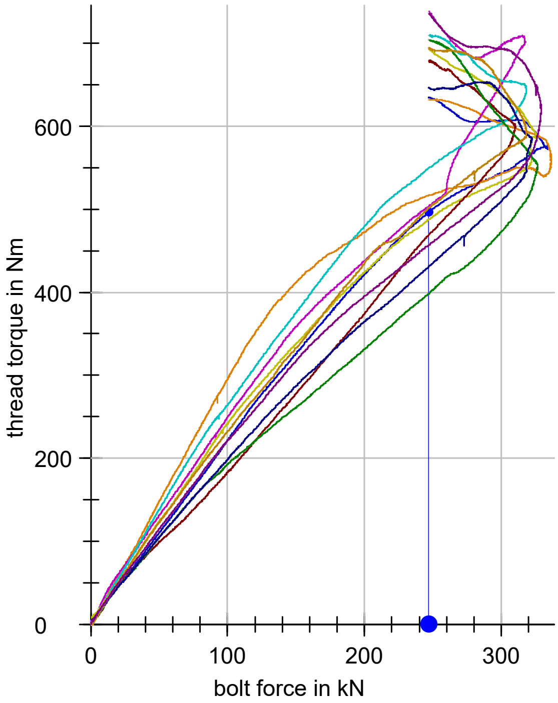


ANNEX B

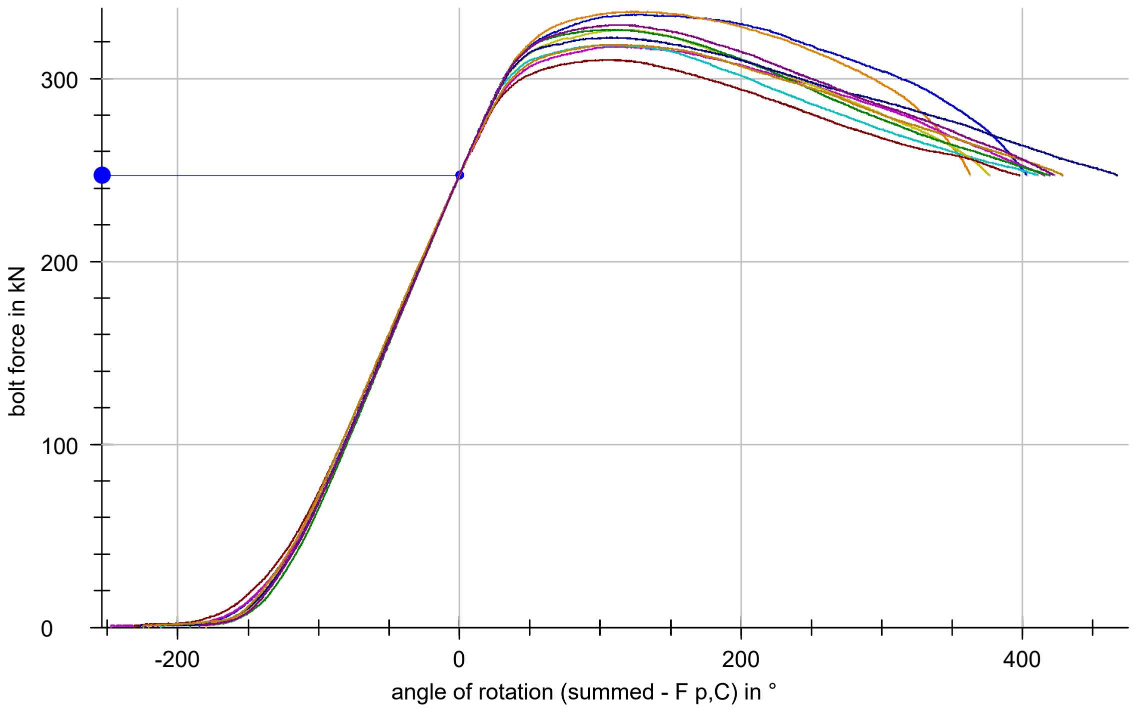
bearing torque-bolt force-curves: M24x100 HV 10.9 - Microgleit HV-paste LP440



thread torque-bolt force-curves: M24x100 HV 10.9 - Microgleit HV-paste LP440

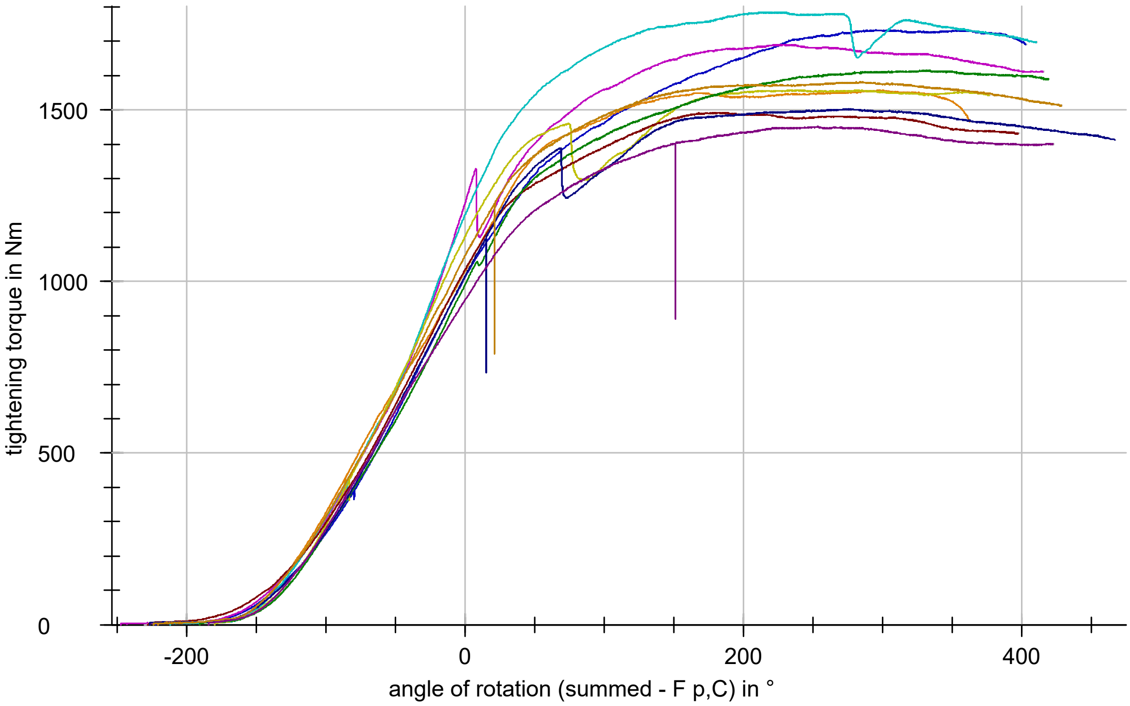


bolt force-angle of rotation-curves: M24x100 HV 10.9 - Microgleit HV-paste LP440



Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

tightening torque-angle of rotation-curves: M24x100 HV 10.9 - Microgleit HV-paste LP440



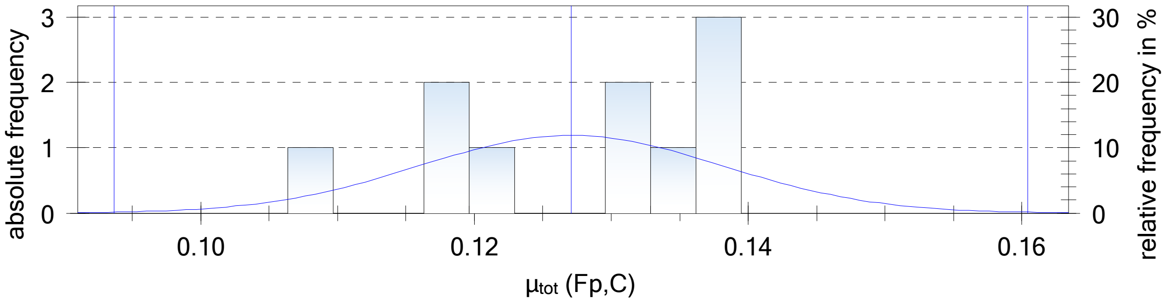
Statistical evaluation: M24x100 HV 10.9 - Factory provided

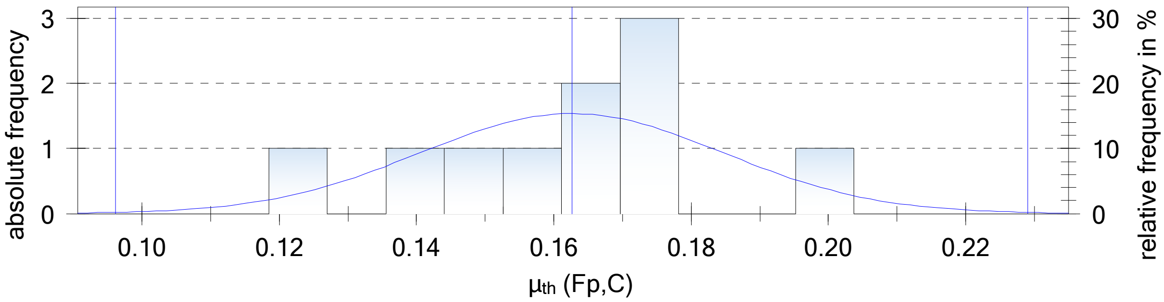
M24x100 HV 10.9 - Factory provided n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	317,0	1565,2	227	331	580	247,0	180	469	0,126
min	282,5	1086,1	176	243	383	246,8	143	283	0,097
R	34,5	479,1	51	88	197	0,2	37	186	0,029
$\bar{x}$	303,9	1304,2	192	285	507	246,9	169	390	0,114
s	10,2	162,4	16	25	69	0,1	13	65	0,011
ν	3,37	12,46	8,30	8,76	13,52	0,03	7,72	16,63	9,55

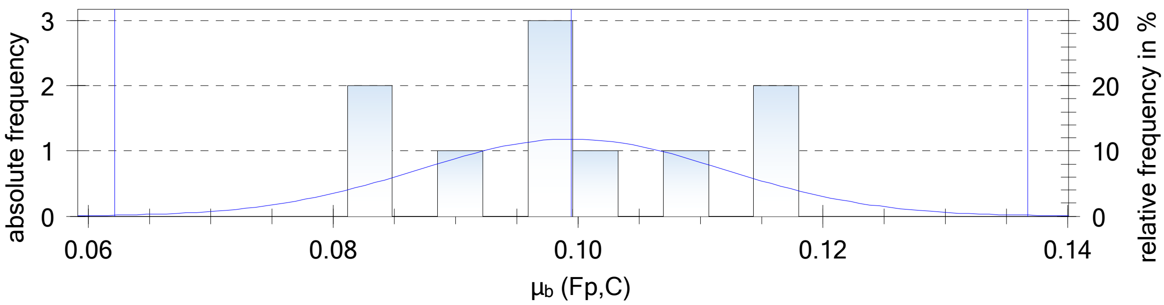
M24x100 HV 10.9 - Factory provided n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C*}$)	M ($F_{bi,max}$) Nm
max	0,168	0,105	1027,7	0,17	939,0	0,176	1369,3
min	0,119	0,072	818,6	0,14	734,5	0,138	1052,2
R	0,049	0,033	209,1	0,03	204,5	0,038	317,1
$\bar{x}$	0,143	0,092	939,4	0,16	856,4	0,161	1186,2
s	0,015	0,013	79,0	0,01	74,5	0,014	89,8
ν	10,44	13,82	8,41	8,33	8,70	8,70	7,57

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M24x100 HV 10.9 - Factory provided







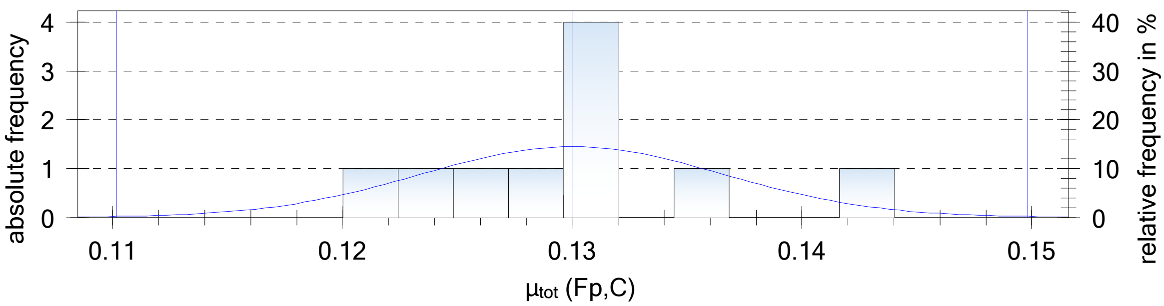
Statistical evaluation: M24x100 HV 10.9 - Gleitmo WSP 5040

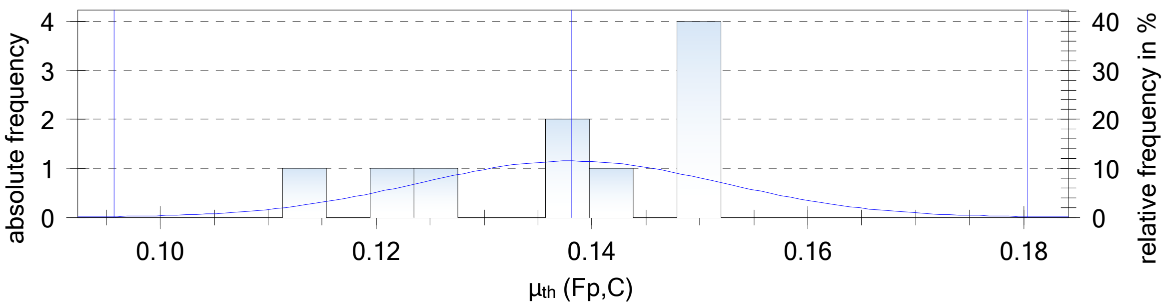
M24x100 HV 10.9 - Gleitmo WSP 5040 n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	337,4	1684,2	237	359	678	247,0	209	535	0,119
min	313,8	1074,1	176	290	560	246,8	180	454	0,101
R	23,6	610,1	61	69	118	0,2	29	81	0,018
$\bar{x}$	325,5	1305,4	209	326	618	247,0	192	484	0,109
s	7,6	189,1	22	25	35	0,1	11	25	0,005
ν	2,33	14,49	10,48	7,81	5,67	0,03	5,65	5,09	4,84

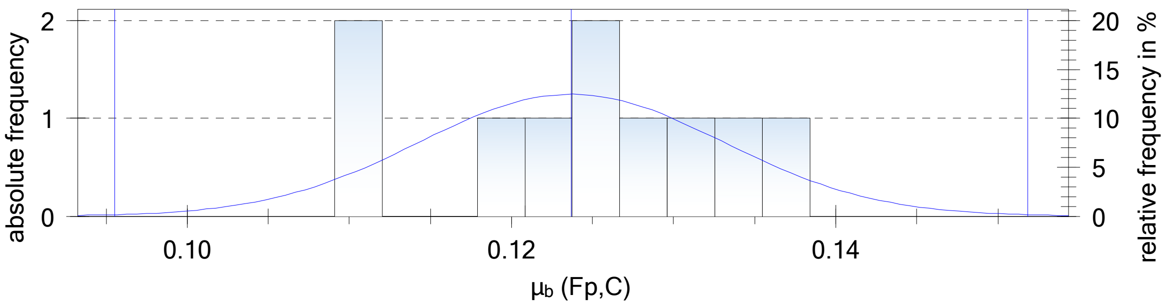
M24x100 HV 10.9 - Gleitmo WSP 5040 n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C*}$)	M ($F_{bi,max}$) Nm
max	0,121	0,125	971,5	0,16	895,7	0,168	1257,0
min	0,092	0,101	844,8	0,14	782,1	0,147	1061,4
R	0,029	0,024	126,7	0,02	113,6	0,021	195,6
$\bar{x}$	0,106	0,111	899,1	0,15	825,7	0,155	1115,2
s	0,008	0,006	37,6	0,01	33,1	0,006	55,7
ν	7,72	5,86	4,18	3,76	4,01	4,04	5,00

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M24x100 HV 10.9 - Gleitmo WSP 5040







Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

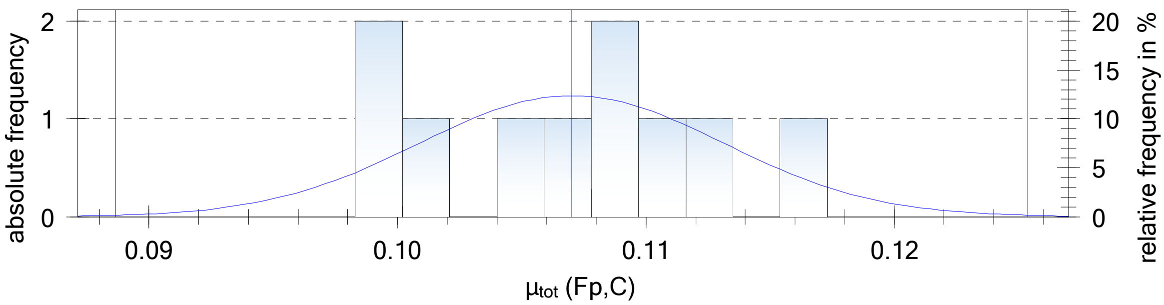
Statistical evaluation: M24x100 HV 10.9 - Molykote 1000 spray

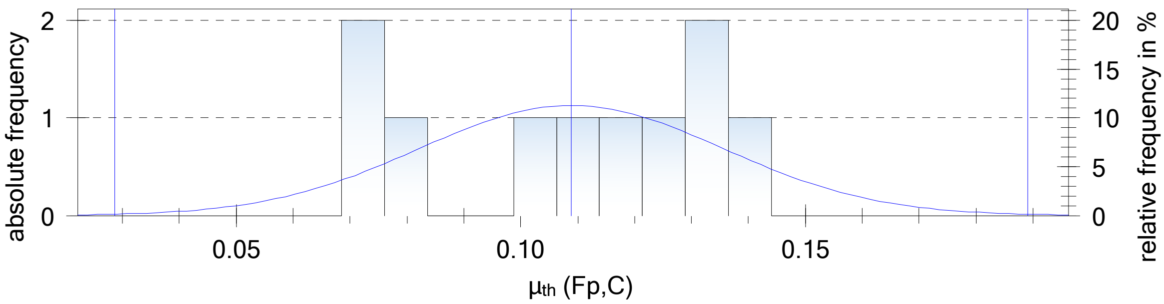
M24x100 HV 10.9 - Molykote 1000 spray n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	341,4	1352,9	267	375	638	247,0	219	493	0,117
min	311,7	990,4	210	335	570	246,8	106	349	0,096
R	29,7	362,5	57	40	68	0,2	113	144	0,021
$\bar{x}$	326,8	1157,0	233	357	601	246,9	162	406	0,104
s	9,1	110,1	17	13	21	0,1	48	48	0,007
ν	2,78	9,52	7,23	3,52	3,47	0,03	29,57	11,87	6,65

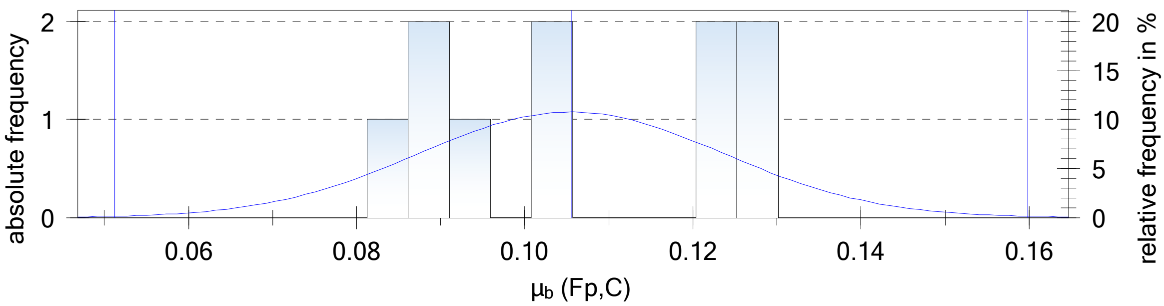
M24x100 HV 10.9 - Molykote 1000 spray n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C*}$)	M ($F_{bi,max}$) Nm
max	0,126	0,130	961,2	0,16	893,8	0,167	1266,0
min	0,069	0,085	810,9	0,14	726,2	0,136	983,1
R	0,057	0,045	150,3	0,02	167,6	0,031	282,9
$\bar{x}$	0,095	0,110	863,2	0,15	787,0	0,147	1125,9
s	0,019	0,015	48,7	0,01	51,0	0,009	90,0
ν	19,51	13,64	5,64	4,88	6,48	6,44	7,99

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M24x100 HV 10.9 - Molykote 1000 spray







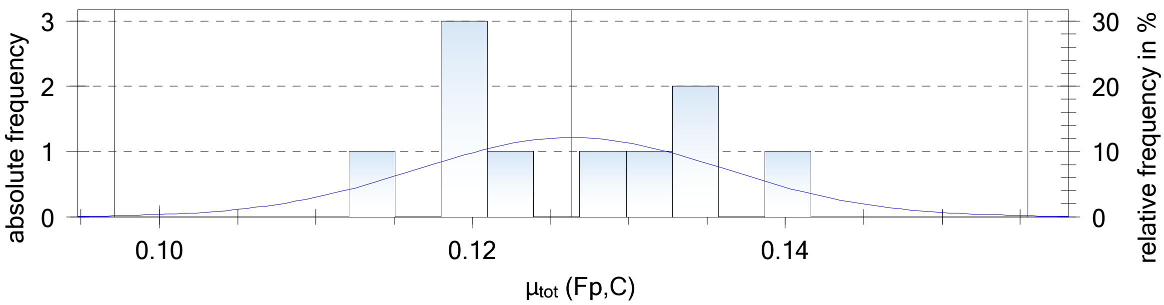
Statistical evaluation: M24x100 HV 10.9 - Microgleit HV-paste LP440

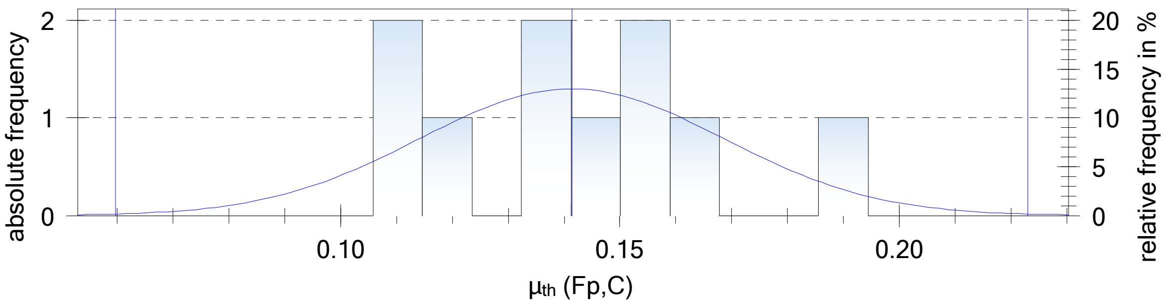
M24x100 HV 10.9 - Microgleit HV-paste LP440 n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	336,5	1785,3	248	358	694	247,0	202	543	0,154
min	310,3	1450,9	180	295	557	246,9	178	439	0,115
R	26,2	334,4	68	63	137	0,1	24	104	0,039
$\bar{x}$	324,1	1596,6	214	326	625	246,9	188	487	0,132
s	8,3	109,3	22	23	39	0,0	9	29	0,013
ν	2,55	6,85	10,37	6,98	6,30	0,02	4,58	5,89	9,64

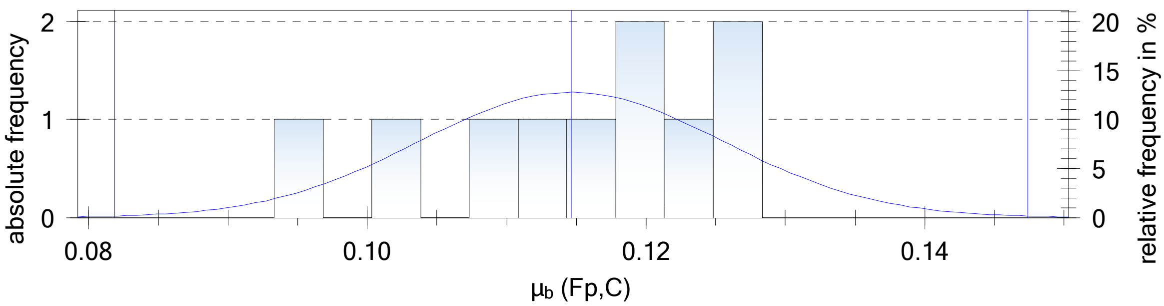
M24x100 HV 10.9 - Microgleit HV-paste LP440 n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C}$*)	M ($F_{bi,max}$) Nm
max	0,137	0,179	1228,7	0,21	1059,7	0,199	1686,3
min	0,089	0,121	946,2	0,16	856,0	0,160	1340,0
R	0,048	0,058	282,5	0,05	203,7	0,039	346,3
$\bar{x}$	0,116	0,145	1066,4	0,18	949,0	0,178	1472,1
s	0,014	0,018	91,0	0,02	70,4	0,014	110,0
ν	11,99	12,13	8,53	8,91	7,42	7,60	7,47

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M24x100 HV 10.9 - Microgleit HV-paste LP440







Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

M36 HV 10.9 - Test protocol

SIROCO - Tightening tests of HV bolting assemblies

Client / Customer	:	SIROCO
Date of reception	:	-
Date of testing	:	09.12.2016 M36x160 HV 10.9
Project	:	RFCS SIROCO WP 1 Task 1.5
Specification	:	According EN 14399-2 and EN ISO 16047
Operator	:	Christoph Abraham B.Sc., Dominik Jungbluth M.Sc.
Number of assemblies tested	:	40
Designation of bolt	:	M36x160 HV 10.9
Marking of bolt	:	-
Designation of nut	:	Hexagon nut HV M36
Marking of nut	:	-
Designation of washer	:	Washer M36 HV
Marking of washer	:	-
Coating / Surface finish	:	M36x160 - tZn
Ambient temperature	:	23,6 °C
Ambient relative humidity	:	25,8 %
Rotated component	:	Hexagon nut
Special testing conditions	:	Different lubrications used: - Factory provided lubrication - Gleitmo WSP 5040 - Molykote 1000 spray - Microgleit HV-paste LP440

Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

Test specimens identification

Si_xx_yy_zz

Si: RFCS SIROCO
xx: thread
yy: strength class
zz: sequential number of bolt

Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

Test series: M36x160 HV 10.9 - Factory provided

Connecting element	:	M36x160 HV 10.9
Coating / Surface finish	:	M36x160 - tZn
Clamp length Σt	:	123,5 mm
Speed of tightening	:	2,0 1/min
Sensor F - T_{th}	:	SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ	:	SNo. 1016241 - 15000 Nm

Specific thread data:

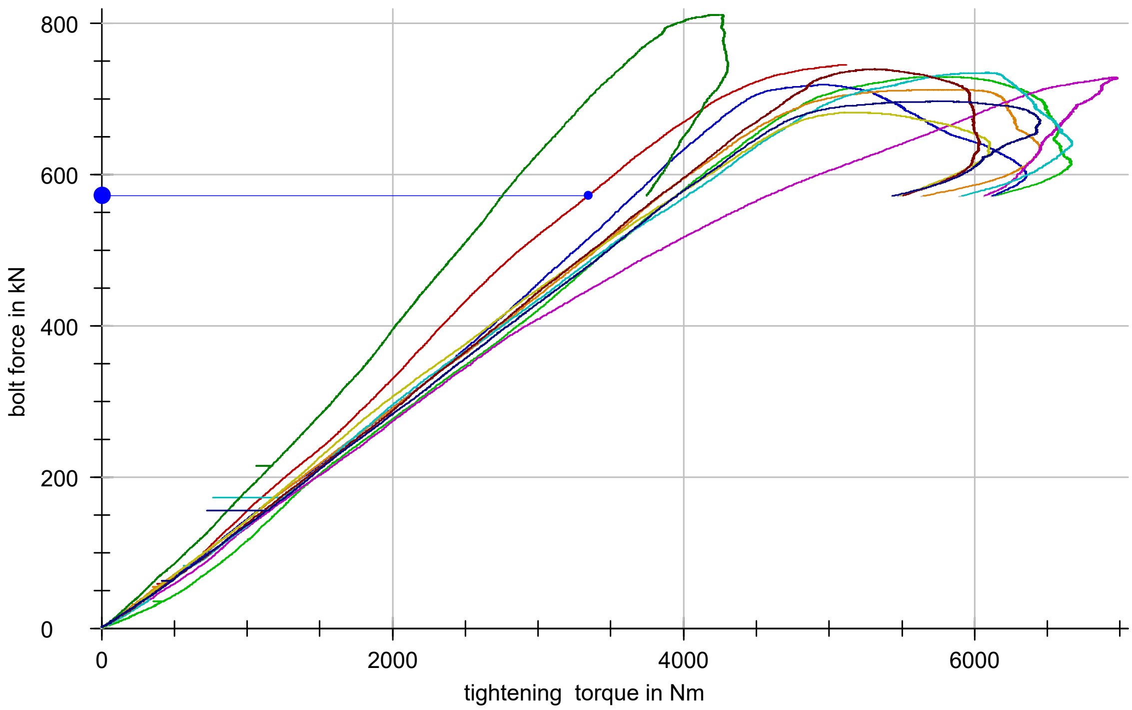
Thread	Thread data	:	M 36/4.00 HV - IML	
d	Nominal diameter	:	36	mm
P	Pitch	:	4	mm
d_2	Pitch diameter	:	33,4	mm
d_o	Outer bearing surface diameter	:	55,9	mm
d_i	Inner bearing surface diameter	:	42	mm
D_b Calc	Bearing surface diameter	:	48,95	mm

Results table: M36x160 HV 10.9 - Factory provided

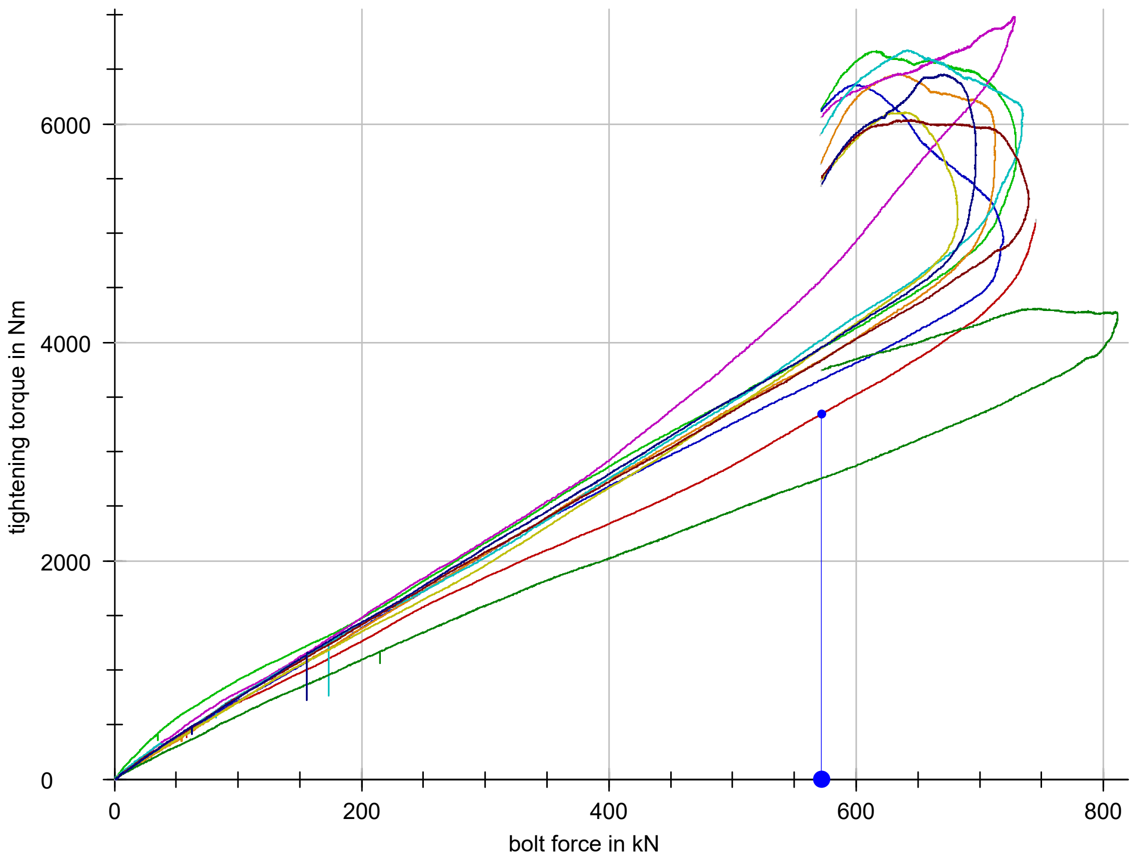
Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		571,9	735,3						120	210	0,10	
	Si_36_HV_10.9-01	571,9	745,4	5122,7	246	366	-	-	208	-	0,16	0,119
	Si_36_HV_10.9-02		<729,8	6666,6	263	386	626	571,2	211	451	>0,19	0,143
	Si_36_HV_10.9-03		<719,0	6360,9	239	365	592	571,5	215	441	>0,18	0,132
	Si_36_HV_10.9-04		<712,6	6456,4	247	364	545	571,1	205	386	>0,19	0,139
	Si_36_HV_10.9-05		<728,7	6982,8	241	389	642	571,4	235	489	>0,22	0,168
	Si_36_HV_10.9-21		<734,8	6673,1	318	461	677	570,9	231	447	>0,20	0,146
	Si_36_HV_10.9-22		<682,3	6106,8	279	353	536	571,0	<74	257	>0,19	0,143
	Si_36_HV_10.9-23		739,9	6035,7	302	464	691	571,6	162	389	>0,19	0,139
	Si_36_HV_10.9-24		811,7	4309,1	262	434	584	571,9	173	323	0,13	0,095
	Si_36_HV_10.9-25		<697,1	6452,5	270	376	564	571,4	<106	294	>0,19	0,143

Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			514,7	0,095			
	0,122	0,116	514,7	0,160	3341,1	2965,5	5120,7
	0,153	0,136		>0,193	3946,7	3580,9	5695,7
	0,167	0,103		>0,180	3658,3	3343,6	4961,9
	0,169	0,115		>0,188	3840,6	3490,2	5833,0
	0,134	0,195		>0,215	4568,9	3980,2	6968,6
	0,167	0,130		>0,192	4020,3	3560,2	6074,2
	0,170	0,122		>0,189	3947,5	3500,6	5123,8
	0,170	0,114		>0,187	3834,6	3467,5	5316,5
	0,098	0,094		0,136	2751,8	2518,7	4223,0
	0,160	0,130		>0,193	3955,1	3570,9	5801,2

bolt force-tightening torque-curves: M36x160 HV 10.9 - Factory provided

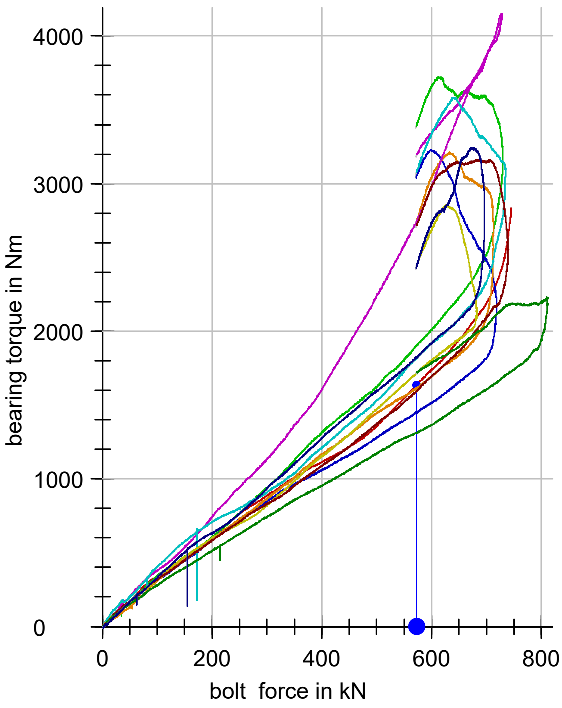


tightening torque-bolt force-curves: M36x160 HV 10.9 - Factory provided

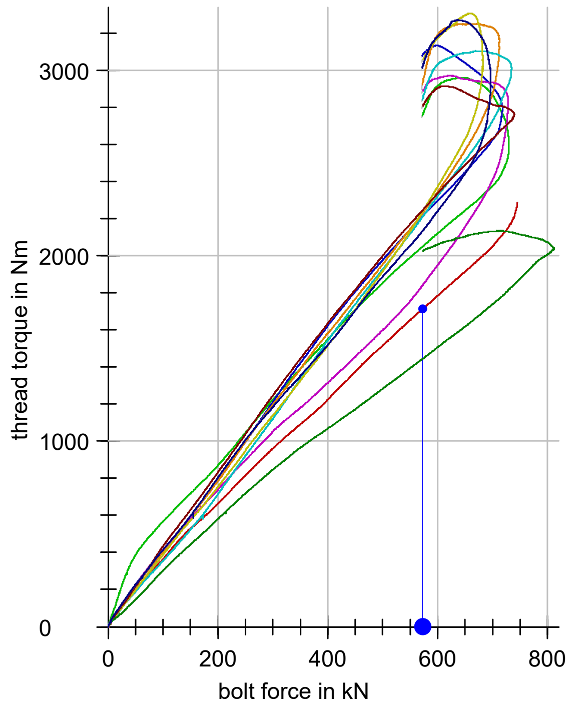


ANNEX B

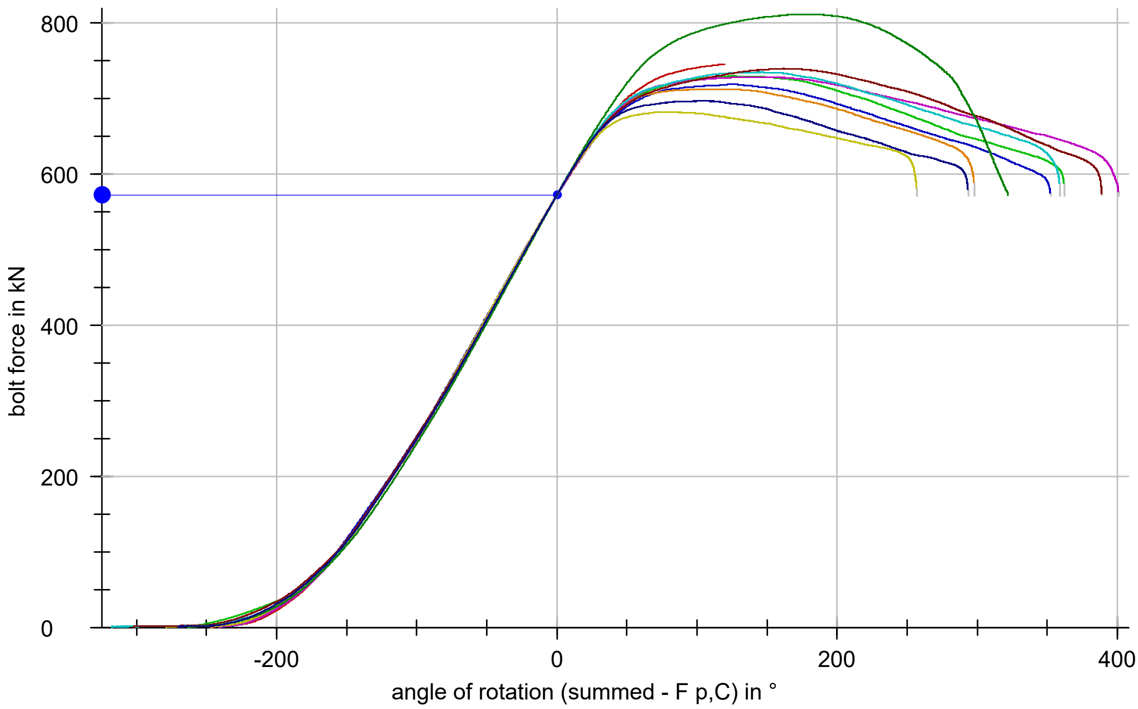
bearing torque-bolt force-curves: M36x160 HV 10.9 - Factory provided



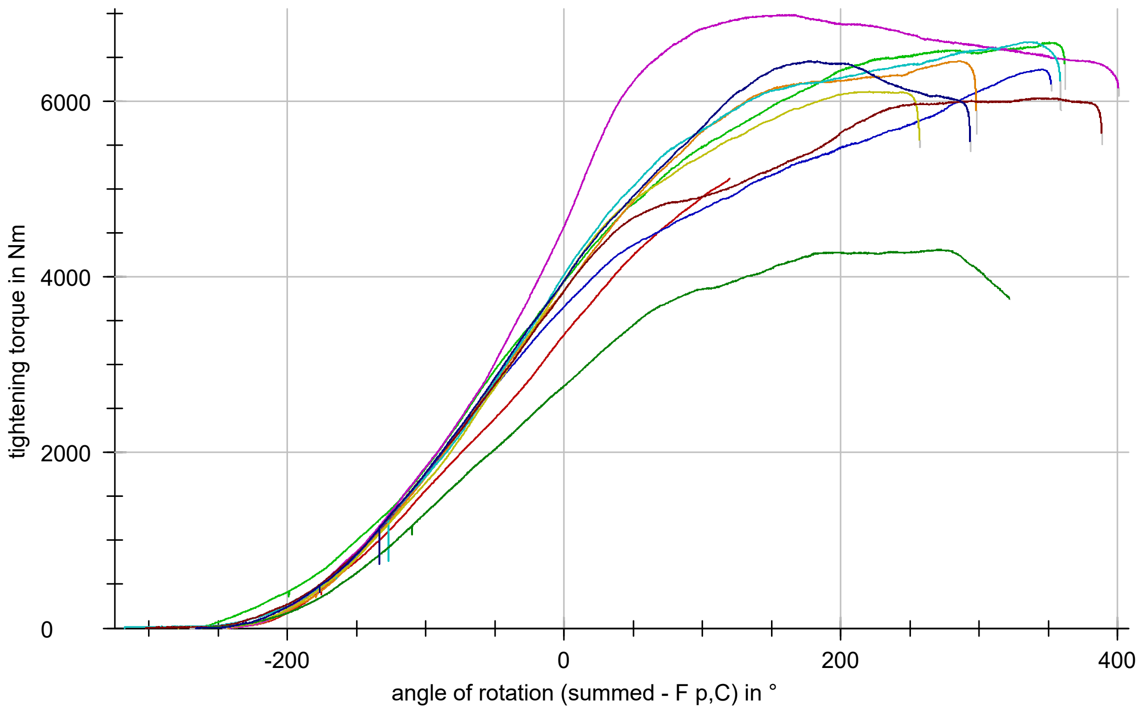
thread torque-bolt force-curves: M36x160 HV 10.9 - Factory provided



bolt force-angle of rotation-curves: M36x160 HV 10.9 - Factory provided



tightening torque-angle of rotation-curves: M36x160 HV 10.9 - Factory provided



Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

Test series: M36x160 HV 10.9 - Gleitmo WSP 5040

Connecting element	:	M36x160 HV 10.9
Coating / Surface finish	:	M36x160 - tZn
Clamp length Σt	:	123,5 mm
Speed of tightening	:	2,0 1/min
Sensor F - T_{th}	:	SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ	:	SNo. 1016241 - 15000 Nm

Specific thread data:

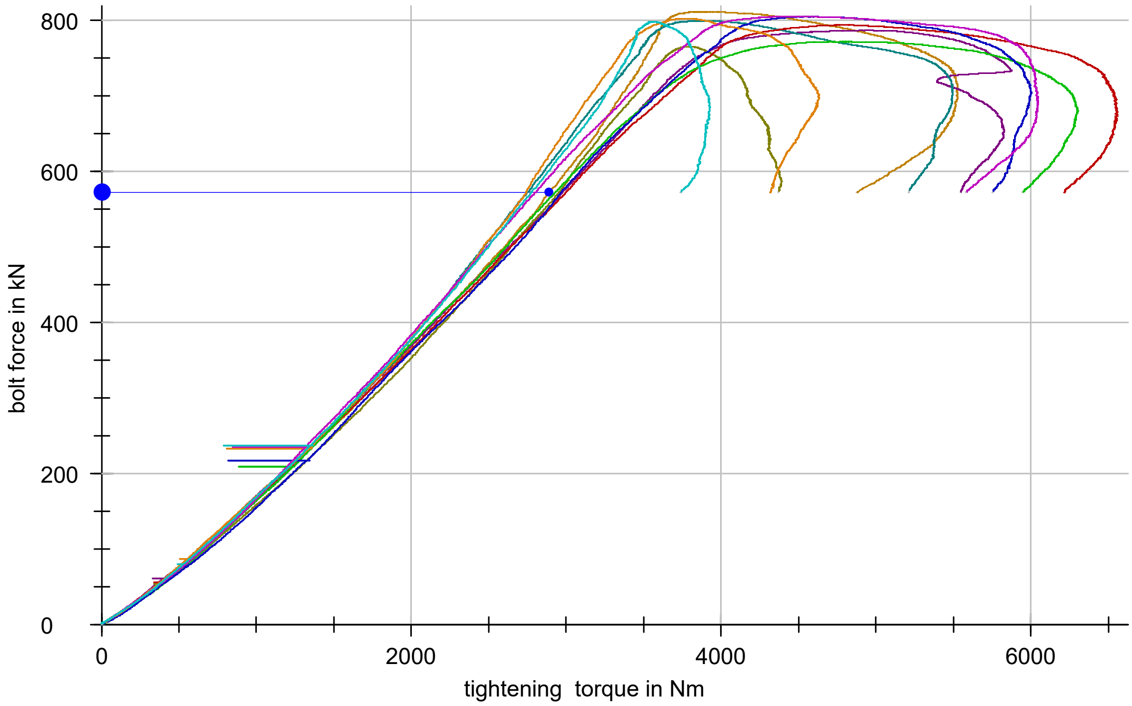
Thread	Thread data	:	M 36/4.00 HV - IML	
d	Nominal diameter	:	36	mm
P	Pitch	:	4	mm
d_2	Pitch diameter	:	33,4	mm
d_o	Outer bearing surface diameter	:	55,9	mm
d_i	Inner bearing surface diameter	:	42	mm
D_b Calc	Bearing surface diameter	:	48,95	mm

Results table: M36x160 HV 10.9 - Gleitmo WSP 5040

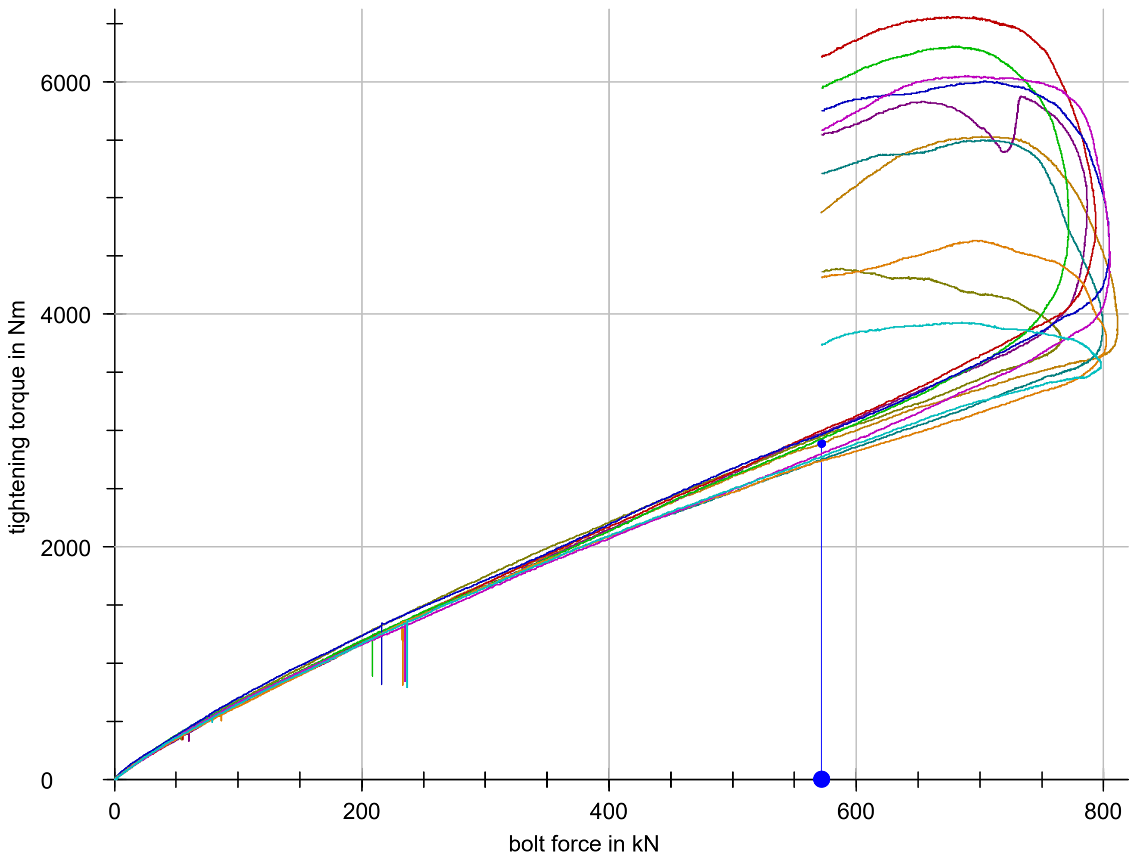
Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		571,9	735,3						120	210	0,10	
	Si_36_HV_10.9-06	571,9	811,5	5526,9	251	431	608	571,4	267	444	0,14	0,101
	Si_36_HV_10.9-07		786,8	5874,1	269	437	595	571,9	256	414	0,14	0,105
	Si_36_HV_10.9-08		799,5	5495,3	248	397	578	571,8	234	415	0,13	0,095
	Si_36_HV_10.9-09		765,6	4392,9	273	419	671	571,8	234	486	0,14	0,103
	Si_36_HV_10.9-10		793,9	6559,8	242	406	621	571,8	250	465	0,15	0,105
	Si_36_HV_10.9-26		771,8	6304,6	254	386	599	571,9	218	431	0,14	0,103
	Si_36_HV_10.9-27		804,9	6003,2	298	476	649	571,8	262	436	0,14	0,104
	Si_36_HV_10.9-28		802,4	4631,8	270	424	576	571,8	238	390	0,13	0,095
	Si_36_HV_10.9-29		805,2	6048,9	267	428	594	572,0	244	411	0,14	0,097
	Si_36_HV_10.9-30		798,1	3929,5	289	465	619	571,9	261	415	0,13	0,096

Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k (F_{p,C^*})	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			514,7	0,095			
	0,100	0,102	514,7	0,144	2886,5	2664,0	3902,1
	0,112	0,099		0,146	2980,4	2702,7	4938,2
	0,081	0,107		0,136	2751,6	2525,1	3884,0
	0,114	0,095		0,146	2953,6	2705,8	3797,9
	0,110	0,101		0,146	2997,8	2713,7	4742,5
	0,098	0,106		0,144	2931,4	2672,6	4686,2
	0,104	0,104		0,148	2962,9	2738,8	4576,6
	0,093	0,096		0,136	2740,4	2526,6	3778,8
	0,088	0,105		0,138	2799,6	2549,5	4423,5
	0,093	0,099		0,138	2772,8	2547,9	3553,1

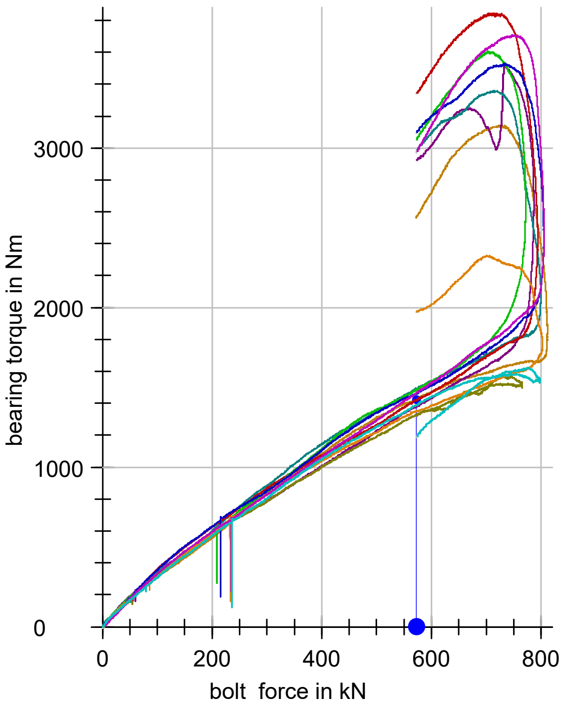
bolt force-tightening torque-curves: M36x160 HV 10.9 - Gleitmo WSP 5040



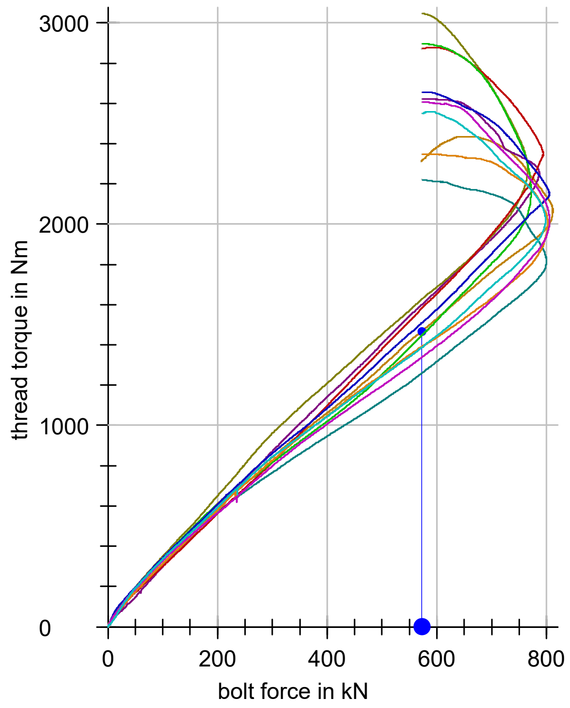
tightening torque-bolt force-curves: M36x160 HV 10.9 - Gleitmo WSP 5040



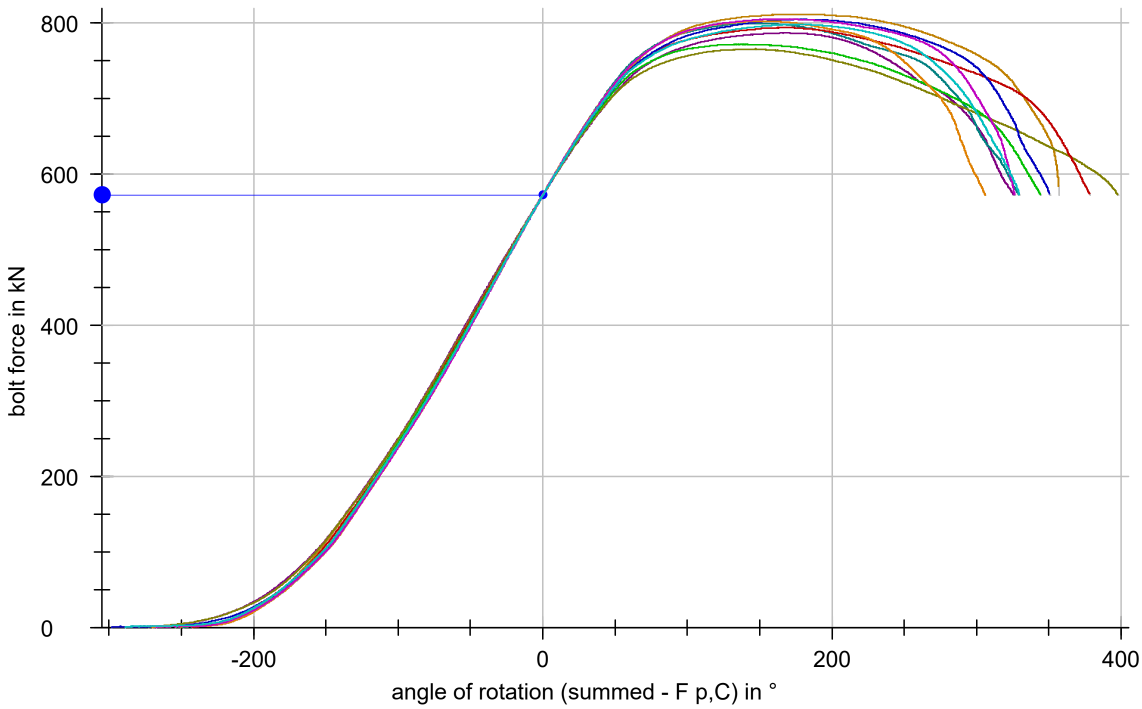
bearing torque-bolt force-curves: M36x160 HV 10.9 - Gleitmo WSP 5040



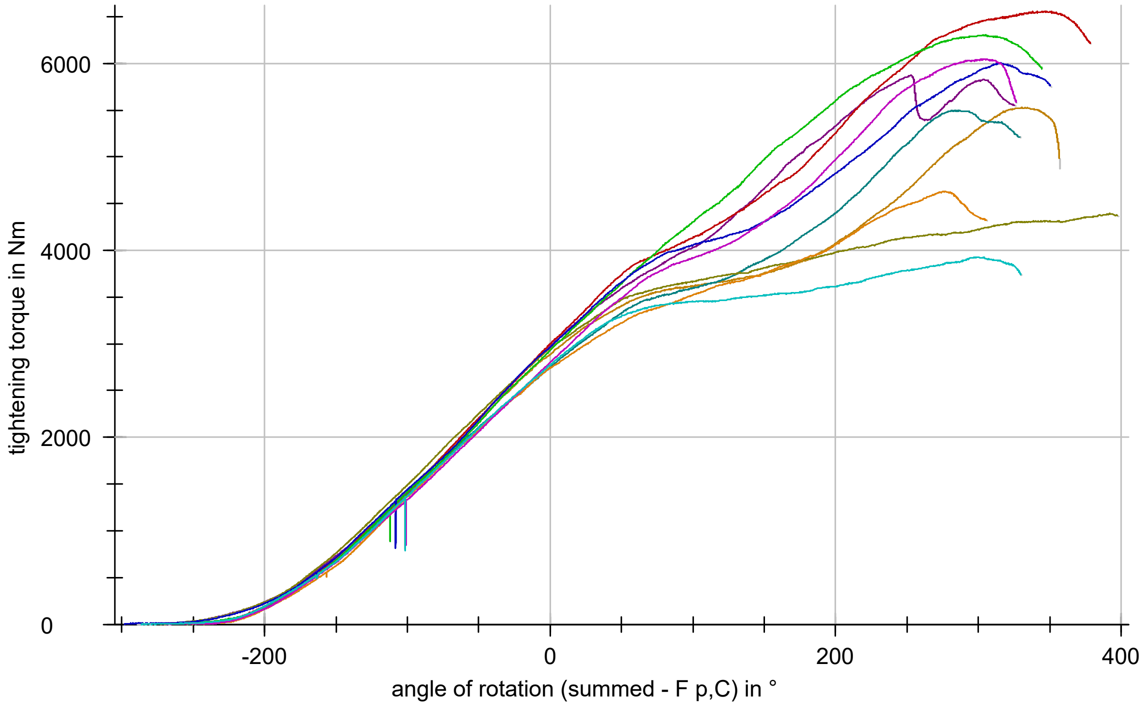
thread torque-bolt force-curves: M36x160 HV 10.9 - Gleitmo WSP 5040



bolt force-angle of rotation-curves: M36x160 HV 10.9 - Gleitmo WSP 5040



tightening torque-angle of rotation-curves: M36x160 HV 10.9 - Gleitmo WSP 5040



Test series: M36x160 HV 10.9 - Molykote 1000 spray

Connecting element : M36x160 HV 10.9
Coating / Surface finish : M36x160 - tZn
Clamp length Σt : 123,5 mm

Speed of tightening : 2,0 1/min
Sensor F - T_{th} : SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ : SNo. 1016241 - 15000 Nm

Specific thread data:

Thread	Thread data	:	M 36/4.00 HV - IML	
d	Nominal diameter	:	36	mm
P	Pitch	:	4	mm
d_2	Pitch diameter	:	33,4	mm
d_o	Outer bearing surface diameter	:	55,9	mm
d_i	Inner bearing surface diameter	:	42	mm
D_b Calc	Bearing surface diameter	:	48,95	mm

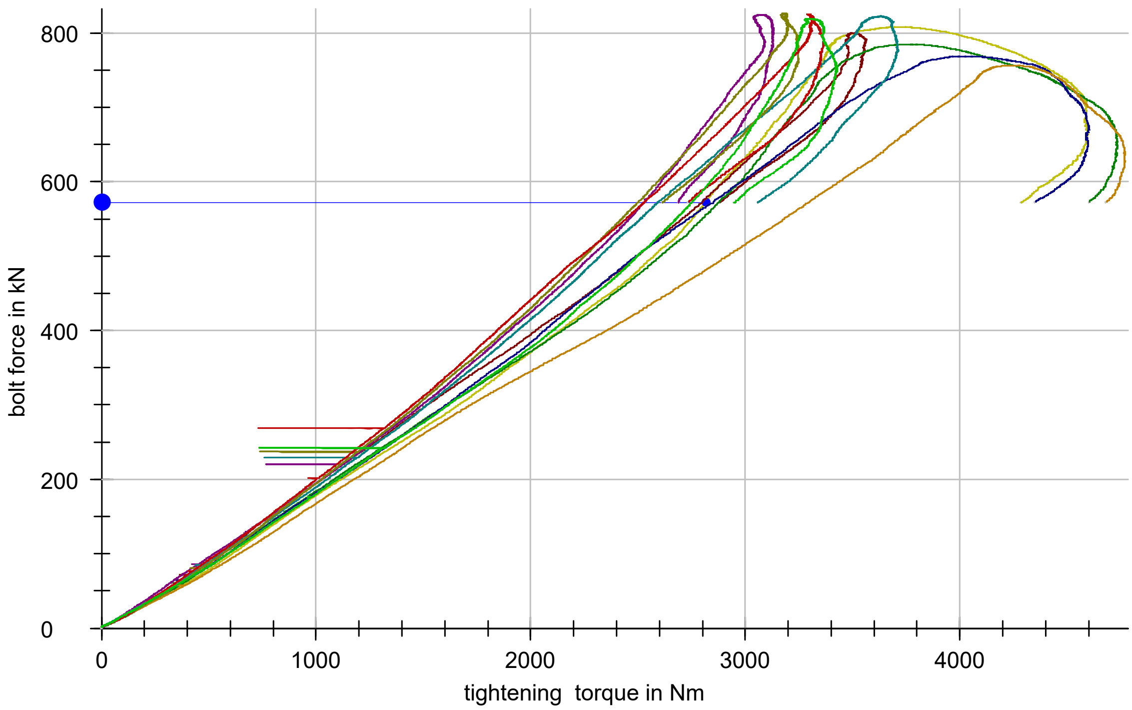
Results table: M36x160 HV 10.9 - Molykote 1000 spray

Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		571,9	735,3						120	210	0,10	
	Si_36_HV_10.9-11	571,9	808,1	4598,1	249	446	582	571,6	285	421	0,14	0,098
	Si_36_HV_10.9-12		799,7	3564,4	270	439	594	571,9	256	410	0,14	0,097
	Si_36_HV_10.9-13		784,6	4735,4	281	449	621	571,8	258	430	0,14	0,100
	Si_36_HV_10.9-14		768,5	4603,6	254	392	547	571,8	224	379	0,14	0,099
	Si_36_HV_10.9-15		756,2	4770,9	263	404	576	571,8	230	401	0,16	0,117
	Si_36_HV_10.9-41		824,4	3131,9	272	451	568	571,8	178	295	0,12	0,087
	Si_36_HV_10.9-42		822,5	3712,2	350	524	649	571,8	174	299	0,13	0,089
	Si_36_HV_10.9-43		826,0	3249,6	342	535	688	571,7	193	346	0,12	0,085
	Si_36_HV_10.9-44		825,1	3369,6	467	664	821	571,6	197	354	0,12	0,086
	Si_36_HV_10.9-45		819,4	3427,2	376	551	681	571,6	175	305	0,13	0,095

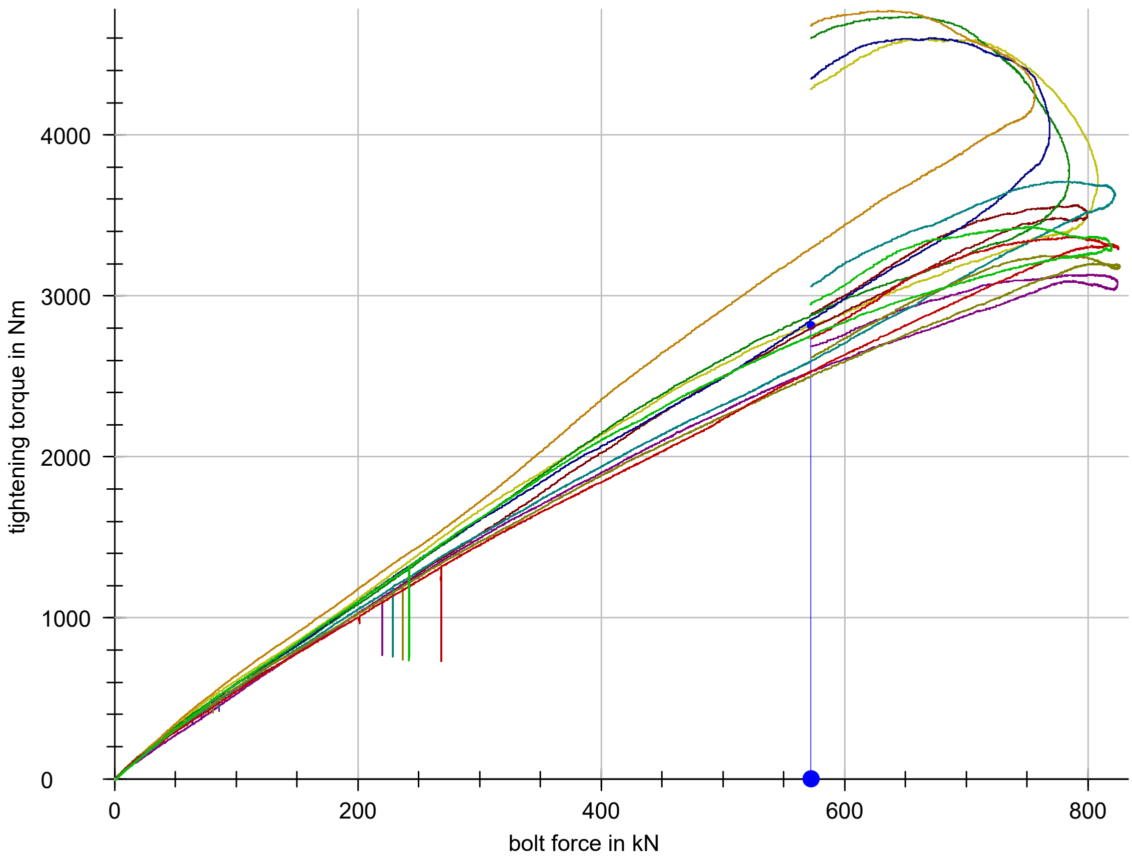
Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			514,7	0,095			
	0,083	0,110	514,7	0,142	2814,7	2629,1	3711,9
	0,093	0,100		0,138	2796,6	2554,3	3497,3
	0,093	0,107		0,144	2877,9	2666,4	3791,6
	0,092	0,105		0,138	2849,4	2563,8	4039,4
	0,110	0,123		0,162	3297,7	2995,4	4247,7
	0,092	0,082		0,126	2530,3	2336,9	3070,3
	0,084	0,093		0,128	2593,5	2376,6	3632,5
	0,065	0,102		0,124	2496,5	2301,4	3182,5
	0,065	0,104		0,124	2525,7	2297,4	3295,4
	0,089	0,100		0,138	2750,7	2557,2	3303,3

ANNEX B

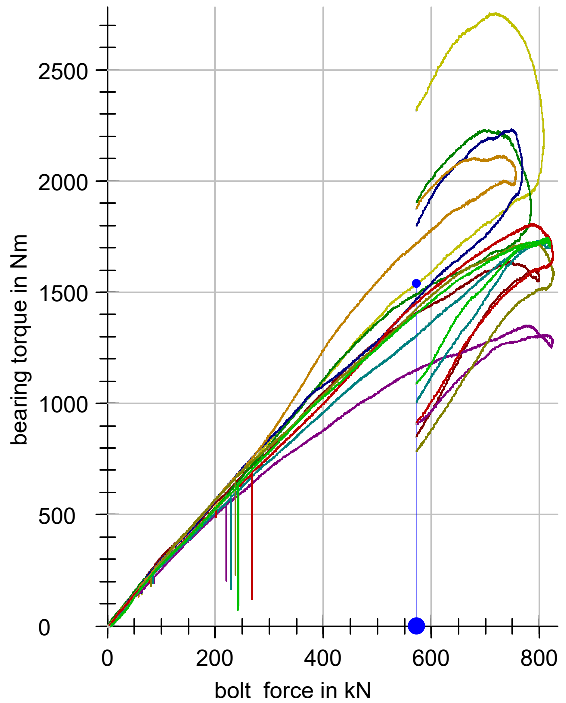
bolt force-tightening torque-curves: M36x160 HV 10.9 - Molykote 1000 spray



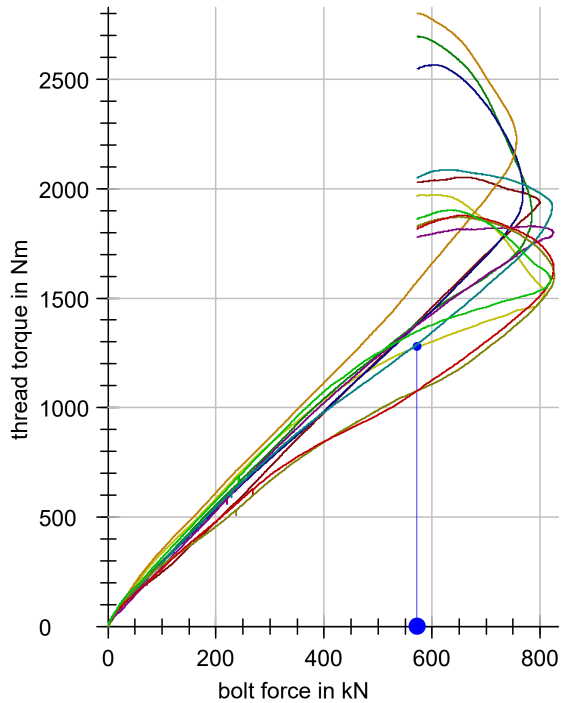
tightening torque-bolt force-curves: M36x160 HV 10.9 - Molykote 1000 spray



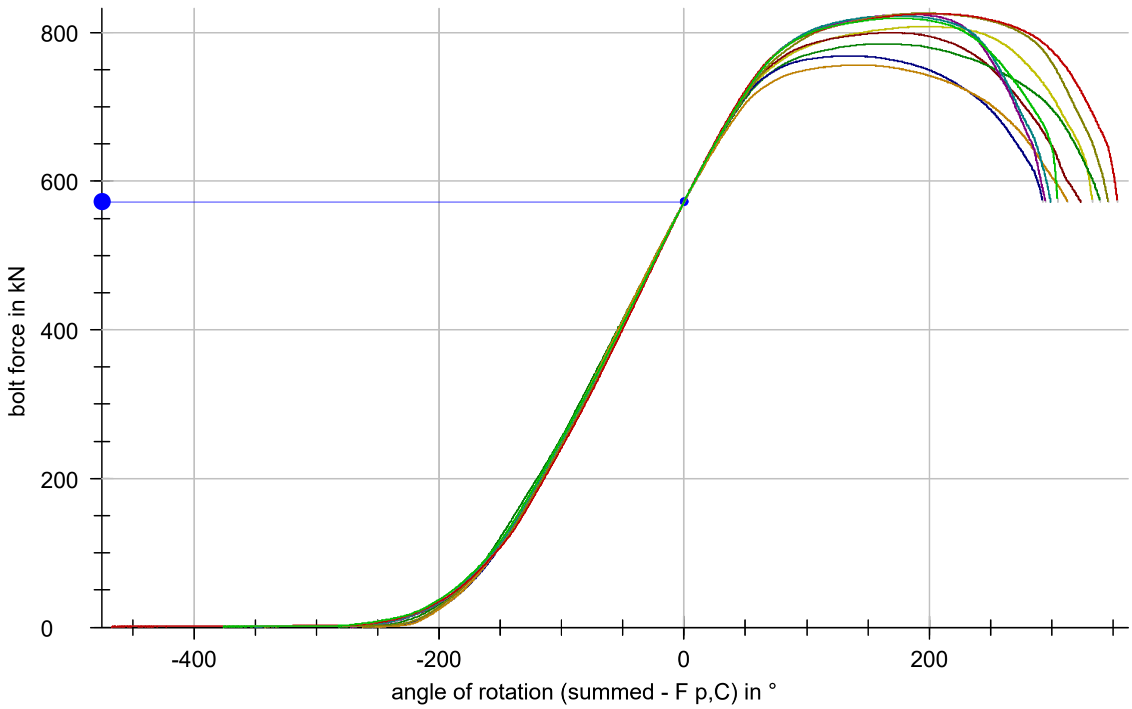
bearing torque-bolt force-curves: M36x160 HV 10.9 - Molykote 1000 spray



thread torque-bolt force-curves: M36x160 HV 10.9 - Molykote 1000 spray

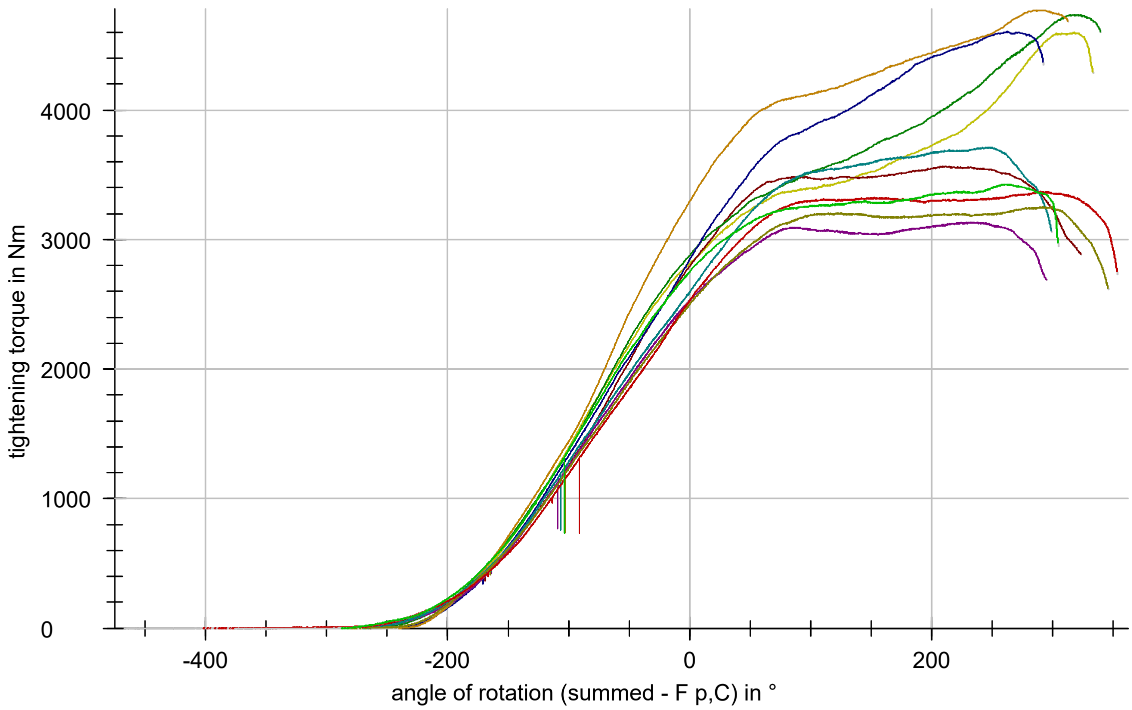


bolt force-angle of rotation-curves: M36x160 HV 10.9 - Molykote 1000 spray



Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

tightening torque-angle of rotation-curves: M36x160 HV 10.9 - Molykote 1000 spray



Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

Test series: M36x160 HV 10.9 - Microgleit HV-paste LP440

Connecting element	:	M36x160 HV 10.9
Coating / Surface finish	:	M36x160 - tZn
Clamp length Σt	:	123,5 mm
Speed of tightening	:	2,0 1/min
Sensor F - T_{th}	:	SNo. 1016242 - 1500 kN / 5000 Nm
Sensor M - Θ	:	SNo. 1016241 - 15000 Nm

Specific thread data:

Thread	Thread data	:	M 36/4.00 HV - IML	
d	Nominal diameter	:	36	mm
P	Pitch	:	4	mm
d_2	Pitch diameter	:	33,4	mm
d_o	Outer bearing surface diameter	:	55,9	mm
d_i	Inner bearing surface diameter	:	42	mm
D_b Calc	Bearing surface diameter	:	48,95	mm

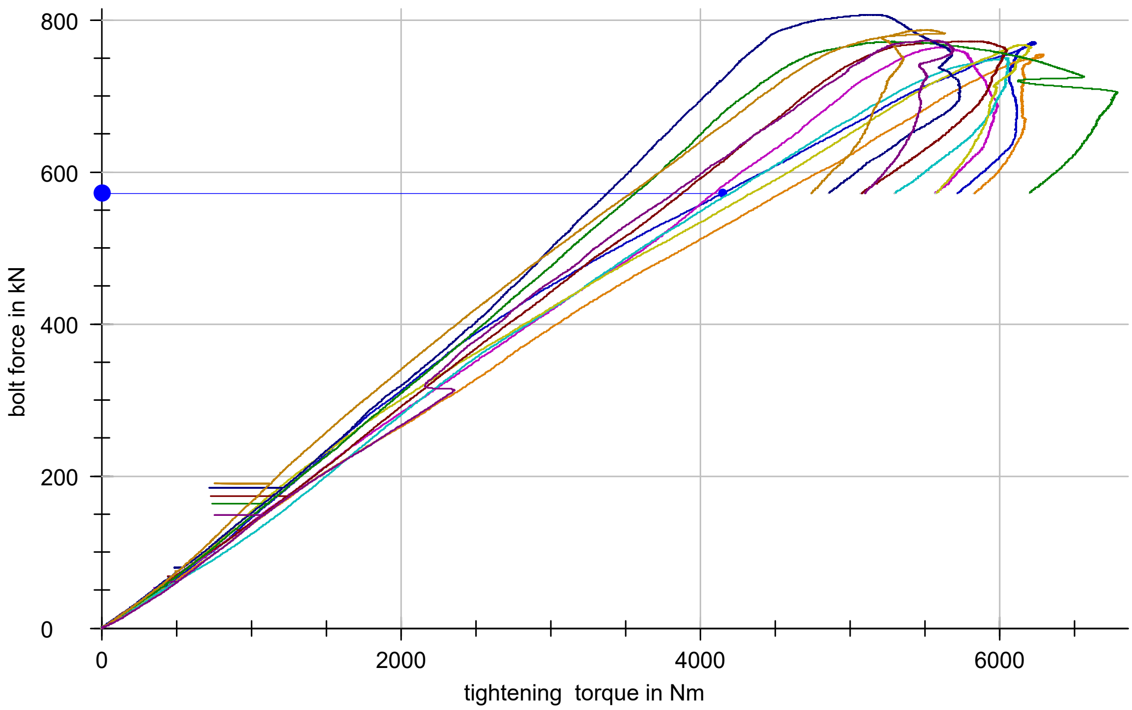
Results table: M36x160 HV 10.9 - Microgleit HV-paste LP440

Legend	Specimens	$F_{p,C}$ kN	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	k ($F_{p,C}$)	μ_{tot} ($F_{p,C}$)
max		---	---						---	---	0,16	
min		571,9	735,3						120	210	0,10	
	Si_36_HV_10.9-16	571,9	770,6	6242,6	276	461	691	571,9	272	501	>0,20	0,151
	Si_36_HV_10.9-17		754,7	6293,9	278	457	676	571,6	268	486	>0,22	0,167
	Si_36_HV_10.9-18		764,0	5987,7	265	387	577	571,6	208	398	>0,20	0,149
	Si_36_HV_10.9-19		750,1	6068,2	272	405	603	571,8	219	416	>0,20	0,153
	Si_36_HV_10.9-20		767,2	6213,4	267	416	686	571,8	235	505	>0,21	0,159
	Si_36_HV_10.9-46		772,1	6051,4	302	453	657	571,7	150	354	>0,19	0,140
	Si_36_HV_10.9-47		771,5	6788,2	256	400	619	571,9	145	363	>0,17	0,128
	Si_36_HV_10.9-48		807,1	5739,0	275	451	640	571,9	177	366	>0,16	0,120
	Si_36_HV_10.9-49		786,8	5634,7	319	512	641	571,9	194	323	>0,17	0,127
	Si_36_HV_10.9-50		773,4	5692,4	275	442	670	572,0	167	394	>0,19	0,138

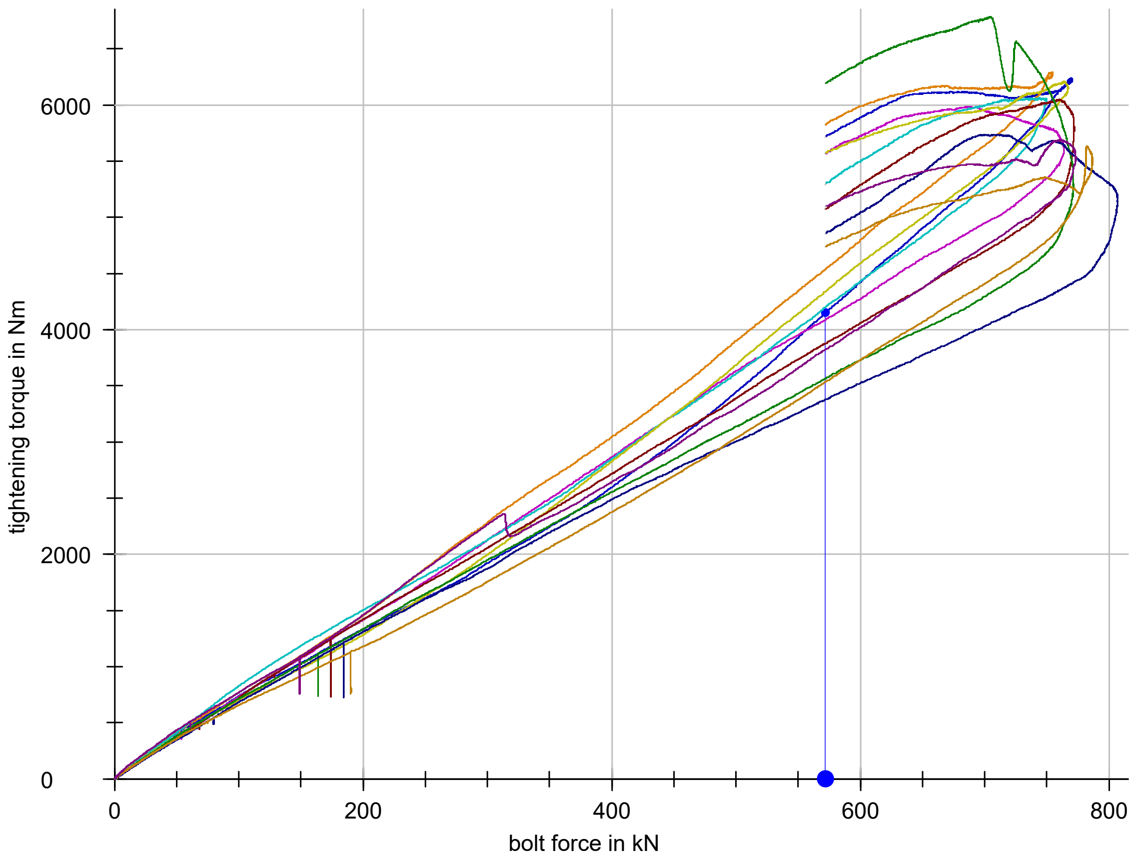
Legend	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	$F_{p,C}$* kN	k ($F_{p,C*}$)	M_i ($F_{p,C}$) Nm	M ($F_{p,C}$*) Nm	M ($F_{bi,max}$) Nm
max			---	0,164			
min			514,7	0,095			
	0,127	0,171	514,7	>0,193	4149,9	3579,4	6227,6
	0,119	0,204		>0,217	4532,6	4028,4	6280,5
	0,110	0,179		>0,201	4089,1	3731,7	5613,7
	0,124	0,176		>0,201	4198,0	3720,6	6014,5
	0,118	0,191		>0,207	4339,3	3826,4	6150,3
	0,123	0,155		>0,189	3878,1	3495,5	5772,1
	0,105	0,146		>0,174	3565,7	3221,7	5293,3
	0,096	0,140		>0,166	3377,1	3077,4	5142,6
	0,109	0,140		>0,169	3534,7	3134,6	5500,6
	0,115	0,157		>0,184	3823,6	3401,4	5503,7

ANNEX B

bolt force-tightening torque-curves: M36x160 HV 10.9 - Microgleit HV-paste LP440



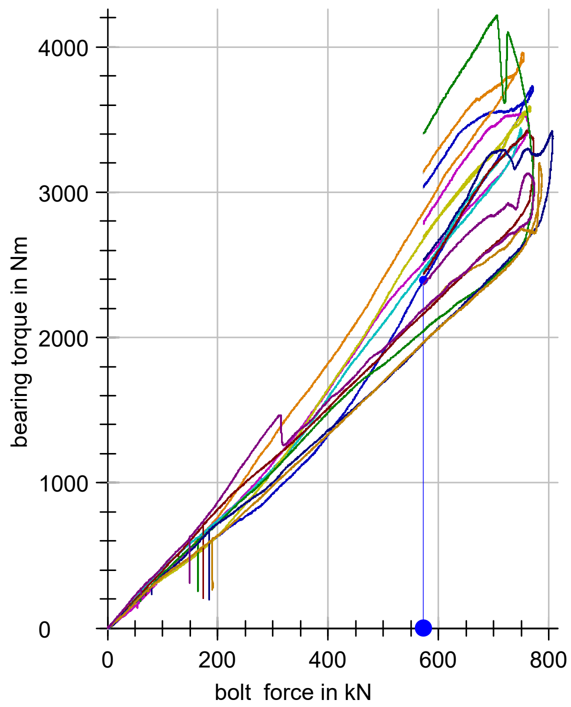
tightening torque-bolt force-curves: M36x160 HV 10.9 - Microgleit HV-paste LP440



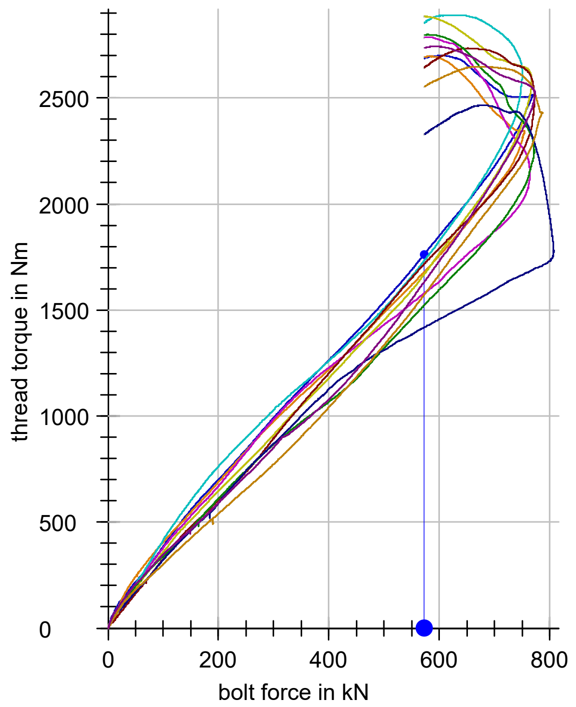
Universitätsstr. 15
45141 Essen
Tel.: +49 201 183 2757
Fax: +49 201 183 2710

ANNEX B

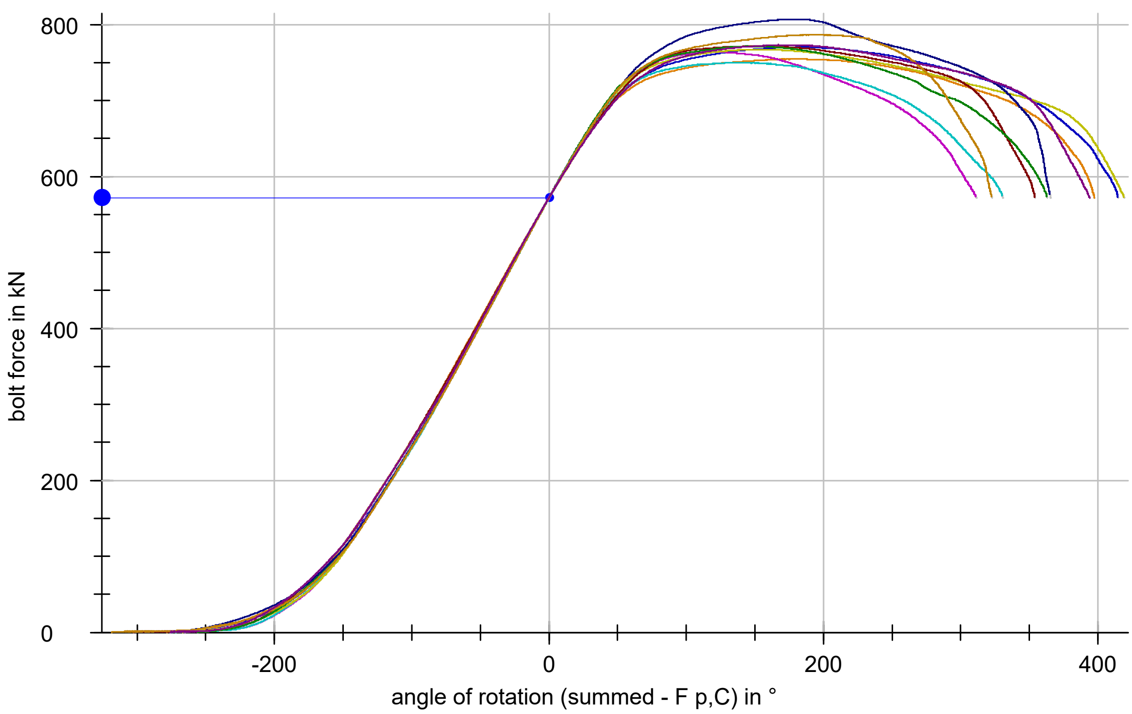
bearing torque-bolt force-curves: M36x160 HV 10.9 - Microgleit HV-paste LP440



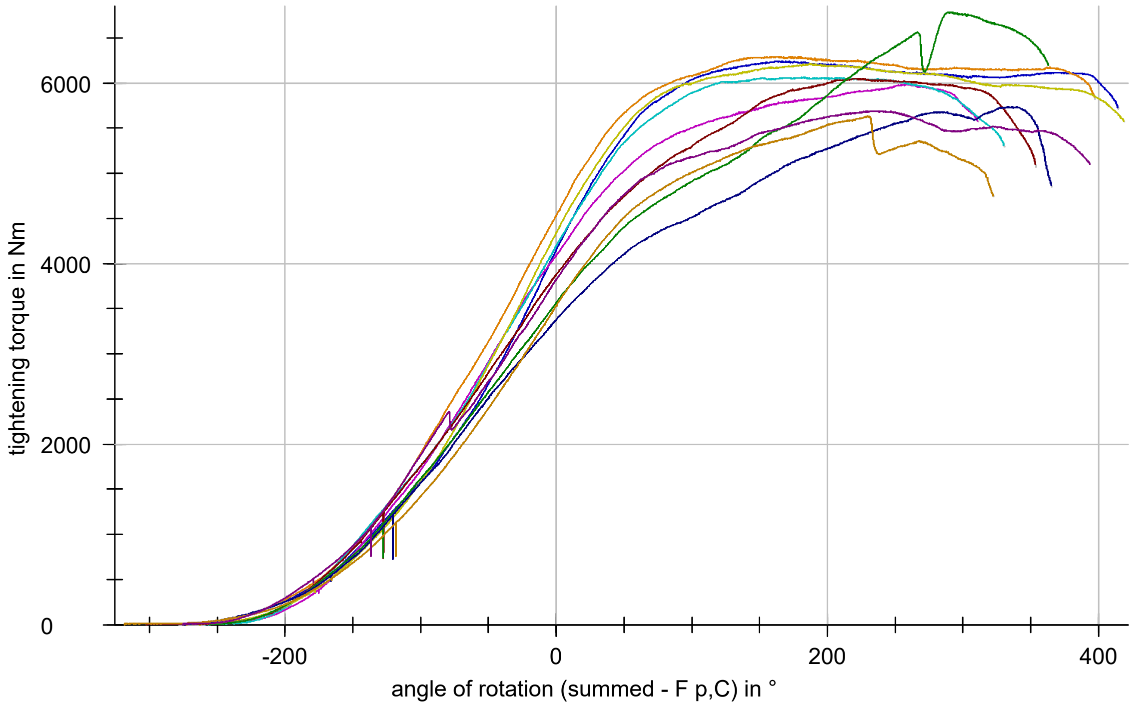
thread torque-bolt force-curves: M36x160 HV 10.9 - Microgleit HV-paste LP440



bolt force-angle of rotation-curves: M36x160 HV 10.9 - Microgleit HV-paste LP440



tightening torque-angle of rotation-curves: M36x160 HV 10.9 - Microgleit HV-paste LP440



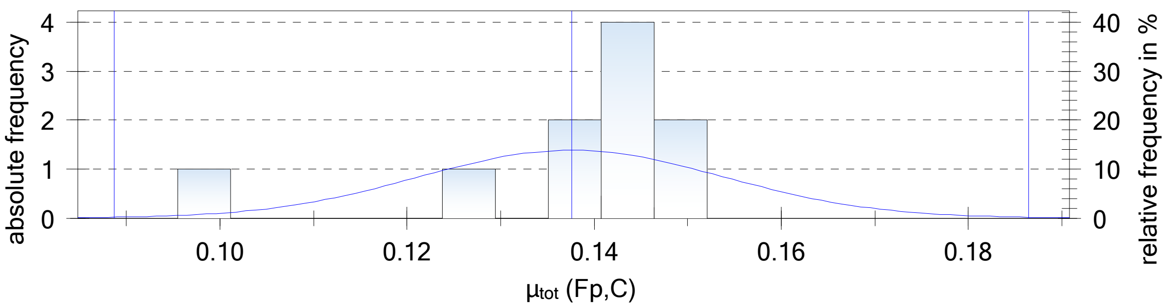
Statistical evaluation: M36x160 HV 10.9 - Factory provided

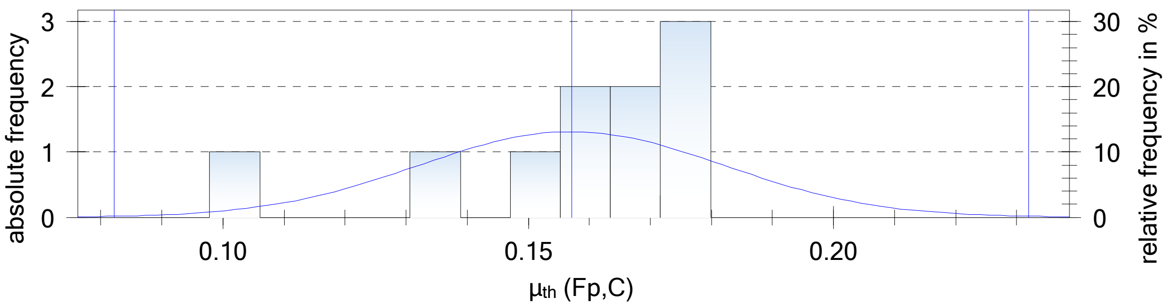
M36x160 HV 10.9 - Factory provided n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	811,7	6982,8	318	464	691	571,9	235	489	0,168
min	682,3	4309,1	239	353	536	570,9	74	257	0,095
R	129,4	2673,7	79	111	155	1,0	161	232	0,073
$\bar{x}$	730,1	6116,7	267	396	606	571,3	182	386	0,137
s	34,7	810,5	26	42	56	0,3	54	80	0,019
ν	4,75	13,25	9,94	10,51	9,22	0,06	29,68	20,60	13,94

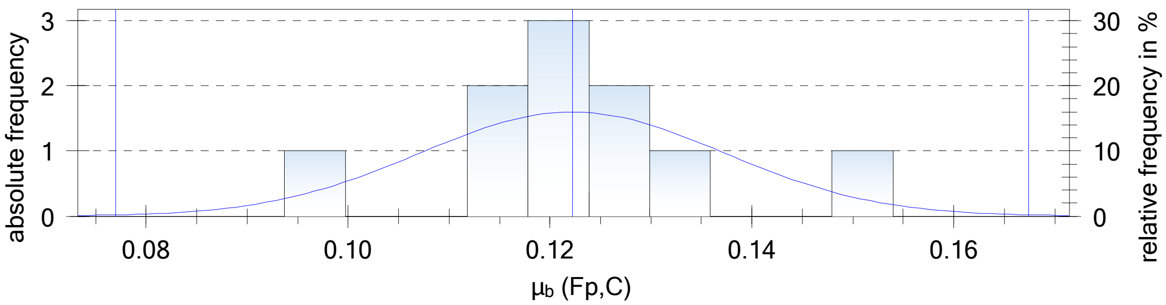
M36x160 HV 10.9 - Factory provided n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M (F_{p,C^*}) Nm	k (F_{p,C^*})	M ($F_{bi,max}$) Nm
max	0,170	0,195	4568,9	0,22	3980,2	0,215	6968,6
min	0,098	0,094	2751,8	0,13	2518,7	0,136	4223,0
R	0,072	0,101	1817,1	0,09	1461,5	0,079	2745,6
$\bar{x}$	0,151	0,126	3786,5	0,18	3397,8	0,183	5511,9
s	0,025	0,028	475,8	0,02	396,6	0,021	742,7
ν	16,49	21,94	12,57	13,11	11,67	11,68	13,47

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M36x160 HV 10.9 - Factory provided







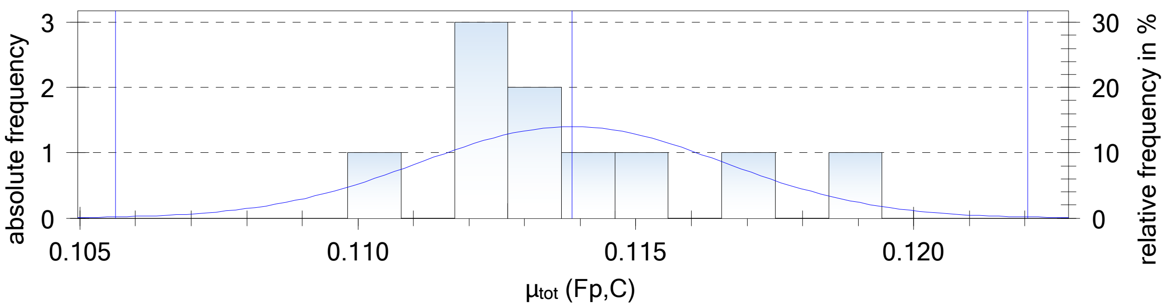
Statistical evaluation: M36x160 HV 10.9 - Gleitmo WSP 5040

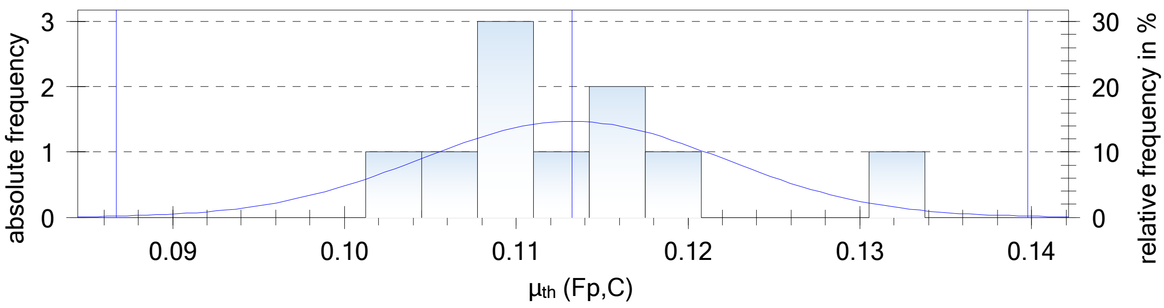
M36x160 HV 10.9 - Gleitmo WSP 5040 n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	811,5	6559,8	298	476	671	572,0	267	486	0,105
min	765,6	3929,5	242	386	576	571,4	218	390	0,095
R	45,9	2630,3	56	90	95	0,6	49	96	0,010
$\bar{x}$	794,0	5476,7	266	427	611	571,8	246	431	0,100
s	15,0	876,0	18	28	30	0,2	16	28	0,004
ν	1,89	15,99	6,74	6,56	4,95	0,03	6,31	6,59	4,18

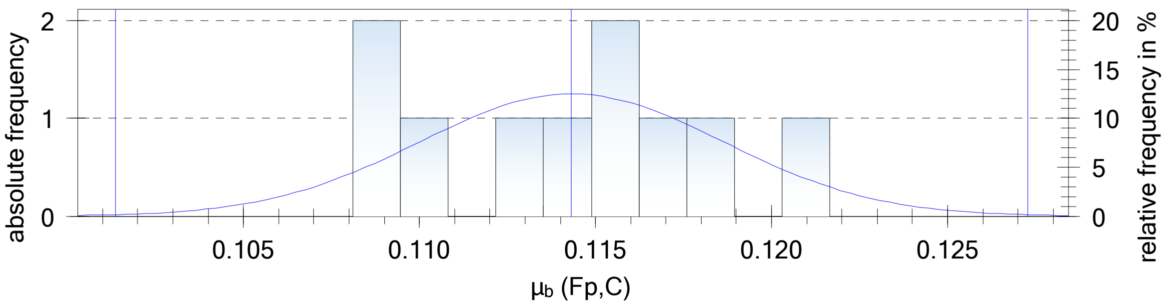
M36x160 HV 10.9 - Gleitmo WSP 5040 n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k (F_{p,C^*})	M ($F_{bi,max}$) Nm
max	0,114	0,107	2997,8	0,15	2738,8	0,148	4938,2
min	0,081	0,095	2740,4	0,13	2525,1	0,136	3553,1
R	0,033	0,012	257,4	0,02	213,7	0,012	1385,1
$\bar{x}$	0,099	0,101	2877,7	0,14	2634,7	0,142	4228,3
s	0,011	0,004	101,5	0,01	86,6	0,005	495,0
ν	10,92	4,08	3,53	4,58	3,29	3,28	11,71

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M36x160 HV 10.9 - Gleitmo WSP 5040







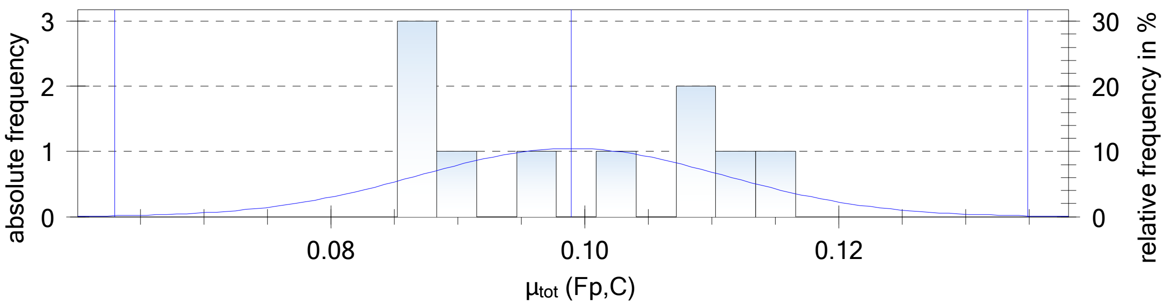
Statistical evaluation: M36x160 HV 10.9 - Molykote 1000 spray

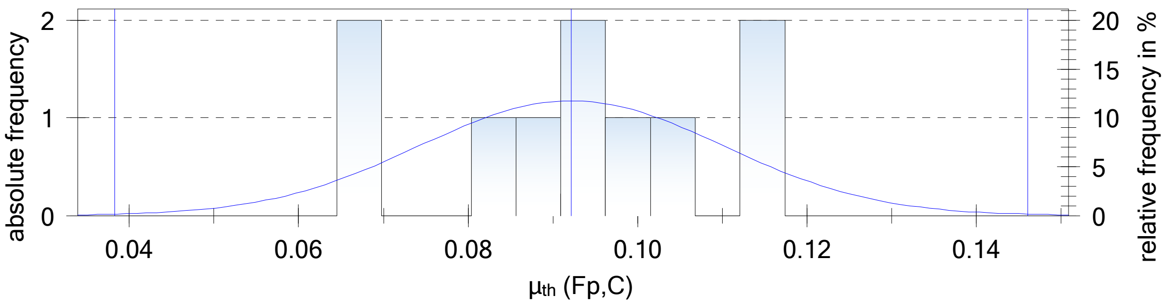
M36x160 HV 10.9 - Molykote 1000 spray n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	826,0	4770,9	467	664	821	571,9	285	430	0,117
min	756,2	3131,9	249	392	547	571,6	174	295	0,085
R	69,8	1639,0	218	272	274	0,3	111	135	0,032
$\bar{x}$	803,5	3916,3	312	486	633	571,7	217	364	0,095
s	25,6	675,1	70	83	82	0,1	40	52	0,010
ν	3,18	17,24	22,51	17,06	12,91	0,02	18,28	14,25	10,00

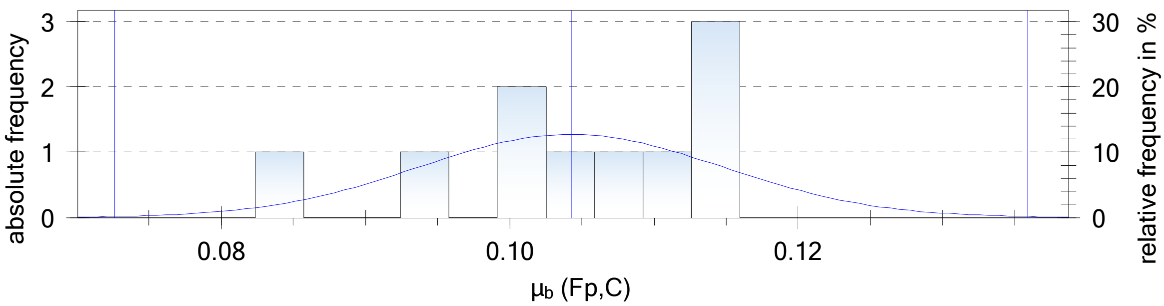
M36x160 HV 10.9 - Molykote 1000 spray n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k (F_{p,C^*})	M ($F_{bi,max}$) Nm
max	0,110	0,123	3297,7	0,16	2995,4	0,162	4247,7
min	0,065	0,082	2496,5	0,12	2297,4	0,124	3070,3
R	0,045	0,041	801,2	0,04	698,0	0,038	1177,4
$\bar{x}$	0,087	0,103	2753,3	0,13	2527,9	0,136	3577,2
s	0,014	0,011	240,3	0,01	214,6	0,012	380,6
ν	15,62	10,42	8,73	9,44	8,49	8,60	10,64

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M36x160 HV 10.9 - Molykote 1000 spray







Statistical evaluation: M36x160 HV 10.9 - Microgleit HV-paste LP440

M36x160 HV 10.9 - Microgleit HV-paste LP440 n = 10	Max F kN	Max T Nm	Θ_{pi} °	Θ_{1i} °	Θ_{2i} °	F_{bi} (Θ_{2i}) kN	$\Delta\Theta_{1i}$ °	$\Delta\Theta_{2i}$ °	μ_{tot} ($F_{p,C}$)
max	807,1	6788,2	319	512	691	572,0	272	505	0,167
min	750,1	5634,7	256	387	577	571,6	145	323	0,120
R	57,0	1153,5	63	125	114	0,4	127	182	0,047
$\bar{x}$	771,8	6071,2	279	438	646	571,8	204	411	0,143
s	16,1	344,0	19	37	37	0,1	45	65	0,015
ν	2,08	5,67	6,65	8,46	5,80	0,02	22,29	15,90	10,60

M36x160 HV 10.9 - Microgleit HV-paste LP440 n = 10	μ_{th} ($F_{p,C}$)	μ_b ($F_{p,C}$)	M_i ($F_{p,C}$) Nm	k ($F_{p,C}$)	M ($F_{p,C}$*) Nm	k ($F_{p,C}$*)	M ($F_{bi,max}$) Nm
max	0,127	0,204	4532,6	0,22	4028,4	0,217	6280,5
min	0,096	0,140	3377,1	0,16	3077,4	0,166	5142,6
R	0,031	0,064	1155,5	0,06	951,0	0,051	1137,9
$\bar{x}$	0,115	0,166	3948,8	0,19	3521,7	0,190	5749,9
s	0,010	0,022	377,3	0,02	314,3	0,017	402,7
ν	8,40	13,20	9,56	10,01	8,92	8,90	7,00

with n: number; R: range; $\bar{x}$: mean value; s: standard deviation; ν: coefficient of variation in [%]

Histogram: M36x160 HV 10.9 - Microgleit HV-paste LP440