Creep and Relaxation Behaviour of Self-tapping Al-bolts in Mg Die cast Alloys for Power train Components

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1 Introduction

Power train components such as gear boxes are currently manufactured predominantly from aluminum alloys. In order to reduce weight, high-pressure die cast Mg alloys are increasingly used in automotive components due to its superior strength to weight ratio. However, the application of the common used die cast Mg-Al based alloy AZ91 (Mg-9Al-1Zn) is limited because of poor creep properties at elevated temperatures exceeding 120°C. Other die cast alloys like rare earth containing AE group [1,2,3] indicate superior creep properties and may therefore be an alternative for components exposed to elevated temperatures.

When designing bolted joints with Mg alloys, material properties like high negative electrode potential and limited high temperature properties have to be taken into account. This leads to the following two major requirements [4,5]:

- Sufficient creep and relaxation resistance at elevated temperatures – minimum clamping load over entire product life time
- Sufficient corrosion resistance

The current state of technology for fastening Mg power train components is the use of metric steel or aluminium bolts. When using steel bolts, difficulties like high loss in clamping load and strong corrosive attack have to be faced. Aluminium bolts are a reasonable alternative to steel regarding relaxation and corrosion due to similar thermal expansion coefficients and standard electrode potentials in comparison to Mg.

1.2 Thread Forming Technology

Thread forming technology means that the bolt forms a thread in the nut material when tightened into a pre-cast core hole. A self tapping bolt is therefore a combination of tool and fastener. State of the art is the use of self tapping steel bolts in aluminium nut materials. Self tapping high-strength aluminium bolts in Mg alloys provide considerable potential for cost and weight reduction as drilling and thread cutting work steps can be eliminated in the mechanical manufacturing process. However, additional requirements must be challenged when using self tapping aluminium bolts in Mg power train components [6]:

- Definition of core hole tolerance for reliable casting processes in bulk production
- Assembly reliability (low forming torques with failsafe against pull-out and breaking)
- Sufficient assembly clamping loads over the entire core hole tolerance range
- Serviceability: Possibility to reuse formed Mg nut threads in service case either with thread forming or metric bolts.

This paper discusses the applicability of selected high-strength self tapping Al-bolts in Mg nut materials AZ91 and AE44 with focus on the creep and relaxation resistance of the Mg-alloys, of the used Al-bolts and of the whole bolted joint.

2 Relaxation

A fundamental parameter to guarantee functionality of the investigated component like leak tightness of gear boxes are sufficient clamping loads of the bolted joints at elevated operating temperatures over the entire product life time. The drop in clamping load at elevated temperatures due to creep mechanisms of the used nut and bolt material is called relaxation. For evaluation of applicability, the following essential parameters which influence the relaxation behaviour of the bolted joint are investigated:

- Type of used Mg-alloy as nut material
- Core hole size
- Heat treatment condition and final production step of the self tapping Al-bolt
- Superimposed service loads

2.1 Test set up

Reference parts of the two alloys AZ91 and AE44 were cast in a cold chamber die cast process (figure 1a). The investigated bolted joint consists of a Mg clamping plate, a steel load cell, an aluminium sleeve, a Mg boss and a bolt (figure 1b). The clamping load was measured permanently using a temperature compensated steel cell with a nominal load of 40 kN.

Figure 1: Reference part (a), bolted joint for relaxation tests (b)

2.2 Influence of Mg-alloy

To investigate the relaxation behaviour of the die cast alloys AZ91 and AE44 and to avoid any additional creep effects of the bolt, a steel bolt was used. It can be assumed that no creep and relaxation effects occur in the steel bolt at the testing temperature of 120 °C due to the high activation energy for creep of steel. Figure 2a and b show the progress in clamping load using a self tapping TT2000® M8 steel bolt, tightened elastically into Mg alloys AZ91 and AE44 for 100 hours.

The initial clamping load values after tightening at room temperature correlate with the material strength of the Mg-alloys (figure 2a). In literature, a ratio of the yield strength between AE44 und AZ91 of about 0,88 is found which accords with the ratio of the initial clamping load values of about 0,85. Due to the thermal expansion coefficient mismatch of the steel bolt and the clamping parts, a change in clamping load appears during heating up and cooling down.

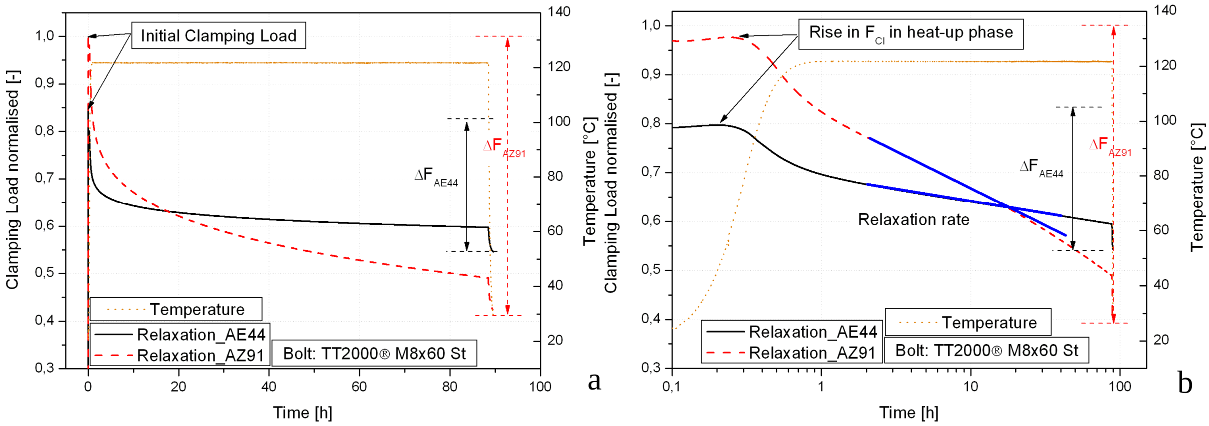

Figure 2: Progress of relaxation of AZ91 and AE44 at 120 °C using a steel bolt (a); in logarithmic scale (b)

The limited high temperature strength of AZ91 leads to increased creep and relaxation effects and causes higher relaxation rates, defined as the slope of the tangent after reaching constant temperature (figure 2b). The more creep resistant Mg alloy AE44 reveals higher final clamping loads after 100 hours and has therefore better relaxation resistance than AZ91.

2.3 Influence of core hole size

Variations in the die casting process as well as wear of the pins during the die cast process lead to variations of the core hole size. To investigate this influence on the relaxation behaviour, a tolerance range was defined together with casting experts. In a next step, reference parts with tightening spots at the upper (UCT…upper core hole tolerance) and lower core hole size limit (LCT…low core hole tolerance) were cast in a cold chamber die cast process.

A small core hole leads to a high thread engagement and to low stresses at the contact spots between bolt and nut material thread, whereas increasing core hole sizes cause higher stresses. Since creep and relaxation is a function of the applied stress, higher stresses lead to intensified relaxation effects and therefore to a higher clamping load loss.

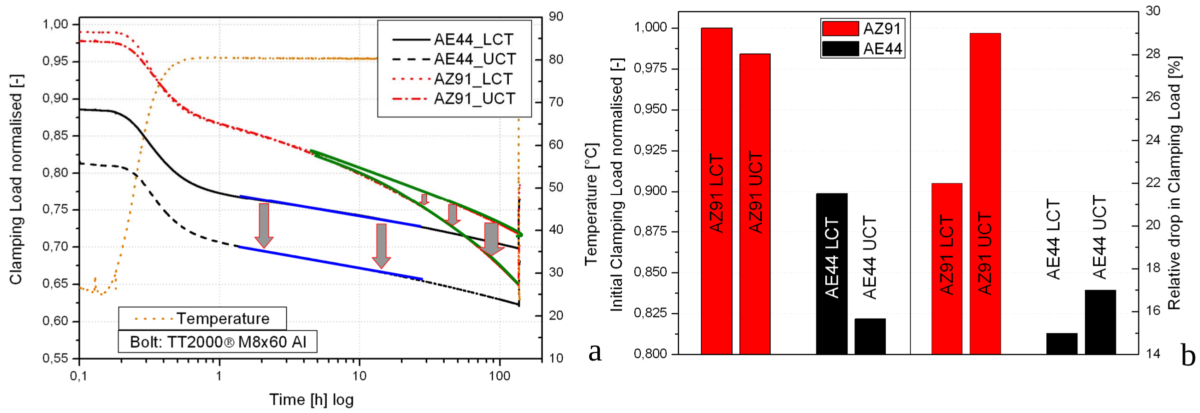

Figure 3: Progress of relaxation of AZ91 and AE44 at LCT (low core hole tolerance) and UCT (upper core hole tolerance) (a); Relative drop in clamping load in dependence of alloy and core hole size (b)

Figure 3a shows the influence of the core hole size on the relaxation behaviour of the two Mg-alloys AZ91 and AE44 using a self tapping EN AW 7075 Al-bolt with TT2000® geometry.

When doing a ranking of the two alloys regarding relaxation resistance in dependence of the core hole size, one has to consider the relaxation rates (drop in clamping load) in combination with the initial clamping loads after tightening. Sohn et al. [1] investigated the relaxation behaviour of metric joints and found that the drop in clamping load rises with increasing initial clamping loads after tightening. Thus, for quantifying the pure influence of the core hole size, the initial clamping loads should be the same as it is the case for AZ91. The relaxation rate of AZ91 rises significantly with increasing core hole size at similar clamping loads after tightening (figure 3a and b).

AE44 reveals only a slight rise in relaxation rate at the upper core hole size but significantly lower initial clamping loads due to intensified plastifications in the nut thread during tightening because of limited material strength of AE44. Thus, both effects are acting simultaneously and the pure influence of the core hole size on AE44's behaviour cannot be determined exactly. Nevertheless, the progress of the relaxations curves in figure 3a indicates that AE44 is less sensible to varying core hole sizes. Extrapolation of the relaxation test data to higher durations is a useful tool in order to estimate the long term relaxation behaviour and gives the possibility to compare the relaxation rates of the two Mg alloys at equal clamping loads.

2.3.1 Modelling of relaxation curves

Creep is the continuous deformation of a material at elevated temperatures when a constant load or stress is applied [7]. Relaxation is the reduction of stress at elevated temperatures when a constant deformation is applied [8]. Creep and relaxation are based on the same mechanisms. Therefore, a creep model by Norton [9] and Arrhenius (cf. equation 1), which is also valid for Mg alloys [10], based on the dependence of the creep rate $\dot{\varepsilon}$ from the applied stress σ and absolute temperature T is used to describe the continuous drop in clamping load at elevated temperatures. B is a constant, Q is the activation energy for creep, n is the stress exponent and R is the gas constant.

$$\dot{\varepsilon} = B \cdot \sigma^n e^{-\frac{Q}{RT}} \tag{1}$$

The law is put in a form where the time dependent drop of stress, which is equal to the clamping load, can be described by use of the Hooke's law (cf. equation 2).

$$\sigma(t) = \left[\sigma_0^{-n+1} - (1-n) \cdot E \cdot B \cdot e^{-\frac{Q}{RT}} t \right]^{\frac{1}{1-n}} \tag{2}$$

As the clamping load changes during the heat-up phase due to the thermal expansion coefficient mismatch between the Al-bolt and the clamped parts, data of the heat-up phase are not used for modelling. Modelling of the relaxation test data was started after one hour at a constant temperature level of 80 °C (cf. figure 4). The temperature was measured by means of a thermocouple type K on the surface of the bolted joint.

After reaching points of equal stress in AZ91 and AE44 at LCT and UCT, it can be seen that the relaxation rate of AZ91 at UCT remains significantly higher even at lower clamping loads than AE44. It can be stated that the creep resistant alloy AE44 reveals better relaxation performance than AZ91 independent from core hole size.

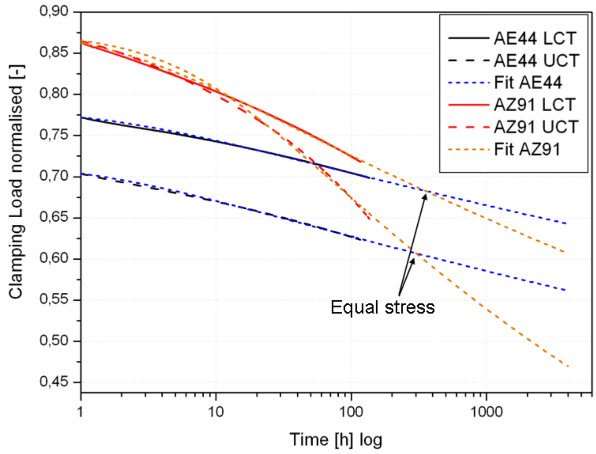

Figure 4: Extrapolation of relaxation data to of AZ91 and AE44 using a creep law based on Norton

2.4 Influence of heat treatment condition and production sequence of Al-bolt

To investigate the influence of the heat treatment condition and the production sequence of the aluminium bolt on the relaxation behaviour, relaxation tests with four different types of bolts were performed. Core holes at the lower tolerance limit of a creep resistant Mg alloy comparable to AE44 were used. EN AW 7075 bolts in the heat treatment condition T6 with highest strength as well as in the defined overaged condition T7x were tested. In both heat treatment conditions, production sequence of the bolts was varied applying either heat treatment (FHT…final heat treatment) or thread rolling (FTR…final thread rolling) as final production step.

Figure 5a shows normalised relaxation curves of the four investigated types of bolts at a temperature of 120 °C for 100 hours. As the time scale starts at 0,1 hours, the relaxation curve of T6-FTR starts at a value lower than one due to embedding processes during and after tightening. The heat treatment as well as the production sequence has a significant influence on the material strength of the bolts as can be seen in figure 5b.

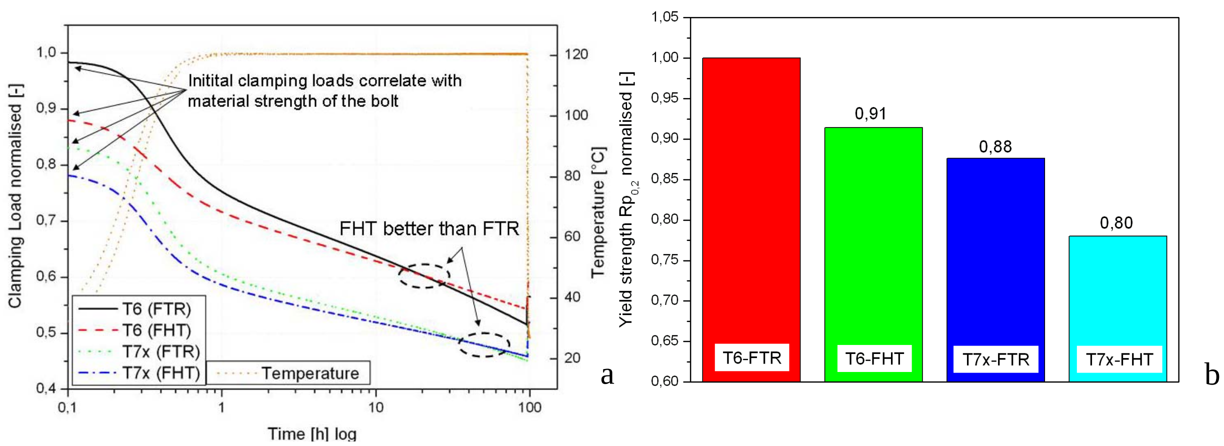

Figure 5: Influence of heat treatment condition and production sequence of the Al-bolt on relaxation (a); on mechanical properties (b)

The initial clamping loads after tightening correlate with the material strength which proofs that the material strength of the bolts is fully used when over-elastic tightening is applied. Bolts with final heat treatment reveal superior relaxation resistance, meaning lower relaxation rates, than bolts with final thread rolling independent from the heat treatment condition. Furthermore, bolts in T6 condition tend to relax more than bolts in T7x condition. However, the production sequence of the bolts has greater impact on the relaxation resistance than the investigated heat treatment conditions.

Microstructural investigations were made in order to explain the superior relaxation properties of the finally heat treated bolts. The bolt T6-FTR shows high deformation degrees in the thread ground due to the thread rolling process (stretched grains) and an average grain size of 1100 μm^2 in the thread flank (cf. figure 6a). On the contrary, the bolt T6-FHT reveals an average grain size of 1900 μm^2 as can be seen in figure 6b.

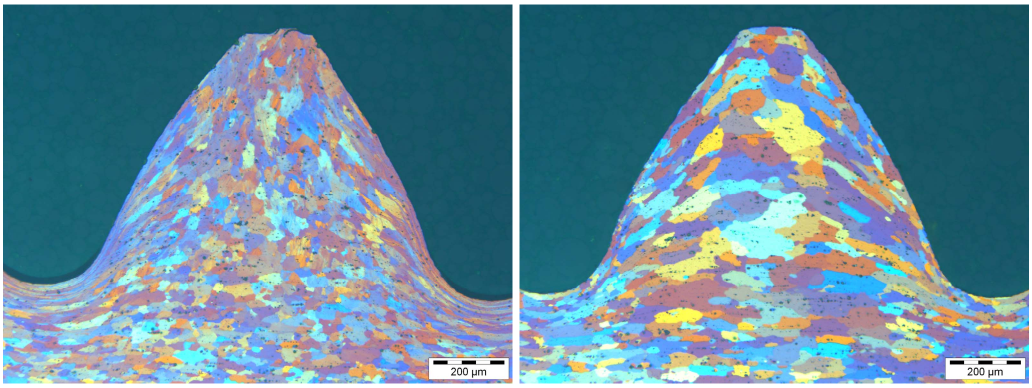

Figure 6: Thread flank of Al-bolt in T6 condition. Barker's electrolytic etch. T6-FTR (a) and T6-FHT (b)

The thread rolling process induces high deformation degrees which lead to enhanced recrystallisation and subsequent grain growth processes in the heat treatment step as these diffusion controlled mechanisms are a function of temperature and deformation [7]. Relaxation is based on creep mechanisms which can be divided in dislocation creep and diffusion creep occurring at lower stresses. Diffusion creep, named Coble and Nabarro-Herring creep, is strongly dependent on the grain size. The stationary creep rate decreases with rising grain size [11].

2.5 Influence of service load

A lot of components in automotive industry, such as gear boxes, are exposed to dynamic loads. Relaxation tests with superimposed dynamic pulsating loads were conducted in order to depict a realistic load case in service (cf. figure 7a). The dynamic load was applied under the bolt's head with a frequency of 12 Hz at a stress ratio of $R = 0,1$.

Figure 7b shows the relaxation behaviour of the Mg alloy AE44 with superimposed load in comparison to a static clamping load retention curve at room temperature. An abrupt drop in the clamping load can be seen when the mean load is applied. The part of the applied service load which is measured by the load cell due to the test arrangement is indicated in figure 7b. At the end of the test the clamping load rises abruptly due to the retraction of the pulsating service load.

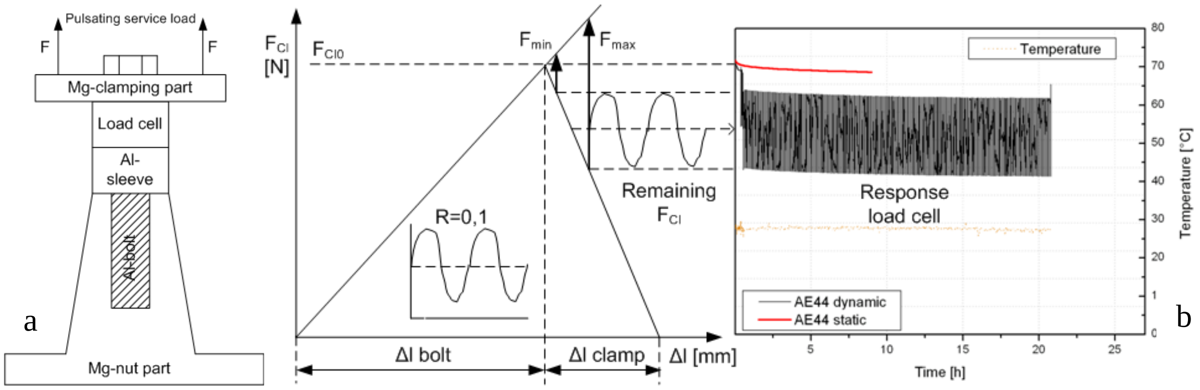

Figure 7: . Dynamic relaxation test arrangement (a), bolting diagram with marked service load (b)

Dynamic relaxation tests were performed at a temperature of 120 °C using the same type of EN AW 7075 M8 bolt with the two die cast Mg-alloys AZ91 and AE44 (cf. figure 8). Despite higher initial clamping loads of AZ91, AE44 reveals significantly higher residual clamping loads after 75 hours. The thermal expansion coefficient mismatch between Al-bolt and clamped parts causes changing clamping loads when cyclic temperature is applied. AZ91 reveals a massive drop in clamping load in the first hours indicating a severe deterioration of material strength caused by elevating temperatures (cf. figure 8b). During the heat-up phase, relaxation effects as well as the thermal expansion coefficient mismatch cause the drop in clamping load. After reaching constant temperature marked by a change in the relaxation rate, the ongoing drop in clamping load is caused only by relaxation.

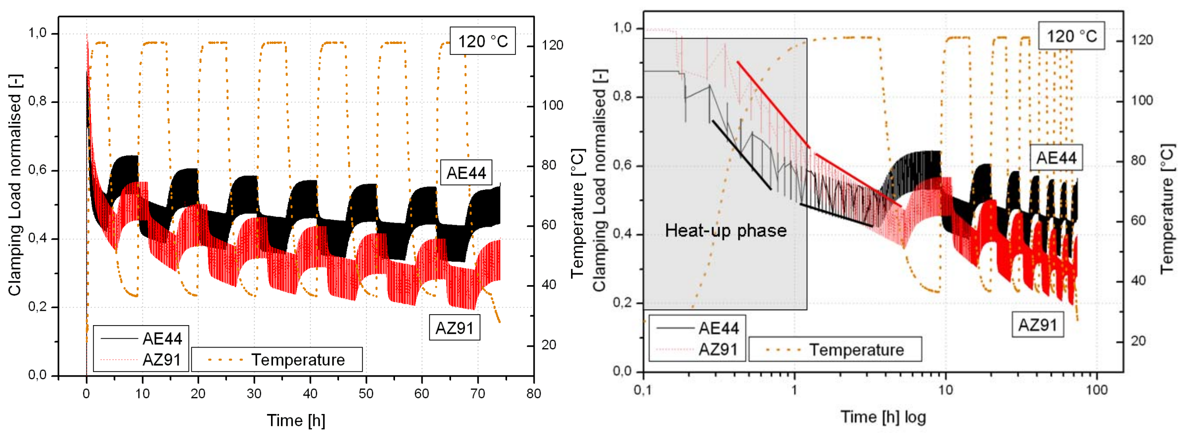

Figure 8: Relaxation with service load of AZ91 and AE44 with Al-bolt at 120 °C (a), logarithmic scale with marked relaxation rate (b)

AE44 exhibits significant higher relaxation resistance than AZ91 when pulsating service load is superimposed.

3 Prototype testing

Prototype gear boxes of the two alloys AZ91 and AE44 were cast in a cold chamber die cast process. All core holes were selected to be at the upper tolerance limit to investigate the critical case concerning relaxation. In order to avoid any modification of the bolted joints by inserting load cells or sleeves, which influence the rigidity as well as the thermal behaviour, ultrasonic measurement of the clamping loads was used. Complete gear boxes in AZ91 and AE44 were assembled. Over-elastic tightening was applied. Following load steps were applied representing the full life time load spectrum of a vehicle (cf. figure 9a), the clamping load was measured between the individual load steps:

- Cyclic thermal load from -20 °C to 120 °C (F_{Cl} thermal load)
- MTS Torque fatigue test at 120 °C (F_{Cl} fatigue test)
- Thermal exposure at 120 °C for 100 hours (F_{Cl} final)

The Taptite2000® EN AW 7075 M8 bolt in AZ91 and AE44 was compared to a metric EN AW 6056 M8 bolt in AE44 (cf. figure 9b). Currently, the metric bolt of alloy AW 6056 (AlMgSi) is already used effectively in engine and power train components of BMW and Daimler [12]. In [13], the thermal stability of the EN AW 7075 bolt is limited to 120 °C whereas the EN AW 6056 bolt reveals stable mechanical properties up to 150 °C. Clamping load retention tests of metric 6056 and metric 7075 bolts in AZ91 at a temperature of 110 °C showed that both types of bolts reveal the same level of clamping load after 100 hours despite higher initial clamping loads of the 7075 bolt indicating superior relaxation resistance of the 6056 bolt [13].

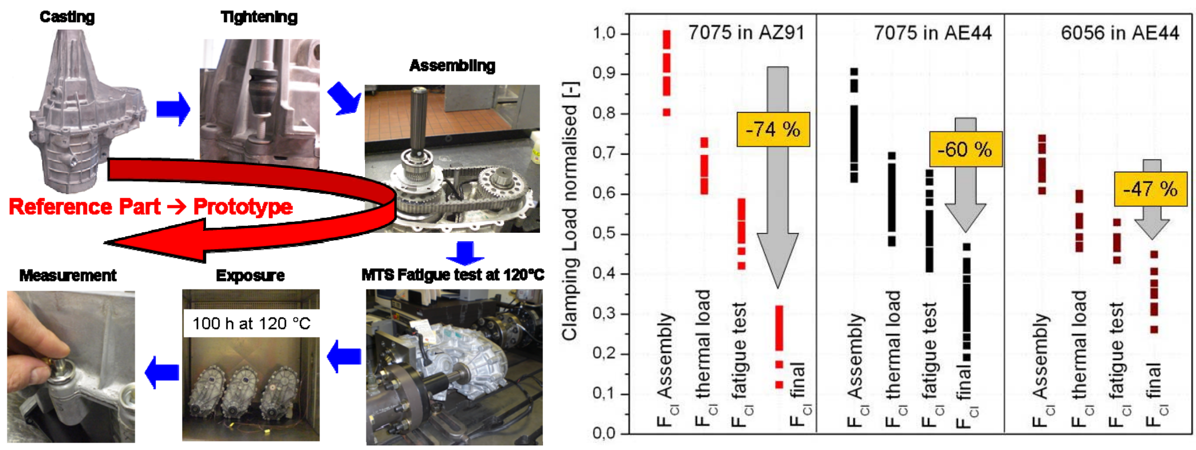

Figure 9: Prototype testing (a); Drop in clamping load after load steps for different bolts and Mg alloys (b)

The combination of self tapping 7075 bolt with AZ91 reveals the highest drop in clamping load of about 75 % (FCl_final). By replacing AZ91 with the creep resistant Mg-alloy AE44, lower initial clamping loads (FCl_Assembly) but higher residual clamping loads are achieved. The metric 6056 bolt with better thermal stability in comparison to 7075 shows the best relaxation resistance and highest final clamping loads.

4 Conclusion

When using steel bolts, the die cast alloy AZ91 reveals strong relaxation effects due to poor elevated temperature properties which lead to a high drop in clamping load at a temperature of 120 °C. The rare earth containing alloy AE44 shows a significantly higher relaxation resistance indicating superior high temperature stability.

However, when using aluminium bolts, relaxation effects of the bolt superimposing with the nut material have to be considered. The influence of the heat treatment condition and the production sequence of the investigated EN AW 7075 bolt with Taptite2000® geometry indicates better relaxation properties of finally heat treated bolts due to larger grains.
By means of prototype testing, the EN AW 6056 bolt in AE44 showed superior relaxation properties in comparison to the EN AW 7075 bolt in AE44. This indicates limited thermal stability of the 7075 bolt. As a deterioration of the mechanical properties is to expect when temperature is elevated to 150 °C, which can appear in service, the creep resistant Mg alloy AE44 should only be used in combination with the metric EN AW 6056 bolt when a temperature of 120 °C is exceeded.

5 References

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