Preload Stability of Modern Bolted Joints

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The design of screw joints is very important for fastened components to ensure reliable transmission of mechanical or thermal loads between components. Suitable fastener selection and proper design are required for increasing product performance while reducing size, weight and cost ratios. A fastening system is basically characterized by component geometry, materials and tightening level. Robust clamping of components depends on time dependent clamp force, which can be represented by Bolt's preload change. In any fastening system preload loss takes place. The contribution shows, why (seating, load plastification, creeping). Furthermore, the loss may not be too large to provide suitable behaviour over time. This means, a higher tightening preload cannot be utilized, if most of the advantage is compensated by preload loss. Important influences are clamped materials, tightening level (from assembly method) and type of thread engagement. For various combinations long time measurements of preload loss over time are shown. The paper shows also how the measurement is done. The outcome of all the combinations is that preload loss significantly exceeds the estimations of existing guidelines, e.g., VDI 2230. The reason is, that in time of development of the guidelines mainly steel components have been used and preloading was moderate. So the conclusion is to extend the calculation with a better and more flexible approach for today´s requirements. Overall, the contribution combines explaining mechanisms for preload loss, results from measurements for analysis as well as calculation for prediction in advance to extend guidelines.

Keywords: *bolted joints, preload loss, influences, prediction, guideline for design*

Introduction to Preload Relaxation and Methods of Measuring

Bolted joints are an important way of connecting components, they are widely used in all sectors of mechanical engineering. The unique combination of high clamping forces and the fact, that such a connection is detachable and reusable, leads to a growing number of screw joints in many modern mechanical devices. Another reason for the growing usage is the increasing use of light metals like aluminum or CFRP, which are difficult for welding. In Germany for example, more than 500,000 tons of steel are annually used for screw production. Only when a sufficient level of preload is ensured in the screw about the entire life

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cycle, the function of the fastening system can be guaranteed. If not, failures can take place from breaking, opening, corrosion or self-loosening (for latest details see Guggolz (2019)).

As mentioned in the abstract above, the loss of preload in a clamped bolted joint can be mainly accomplished by the following three mechanisms. It is able to summarize them as "preload losses due to relaxation":

1. Seating: While the assembly and tightening process, the different rough clamping parts are getting into contact. Even fine manufactured parts are having roughness peaks (maxima) and corresponding minima. Seating means a flattening of those peaks of the clamped parts, screw (under the head, in the thread) and nut thread during and afterwards the tightening process. The flattening is caused by local plastifications of the peaks. This leads to a reduction of the compression (extension) of the clamped parts (the screw), which again leads to a loss of preload, the seating loss. Its amount can be calculated with a simple formula given in the VDI 2230-1 (2015) guideline. The seating effect begins directly after the finished assembly procedure and continues at maximum to 48 hours, the main part of 80% is relaxed within the first hour in operation. In detail, the seating processes are acting already during the assembly process, but are getting equalized by the more and more increasing preload.

2. Load plastification: Local plastic deformations at the highest stressed areas (bearing surfaces under the screw head and nut position as well as thread contact and component contact zone) in the bolted joint, initialized by thermal and/or additional loads. Thereby, the preload increases first, but if the additional factors are gone, it supposes a lower amount as before. This process occurs, if the surfaces are overloaded above their plastic limit, this leads in the further development to a loss of preload in the screw.

3. Creeping: Longtime global plastic deformations of the solid materials in the entire clamping system because of the mechanical stress and especially increased thermal loads. This effect runs clearly stronger above 40% of the melting temperature of the clamped materials. For aluminum, those effects can occur already at temperature levels from T = 100°C (Peth and Friedrich 2018). This is especially of interest, because aluminum alloys are often used for modern lightweight applications. The difference between creeping and load plastification is, that for creeping the yield strength of a material is not reached. The creep plastification of a screw connection (and the resulting preload loss due to creep) cannot be estimated from uniaxial creep tests. One of the reasons is the difference of stress distribution. While the uniaxial creep sample usually has a circular stress area, the parts of the screw connection have an inhomogeneous stress distribution in the component contact and furthermore also over the length of the clamped parts and threads. Additionally the resilience of the screw and clamped parts lead to less plastic deformation as a plastification will directly reduce the preload and therefore reduce the stress and temperature driven creep mechanisms.

In Figure 1, these mechanisms are illustrated schematically for two types of bolted joints. For this, the preload level is plotted versus time. In the first system (top), steel based clamping parts were used, aluminum based in the second one (bottom). All other parameters like clamping length or assembly preload are already equal.

Figure 1. *General Approach for Determining Preload Loss with Two Different Systems (Hubbertz and Friedrich 2013)*
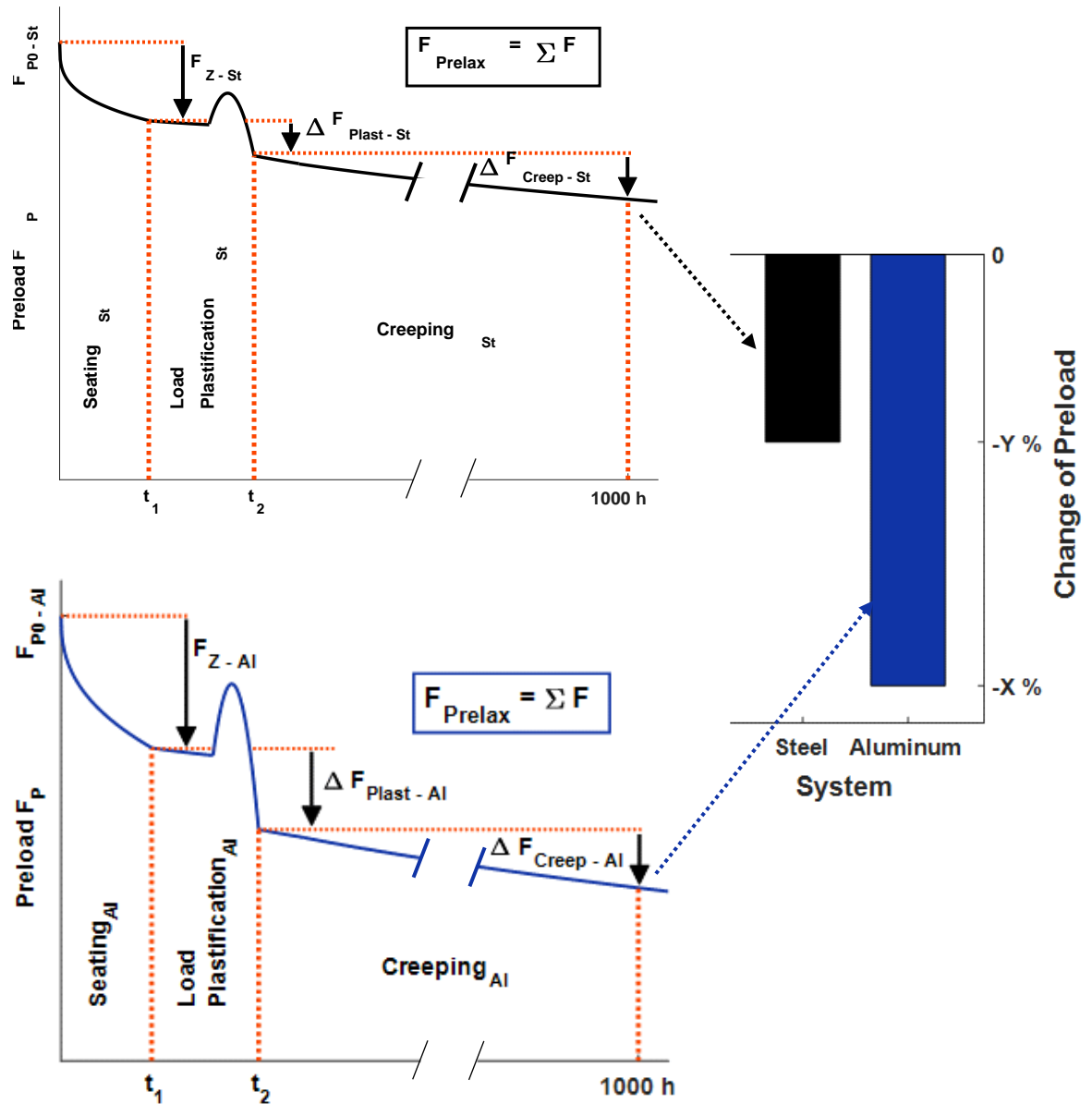
The bar graph below illustrates, that the preload losses because of relaxation processes are significantly higher for an aluminum system than for a steel system. Further it can be seen, that each Phase 1-3 within $t_1 - t_3$ has an own contribution to loss of preload, which ensures to differ the single phases (F_Z, ΔF_{Pplast}, ΔF_{Pcreep}).

The sum of them can be expressed as ΔF_{Prelax}, the above mentioned "preload losses due to relaxation". Besides this, it can be seen very good, that the preload increases, if the seating processes are finished and additional loads are acting.

The established guidelines are mainly focusing on the assembly process of a bolted joint or even on a short time after it. The loss of preload of such a connection can be estimated based on measurements, engineering standards or special literature, but in many cases, the loss is higher than the given information in these instruction textbooks. This is especially the case for modern lightweight - connections (e.g., aluminum) or if critical parameters are additionally acting, e.g., an increased temperature. Another important problem is that these guidelines are providing equations for the preload losses due to seating processes only, the additional mechanisms load plastification and creeping are not considered with the help of equivalent terms. For example, the very well respected and often used engineering standard VDI 2230-1 (2015) just says about rules for load plastification and creeping: "Due to the variety of influencing factors it is not possible to lay down any rules of universal validity nor even formulate any equations for evaluating the preload loss due to relaxation". It will be shown, that the losses of preload can be much bigger though. However, this paper will consider all of these processes and give further information to them, all are accompanied with a loss of the preload force. For the measurement of the preload itself, there are numerous methods available (Jenne et al. 2015), the different sources of literature of this paper are using divers methods. An interesting and modern way is the measurement with strain gauges (applied on or in the screw), which is a current research focus of MVP. The main benefits are the realistic and continuous in-situ recording of the forces as well as the unchanged screw system (clamping length). However, other ways of preload measurement like ultrasound (utilizing the duration between sending and receiving a sound wave in a sample, used in Hörnig (2016)), micrometer screw (utilizing the correlations between force, resilience of the screw and the belonging elongation, used in Peth (2021)) or load cell (combinations of strain gauges in a special cell, used for Figure 4) are as well reliable as accepted by professionals.

In this paper, various combinations of longtime measurements will be shown and different systems will be presented. Longtime means a considered time period of t = 1,000 h, the loss of preload will always be compared at this point. The different systems are all existing out of a steel screw and clamping parts made of steel, aluminum or CFRP.

Literature Review

The subject area of bolted joints is a research focus of MVP for many years, especially the loss of preload for different systems and conditions (Jenne et al. 2014, Hörnig 2016, Peth 2021). Regarding this, also different methods for preload measurements are investigated (Jenne et al. 2015). This results in the diagrams below.

Experimental Results

As introduction to this chapter, the abbreviations used below will be explained at first:

- M : metric thread
- T : level of thermal load
- F_{P0} : assembly preload
- D_A : outside diameter of the samples

- d : nominal screw diameter
- l_k : clamping length
- t_e : length of thread engagement
- N : quantity of single experiments

Impact of Different Clamping Materials in Combination with a Thermal Load

The classical, often used bolted joint system is consisting out of a steel screw in combination with steel clamping parts. The calculation rules and standards are elaborated well for this situation. Modern bolted joints are still using steel screws, but the clamping parts are getting substituted apart from steel. But for the estimated preload losses, the material of the clamping part is having an influence. Especially, if an additional thermal load is acting. Figure 2 illustrates the difference between a screw joint using steel and aluminum clamping parts for a longtime period in combination with a thermal load. Therefore, the time t is plotted versus the relative preload F_P/F_{P0}. Generally, the first 48 hours (-48 h until 0 h) of the experiment was conducted by a temperature of $T_1 = 20$ °C (Room temperature RT). Then the thermal load was increased to the amount of $T_2 = 150$ °C (120 °C) for the rest of the period. Three curves were recorded, the assembly preload was in all cases $F_{P0} = 30$ kN.

It can be seen that the steel curve shows a very low loss of preload across the measurement although a higher temperature level was acting. Also the explicit loss of preload can be mentioned for the aluminum systems combined with the increased temperatures. Facing a thermal load of T = 120 °C, the dotted line loses up to 25% of initial preload, even around 52%, when the temperature is increased for another 30 °C to T = 150 °C (triangular markers). This is a problem for many modern bolted joints, because due to the effort of generating light connections as much as possible with clamped parts using light alloys, the loss of preload for often-used bolted joints are very high and need to be considered already in design state. If a thermal load occurs additionally, an aluminum system will lose even more of its initial preload. This means, that the prediction of preload loss must be taken into account of a material and temperature dependency. Thereby, the temperature - caused characteristics between materials like steel und light alloys like aluminum are differing: For metals (steel and aluminum), the beginning of the creeping processes are being stated generally at around a homologous temperature $T_H = T/T_M = 0.4$. The homologous temperature is the ratio between the temperature of an element and its melting temperature (Kelvin scale), so it is a dimensionless parameter. For steel, the corresponding value is $T_{Creep\ St} \approx 724$ K (450 °C), for aluminum $T_{Creep\ Al} \approx 373$ K (100 °C). This explains the development of the lowest

curve while facing T = 150 °C in Figure 2. Therefore, the first message is that the preload loss of lightweight systems using light alloys is much bigger than the loss for a classical steel system, especially under high thermal loads. Another notable statement is, that bolted joints using steel clamping parts can be used without any problems at increased temperatures like T = 150 °C, because this temperature is much smaller than $T_{Creep\,St}$.

Figure 2. *Impact of the Material of the Clamped Parts and an Additional Thermal Load for the Measuring via Micrometer Screw (The Samples Were Cooled Down to Room Temperature)*
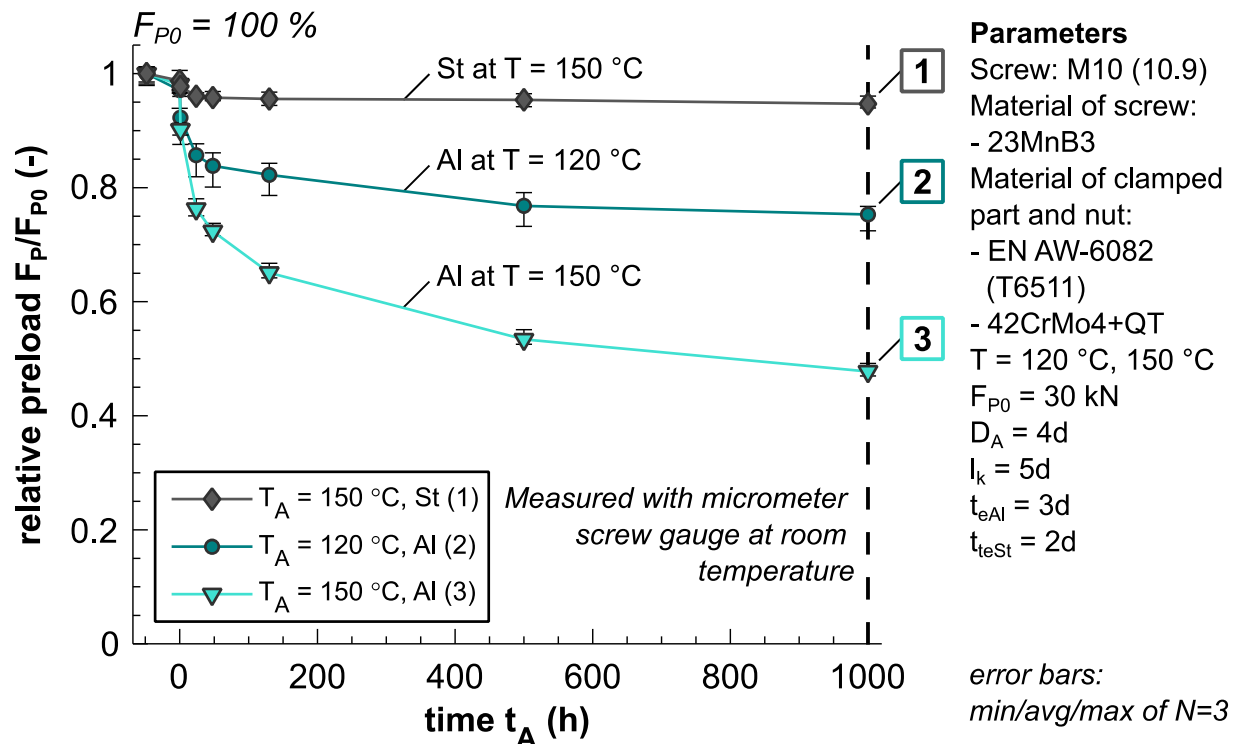
Impact of Different Assembly Preload

Variable assembly preloads can result easily out of the different ways to tighten a bolted joint. In detail, this is described by the tightening factor $\alpha_A = F_{Mmax}/F_{Mmin}$. The bigger α_A, the bigger the difference between minimal (F_{Mmin}) and maximal (F_{Mmax}) assembly preload. Of course it is interesting to use a method, which generates a small value of α_A (like yield-point-controlled tightening, $\alpha_A \approx 1.2$), because the resulting preload is even more precise. An example for an imprecisely method is the torque-controlled tightening ($\alpha_A \approx 1.6$), which is often used in mechanical engineering. Besides this, the value of the assembly preload has an influence on the three mechanisms seating, load plastification and creeping, and with them for the loss of preload, too. This is shown in Figure 3.

Figure 3. *Impact of Different Assembly Preloads for the Measuring via Micrometer Screw (The Samples Were Cooled Down to Room Temperature)*
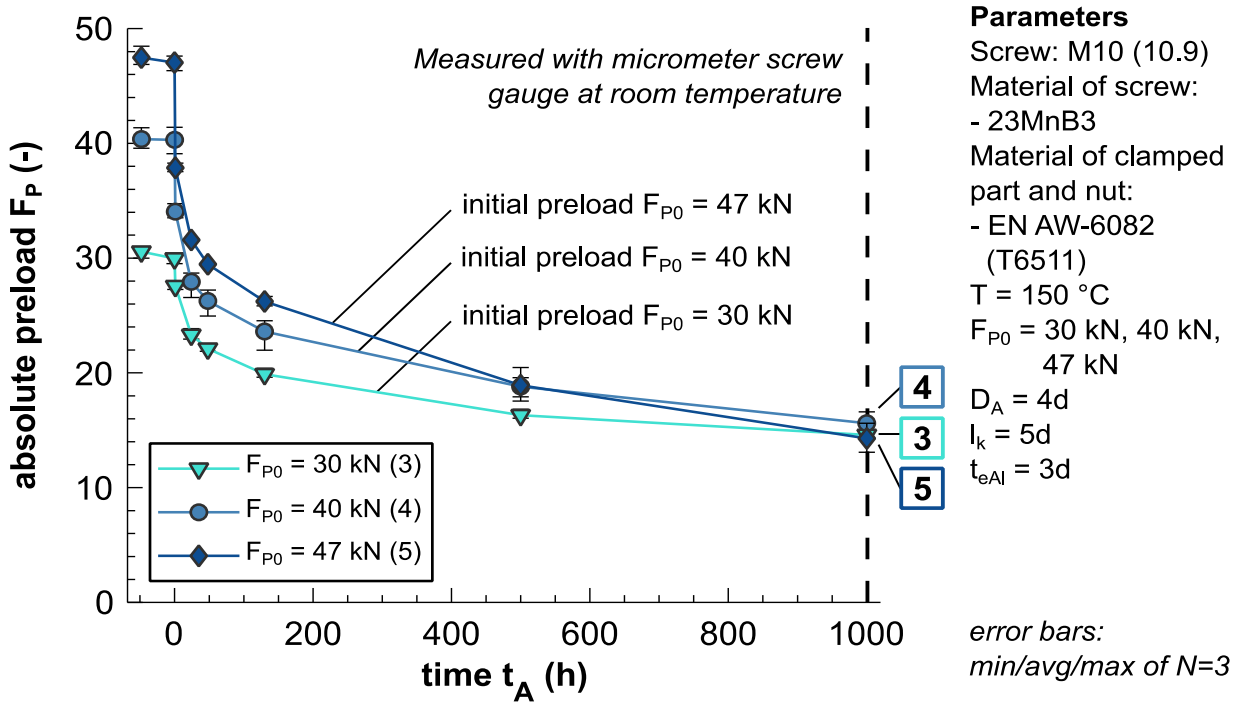

In Figure 3, the preload (scale using absolute, not percentage values) is again plotted versus time, three different curves are shown. The dark blue (light blue, turquoise) belongs to an assembly preload of F_{P0} = 47 kN (40 kN, 30 kN), a thermal load of T = 150 °C was acting in all cases. At the beginning the assembly preload differs, but at exposure of t = 1,000 h deviations are gone. This behavior is typical for systems with large preload loss. So the higher the assembly preload, the higher the loss of it in a period of t = 1,000 h under a thermal load of T = 150 °C. The reason is that the creeping processes are not just depending on the height of the thermal load, but also on the value of the surface pressure. For F_{P0} = 47 kN, this amount is larger than for F_{P0} = 30 kN, the effects are stronger. MVP - research studies have shown that the screw in combination with a high preload level contributes to a preload loss due to load plastification processes (Peth 2021).

At MVP, further experiments were done to examine the influence of different assembly preloads on the processes of preload relaxation. The aspect, which should be investigated, was the behavior of the actual preload, if the level of the thermal load is rising (From T = RT until T = 120 °C) respectively decreasing (From T = 120 °C until T = RT). Therefore, a load cell was used, which enabled the continuous recording of the preloads values. Just like Figure 3, Figure 4 compares different assembly preloads (10 kN, 30 kN, 40 kN & 47 kN) versus time. Similarly to Figure 3, clamping parts and nut were made from aluminum. The profile of the thermal load versus time is stated under the diagram. It must be considered, that the different way of preload measurement affects the result (higher clamp length

by using a load cell), but mainly Figure 4 emphasizes further topics in addition to Figure 3.

**Figure 4.** *Further Impact of Different Assembly Preloads in Combination with Thermal Load*
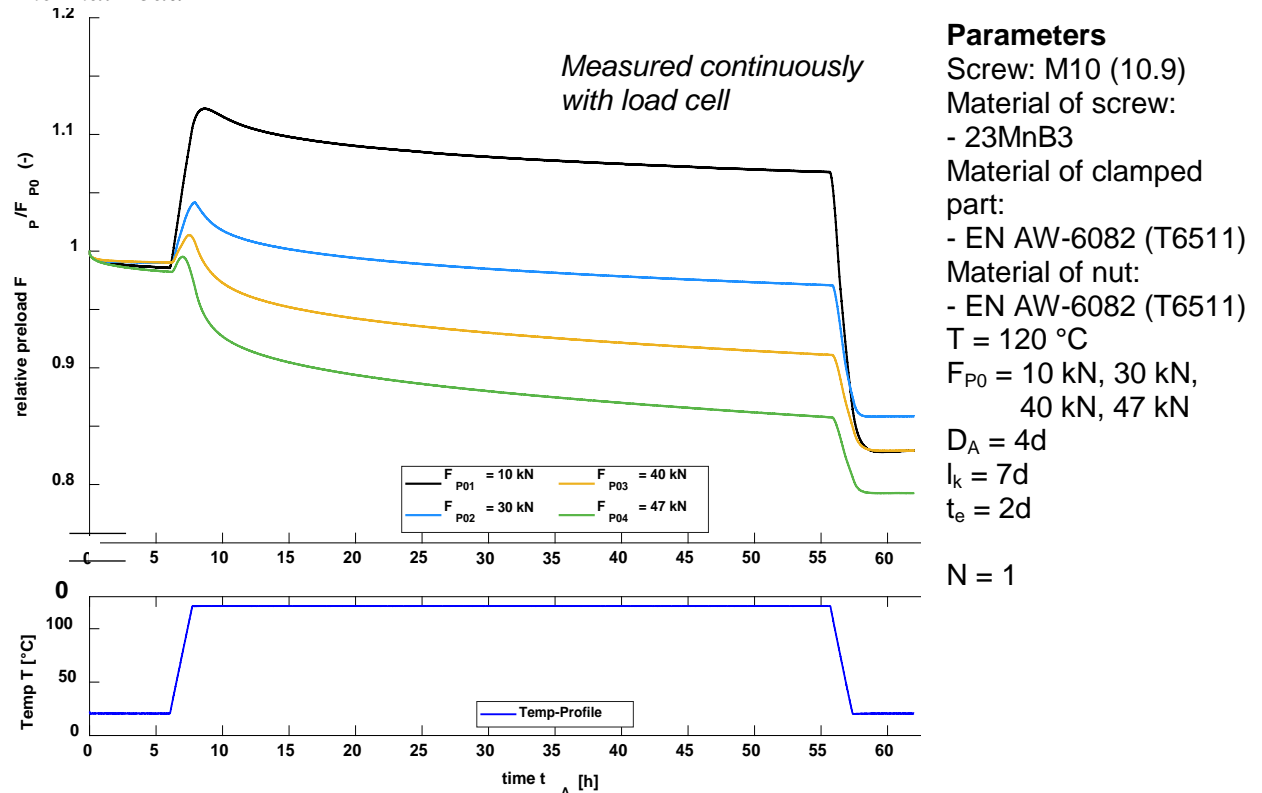
It can be seen that the preload loss due to seating are almost equal for all curves in the first 6 hours since beginning of the measurement. This is caused by the low level of roughness ($R_Z = 3$ µm). If the temperature increases, the preload of a screw system with a higher amount of F_{P0} will not rise as much as a system with a lower. The reason is that plastification processes are already taking place in the high preloaded screw joint systems. The screw as well as the higher loaded contact surfaces are beginning to yield, which leads to a loss of preload.

Impact of Nut Type and Length of Thread Engagement

In this section it will be shown that the material of the nut as well as the length of thread engagement in combination with aluminum clamping parts has an impact on the expected loss of preload as well. Generally, screw joints can be separated in the two classes tapped thread joints (TTJ) and through-bolt joint (TBJ). Using a TTJ, a threaded hole will be drilled in the lower clamping part, so that the connection will not have an additional nut. Using a TBJ, a classical nut is going to be installed. The general characteristics between these classes are always differing (e.g., different resiliencies between a TTJ and TBJ because of a different clamping length). You have to consider, that a TTJ can be tightened in the most cases only

on the side of the screw head. For lightweight applications, the facility of TTJ's is very interesting, because it reduces the nut at of bolted joint. Considering a car for example, several hundred individual screw connections are assembled, the use of TTJ's will lead to weight reduction which is desirable. Figure 5 shows a comparison of screw systems using steel and aluminum nuts, partly with higher length of thread engagement, facing an increased thermal load of T = 150 °C:

Figure 5. *Impact of the Nut Type and Length of Thread Engagement for the Measuring via Micrometer Screw (The Samples were cooled Down to Room Temperature)*
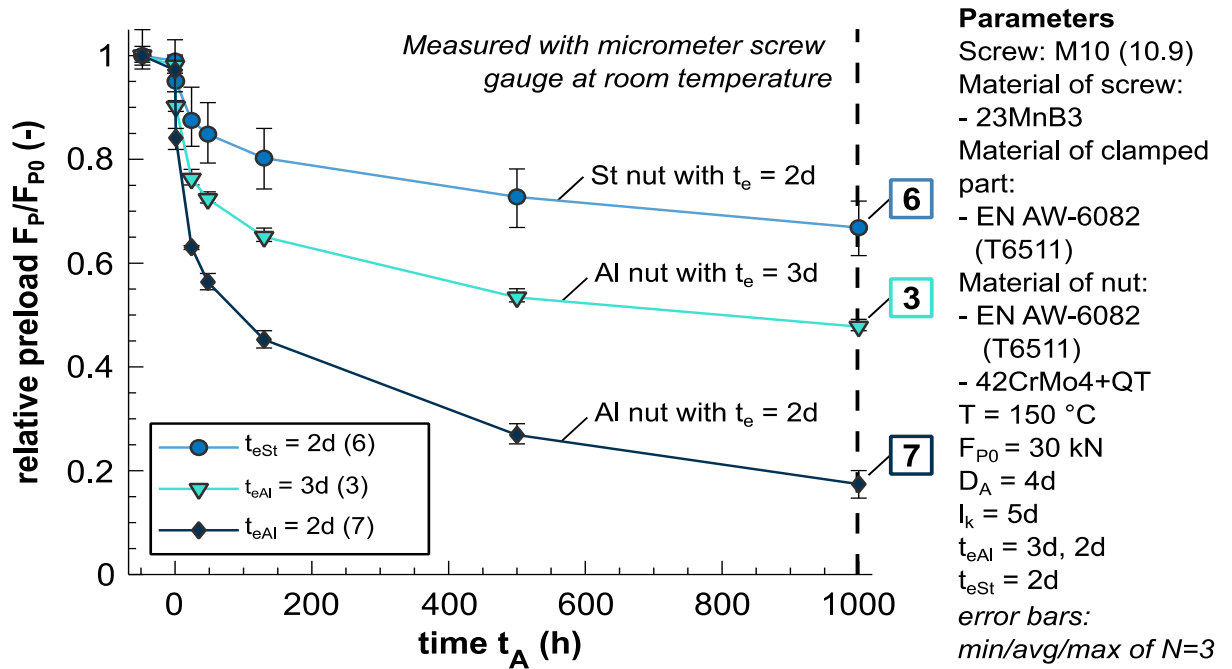

In Figure 5, the relative preload (percentage scale) is plotted versus time, this scheme was already used at Figures 2 and 4. All experiments were done with aluminum clamped parts. The first thing, which can be seen, is the lowest loss of preload ($\approx 30\%$) by using a steel nut (length of thread engagement: $2 \cdot d$). For the same parameters, just using an aluminum nut, the preload loss is significantly higher (around 80%), so that the function of the connection will be clearly not given further. By increasing the length of thread engagement to $t_e = 3 \cdot d$, the loss is decreasing, but it is even reaching around 50% of the assembly preload. The reason for the high losses are not just creeping processes, a damaging of the aluminum nut can occur as well. If the length of thread engagement is being reduced, the acting preload is dividing to a smaller area in the nut thread, which leads to a rise of specific stress in the thread. If the stress is getting to high or/and a higher thermal load applies additionally, a damage case and with it a loss of preload can happen.

Impact of Clamped Materials Made of CRFP

Additional to the mentioned aluminum systems above, further information about the preload loss of another modern systems will be given at this point. CFRP (short for Carbon Fiber Reinforced Plastic) clamped parts are very interesting for modern future lightweight applications. In comparison to aluminum for example, the density is about 33% lower (Al: 2700 kg/m³ - CFRP: ≈ 1500 - 1800 kg/m³), which enables to design even lighter components. Basically, CFRP are providing complete different material attributes compared to steel or aluminum based materials, so these attributes have to be investigated carefully. Generally, the common aspect from all CFRP-types is the combination of carbon fibers, which are embedded in a synthetic plastic matrix. Due to the impact of heat and pressure, these two components are getting merged together to a very light and stiff material. The plastic matrix can and should be designed for the desired use case. Today´s prices for CFRP are still comparatively high, but they will become cheaper in future because of new and enhanced ways of manufacturing. Like every material, there are as well cheaper and more expensive types of CFRP. The version "EP (Epoxy Resin - Matrix)" is an example for a low cost CFRP. On the other hand, an example for an expensive type of CFRP, is the CFRP "PEEK (Polyether Ketone, a thermoplastic material)", which can be rather used by higher thermal loads (look at the following diagram). A notable attribute of every CFRP is the anisotropic character of their material constants. The Young's modulus for example is around 140 GPa parallel to the carbon fibers, but rectangular to them only at around 12 GPa. The different types of CFRP, to be more precise their matrices, are providing an influence on the estimated loss of preload, too. Especially, if an increased thermal load is acting. The following Figure 6 shows the different behavior of bolted joints, which are clamped with several materials, considered for a period of t = 1,000 hours. Information about clamping aluminum types were given above, Figure 6 claims additionally further information about using aluminum and magnesium clamping parts. The interesting statement here are the curves for the two different CFRP types "PEEK" and "EP". In that, three single curves from three individual experiments are bundled to one common line (arithmetic mean), which are plotted versus time (here we need to consider, that the X-Axis is not subdivided in a linear time-scale like all other diagrams). The colored and numbered boxes were added additionally. The illustrated Al-curves do not belong to the ones shown above.

Figure 6. *Impact of Different CFRP-Materials in a Bolted Joint (acc. to Hubbertz (2020)) (The Colored and Numbered Boxes Were Added Additionally)*
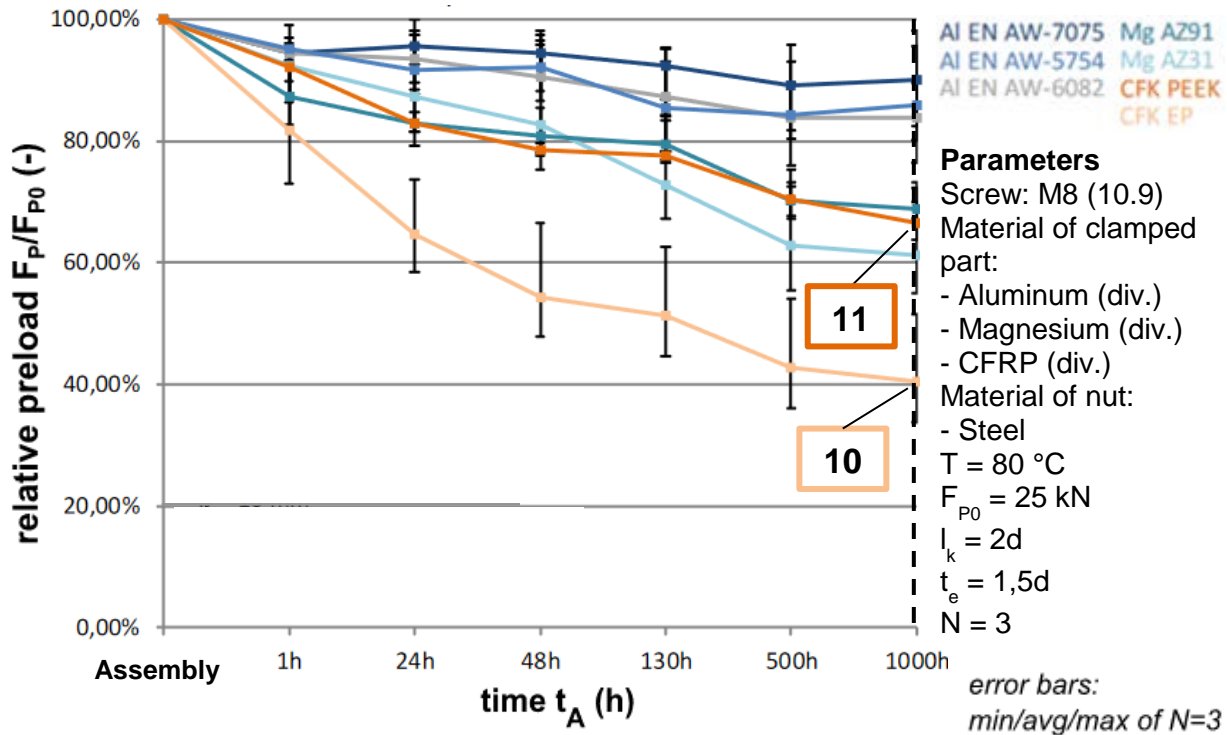

A thermal load (T = 80°C) was additionally acting. Figure 6 illustrates, that the individual kind of CFRP is having a unique behavior of losing preload while facing a thermal load. While the PEEK-Matrix-CFRP loses a smaller amount of preload during the time of exposure, the CFRP with EP-Matrix loses a higher percentage value already directly after assembly. The reason is the matrix itself, in which the carbon fibers are embedded. For increased temperatures, the EP is getting softer, the material is getting more and more rubber-like. However, this can be described by the "glass transition temperature" (Hubbertz 2020). In contrast, the PEEK-Matrix stays harder, so the PEEK-CFRP is rather useful by higher temperature levels instead of the EP-CFRP. Summarized, using PEEK-Matrix-CFRP the preload of the screw rather sustains, and with it the function of the connection.

Impact of Thread Inserts

The function of every screw joint is achieved by a thread engagement between screw and nut. The thread can be part of a nut as well as a part of the clamping components (TTJ or TBJ, mentioned above). The lightweight design approach in modern mechanical engineering requires the development of components, which are not only light weighted, but also efficient. It has to be ensured that the weight reduction of a part (e.g., due to lowering of wall thickness) does not affect the

function of the component. This explains the growing commitment of (heat-treated) aluminum alloys in many sectors. On one hand, the material constants of aluminum (e.g., the tensile strength) are clearly lower as values corresponding to steel, on other hand, the occurring loads are increasing more and more, so screws with even higher strength classes are chosen for the design process. Because of the (often reduced) values of the wall thickness and the substitution from steel to aluminum, the thread engagement of the screw system is not as sustainable as in the classical cases. Problems can occur regarding the necessary length of thread engagement, which leads to general problems for the functioning connection. Only deep enough assembled screws are enabled to guarantee the function. To correct this, thread inserts can be used: the screw is assembled in this insert, the insert again gets assembled in the clamping part. This is called a "multiple thread engagement" (MTE), a benefit for modern lightweight constructions is given (Hörnig 2016). Furthermore, these multiple thread engagements are having a positive impact on the loss of preload for general screw joint systems over time as well. It can be shown, that this loss over an estimated time of t = 1,000 h in combination with an additional temperature load of T = 100 °C is significant lower during the use of MTE instead of STE, especially, when the length of thread engagement is increased from 1•d to 2•d. Figure 7 shows this.

Figure 7. *Difference Between Single Resp. Multiple Thread Engagement (acc. to [2]) (The Colored and Numbered Boxes Were Added Additionally)*
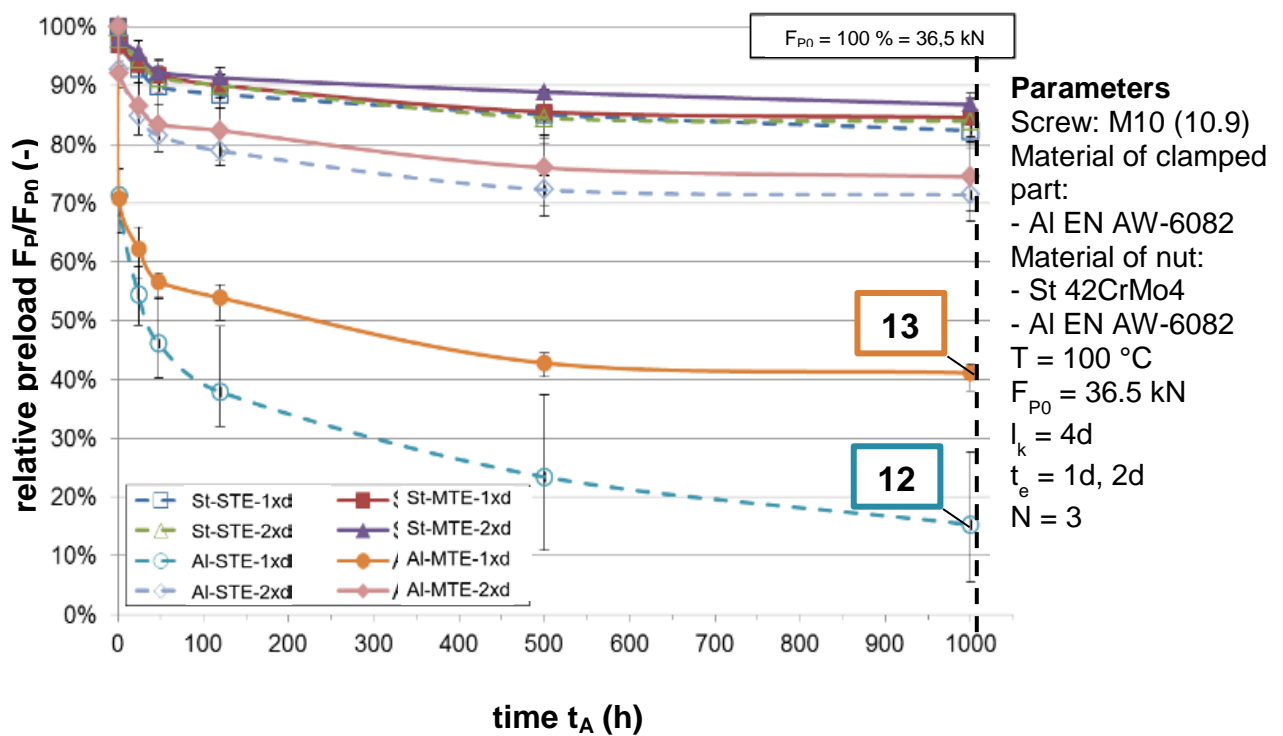
In Figure 7, the relative preload is plotted versus time. Curves for two thread types are shown: first, the screw is assembled directly into the clamping part

(STE), second, the screw is combined with a thread insert made of steel (MTE), which again is assembled in the clamping part. Besides, the length of thread engagement (clamping part material) is varied between 1•d and 2•d (St 42CrMo4 and Al EN AW-6082), so that 8 graphs are demonstrated overall. Now, this figure mainly points out the following aspects:

1. By comparing to STE, the use of MTE leads to a lower loss of preload during the time of t = 1,000 h. This is the case as well for inserts combined with aluminum and steel based materials. All curves for MGE are exceeding the corresponding curves for STE.
2. The length of thread engagement of the screws in the inserts is having a big influence on the estimated preload loss as well: The deeper the screws are assembled, the lower the influence on the following measured preload loss. The reason is that the acting preload can distribute on a larger area, the specific mechanical stress is lower.
3. In comparison to steel systems, aluminum screw systems are far more vulnerable for preload losses. The usage of MTE can partly mitigate the preload loss.

The points 2. and 3. were already shown in the upper chapters. Summarized, the use of thread inserts in combination with a higher length of thread engagement is a good possibility to reduce the estimated losses of preload, even when longer time periods are favored or an additional thermal load is acting. This is an important point for modern lightweight design (LWD) shown by the impacts above.

Conclusion

Finally, the illustrated and described systems and their unique values of preload loss will be compared in a percentage way with the help of a bar graph, look at Figure 8. Additionally, a calculation of the estimated loss for a classical Steel system at room temperature (seating losses F_Z) according to VDI 2230 was conducted (black bar, left). Directly aside, the result of the measured preload loss for the identical system is stated (grey bar).

Figure 8. *Comparison of the Illustrated Mechanisms*
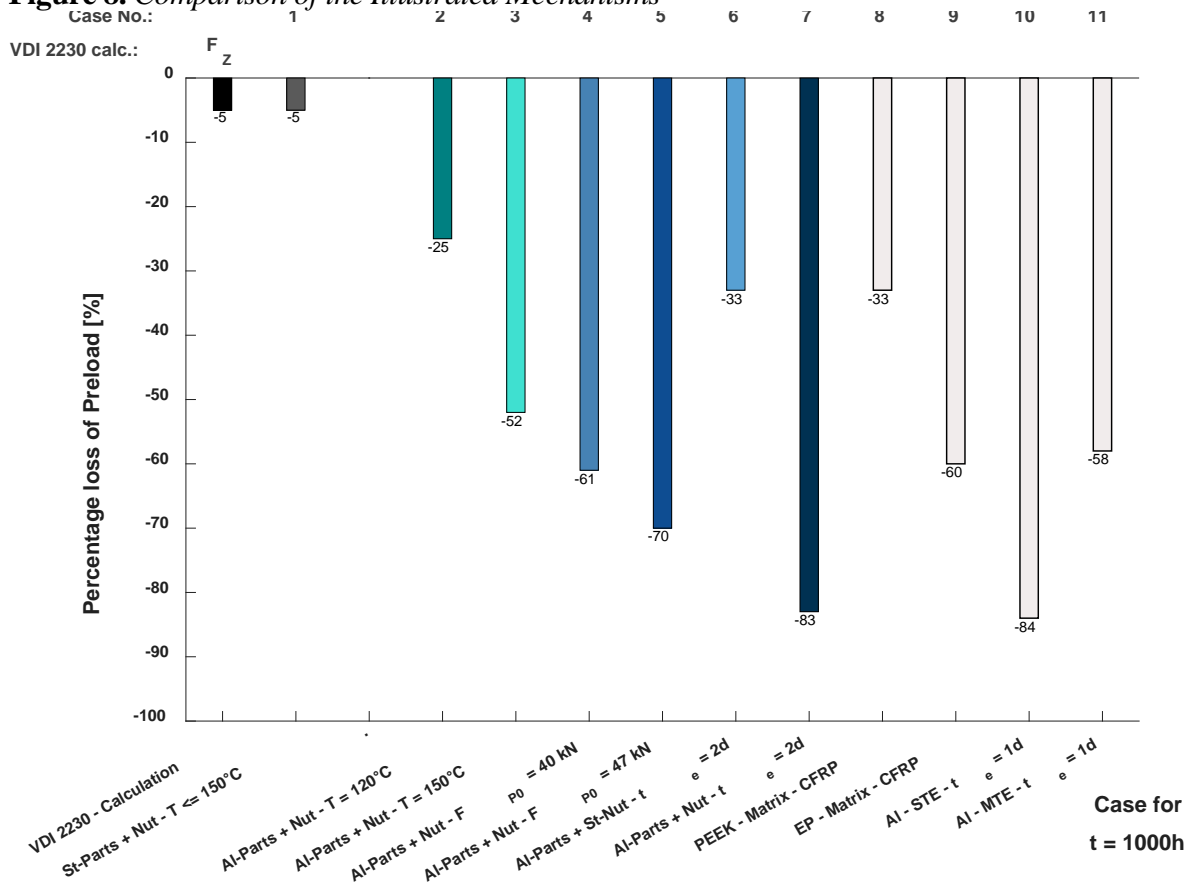
Due to Figure 8, several aspects can be identified: It can be seen, that the temperature influence is determining the preload loss, especially in combination with aluminum parts (or LWD materials). In contrast, components made of steel are not as problematic for those aspects. The homologous temperature for steel materials in relation to creeping processes (724 K ≙ 450 °C) is not being reached. In this case, the calculation for the estimated loss of preload according to VDI 2230-1 (2015) caused by seating (F_Z) is equal to the measured value. Eminently high losses could be expected while clamping aluminum parts with STE and low length of thread engagement, EP-Matrix-CFRP or aluminum parts with an aluminum nut with an increased assembly preload, all in combination with a thermal load. However, a comparing statement is possible though.

Generally, bolted joints need a stable level of preload during the entire life cycle. There are three meaningful mechanisms, which are leading to a decrease of preload (seating, load plastification, creeping processes). In fact, there are numerous literatures of rules and standards, which engineers can try to use for the design of a bolted joint, but these are mainly focusing on the assembly process. Equations for the preload loss due to seating processes are provided, further terms for the estimation of losses due to load plastification or creeping are missing though. So the sum of the preload loss is excelling VDI 2230-1 (2015) clearly. An important

point is that today's material combinations apart from steel do not play an adequate role in guidelines. An adaption is consequently necessary.

In this paper, with the help of different screw systems it was analyzed, that the longtime loss of preload could be meaningful higher, as the established guidelines are supposing. This is especially the case for an aluminum system. The belonging systems and the individual influencing factors were shown and compared, always for a longtime measurement of t = 1,000 h. Another focus of this paper were configurations using modern CFRP clamping parts. It was illustrated, that the preload loss of those systems is different for each type of CFRP. Useful methods against a strongly loss of preload are named, e.g., the use of multiple instead of single thread engagement or increasing the length of thread engagement.

Summarized, the following statements can be conducted to findings in this paper:

1) The real preload loss of preload is significantly higher than the established guidelines are predicting. These are mainly focusing on seating processes in combination with steel systems. They need to be revised and should be extended. Equations for the loss mechanisms load plastification and creeping need to be developed. While doing so, further and modern materials like aluminum, magnesium or CFRP have to be considered.

2) The main influence for preload loss is thermal load, especially if lightweight materials with temperature-sensitivity and low strength compared to steel are used. Also to consider is the additional preload loss when cooling down after exposure (see Figure 4).

3) Another important influence is the length of the thread engagement. The higher its number, the lower the preload loss. For aluminum in combination with a thermal load, the preload losses are increasing from $t_e = 3 \cdot d$ to $2 \cdot d$ from 52% to 83%. In contrast, the identical steel system losses just 33% of its initial preload ($t_e = 2 \cdot d$). Multiple-thread-engagements are an interesting method for design of applications with reduced preload loss.

Finally, as an outlook to the ongoing work an extension of guidelines has to be mentioned (important for reliable and fast product development). This has also to include investigations on typical roughness situations.

References

Guggolz D (2019) *Auslegungsprozess zur Absicherung des selbsttätigen Losdrehverhaltens von Schraubenverbindungen in realen Bauteilsystemen.* (Design process for validating the self-loosening behavior of bolted joints in real component systems). Aachen: Shaker Publishing Company.

Hörnig T (2016) *Beitrag zur Tragfähigkeit des Gewindeeingriffs bei Schraubenverbindungen im Leichtbau.* (Contribution to the load-bearing capacity of the thread engagement in lightweight bolted joints). Aachen: Shaker Publishing Company.

Hubbertz H (2020) Beitrag zur Auslegungsrechnung von Leichtbauschraubenverbindungen im Hinblick auf die Vorspannkraftrelaxation. (Contribution to design calculation of

lightweight bolted joints with regard to preload relaxation). Siegen: Universi Publishing Company.

Hubbertz H, Friedrich C (2013) Relaxation of clamp force in fastened carbon composite structures with thermal load. In *International Conference on Composites Engineering ICCE-21*. Santa Cruz de Tenerife, 21.07.2013. - 27.03.2013.

Jenne M, Hubbertz H, Friedrich C, Bär C (2015) Improved mechanical preload measurement of bolted joints for lightweight design with CFRP components. In *ASME International Mechanical Engineering Congress and Exposition*. Houston, 13.11.2015 - 19.11.2015.

Peth J (2021) *Einflüsse auf das Vorspannkraftrelaxationsverhalten von Schraubenverbindungen im Leichtbau*. (Influences on preload relaxation behaviour of bolted joint connections in lightweight constructions). PhD Thesis in Progress at MVP. Siegen.

Peth J, Friedrich C (2018) Design Influences of preload relaxation behavior in bolted joints using aluminium parts. In *Recent Developments Conference Integrity - Reliability - Failure*. Lisbon, 22.07.2018 - 26.07.2018.

VDI 2230-1 (2015) *Systematic calculation of highly stressed bolted joints - Joints with one cylindrical bolt*. Berlin: Beuth.