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Influence of Lubrication Systems on the Fatigue Strength of Bolted Joints

Fabian Kraemer [1,*], Michael Stähler [2], Marcus Klein [1] and Matthias Oechsner [1]

[1] Chair and Institute for Materials Technology, Technical University of Darmstadt, Grafenstrasse 2, 64283 Darmstadt, Germany; marcus.klein@tu-darmstadt.de (M.K.); matthias.oechsner@tu-darmstadt.de (M.O.)
[2] Dörken Coatings GmbH & Co. KG, Wetterstrasse 58, 58313 Herdecke, Germany; mstaehler@doerken.de
* Correspondence: fabian.kraemer@tu-darmstadt.de

Abstract: The fatigue behavior of bolted joints is critical to failure for many applications due to the high notch effect. Among other parameters, the lifetime is based on the influence of the surface system, consisting of corrosion protection and lubricant. With the intention of considering the surface system in the design and dimensioning process of bolted joints, experimental investigations are carried out systematically for an exemplary selected basecoat and various lubricant systems. The basis is given by fatigue tests supported by selected methods of material analysis for the fractographic evaluation. A reproducible method to determine the crack initiation as well as the crack propagation is developed and used for the evaluation of lubricant systems. Defined damage can be reproducibly assigned on the basis of a critical frequency change rate of the resonance test machine. A high durability of the friction in the load-bearing contact (e.g., greases) reduces the stress and delays the crack initiation. Lubricants which are able to creep (e.g., oil) slow down the crack propagation and increase the lifetime, which is proved by a higher number of cycles to failure and an increased fatigue strength.

Keywords: fatigue behavior; surface influence; crack initiation; crack propagation; bolted joint; VDI guideline 2230

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1. Introduction

In joining technologies, the bolted connection is a frequently chosen technical solution used to establish a detachable and high-strength connection. Bolted joints are often used in applications that are subject of cyclic loads, which is why fatigue failure is one of the most frequent causes in the event of damage [1]. As a result of high notch stresses, given by the function-related shape, screws can only transmit low cyclic loads. The durability under cyclic loading is reduced to less than 10% of the static strength and is determined by high local stresses in the thread root [2]. The fatigue strength and the lifetime of bolted joints depend on a large number of overlapping factors [2–10], which are insufficiently considered in the relevant design methods and guidelines. In addition to the design parameter, such as the depth of engagement, the nut material and also the manufacturing process for the nut thread itself [3], the surface system, consisting of corrosion protection and a lubricant, has a significant influence on the fatigue strength [11–14]. Depending on the choice of coating system, there is a significant influence on the lifetime [15,16]. In mechanical engineering and plant construction, the design process is carried out in accordance with the VDI guideline 2230 (Verein Deutscher Ingenieure, Association of German Engineers) [17]. In this guideline, the fatigue strength is evaluated only by the notch size in the form of the bolt diameter. With the exception of hot-dip galvanizing, for which the VDI guideline proposes a reduction of 20%, no consideration is given to the surface influence. In steel construction, where the design is carried out in accordance to Eurocode 3, there has been no consideration of the influence of the corrosion protection system, which is usually represented by hot-dip

galvanizing [18]. Hence, the relevant corrosion protection systems, such as galvanized coating systems according to DIN EN ISO 4042 [19] and non-electrolytically applied zinc flake coating systems according to DIN EN ISO 10683 [20], are not taken into account in present guidelines for the design process for bolted joints. In ref. [16], the effect on fatigue strength comparing galvanized zinc coated bolts against zinc flake coated bolts was investigated. The zinc flake coatings resulted in an improved lifetime. In industrial practice, screws are installed in a defined state of friction in order to achieve a reproducible preload for reliable connections [21]. Therefor dry or liquid lubricants are applied to the various coatings. Lubrication not only determines the friction in the contact zones, but also has a significant influence on the durability and the lifetime under fatigue loading. There is a need to investigate in more detail the influence of surface systems with additionally applied lubricants with a focus on the mechanisms in order to understand the failure development, beginning with crack initiation. Test results from various research projects show that not only does the corrosion protection of hot-dip galvanized components have an influence on the fatigue strength, but the presence of a coating system in principle also has an adverse effect on the lifetime [4,10–16]. In ref. [22], the effects of both the thread pitch and the thread style ISO or American Unified bolts on the fatigue strength were investigated. Geometric influences appear more obvious and are also easier to quantify numerically, for example by means of stress concentration factors. The influence of coatings systems and lubricants which affect the contact area or rather the load introduction is more difficult to assess. Evaluating only the total number of cycles to failure is not sufficient. The inherent failure mechanisms have to be identified.

1.1. Theoretical Background

In bolted joints, the force is transmitted by contact between the bolt and the nut threads. The resulting local stress in the bolt is critical to failure and determines the time of crack initiation under fatigue loading. Fatigue failure occurs at the location of the highest stress concentration, which is in the first load-bearing thread due to the initial redirection of the force flow from the bolt into the nut. This results in an inhomogeneous load distribution over the depth of engagement, where the first load-bearing thread transmits about 40% of the total load [23]. Numerical studies comparing metric ISO, Unified and Whitworth standard threads [24] as well as simulations evaluating the effect of nut material and depth of engagement [3] are in accordance with the experimentally gathered stress distribution [23].

In contrast, under quasi-static load, the screw fails in the weakest cross-section, which according to the design principle is present in the free-loaded thread [2].

The fatigue strength of the bolt, in the form of a permanently transmissible amplitude, is determined in an axial fatigue test according to DIN 969 in the bolt-nut test [21]. For this purpose, the bolt is usually preloaded to a constant mean load level of 70% of the yield strength via the test system and a sinusoidal operating load with constant amplitude is superimposed as a fatigue load. The test is completed when the bolt reaches a limited number of cycles N_G without failure (often 5 or 10 million) or failure occurs [25]. The selection of the test loads and the required minimum number of individual tests as well as the statistical evaluation are further described in the standards DIN 969 and DIN 50100 [25,26].

According to the VDI guideline 2230, the estimation of the fatigue strength in the form of the permanently transmissible amplitude with 50% probability of failure is carried out for bolts rolled before heat treatment exclusively via the size of the screw diameter.

$$\sigma_{ASV,\ 50\%} = \frac{150}{d} + 45 \quad (1)$$

d: nominal diameter.

σ_{ASV}: permanently transmissible stress amplitude in N/mm^2 for bolts rolled before heat treatment

For high operational reliability, the amount of the initial preload after tightening was designed to compensate for losses in preload by setting effects and mechanical and thermal operating loads. The reliability is given as long as the residual clamping force is able to keep the clamped parts together, and thus they were acting as one part. The coefficient of friction, the tightening torque and the preload are influenced by the material and surface pairing as well as by assembly parameters such as the speed of the tightening. In order to achieve reproducible preloads independent of the tightening method, bolted joints are adjusted to a defined friction coefficient range with the aid of lubricants. According to VDI Guideline 2230, the limits for the total friction coefficient μ_{tot} are 0.08 to 0.16 [17]. The VDA sheet 235–101 (Verband der Automobilindustrie e.V., German Association of the Automotive Industry) further restricts the permissible total friction coefficient and defines the limits in the range of μ_{tot} = 0.09 to 0.14 [19].

Friction coefficients are determined in the torque/preload test according to DIN EN ISO 16047 [27]. In this test, a bolt-nut connection is preloaded against a reference base with a continuously applied tightening torque. The total friction coefficient and the partial friction coefficients for the thread (μ_{th}) and under the head (μ_b) are determined for a defined test force F_p. The applied tightening torque T is subdivided into the thread pitch torque, the thread friction torque and the head friction torque.

$$T = F \cdot \left[0.159 \cdot P + 0.577 \cdot d_2 \cdot \mu_{th} + \frac{D_b}{2} \cdot \mu_b \right] \quad (2)$$

T: tightening torque, F: preload, P: thread pitch, d_2: pitch diameter,
μ_{th}: thread friction coefficient, D_b: head friction diameter, μ_b: head friction coefficient.

The thread friction torque and the head friction torque represent loss torques, whereas the thread pitch torque generates the preload F.

Depending on the test system configuration, the tightening torque and a partial torque, for example the thread friction torque, are measured directly. The partial friction coefficient is calculated via the partial torque measured at the defined test force. The missing third variable, in this example the head friction torque, is determined mathematically via the relationship with the total torque [27].

$$\mu_{th} = \frac{\frac{T_{th}}{F} - \frac{P}{2 \cdot \pi}}{0.577 \cdot d_2} \quad (3)$$

F: force, T_{th}: thread friction torque, P: thread pitch, d_2: pitch diameter.

In industrial practice, the friction coefficients are adjusted by precisely matching the basecoat and topcoat. The basecoat forms the first layer to protect the base material from corrosion. In the automotive industry in particular, non-electrolytically produced zinc flake protection systems are used as basecoat in addition to electroplated coating systems, due to hydrogen-free production. This provides heavy-duty corrosion protection for exterior applications. The salt spray resistance is greater than 720 h in laboratory tests according to DIN EN ISO 9227, depending on the coating thickness [28].

The zinc flake surface represents a cathodic corrosion protection in which the zinc is applied mechanically, rolled out in an inorganic binder matrix with the addition of aluminum in a dip spinning process. With the addition of temperature, the paint is baked into the base material to be coated. The heat input creates a metallic bond between the flakes themselves and between the flakes and the substrate. The coating process does not change the mechanical and physical properties of the base material [20].

Typical applications for components protected with zinc flake coatings include wheel bolts, chassis attachments and gearbox connections in the wind power sector. Exceptions, for which no corrosion protection is required due to an existing oil bath, include, for example, bolted connections in the engine and gear box applications.

The topcoat forms the next optional top layer on the basecoat and can fulfill both the task of higher corrosion protection and take on a lubricating effect. For bolted joints, there are applications with a lubricant integrated into the topcoat or additional lubrication is applied before assembly. The screw and nut thread as contact partners form a tribological system with the lubricant. For initial assembly, the lubrication fulfills the function of defined and constant friction conditions, with the aim of ensuring a reproducible preload level under defined assembly parameters, even for a large number of joints. The following lubricant groups are typically used for the setting of the friction coefficient:

- Oil
- Grease
- Bonded coating

In operation, the lubrication additionally fulfills the function of minimizing wear in the thread contact, where corrosion and wear phenomena can occur due to load-induced relative movements or environmental influences. A further requirement is long-term resistance to ensure that the connection can be detached for component replacement or repair.

Lubrication is selected specifically and depending on the requirements of the application. Ambient media, temperatures and static or cyclic operating loads represent a wide variety of boundary conditions.

Lubricating oils are high-boiling temperature mixtures of hydrocarbons to which lubricant additives are added. On average, the mixture consists of 90% base oil and 10% chemical additives [29]. For bolted joints, corrosion protection oils with very good wetting properties that completely cover the bolt surface are used in practice. For this purpose, either phosphated surfaces are created, which act as a carrier material for the oil, or a quenched and tempered black surface is created by immersing the bolts in preheated oil after tempering and allowing the oil to burn into the surface of the bolt. The function of the oil, in addition to the lubricating effect and the task of corrosion protection, is to prevent the penetration of water. For lubricating oils, viscosity is therefore a characteristic property. The viscosity describes not only the creep of the medium, but also the internal friction of the lubrication itself.

Lubricating greases consist of a mixture of lubricating oil and lubricant additives thickened in soap. The soap usually serves as a fibrous framework which encloses the lubricating oil. Typical screw applications are connections in large machine constructions, for example in crane constructions where frequent assembly and disassembly may occur.

The group of bonded coatings mostly characterizes an organic binder with various solid lubricants. Molybdenum disulfide (MoS_2) or polytetrafluoroethylene (PTFE) are the most commonly used additives. In order to be able to apply the bonded coating in the liquid aggregate state, solvents are used which evaporate after application. [29]

The influence of thread friction as well as the properties of the lubricant influencing bolt stress have not yet been considered in the lifetime analysis and will be considered further in the following.

1.2. Objectives and Concept

IGF project 20412 is currently investigating the influence of zinc-based corrosion protection systems on the fatigue resistance of bolted joints. With the aim of considering the lubricant influence for the bolt design, different lubricants are selected for a typical chosen basecoat and systematically compared in the fatigue test, as shown in Figure 1.

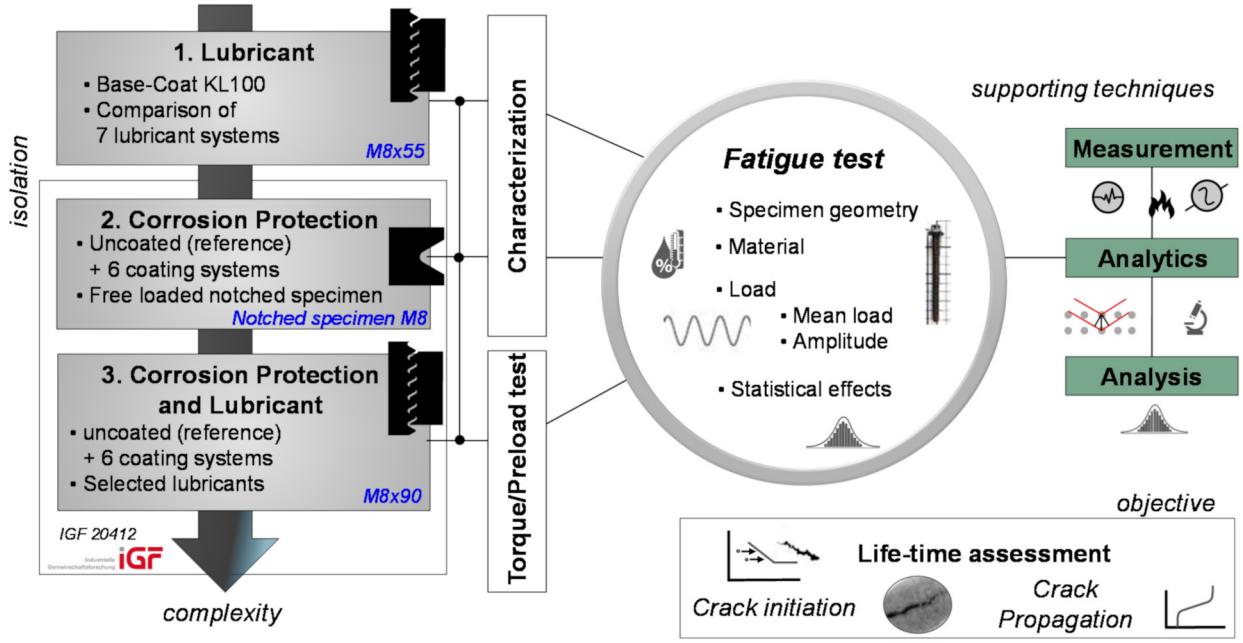


Figure 1. Concept—systematical investigation program.

The concept is based on the fatigue tests, which are carried out accompanied by supporting methods for crack detection and for evaluating the damage development. The measurement technology developed for this purpose includes, for example, frequency analysis, potential measurement or the heat-tinting method. The present paper deals with the first key point '1. Lubricant', in which the influence on the fatigue resistance due to the selection of the lubricant is investigated separately from the influence of the corrosion protection system. The objective of this investigation is to determine the lubricant's influence on the initiation of cracking and the crack propagation behavior up to the end of lifetime, which is reached by the limited number of cycles N_G or by failure due to fracture. For this purpose, the following investigations are carried out systematically on a representative chosen bolt–nut connection:

- Tightening test according to DIN EN ISO 16047, with the aim of determining the thread friction coefficient for selected lubricants
- Experimental investigation of lifetime in the fatigue test, with the determination of crack initiation time and crack propagation phase by means of suitable measurement technology
- Fracture surface analysis, using the methods of material analysis

Based on the experimental test results, a crack initiation criterion is defined by means of frequency analysis and the heat-tinting method. The crack initiation time is compared for the lubricant systems investigated.

2. Materials and Methods

2.1. Test Material and Lubrications

In order to evaluate the lubricant influence, a bolt M8x55 in strength class 8.8 with basecoat KL100 was selected as an example, which was combined with a steel nut ISO 4032 M8-10 in the fatigue test (Figure 2).

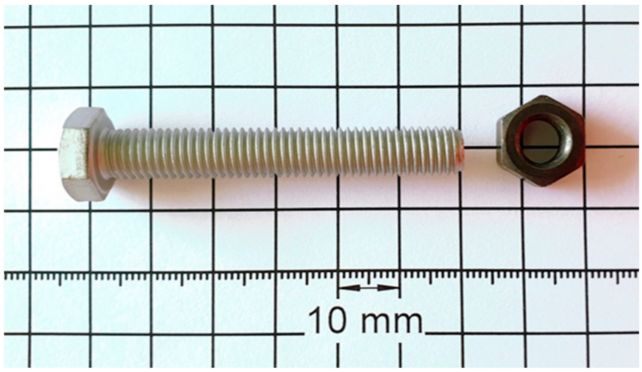


Figure 2. Screw M8x55-8.8 and ISO-4032 nut M8-10.

This application-oriented selected zinc flake coating was provided with different topcoats. The following lubrication systems were considered:

1. Without lubrication (reference)
2. Silicate sealant with integrated lubricant VH351 GZ
3. Oil, Castrol Rustilo 66VCI
4. Bonded coating, DF 977S (microGLEIT®)
5. Bonded coating, LS 855S (microGLEIT®)
6. Grease, LP 475 (microGLEIT®)
7. Grease, LP 410 (microGLEIT®)

The reference for all further tests was the first variant without lubrication. This silicate sealant with integrated lubricant is the usual combination of basecoat and topcoat for zinc flake coatings. The topcoat represents an additional passive corrosion protection to zinc flake coating and contains dry lubricants, such as polytetrafluoroethylene (PTFE), rigidly integrated into the silicon structure of the binder. The coating thickness was approximately 2 µm.

Castrol Rustilo 66VCI corrosion protection oil is an oxidation-resistant and solvent-free oil that forms a thin lubricating film completely covering the thread. Homogeneous wetting was generated by immersion. The resulting oil film thickness was approximately 2 µm.

The selected bonded coating systems contained either white solid lubricants (DF 977S) or metallic solid lubricants such as molybdenum disulfide MoS_2 (LS 855S). The bonded coating DF 977S formed a dry, barely visible dry sliding film and was applied as a spray. The thickness of the sliding film was about 0.5 to 3.0 µm.

The bonded coating LS 855S was also applied as a spray and cured at room temperature after evaporation of the solvent. The result was a gray-black bonded coating film with a film thickness of approximately 3 µm. Compared with bonded coating DF 977S, the solid lubricants were integrated more strongly in the inorganic binder matrix.

Further lubricant variants were the selected greases LP 475 and LP 410. LP 410 is the classic molybdenum disulfide-containing assembly paste based on a mineral oil and a combination of solid lubricants. The grease is characterized by high pressure resistance and a temperature application range up to 450 °C. The grease LP 475 is based on a mixture of synthetic oil and solid lubricants. It is used in high-temperature applications up to 1200 °C. Example applications include turbine bolts, exhaust or heating systems. The greases were applied to the bolt thread by brush before assembly and created an effective separating layer to the nut thread.

2.2. Experimental und Numerical Methods

In order to evaluate the coefficients of friction for the comparison of the selected lubricants, tightening tests were carried out on a tightening test system from the manufacturer SCHATZ at Dörken Coating GmbH & Co. KG, Herdecke, Germany. The test bench was designed for torque/preload testing according to DIN EN ISO 16047 [27]. With regard to

the fatigue tests to be performed, in which the preload was controlled as a constant mean load by the test system, the partial friction coefficient in the thread was of particular interest, since this influenced the local stresses in the bolt. The installation speed n was 10 rpm, and the head-bearing clamping part was a through-hardened steel washer of type HH (hardness high) [27]. The bolt was tightened with a steel nut DIN EN ISO 4032 M8-10 [30].

Numerical simulation was used to validate hypotheses derived from the experimental results. The influence of thread friction on the local stress in the bolt was investigated. The software ABAQUS 6.14 was used for the numerical calculations. Based on the findings from [3] for the determination of local stresses, an axially symmetrical model of the bolt-nut connection was created. For the simulation of stress under fatigue loading, an ISO metric M8 bolt (tolerance 6 g) was paired with a standard M8 ISO 4032 nut (tolerance 6 H). The load was applied to the reference point which was coupled to the head bearing area. The nut was fixed in the axial direction and was able to move laterally. The normal contact behavior was set as hard contact using the augmented lagrange method. The tangential behavior was chosen as the penalty method, whereas the coefficient of friction was $\mu = 0.12$. The connection was stressed to a preload of 23 kN load, and a fatigue operating load of 5 kN was superimposed. Three load cycles were calculated until a cyclically stabilized behavior was established. Plastic behavior was approximated bilinearly in ABAQUS using yield curves from [3] and implemented with kinematic hardening. Exemplary stress simulation was carried out for three thread friction coefficients. The damage evaluation was performed using the parameter P_{SWT} according to Smith, Watson and Topper [31]. According to the local concept, the calculated local stress was compared with the stressability of unnotched material specimens ($K_t = 1$) determined at a stress ratio of $R = -1$. Bolted joints have a mean stress due to the preload required for operational safety. Therefore, the Bergmann mean stress correction was applied here, taking into account the location of the local hysteresis and thus reducing the strong mean stress dependence of P_{SWT} [32].

The numbers of cycles to crack initiation were calculated by comparing the calculated local damage with the material strain curve.

The fatigue tests were performed on a high-frequency resonance test system as a bolt–nut connection. The joint was axially pre-stressed to a defined mean load F_m ($F_m = 0.4 \cdot F_{0.2}$, with $F_{0.2}$ as the force at the yield point), which was kept constant by the controlling of test system. A sinusoidal force with constant amplitude F_A was superimposed as the fatigue operating force (Figure 3). The test was carried out in accordance with the specification DIN 969 [25].

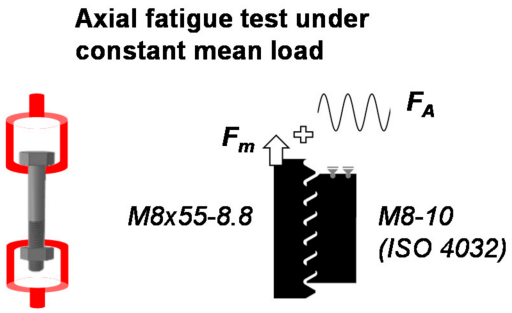


Figure 3. Test set-up of axial fatigue test with preload F_m and fatigue load F_A.

The resonance test system represents, in a simplified form, a single-mass oscillator as an analogous model. By setting up the equation of motion for this oscillatory system, the solution of a harmonic sinusoidal oscillation from the differential equation resulted in the relationship that the frequency being equal to the root of the stiffness divided by the mass of the system. Fatigue loading led to cracking in the bolt material, which resulted from dislocation movements and surface roughening due to the formation of intrusions and extrusions. In bolted joints, there were predominantly several crack locations in the first load-bearing thread of the bolt, which were distributed around the circumference

and grew together to form a fracture surface as the crack progressed. As crack growth progressed, the compliance of the bolt increased, which corresponded to a reduction in stiffness. Consequently, the onset of damage resulted in a decreasing frequency, which was used as an evaluation measure for the crack definition. For the assignment of the already existing damage, tests were stopped at different frequency drops and the crack area was marked by heat tinting. Heat-tinting describes the marking of the crack area by temperature-specific annealing colors of the steel. For this purpose, the cracked bolt was heated in the installed condition and the already damaged area was marked in color by oxidizing the crack surface.

3. Experimental and Numerical Investigations

3.1. Tightening Test Acc. DIN EN ISO 16047

Five assembly tests were carried out for each of the different lubricants and the torque-rotation angle curve was measured (Figure 4).

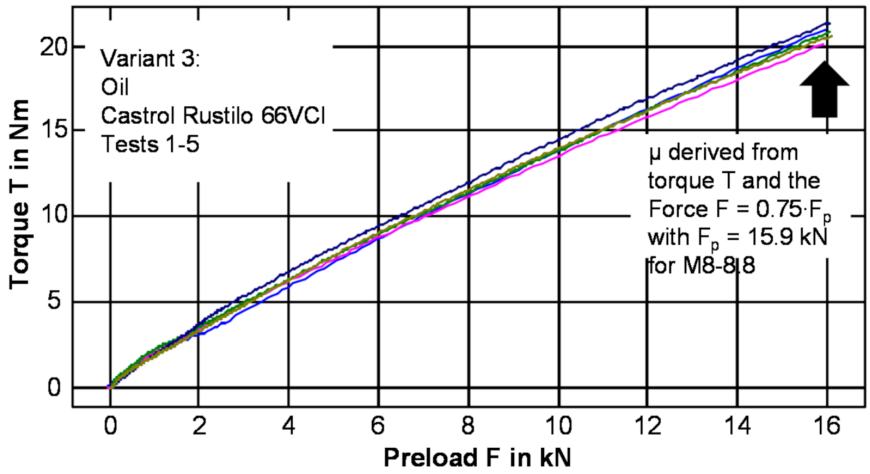


Figure 4. Torque–clamp force plot for Castrol Rustilo 66VCI.

The thread friction coefficient is determined at the force F = 0.75 × F_p [33]. The comparison of lubricants shows pronounced differences of the thread friction coefficient (Figure 5).

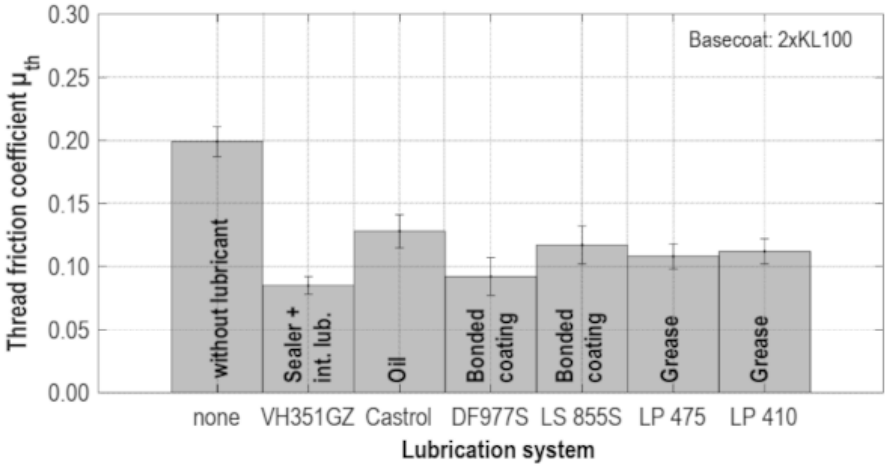


Figure 5. Thread friction coefficients for different lubricants.

The pure zinc flake version without lubrication leads to the largest thread friction coefficient, $\mu_{th,\ none} = 0.200 \pm 0.012$. The silicate sealant with lubricant additive integrated in the topcoat leads to the lowest thread friction coefficient, and at the same time shows the lowest scatter of the measured values, $\mu_{th,\ VH51GZ} = 0.085 \pm 0.007$.

The friction coefficients for the bonded coatings and greases are approximately in the average range for this comparison. The molybdenum disulfide-containing lubricants tend to have higher friction coefficients. The liquid lubrication, represented here by Castrol Rustilo 66VCI oil, has worse lubrication properties in the tightening test than the dry lubricants and greases, with $\mu_{th,oil} = 0.130 \pm 0.013$. For the fatigue tests, the effect of thread friction on stressability in terms of crack initiation and crack propagation to fracture event is evaluated.

3.2. Fatigue Tests

Determining the fatigue strength requires a very large experimental effort. In order to reduce the scope of testing and still be able to make a statistical observation for the comparison of the selected lubricant portfolio, the testing, consisting of five individual tests each, is carried out at three selected load levels above the fatigue strength $F_{ASV,50\%}$. The load amplitude is selected in the range of $\approx$1.24–2.14 $\times$ $F_{ASV,50\%}$. This results in fracture load cycles in the upper high cycle fatigue range (HCF, $N_B \approx 50{,}000$ cycles) depending on the lubrication, up to the transition range where specimens without failure reach the limited number of cycles $N_G = 5 \times 10^6$. The individual test results and the 50% regression line through the mean values of the three load levels tested in each case are shown as a Wöhler diagram (Figure 6). The comparison of the fracture load cycles shows that the bolted joint can fail over a very wide range of cycles depending on the applied lubricant. Consequently, the lubrication in the thread contact significantly influences the lifetime to failure, as well as the fatigue strength. In comparison, without lubrication, the lowest lifetime was observed by failure due to fracture. Regardless of the type of lubrication, failure with lubricated threads occurs at higher numbers of cycles. Minimal improvement is achieved by sealing with lubricant additive integrated in the topcoat. Here, solid lubricants are rigidly anchored in the glass-hard thin sealant, which resulted in very low thread friction during the one-time assembly in the torque-preload test. In comparison, screws lubricated with bonded coatings and grease lubricants show significantly higher lifetimes despite slightly higher thread friction in the tightening test. Depending on the stress level, the lifetime is improved by a factor of five to 17 compared with the unlubricated screw with a zinc flake coating only.

The oiled variant, with high creep capacity of the lubricant, shows not only a shift to higher numbers of cycles to failure, but also an increase in fatigue strength. For the lowest test load level with $F_A = 2.9$ kN, five out of five specimens for this variant reach the fatigue limited number N_G without failure due to fracture. If higher fatigue loads were applied to the oiled variant, cracks in several threads were observed by means of metallographic micrographs and scanning electron microscope (SEM), (Figure 7). As the crack progresses in the first load-bearing thread, it is relieved, which changes the load distribution and consequently increases the local stress in the subsequent threads. With the exception of the oiled variants, the crack and the subsequent failure due to fracture only occur in the first load-bearing thread for all other variants. The fracture surface is characterized by circumferentially distributed incipient cracks that converge to a main fatigue crack. The microstructure of the fatigue fracture is transgranular and ends in a ductile fracture.

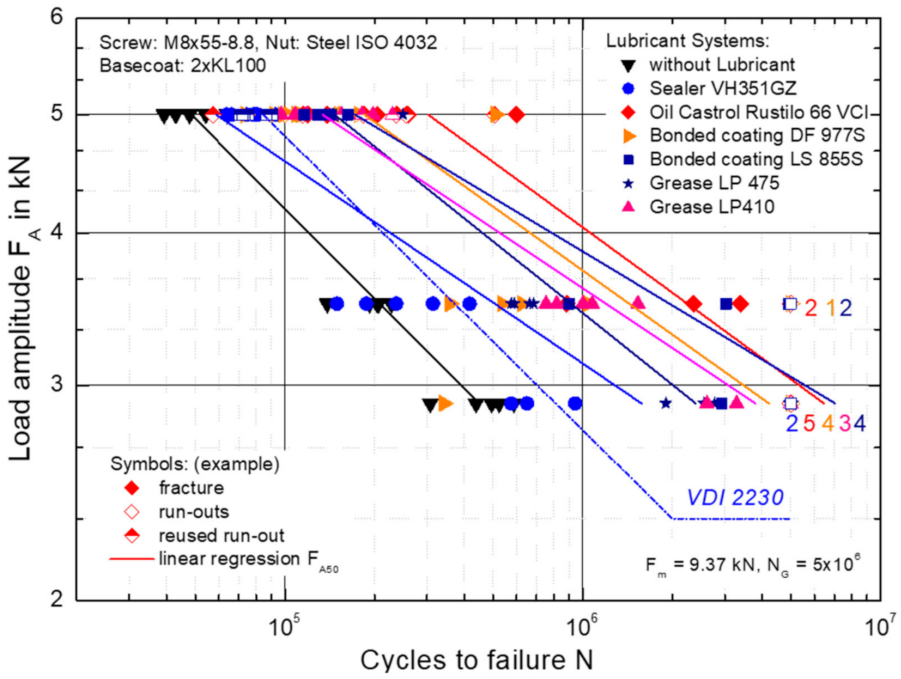
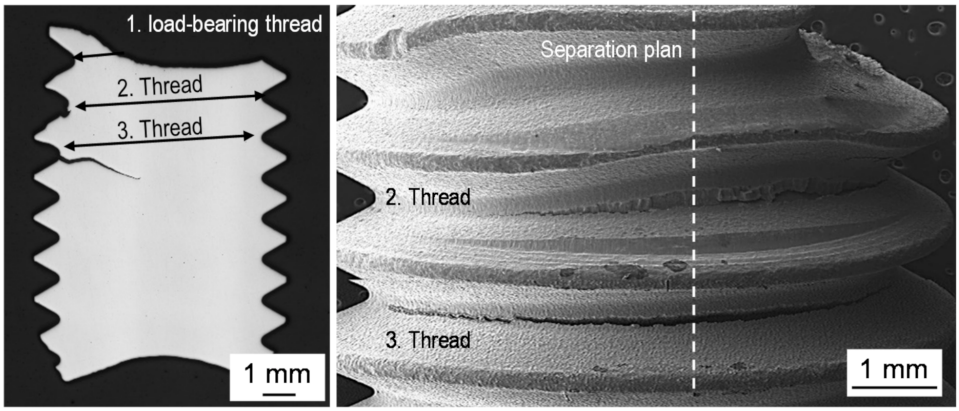


Figure 6. Fatigue tests for M8x55-8.8 with basecoat KL100 and different lubricants.



(**a**) (**b**)

Figure 7. (**a**) Cross-section of the oiled variant with multiple cracks in different threads; (**b**) macroscopic detailed SEM view.

Two hypotheses are proposed to explain the extended lifetime and the increased fatigue strength, as shown in Figure 8.

The load transmission via the 60° flank angle of the metric thread results in a cyclic radial force in the thread contact due to the changing direction of the operating load. This leads to a permanent alternating movement between the screw and nut threads. Hypothesis I is based on the assumption that lower thread friction facilitates relative movement between the bolt and nut threads in the form of alternating sliding, thus influencing local stress and crack initiation.

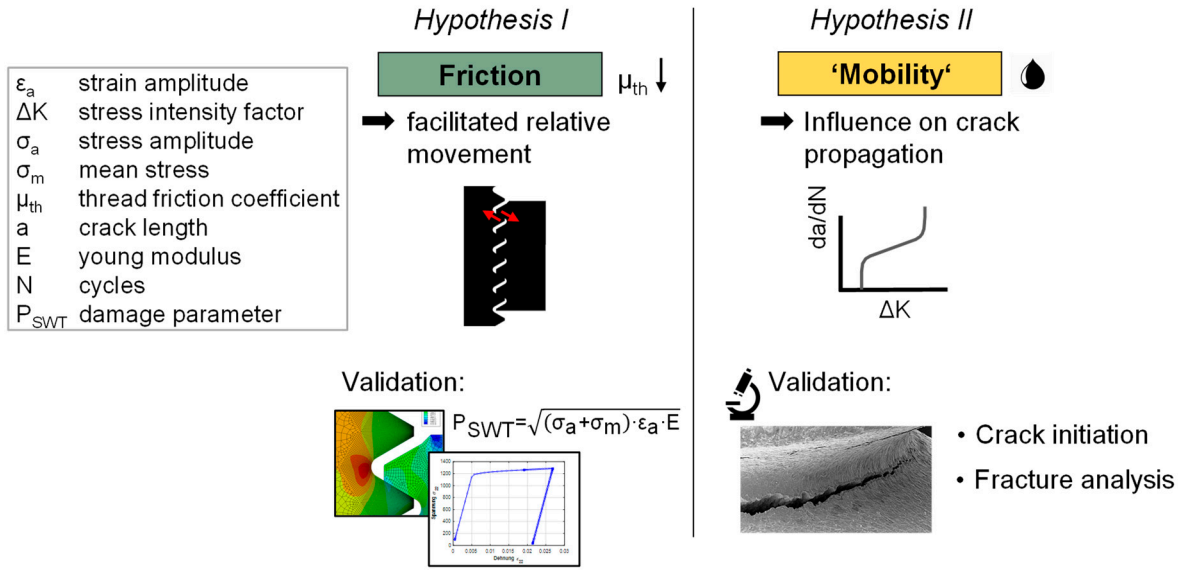
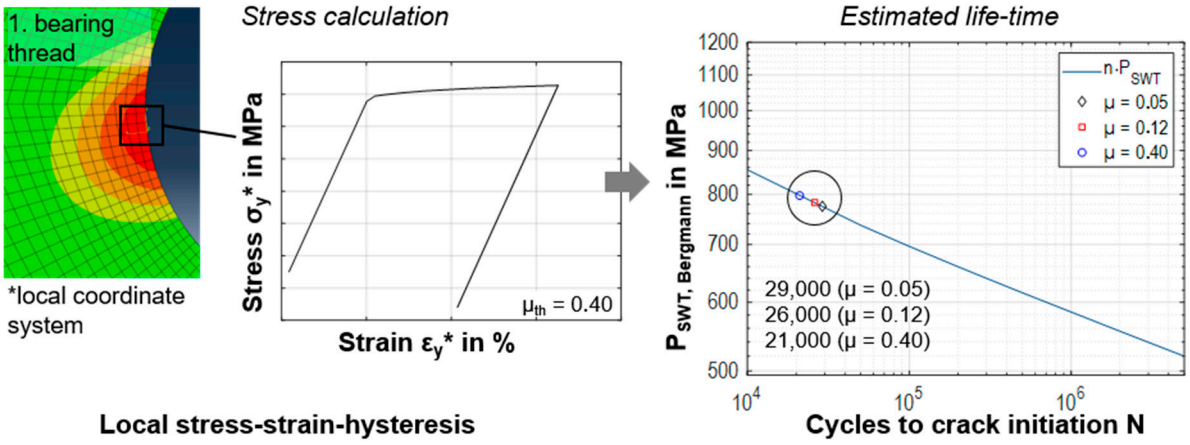


Figure 8. Hypotheses to explain the enhancement in lifetime and fatigue strength due to the influence of lubricant systems under fatigue load.

Hypothesis II is based on the assumption of an extended crack propagation phase that occurs due to the mobility of the lubricant. A creeping lubricant, such as the selected oil, settles at the crack front by capillary action and can both promote crack closure effects and shift up the local threshold required for crack growth.

3.3. Effect of Friction Coefficient on Local Stress

The effect of different thread friction coefficients on the local stress–strain hysteresis at the most highly stressed location in the first load-bearing thread of the bolt thread was evaluated by means of numerical simulations (Figure 9).



(**a**) (**b**)

Figure 9. (**a**) Local stress–strain hysteresis ($\sigma_y^* - \varepsilon_y^*$) at the most loaded thread; (**b**) numerical estimated number of cycles to crack initiation for different thread friction coefficients as a P_{SWT}–N curve.

For the evaluation, a local coordinate system is introduced and laid out tangentially to the largest principal stress. The evaluation of the local stress σ_y^* and local strain ε_y^* is carried out in the direction of y in which the crack is opened.

The local stress–strain hysteresis was derived exemplarily for the coefficients μ_{th} = 0.05, 0.12 and 0.40. The conversion into the expected lifetime was made by means of the damage parameter P_{SWT} in accordance with Bergman's modification [33]. The numerical calculation

confirms the hypothesis that reduced thread friction in the contact area reduces the local stress and shifts the initiation of cracking to higher load cycles. The differences in the calculated number of cycles to crack initiation depending on the friction coefficient are relatively small compared to the number of cycles to failure observed experimentally. For a more detailed evaluation, the number of cycles to crack initiation was determined experimentally. The aim is to evaluate the influence of the lubricant properties on crack initiation and crack growth.

3.4. Crack Initiation and Crack Growth

The crack growth phase is defined by the difference between the number of cycles to failure and the number of cycles to crack initiation. For this purpose, a methodology was derived which, based on the change in frequency of the test system, allows direct assignment of the damage that has already occurred over the crack area. As an example, five individual frequency curves are shown for the variant without lubrication for the load amplitude F_A = 5 kN (Figure 10). In addition, a master curve is derived as the mean value of the individual tests, and the beginning of the continuous frequency drop for this curve is shown as an example.

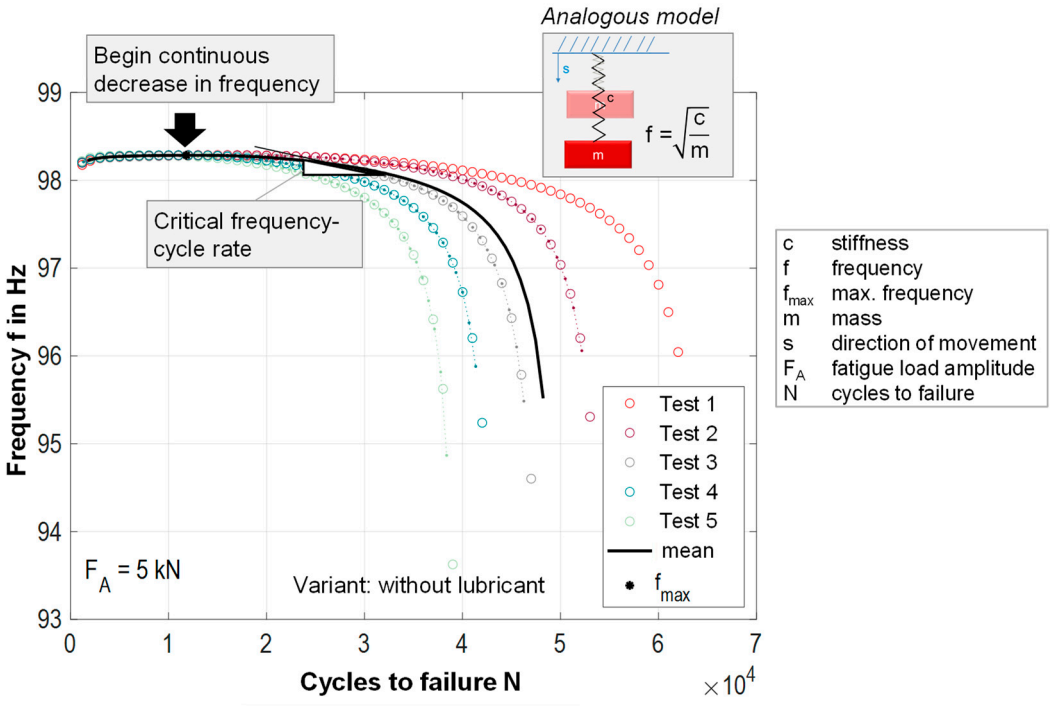
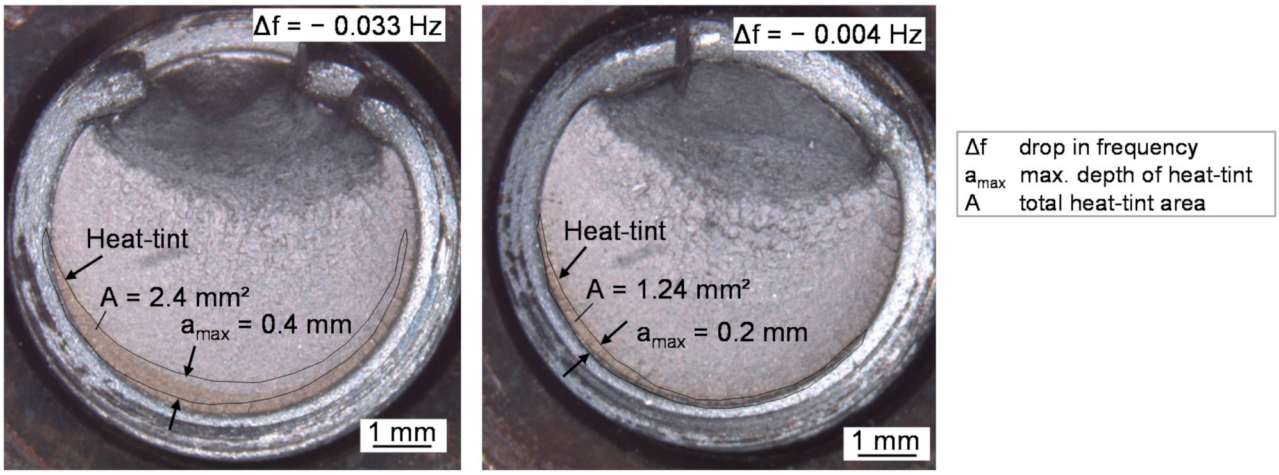


Figure 10. Frequency–load cycle curves derived from the fatigue test for the samples without exemplary lubrication exemplary.

The central issue describes the definition of the onset of damage, described as crack initiation. For example, the beginning of the continuous frequency drop ($N(f_{max})$) or a critical frequency change rate (df/dN) can be defined as the crack initiation criterion. As the crack progresses, the frequency drops faster until an unstable behavior concludes with the failure by fracture. To define a crack initiation criterion, tests were stopped at different frequency drops to mark the already damaged area by heat-tinting (Figure 11).



(**a**) (**b**)

Figure 11. Exemplary illustration of heat-tinted fracture surfaces stopped at different drops in frequency. (**a**) Example 1, frequency drop of −0.003 Hz; (**b**) example 2, frequency drop of −0.004 Hz.

By subsequently measuring the fracture surface, this procedure can be used to directly assign damage to the frequency drop. The greater the frequency drop, the larger the crack area marked by the heat tint. A correlation between crack depth and crack area with frequency behavior can be derived from a large number of tests. It can be seen that for a defined frequency drop, different maximum crack depths are produced, which can be attributed to the large number of different crack locations and the local loading there in each case. The systematic analysis of the frequency change df/dN shows that for a defined frequency change rate, a reproducible size of the crack area can be assigned.

The load-dependent crack criterion chosen here is defined by the frequency change $df/dN = -2 \cdot 10^{-6}$ Hz/cycle (Figure 12).

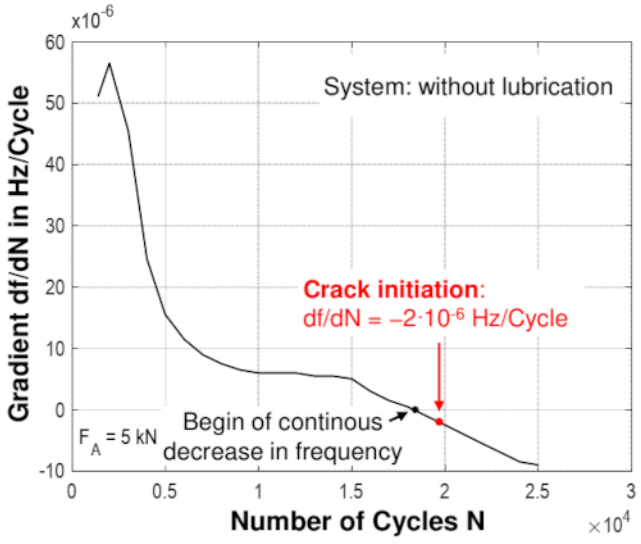


Figure 12. Definition of crack initiation criterion by a critical frequency–load cycle ratio.

Considering this methodology, the comparison of the number of cycles for the beginning of the continuous frequency drop, the crack initiation, the crack propagation and to failure via fracture for the investigated lubricant variants is presented in Figure 13.

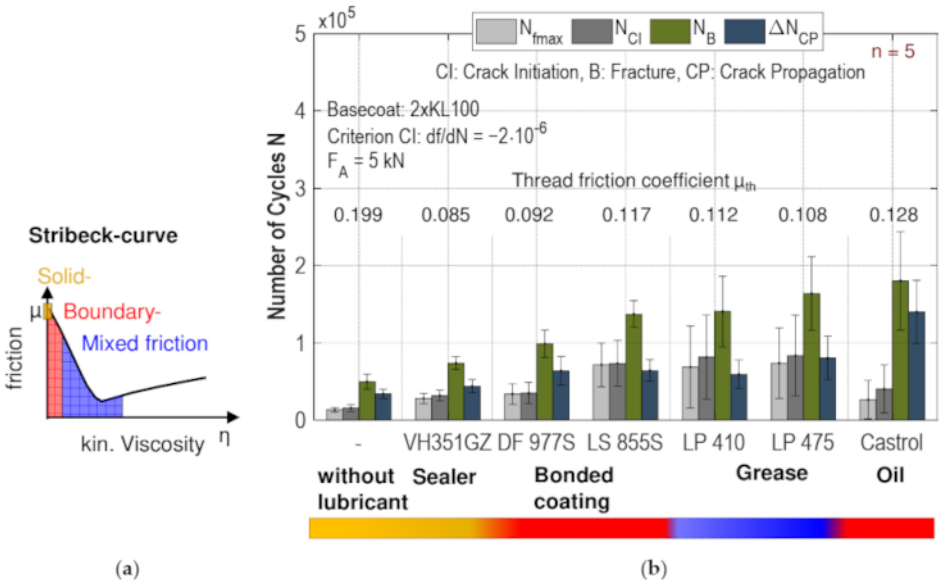


Figure 13. (**a**) Schematic Stribeck curve; (**b**) frequency drop, crack initiation, crack propagation and number of cycles to failure by fracture.

By lubricating the thread, it can be deduced, regardless of the type of lubricant, that not only is the time of fracture shifted to a higher number of cycles, but also the time of the crack initiation occurs later than without lubrication. Consideration of the thread friction coefficients determined in the torque/preload test does not allow the conclusion that the lowest thread friction coefficient leads to the latest crack initiation time. The relative movement resulting from the cyclic loading requires a more differentiated consideration of hypothesis I and of the experimental determination of the coefficient of friction. The simplified alternating sliding between the screw and nut thread due to a lower thread friction coefficient requires a characterization of the resistance of the friction conditions. Compared to the one-time tightening of the bolted joint in the standard test according to DIN EN ISO 16047, the repeated installation test or oscillating friction wear test represent approaches to characterize the friction conditions for cyclic loading. One way of classifying the friction conditions is given by the Stribeck curve [29] (Figure 13). The Stribeck curve subdivides for the comparison of the friction coefficient μ with the kinematic viscosity η into the following ranges: solid, boundary and mixed friction up to hydrodynamic friction. The variant without lubrication and the sealing with lubricant integrated into the topcoat are in the solid-state friction range. In the case of solid-state friction, the contact partners are in direct contact. The sealant is very thin and the rigidly anchored lubricant does not form a homogeneous film on the surface. Due to the onset of wear as a result of initial assembly and relative movement, there is direct contact between the screw and nut threads. The bonded coating systems and the lubricating oil are in boundary friction, where the surfaces are covered with a molecular boundary film and come into contact with the nut thread. In the case of the variants lubricated with grease, there is a local separation of the contact partners in certain areas due to the more pronounced thickness of the lubricating film. This results in its allocation to the mixed friction range. In principle, there is a dependence on the lubricant film thickness d and the roughness [25]. The assignment of the friction states represents an explanatory approach that can attribute the different crack initiation times to the different characteristics of the lubricant. The scatter of the crack initiation numbers is significantly larger for the lubrication with bonded coatings, greases or the oil than without lubrication or for the variant with sealing. Since the application of lubrication for these variants is manual, variation in the resulting lubricant film thickness cannot be ruled out and must be further characterized. Further validation of the durability of the lubrication

properties is carried out in the form of experimental testing of the friction conditions under and after cyclic loading.

Based on the different crack initiation times and the experimentally determined fracture load cycles, the length of the crack propagation period can be evaluated via the difference between these variables. A comparison of the lubricant variants investigated shows that the crack growth is slowest for oiled bolts and that the phase from the time of incipient cracking to fracture is the longest.

Hypothesis II is confirmed by the fact that the mobility of the lubricant has an influence on the crack propagation behavior. The prolongation of the crack propagation time is slightly improved for the sealant with lubricant integrated in the topcoat, which is due to the low mobility of the lubricant. In contrast, for bonded coatings and greases, there is a prolonged crack propagation phase, whereby the creep ability of the lubrication is lower compared to the lubricating oil and therefore the prolongation of the crack propagation phase is correspondingly less pronounced. The theory that the creep-capable oil settles at the crack front due to the onset of capillary action with a developing crack could be proven with the methods of material analysis, such as the scanning electron microscope (SEM) (Figure 14).

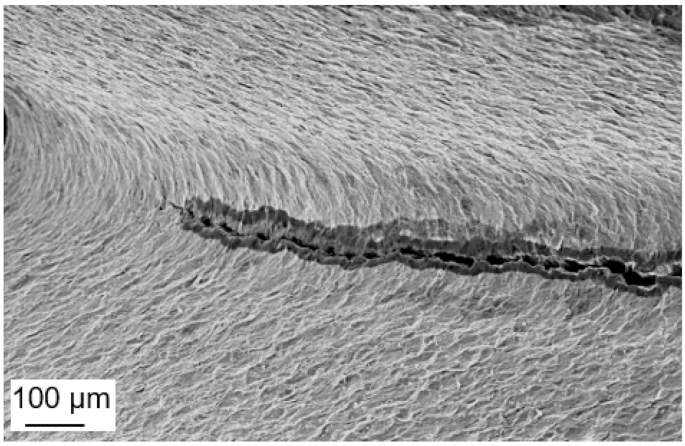


Figure 14. Dark covered surface on the crack edges and inside the opened crack.

By means of energy dispersive X-ray analysis (EDX), an increased carbon content can be detected at the crack front and between the crack egdes. The optical discoloration and the increased C-content are evidence for the presence of the oil.

4. Summary and Discussion

In order to evaluate the influence of corrosion protection layer and lubrication separately, a bolt M8x55-8.8 with non-electrolytically applied zinc flake coating was selected [18] and investigated with a selection of different lubricants in the fatigue test. The reference-forming variant without lubrication was compared with a sealant with lubrication integrated into the topcoat, two bonded coating systems, two lubricating greases and one lubricating oil.

For initial characterization, thread friction coefficients were determined for the selected variants in the torque/preload test according to DIN EN ISO 16047 [23]. The friction coefficient was from μ_{th} = 0.085 (sealing) to μ_{th} = 0.200 (without lubrication). Subsequently, the fatigue strength was evaluated in the axial fatigue test according to DIN 969 [21]. For this purpose, the bolts provided with different lubrication were paired with standard steel nuts according to DIN EN ISO 4032 [26] on a resonance test system preloaded to a constant mean load and a sinusoidal operating load with constant amplitude was superimposed. Five individual tests were performed for each variant at three load levels, so that failure due to fracture occurred as a function of thread lubrication in the range of fatigue strength

from $N_B \approx 50{,}000$ cycles to $N_B > 10^6$ cycles, or the limited number of cycles $N_G = 5 \times 10^6$ was reached.

The lubrication in the thread contact significantly influences the lifetime as well as the fatigue strength. Regardless of the type of lubrication system, lubrication increased the lifetime and durability compared to the unlubricated bolted joint. For the standard surface system, consisting of a basecoat and lubricant additive integrated with the topcoat, the smallest improvement in lifetime was achieved, although this variant has the lowest thread friction with one-time tightening in the torque/preload test. In comparison, bonded coatings and grease lubricants lead to longer lifetimes despite slightly higher thread friction in the assembly test. The greatest improvement was achieved by the oiled bolt variant, which at the lowest test level of $F_A = 2.9$ kN was the only variant where five out of five specimens were able to reach the fatigue limit without failure due to fracture. Consequently, not only is the lifetime increased, but also the fatigue strength. Based on the determined load cycles to fracture, the greases and bonded coatings rank between the sealed and oiled variants. Two hypotheses were formulated to account for the improved lifetime due to lubrication and the increased fatigue strength due to the properties of lubrication. The first hypothesis is based on the assumption that low thread friction reduces the local stress in the bolt, thereby shifting the initiation of cracking to higher load cycles. Validation was performed via the numerical simulation of local stresses for different thread friction coefficients and by evaluating the crack initiation times via the frequency signal of the resonance test system. The evaluation of the damage parameter P_{SWT} confirms that a lower thread friction coefficient reduces the resulting local stress–strain hysteresis and shifts the crack initiation times to higher load cycle numbers.

The numerical study conducted was used to verify hypothesis I. It represents a simplification compared to the real conditions, as no wear or long-term conditions of the lubricant was taken into account. In particular, the resistance of the friction conditions under cyclic loading influences the crack initiation. Furthermore, the greases also have a damping property due to the present lubricant film thickness. In order to evaluate and take the specific lubricant properties into account, the crack initiation time was determined experimentally. In this way, the influence on crack initiation and crack growth depending on the lubricant could be differentiated. For the experimental evaluation of the crack initiation times, a method using frequency analysis was developed. Due to the oscillating properties of the test system, an increase in compliance, which occurs with the onset of crack initiation and increasing crack growth, can be assigned to a frequency decrease. Using the developed analysis method, a reproducibly damaged area could be detected for a critical frequency change rate. Via stopped tests and by means of heat-tinting marked cracking surfaces, the frequency change rate $df/dN = -2 \times 10^{-6}$ Hz/cycle was defined as a load-dependent cracking criterion.

Comparison of the crack initiation cycles shows that regardless of lubricant selection, with thread lubrication compared to the unlubricated reference, the crack initiation time is shifted to higher load cycles. Thread lubrication facilitates an alternating sliding motion between the screw and nut threads. This relative movement is forced on the thread flanks by the radial force resulting from the alternating axial operating load. If the alternating sliding is continuously facilitated by consistent lubrication properties under fatigue loading, the local bolt stress can be reduced and the crack initiation point can be shifted. On the basis of the test results, the greases in particular, with the comparatively greatest lubricant film thicknesses, are assigned the greatest resistance to the friction conditions for the comparison of lubricants carried out here. Compared with the standardized tightening test, which only records the initial thread friction during one-time tightening, wear phenomena and the resistance of the lubrication properties must be further specified for evaluation under fatigue loading. By comparing the number of cycles to crack initiation, the longest lifetime of the oiled screw variant cannot be justified. Therefore, to explain the significantly improved lifetime, the second hypothesis was formulated, which describes the influence of the mobility properties of the lubricant on the crack propagation phase. Due to a high

creep ability of the oil, upon crack initiation the lubricating oil settles at the crack front by capillary action and slows down the crack propagation. Underlying mechanisms include, for example, crack closure effects, the damping effect of the oil and the changed local threshold value which is necessary for crack growth [4,13]. In general, crack growth in bolted joints occurs quickly. The rate of crack growth da/dN is load-dependent. The higher the local stress/strain, the greater the stress intensity factor is, and thus crack growth will be quicker. For the investigated lubricant systems, the required crack opening stress differs compared to unlubricated bolts [14]. Therefore, the crack grows more slowly. By means of the measuring methods developed, it could be proven that there is already a crack related to a specific drop in frequency respectively the rate of change in frequency. In particular, oil, based on its capability to creep, will go directly in between the crack. At the very beginning of the crack initiation, the rate of crack growth is very small. Then, the rate of crack growth may increase very rapidly depending on the lubricant, until it becomes unstable and fails by fracture. Oil is the example to be emphasized, as it enlarges the phase of crack propagation extraordinarily. If the crack initiation is recognized, it will take a longer time until failure compared to the other variants investigated. The ratio of crack-free and cracked lifetime is strongly load-dependent. The smaller the fatigue load, the greater the crack-free portion of the total number of cycles to failure is. In the given example, 5 kN is a high load amplitude. Thus, the crack initiation is going to be very early depending on the lubricant, and the portion of crack propagation can be greater than the crack-free portion. As the method developed for detection of the crack initiation is load-dependent, the selected rate of change in frequency should be validated individually for each test series.

5. Conclusions

For bolted joints, this study shows an important gain in knowledge, since lubricants systems are given no consideration as factors influencing fatigue strength in the design process.

- Lubrication has a positive effect regarding crack initiation and crack growth on bolted joints under fatigue load. Depending on the lubricant properties, lifetime and fatigue strength improvements can be observed, e.g., oiled bolts did not break at all at a fatigue load amplitude of 2.9 kN in five out of five cases, whereas unlubricated bolts failed by fracture at an average of approx. 470,000 cycles.
- Based on the results, which show large differences in lifetime depending on the lubricant, two hypotheses were derived and validated. Hypothesis I: reduced thread friction facilitates relative movement in thread contact and reduces local stress. Hypothesis II: a mobile creep lubricant settles at the crack front and expands the crack growth phase.
- A method to determine the crack initiation has been derived from detailed frequency analysis. By means of stopped tests at different drops in frequency and marking of the already damaged area by heat-tinting, a critical frequency change rate, e.g., of -2×10^{-6} Hz/Cycle for 5 kN fatigue load, has been identified as the crack initiation criterion. This criterion can be determined load-dependently.
- The resistance and creep properties of the lubricants determine the onset of damage due to cracking and the progress of cracking until failure due to fracture. It could be observed that greased bolts crack later and the crack growth is slower compared to unlubricated bolts. For oiled bolts, the crack initiation is earlier than for greased bolts, but the crack growth phase is significantly expanded and leads to a pronounced improvement in the stress resistance under fatigue loading
- In order to take the findings into account in the design process, the preload dependence must be investigated. Based on numerical studies [3], the preload influences the relative movement in the thread contact, and thus the crack initiation is affected. The stability of the lubrication properties and the load transmission at the contact area under fatigue load is difficult to represent numerically. Experimental investigations should follow to evaluate these influences.

6. Outlook

Tests on single circumferentially notched specimens represent an interesting point of focus for further investigations. In addition to the frequency analysis method developed, the influence of the corrosion protection system on the cracking behavior is investigated by means of a potential measurement. With the aid of the notched specimens, it is possible to evaluate the influence of the corrosion protection layer in isolation, without the influence of load transfer through contact and the inhomogeneous load distribution existing in bolted joints. For this purpose, a comparison is made for electrolytically coated systems with non-electrolytically applied surfaces and other bolt-typical coating systems. Finally, the complex system consisting of corrosion protection and lubrication is investigated with regard to lifetime, with the aim of being able to take the influence of the surface protection system into account in the computational design (Figure 1).

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