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DESIGN INFLUENCES OF PRELOAD RELAXATION BEHAVIOUR IN BOLTED JOINTS USING ALUMINIUM PARTS

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ABSTRACT

This work shows the preload relaxation behaviour of a bolted joint between a steel screw and an aluminium clamped part and nut thread part. First, the paper shows limits for the bolted joint by varying the preload force and temperature for a fixed geometry. As expected, an increasing loss of preload can be seen at elevated temperatures.

The second step shows the influences of changing geometry details like clamping length and length of thread engagement for selected combinations of preload and temperature to demonstrate the impact of lightweight design. The gathered information is used to determine the remaining preload after 1000 hours of temperature load and estimate the process of preload relaxation to prevent a failure of the connection.

Keywords: preload relaxation, bolted joints, aluminium, lightweight design.

INTRODUCTION

Bolted joints are used in all industry sectors. The functionality of a bolted joint primary depends on the preload force. Preload relaxation is a most likely reason for failure of bolted joints, especially for components with lightweight materials and temperature loading, which are in focus in this paper. More detailed, a loss in preload can cause a joint opening (e.g. leakage of flange connections), self-loosening of the screw (micro-slipping in contacts) or even lead to breaking in fatigue. Preload relaxation depends on superposed damage mechanisms such as seating (roughness embedment during and within first hours of tightening), load plastification (in this case caused by thermal loading) and creeping (long-time permanent deformation caused by mechanical stress) as shown in Figure 1 (Friedrich, 2013)

When a bolted joint is tightened, surfaces with different roughness get into contact. Due to the axial preload from tightening, an embedment takes place, which leads to a loss of preload as a result of embedding during operation F_Z. This behaviour is well known and usually takes place in the first hours of tightening. Guidelines like the VDI 2230 (VDI 2230, 2015) have rough estimations for this value, which are gathered from experiments with steel. It remains open in the reference, if these experiment-based values from steel can be used for other materials such as aluminium.

The load plastification takes into account that the connection will undergo additional loads in its lifespan. This mechanical or thermal loads cause plastic deformations in the contact areas, where high stresses occur. The highest stresses can be found in the contact of the screw head and clamped part, the clamped part and nut (if a through-bolt joint is used), in the free loaded thread or shank of the screw and in the nut thread. Thermal loads have a huge influence on the preload relaxation as the material properties such as material strength might change. Besides that, different expansion coefficients and thermal conductivity might lead to higher preloads. In this paper a bolted joint with steel screw ($\alpha_{St} = 11{,}8 \cdot 10^{-6}\ K^{-1}$) and clamped part made of aluminium ($\alpha_{Al} = 23{,}1 \cdot 10^{-6}\ K^{-1}$) is used. When exposed to temperature, the aluminium part will expand about twice as much as the steel screw and therefore generate an additional preload in the connection. With the changing material properties due to temperature exposure (mostly of the aluminium part in this example) and the additional mechanical load, the risk of plastic deformation is increased.

Creeping describes the tendency of a solid material to deform permanently under a specific mechanical stress and temperature. This plastic deformation of course also leads to a loss of preload ΔF_{Pcreep}. Usually the critical temperature for beginning creep effects for metals is around 40 % of its melting point (measured in Kelvin). The melting point of aluminium is 933 K and therefore the creep relevant temperature starts at 373 K or 100 °C.

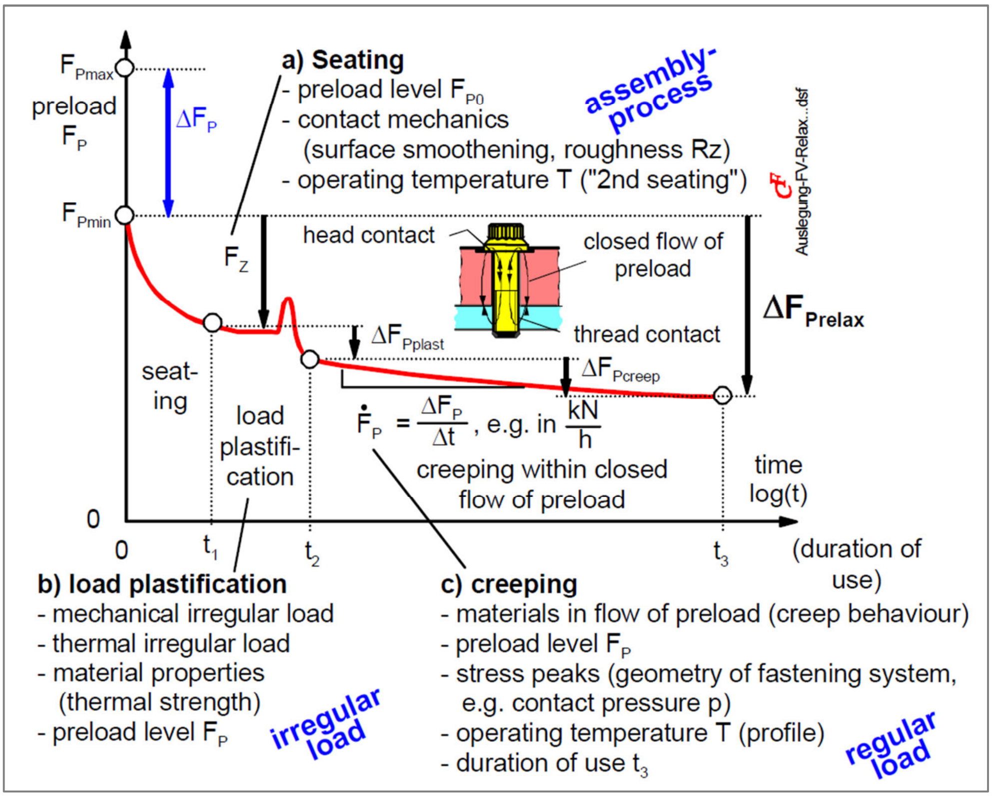

Fig. 1 - Preload Relaxation behavior (Friedrich, 2013)

DESIGN OF EXPERIMENTS

For the experiments a steel screw DIN 6921 M10x100 - 10.9 (material: 23MnB3) is used. It is full threaded, which means that there is no shank as also seen in Figure 2. For a better stress distribution, the screw has a flanged head. The clamped part is made of EN AW 6082 (T6) with an outer diameter of 22.5 mm. The clamping length l_c will be varied and is 50 mm by default and 20 mm to investigate the influence. The nut thread component has the same outer diameter as the clamped part. The length of thread engagement t_e is 30 mm, 20 mm or 15 mm, if the nut is made from aluminium (6082 T6), or 15 mm if the nut is made from steel (42CrMoS4), respectively. The preload relaxation behaviour, as described before, strongly depends on stress and temperature. Therefore the preload and loading temperature will be varied as well.

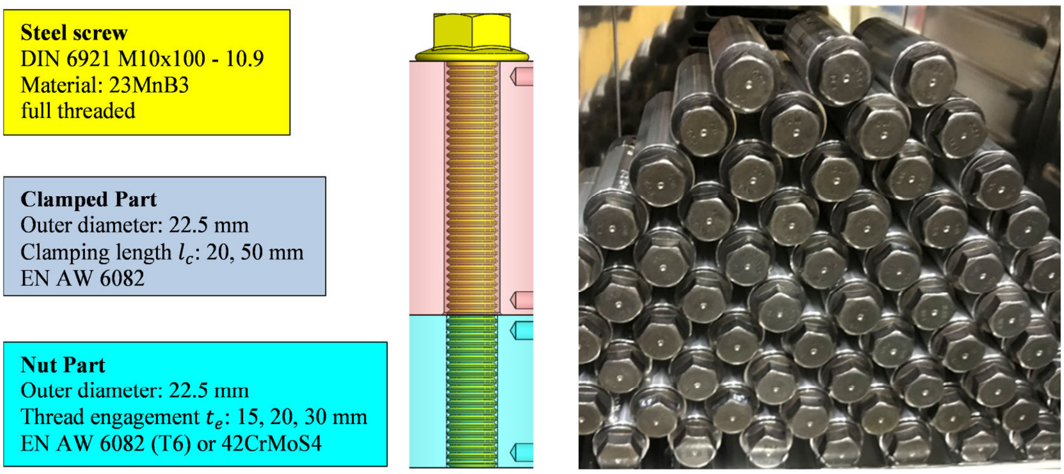

Fig. 2 - Overview of used specimen

Because a full factorial experiment plan will have an enormous number of specimen, the following experiment plan is used for this investigation.

First of all, the temperature influence is tested. Therefore, a standard connection of a steel screw and an aluminium clamped part (clamping length $l_c = 50\,mm$) and aluminium nut thread component (thread engagement $t_e = 30\,mm$) is tightened elastic. The temperature will be varied from T = 80 °C, 100 °C, 120 °C and 150 °C.

For temperatures below the critical point of 40 % of the melting point temperature of aluminium T_m (80 °C and 100 °C) the tightening force will be varied with the same geometric parameters as before. The aim is to tighten elastic (around $F_M = 30\,kN$), at 90 % of yield point (around $F_M = 40\,kN$ for this connection), directly at the yield point (around $F_M = 45\,kN$) and beyond-yield (ca. $F_M = 47\,kN$). The calibration for this is shown in the next chapter.

Also, for the temperatures 80 °C and 100 °C, the clamping length will be reduced from 50 mm to 20 mm at elastic tightening to see the impact.

The last variation parameter is the influence of the thread engagement t_e. Because of the changing material parameters, a critical point where the connection loses almost all its preload might be reached. With an aluminium nut the thread engagement t_e will be varied at 15 mm, 20 mm and 30 mm. Besides that, a steel nut ($t_e = 15\,mm$) will be used to show the difference of the material parameters regarding their preload relaxation behaviour.

Preload Relaxation Measurement in bolted joints

Measurement techniques to determine the current preload in a bolted joint are shown in (Hubbertz, 2014), (Jenne, 2016) and (Jenne, 2015). They can be divided into two groups. The first group has an influence on the stiffness of the bolted joint as either a force sensor is placed in the flow of force, which changes the stiffness of the clamped parts or a strain gauge

(German: DMS) is applied at the screw. Depending on the placement (bolt shank, inner hole, head of the screw) and the screw dimensions, the axial load deformation behaviour of the screw is influenced. The second group has no influence on the stiffness of the bolted joint and can be done by different length measurement methods such as ultra-sonic, the use of capacity sensors, a micrometer screw gauge or inductive displacement measurement sensors. Figure 3 shows the test setup with an inductive displacement sensor (HBM type K-WA-T-010W) used in this publication. As the expected length changes are just a few microns, coupling points with compressed grounds in the screw head and bottom are used to ensure that the length change measurement is done at the exact same spots of the screw. As seen in the figure, the sensor is held and can be moved up and down by an adjustment screw. In this way the sensor gets slowly into contact with the coupling point at the screw head, which ensures that only a very small force (circa 10 N) is applied and a deformation of the coupling point is avoided.

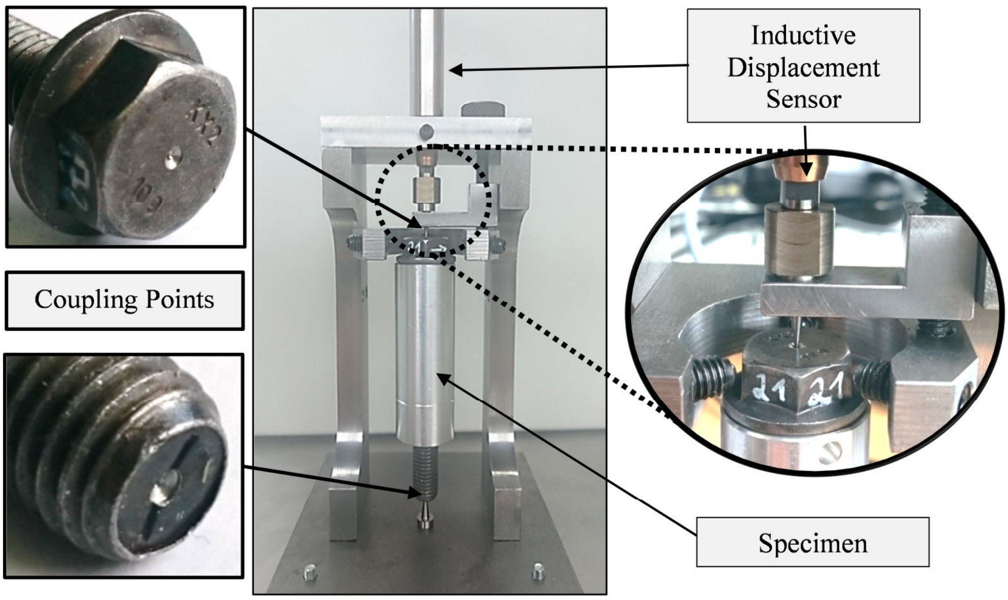

Fig. 3 - Length change measurement of bolted joints with inductive displacement sensors

All measurement techniques to determine the current preload in a bolted joint have in common, that they use the correlation of applied force and resulting length change (Duchardt, 2013).

For an elastic material behaviour Hooke’s law can be used to calculate the resilience of a screw δ_S as seen in Eq. 1.

$$f_S = \frac{l_S \cdot F}{E_S \cdot A_S} \leftrightarrow \delta_S = \frac{f_S}{F} = \frac{l_S}{E_S \cdot A_S} \leftrightarrow F = \frac{f_S}{\delta_S} \qquad \text{Eq. 1}$$

As seen in the equation, the resilience of a screw depends on the cross-sectional area and is therefore divided into parts with the same cross-sectional areas. Because screws can be handled as a series of springs, the total resilience of the screw δ_S is calculated as the sum of every single resilience (VDI 2230, 2015) as showed in Eq. 2.

$$\delta_S = \sum \delta_i = \delta_{SK} + \delta_{Gew} + \delta_G + \delta_M = \frac{l_{SK}}{E_S \cdot A_N} + \frac{l_{Gew}}{E_S \cdot A_{d_3}} + \frac{l_G}{E_S \cdot A_{d_3}} + \frac{l_M}{E_M \cdot A_N} \qquad \text{Eq. 2}$$

with

$$l_{SK} = 0{,}5 \cdot d \qquad \text{Eq. 3}$$

$$A_N = \frac{\pi}{4} \cdot d^2 \qquad \text{Eq. 6}$$

$$l_G = 0{,}5 \cdot d \qquad \text{Eq. 4}$$

$$A_{d_3} = \frac{\pi}{4} \cdot d_3^2 \qquad \text{Eq. 7}$$

$$l_M = 0{,}33 \cdot d \qquad \text{Eq. 5}$$

With the given parameters of Table 1 the elastic resilience of the screw δ_S can be calculated in dependency of the nut material and used clamp length (Table 2).

Table 1 - Parameters of the specimen

Symbol	Designation	Value	Unit
d	Bolt diameter (is outside diameter of thread (nominal diameter))	9.8277 [1)]	[mm]
d_3	Minor diameter of the bolt thread	8.0007 [1)]	[mm]
l_{Gew}	Length of the free loaded thread	20 or 50 [2)]	[mm]
E_S	Young's modulus of the bolt material (23MnB3, 1.5507)	205 000	[N/mm²]
E_M	Young's modulus of the nut • AlSi1MgMn (EN AW 6082 T6, 3.2315) • 42CrMoS4 (1.7227)	 72 000 206 000	 [N/mm²] [N/mm²]
Additional Parameters (not needed for resilience calculation)			
D	Outer Diameter of clamped part and nut	22.5	[mm]
l_c	Clamping Length (according to l_{Gew})	20, 50 [2)]	[mm]
t_e	Thread engagement	15, 20, 30 [2)]	[mm]

[1)] Average of 10 measurements with contour measurement station MarSurf XCR 20
[2)] Variation parameter for this study

Table 2 - Resilience of screw

	Material of Nut	
Length of clamped part	**AlSi1MgMn (3.2315)**	**42CrMoS4 (1.7227)**
$l_{Gew} = l_c = 20$ mm	δ_S = 3,32715E-06 [mm/N]	δ_S = 2,94089 E-06 [mm/N]
$l_{Gew} = l_c = 50$ mm	δ_S = 6,23801E-06 [mm/N]	δ_S =5,85175 E-06 [mm/N]

To estimate the force-displacement behaviour of the screw, the screw is tightened with a force sensor (type Haehne RKS01) which has the same clamp length l_c as the specimen used in this publication and a nut thread component made of aluminium (3.2315, EN AW 6082) or steel (1.7227, 42CrMoS4). The screw is tightened with a torque wrench and at specific preloads (every 5 kN starting from 10 kN) the elongation of the screw is measured. Figure 4 shows the experimental results and corresponding calculation of VDI 2330 (VDI 2230, 2015). The gradient of the curves represents the resilience of the screw δ_S. Depending on the material of the nut and thread engagement, plastic behaviour can be seen at 40 kN for an aluminium nut with 15 mm thread engagement and around 45 kN for bigger thread engagements or when using a steel nut (gradient of steel nut is changing at 45 kN, but increase dramatically at around 50 kN). Based on that data, preload levels will be defined at 30 kN, 40 kN and 47 kN to represent different tightening methods like elastic tightening, yield-point tightening and beyond-yield tightening.

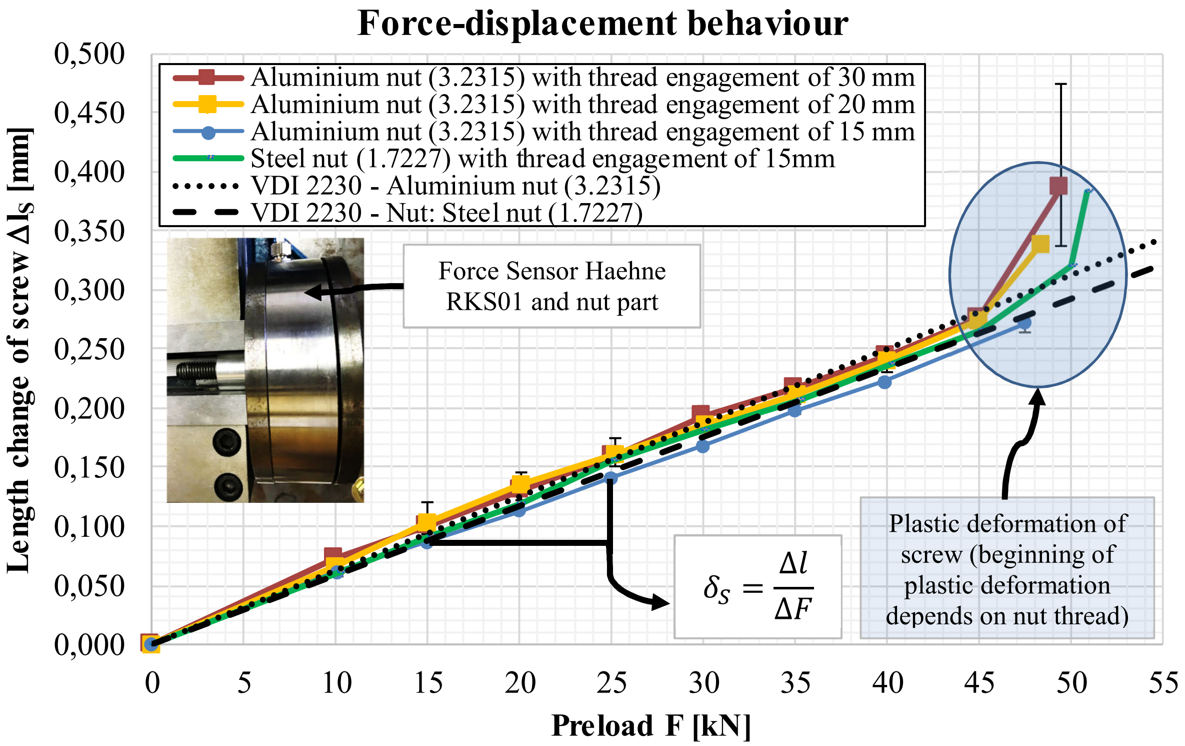

Fig. 4 - Measurement result of force-displacement behaviour

As seen in Figure 1 the preload relaxation of a bolted joint can be divided into three parts. Usually the biggest preload loss occurs in the first hours, primary during the part of seating and load plastification. Therefore, the procedure of testing the preload relaxation behaviour of a bolted joint is as follows:

1. Measure the initial length of the screw $\Delta l_{S,0}$ at room temperature
2. Tighten the specimen (screw, clamped part and nut part) with a torque wrench until the designated elongation for tightening of the screw has been reached $\Delta l_{S,M}$
3. Wait for 48 hours to ensure seating is completed and measure the elongation $\Delta l_{S,Seat}$ at room temperature
4. Apply thermal load (oven at target temperature T) for, e.g. 1 hour, cool down the specimen at 20 °C for 12 hours and measure the elongation after $t_{temp\,=}$ 1 hour ($\Delta l_{S,1}$). Repeat for total load times of $t_{temp\,=}$ 24, 48, 130, 500 and 1000 hours ($\Delta l_{S,2,\ldots,1000}$).
5. Loosen the connection to measure the elongation of the screw $\Delta l_{S,untied}$ when no force is applied anymore to see, if the screw shows some plastifications $\Delta l_{S,plast}$

The temperature load history for every specimen can be seen in Figure 5.

Experimental Results and Discussion

Temperature influence

If a joint with an outer diameter of 22.5 mm, a clamping length of 50 mm and a nut thread component of 30 mm (both parts made of aluminium) is exposed to different temperatures and the length change of the screw Δl_S is measured at discrete times, as described before, a time dependent process of length change can be determined as shown in Figure 6.

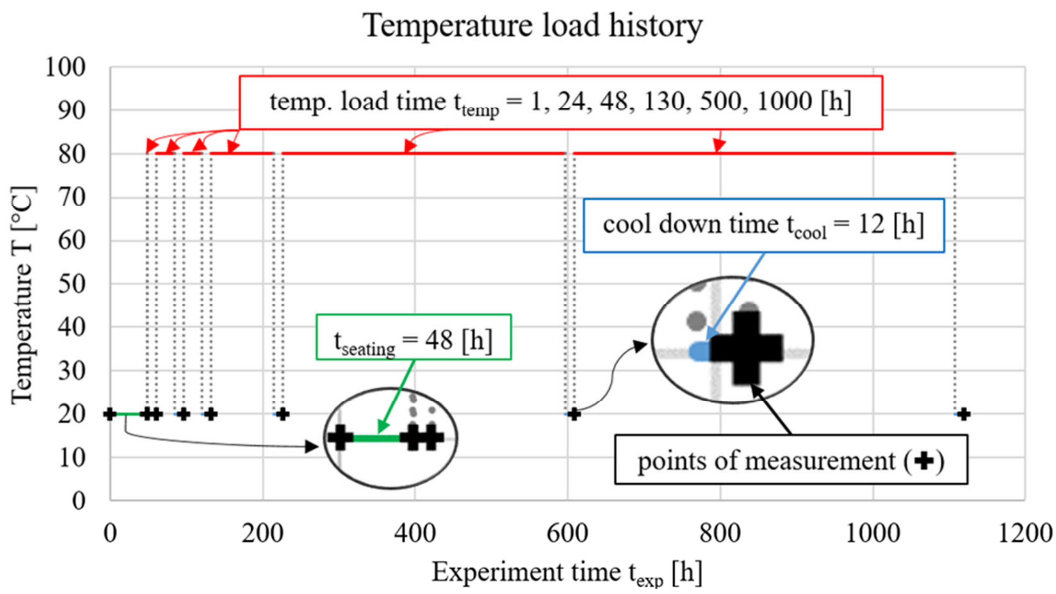

Fig. 5 - Temperature load characteristics and measurement points for experiments

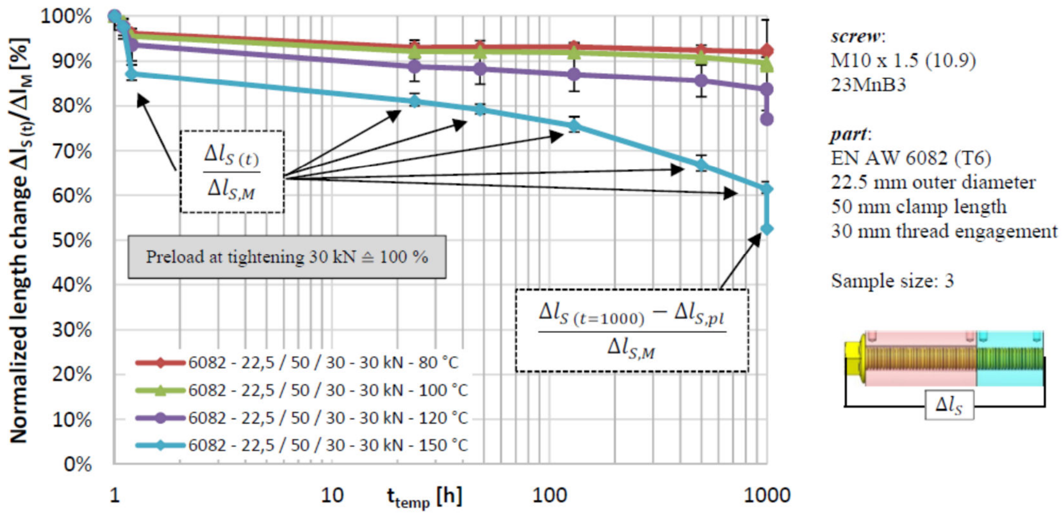

Fig. 6 - Length change of screw at different temperatures over time

All measuring points are based on the initial length change because of tightening $\Delta l_{S,M}$. After disassembling the connection, a plastic deformation of the screw $\Delta l_{S,pl}$ can be measured. With higher temperatures (T > 100 °C) the additional thermal load causes a plastic elongation of the screw. Considering elastic tightening for this connection (see Figure 4, load-deformation behaviour), this plastification causes a noticeable drop of the elastic elongation of the screw $\Delta l_{S,el}$, which generates the preload in the connection. As the information of the plastic deformation can be only accessed when untightening the connection, it is not known if it evolves during time or occurs directly after the first temperature load. Either way it is noticeable that in the first hours of temperature load a drop of length takes place. This process is of course positively correlated with the height of temperature load T. Temperatures of 80 °C and 100 °C seem to be very stable after the first 24 hours, while specimen at 120 °C and especially at 150 °C will continue decreasing.

Assuming, that the load-deformation characteristics of the screw do not change after a plastic deformation of the screw, the remaining preload after t_{temp} = 1000 hours of temperature load can be calculated with the remaining elastic elongation of the screw divided by the screw resilience δ_S (Eq. 8).

$$F_V = \frac{\Delta l_{S,el}}{\delta_S} \qquad \text{Eq. 8}$$

Figure 7 shows the remaining normalized preload (based on tightening preload F_M) after t_{temp} = 1000 hours of temperature load T. As already seen in the previous Figure 6, the biggest drops in preload can be seen with higher temperatures starting at 120 °C. It can be assumed that an increase of temperature load time t_{temp} will have a small effect on the specimen with T = 80 °C and 100 °C, but will result in even more preload loss for specimen exposed to T = 120 °C or 150 °C.

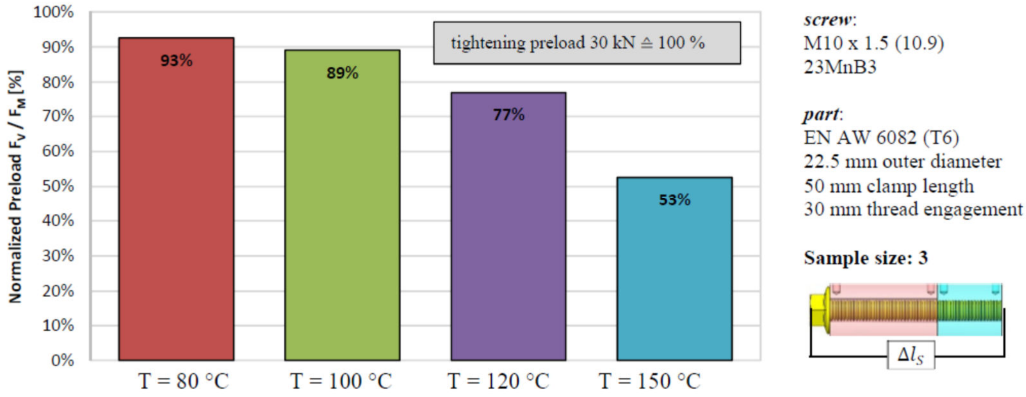

Fig. 7 - Normalized preload after t_{temp} = 1000 h at different temperatures T

The main reason of the preload loss is based on plastification of the screw, clamped part and nut thread part. While the plastic deformation of the screw $\Delta l_{S,pl}$ presumably is caused by the additional generated preload due to thermal load, the plastic deformation of the aluminium clamped part and nut can be seen as load plastification (see Figure 1) which is followed by creep mechanisms. The plastic compression of the clamped part $\Delta l_{CP,pl}$ is measured by a microscope (to find a fixpoint in a countersunk hole at the top and bottom of the clamped part) and a measuring table. Figure 8 shows that the plastic compression of the clamped part is increasing with higher temperatures.

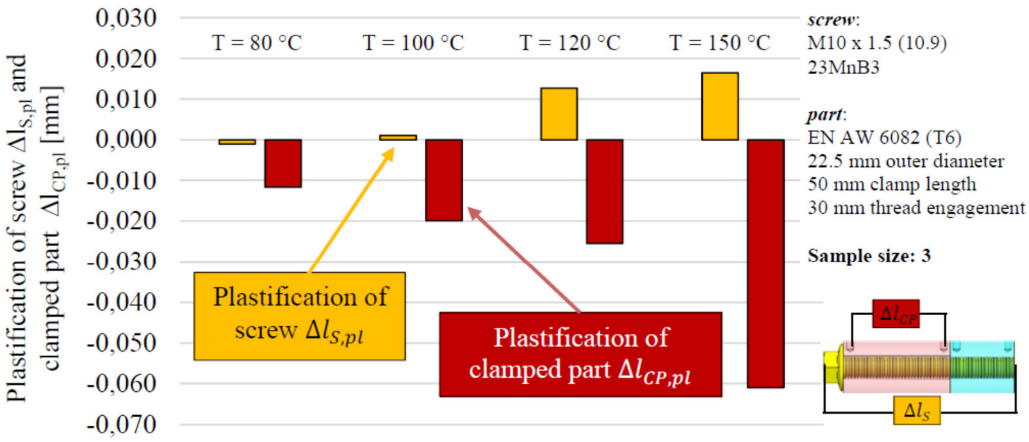

Fig. 8 - Plastification of screw and clamped part after t_{temp} = 1000 h at different temperatures T

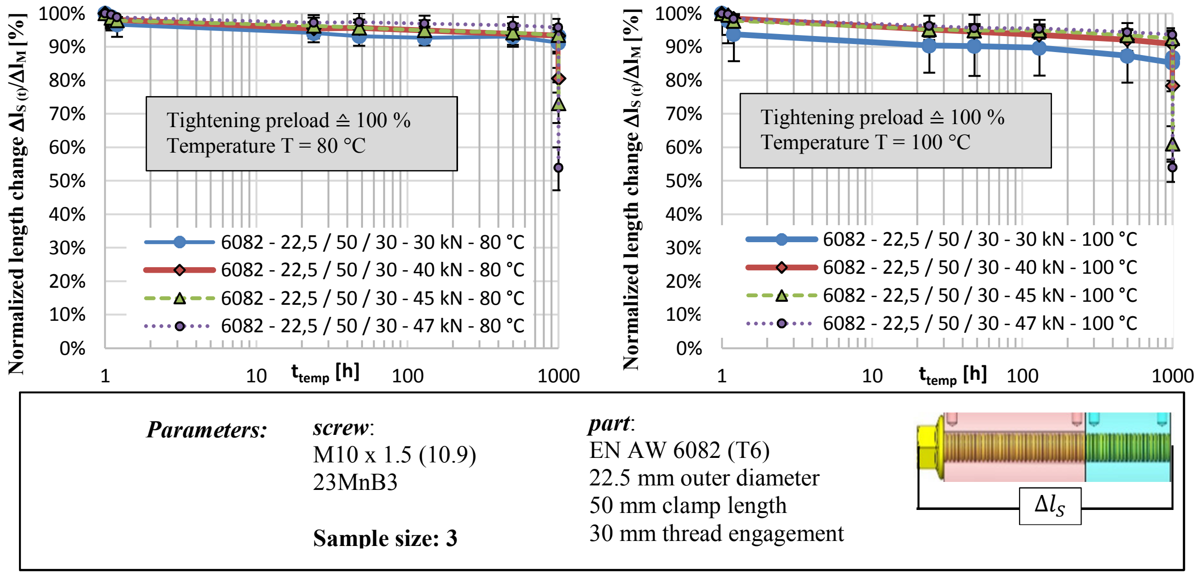

Fig. 9 - Length change of screw for different tightening preloads at T = 80 °C and 100 °C over time

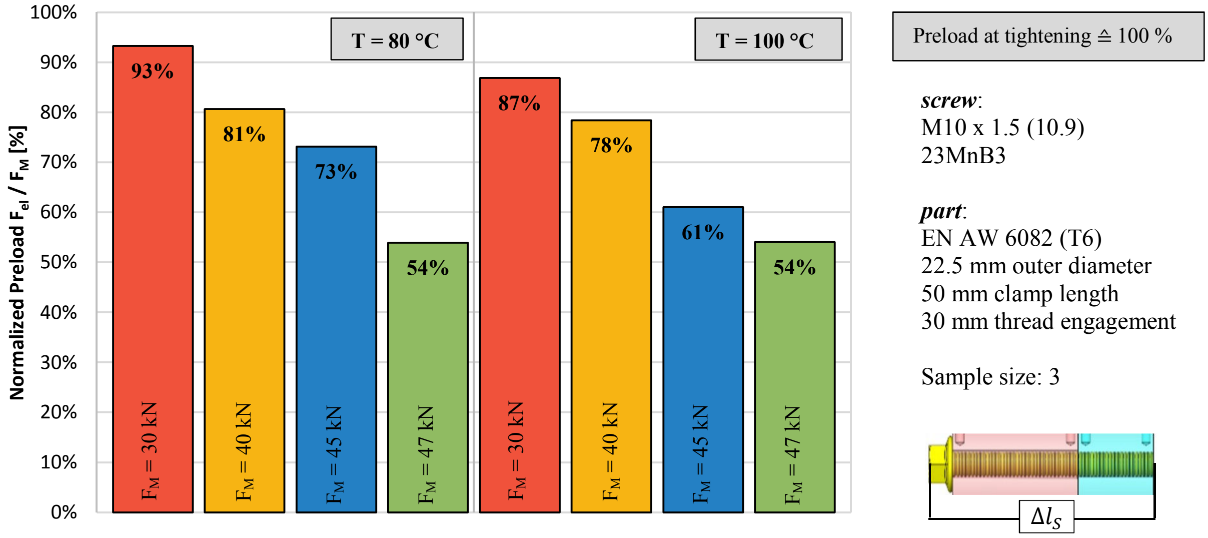

Fig. 10 - Normalized preload after t_{temp} = 1000 h at different tightening preloads F_M

Initial preload influence

As seen before at temperatures of T = 80 °C and 100 °C there's only neglectable plastic deformation of the screw visible, when tightened at F_M = 30 kN initial preload. With higher tightening preload F_M the screw gets also a plastic deformation, which directly leads to a loss in preload (Figures 9 and 10). Similar results with steel screws and parts at temperatures of 160 °C can be seen in (Granacher, 1995).

This compression is a main reason for preload loss in the connection. Test measurements were also performed in the same way on the nut thread component, but did not show any noticeable deformations. The reason might be that most deformation and stress is located directly at the thread. Further investigations are planned to identify the contribution of the nut thread deformation to the preload relaxation behaviour. As already discussed, the figure also shows the plastification of the screw $\Delta l_{S,pl}$ at higher temperatures.

Influence of clamping length

As seen in table 2, the resilience δ_S is strongly influenced by the length of the free loaded thread l_{Gew}, which is also the clamping length l_c in this example. Changing the clamping length from l_c = 50 mm to 20 mm results in a decrease of the resilience of the screw δ_S of around 50 %. Therefore, small length changes of the screw Δl_S will lead to higher preload losses. At moderate temperatures of T = 80 °C and 100 °C the specimen have quite the same level of remaining preload left (Figure 11).

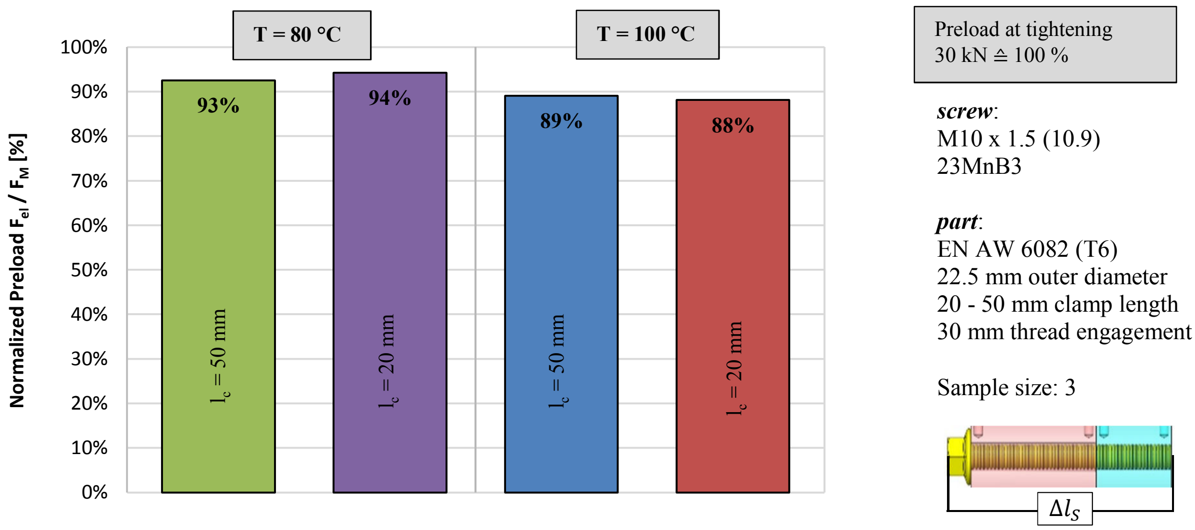

Fig. 11 - Normalized preload after t_{temp} = 1000 h with variation of clamping length at T = 80 °C and 100 °C

Further researches should also look at higher temperatures and tightening forces as smaller clamping lengths might cause less additional forces for the screw and therefore an plastification of the screw might be prevented.

Influence of the nut thread component

The requirement to minimize the thread engagement is one main target when it comes to cost and weight optimization of a bolted joint. If a steel nut is used, the tightening preload lead to high stresses in the first thread turns of a bolt. Using an aluminium nut generates a more homogeneous stress distribution, mainly because of the lower elastic modulus of aluminium (Hörnig, 2016). Therefore, with every thread engagement reduction, the stress of each thread will increase. If the connection is exposed to temperature, as discussed before, the additional caused preload and reduction of the elastic modulus lead to plastifications in the nut thread part. For temperatures of T = 80 °C and T = 100 °C, Figures 12 and 13 show the impact of a thread engagement t_e reduction from 30 mm to 20 mm and 15 mm when using am aluminium nut. To show the impact of the nut thread material, a steel nut (t_e = 15 mm) was used as well. As expected, the preload relaxation is minimal when using a steel nut (3% at 80 °C and 7 % at 100 °C). It is also noticeable that the difference between a thread engagement t_e of 30 mm and 20 mm is only around 2% for temperatures of 80 °C and 100 °C. If the thread engagement is reduced to 15 mm with an aluminium nut, the connection have a high preload relaxation rate after 130 hours of temperature with T = 80 °C and already after 48 hours when exposed to T = 100 °C. These connections already lose 22 % (T = 80 °C) and 36 % (T = 100 °C) of preload after 1000 hours of temperature exposure. From the preload relaxation curve seen in Figure 12 it can be assumed, that the preload relaxation loss will continue beyond 1000 hours.

Using higher tightening preloads and temperatures will lead to even higher preload losses, which will be the topic of further researches.

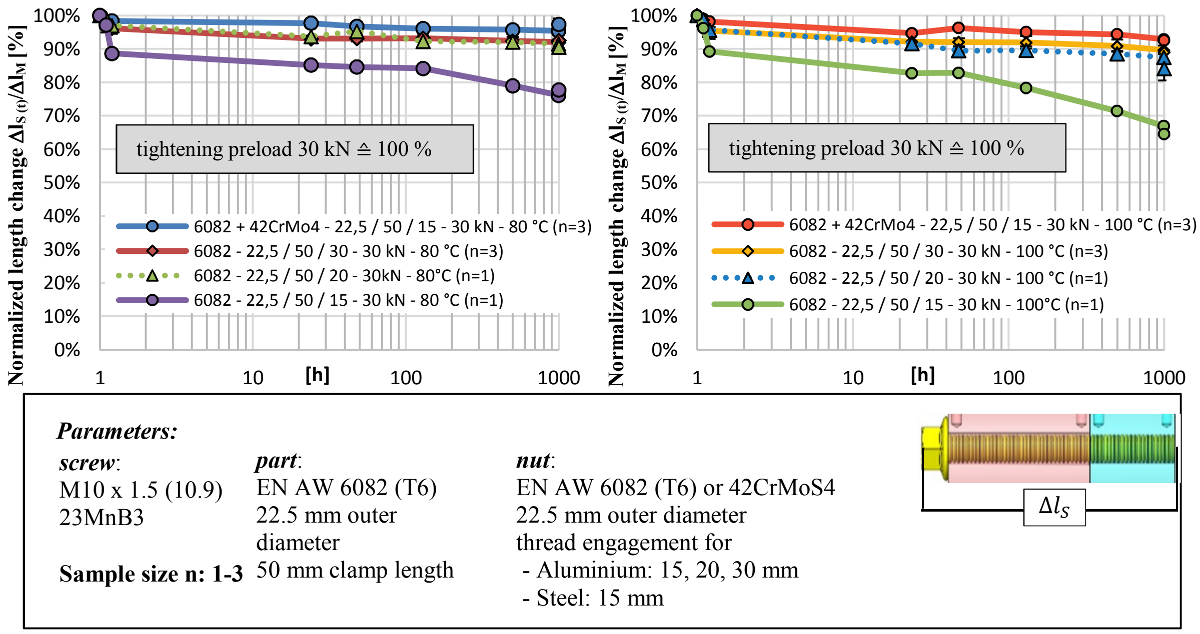

Fig. 12 - Length change of screw with variation of thread engagement t_e = 15, 20, 30 mm of aluminium part and t_e = 15 of steel part at T = 80 °C and 100 °C over time

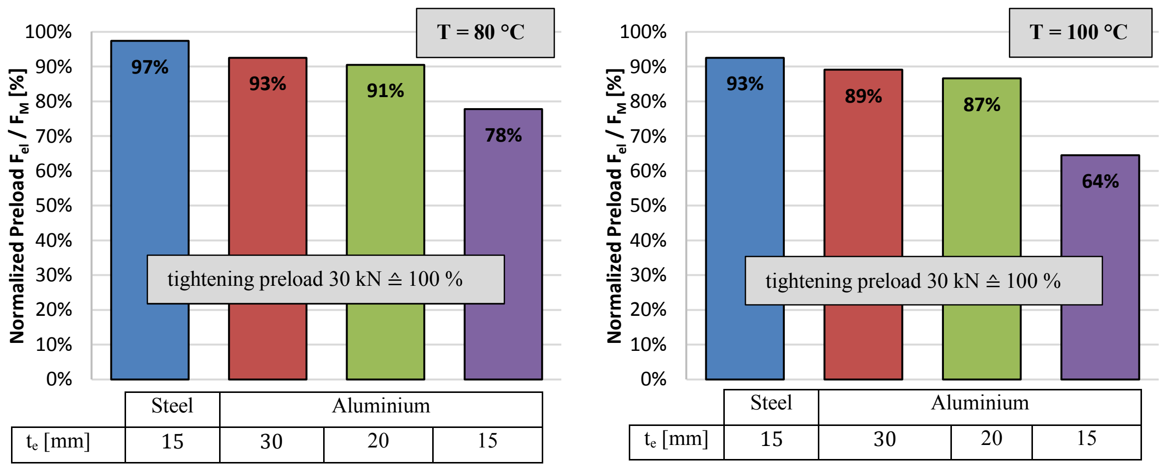

Fig. 13 - Normalized preload after t_{temp} = 1000 h with variation of thread engagement t_e = 15, 20, 30 mm of aluminium part and t_e = 15 of steel part at T = 80 °C and 100 °C

CONCLUSIONS AND FURTHER WORK

The experiments show that the temperature influence on bolted joints with a steel screw and an aluminium part can be seen in all temperature ranges from 80 °C to 150 °C. Specimen, which were tightened at 30 kN and exposed to temperatures of 80 °C or 100 °C showed a preload drop of around 10 %. It can be assumed that most of the preload loss is due to load plastifications of the aluminium part in the first hours of heating. When reaching higher temperatures not only the aluminium part but also the screw plastificates (higher thermal conductivity and expansion coefficient of aluminium lead to higher stresses in the steel screw). Therefore, the preload loss is over 20 % for T = 120 °C. Figure 6 shows that the creep process in the aluminium part will result in even higher preload losses over time (t_{temp} > 1000 hours). The same tendency can be seen for specimen that were exposed to 150 °C thermal load. They lose around 50 % of their preload and the creep process will lead to more preload relaxation after 1000 hours.

Over-elastic tightening (yield or beyond-yield) is widely used in mechanical engineering but might be critical when using materials with differing thermal characteristics (expansion coefficient, thermal conductivity), because it might cause additional loads to the screw which lead to further plastification and at the end to a significant preload loss. A change of the clamping length has no significant impact on the preload loss for the selected variation parameters (T = 80 °C, 100 °C and elastic tightening). This behaviour might change for higher temperatures or loads, as very small length changes will lead to higher preload loss due to smaller resilience of the screw δ_S. When a critical thread engagement of the aluminium nut is reached (in this research $t_e = 15$ mm), the stresses in the threads lead to significant preload relaxation losses, even at elevated temperatures of T = 80 °C and 100 °C. With thread engagements starting at $t_e = 20$ mm the main loss is caused by the first plastifications after the very first hours of temperature exposure and is quite stable afterwards. Using steel nuts minimize the preload loss as expected.

Overall, the investigation showed that the preload loss can be influenced strongly by the design of the bolted joint; very critical is high operating temperature and low length of thread engagement. Future work focuses on design rules for such connections to avoid very high preload loss as a main reason for failures.

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