Strength behaviour of aluminium bolts under static and cyclic loading

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Abstract

The increasing use of light metal alloys (e.g. magnesium and aluminum) in the automotive industry could lead into severe problems when components made of these alloys are fastened with conventional high strength steel bolts. These problems can be avoided, or at least reduced when aluminum bolts are used instead of steel bolts.

The knowledge about the endurance and the permissible load application of aluminum alloy bolts is low. This paper describes the results of investigations of the static and cyclic strength of high strength aluminum-alloy bolts as well in the as received condition and after aging at 120 °C and 150 °C for 1000 h to 4000 h.

Keywords: Light metals; Bolts; Aluminium; Magnesium; Fatigue strength

1. Introduction

The increasing use of light metal alloys in vehicle construction can result in complications when components made of these alloys are fastened with standard high strength steel bolts. For example, the classical concept of fastening magnesium parts with steel bolts provides new tasks. Magnesium components with bare surface have to be protected against contact corrosion when electrolytes are present.

In the case of gearbox the increasing engine performance and the growing power train encapsulation leads to higher operating temperatures and, caused by the different thermal expansion coefficients of steel and magnesium, to a significant rise of the bolt load. The increase of the temperature of the bolted system causes surface pressures in the contact areas, which can exceed the maximal sustainable value (limit surface pressure– start of compression yield). In addition the length of thread engagement has to be increased as well to fulfill the design principle that only bolt fracture in the length of the free loaded thread is permissible under tensile overload. This results in considerably oversized light metal components.

The majority of these disadvantages can be avoided by the use of high strength aluminum-alloy bolts. Due to a smaller electrochemical potential difference and similar thermal expansion coefficients the contact corrosion and the additional bolt load under temperature is decreased. This affects as well positively the surface pressure in the contact areas. Because of the lower strength of the aluminum-alloy the thread engagement and as a result the component dimensions and the component weight can be reduced.

The following article presents the achievable tensile, shear and fatigue strength of presently available production part aluminum bolts. In addition to that the strength behavior influenced by aging at 120 °C and 150 °C is also investigated.

2. Main body of paper

2.1. Static strength

For the production of high strength aluminum bolts materials of the 2xxx (Al-Cu), the 6xxx (Al-MgSi) and the 7xxx-series (Al-Zn) according to DIN 573 are suited. The final tensile strength of the materials can be achieved both by cold and heat treatment higher than $R_m > 300\,N/mm^2$.

Owing to the risk of stress corrosion cracking among higher alloyed Cu-free AlZnMg-alloys of the 7xxx-series the amount of Zn and Mg is limited from 6% to 7%. Heat treatment can increase the medium strength of

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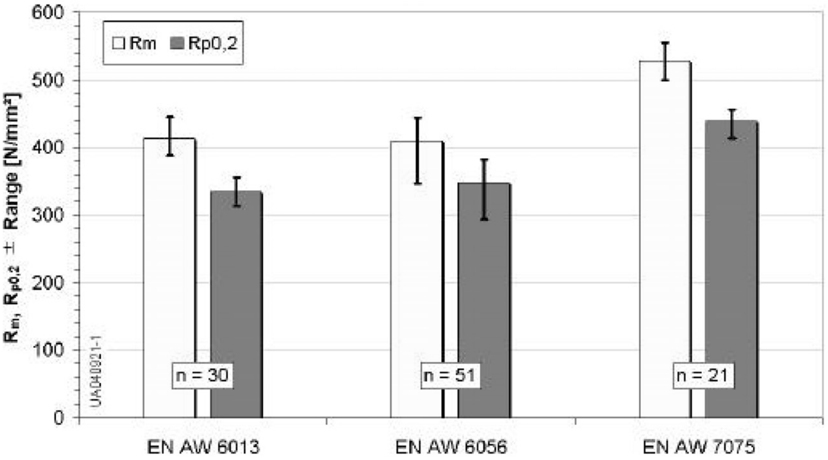

Fig. 1. Tensile strength values of aluminum bolts (M8) from different batches and alloys.

these alloys. If Cu is added to the 7xxx-series alloys the tendency to stress corrosion cracking is reduced and the tensile strength is increased simultaneously [1].

In Fig. 1 the tensile strength R_m and the 0,2%-yield strength $R_{p0,2}$ of bolts of the dimension M8 are shown. Three batches of high strength Cu-containing alloys of the 6xxx-series and the 7xxx-series have been tested with the indicated sample range of n. The tested bolts derive from five manufactures and were delivered in finally thread-rolled respectively finally heat-treated condition. The production sequence was not considered in particular. The bolts were not subjected to an additional surface treatment and were tested after cleaning in delivery condition ('oxide gray').

It is apparent that bolts of the alloy EN AW 6013 (AlMg1Si0,8CuMn) and EN AW 6056 (AlMg1SiCuMn) can reach on an average a tensile strength of 410 N/mm^2 and a 0,2%-yield strength of 330 N/mm^2. Bolts of the alloy EN AW 7075 (AlZnMgCu1,5) in contrast reach on an average a tensile strength of 520 N/mm^2 and a 0,2%-yield strength of 440 N/mm^2 at room temperature (RT).

Bolted joints are not only exposed at room temperature during operating time but as well at varying elevated temperatures. It is supposed that fasteners in engine applications are subjected to static temperatures of ca. 120 °C with peaks up to 150 °C. While according to Hufnagel [2] the tensile strength is constant up to a temperature of 100 °C it rises at lower temperatures. According to Peters [3] the application limit of conventional aluminum alloys is reached at 120 °C to 150 °C since at these temperatures the precipitation phases are coarsening (over aging) and the mechanical properties are worsened.

In Fig. 2 the tensile strength of above mentioned alloys after aging is shown. The bolts have been aged in a hot-air furnace over a time period of 4000 h at temperatures of 120 °C and 150 °C. Afterwards $n = 10$ bolts were tested in an axial tensile test at room temperature. The component tensile strength of bolts is calculated with the maximum force $F_{\max}$ referred to the stress cross section of the bolt thread A_S:

$$R_m = \frac{F_{\max}}{A_S} \tag{1}$$

Looking at the results it is noticeable that bolts of the tested 6xxx-series alloy show a 'slight' increase in the tensile strength after 1000 h aging at 120 °C. This could be attributed to a not fully completed heat treatment process during manufacturing. Compared to this bolts of the tested alloy EN AW 7075 show a loss in tensile strength of 10% after 4000 h aging. Here the elevated temperature causes already a slight over-aging of the alloy.

At an aging temperature of 150 °C the tensile strength of every of the three tested alloys decreases differently. The two 6xxx-series batches show a more moderate drop that is still under 10% after the first 1000 h, against which the 7xxx-series alloy already shows a drop of ca. 18% after 1000 h. Coming from a higher starting point alloy EN AW 6013 falls below its as received strength already after 2000 h aging time. The tensile strength of alloy EN AW 7075 approaches like the alloys of the 6xxx-series asymptotically a limit value. This value is in-between that of the tested 6xxx-series alloys and compared to the initial tensile strength on a lower level (ca. 33% reduction).

The relatively high temperatures generate in particular with alloy EN AW 7075 an increasing coagulation of the intermetallic phases. But apart from a deterioration of

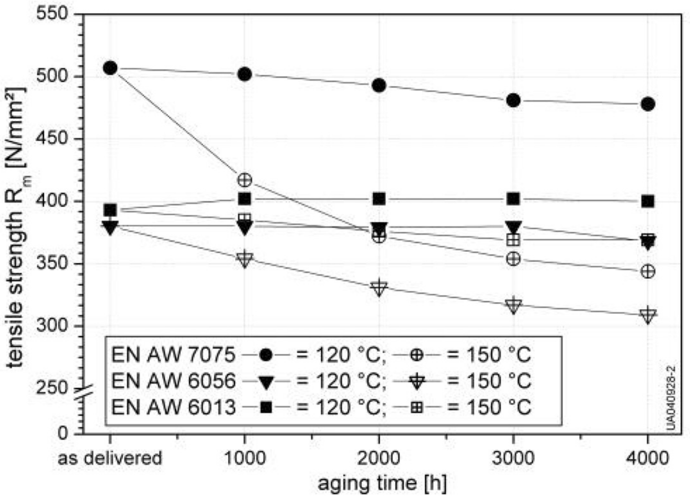

Fig. 2. Influence of heat aging at 120 °C and 150 °C on the tensile strength of aluminum bolts (M8) at room temperature.

the tensile strength this results in an increase of the ductility. Looking at Fig. 2 the conclusion can be drawn that the tested aluminum bolts of the alloy EN AW 7075 are not suited for temperatures of 150 °C and are only restricted suitable for temperatures of 120 °C. Bolts of the alloy EN AW 6013 and EN AW 6056 can be used at temperatures of 150 °C.

2.2. Cyclic load

In most technical applications bolted joints are subjected not only to static but as well to cyclic loads. The by far predominant design principle for cyclic loaded joints is the fail-safe concept. Only a small share of joints is laid out according to the safe-life concept. An overstrain of the surface pressure limit and as a result an increasing clamping force loss due to relaxation can result in a rise of the axial additional bolt load. Because most bolted joints are exposed to an eccentric load a gap between the clamped parts is likely to occur if the clamping force is insufficient. The result is the substantial risk of a fatigue fracture [4,5,6].

To ensure a long-term load-bearing capacity of bolted joints the fatigue strength properties of the aluminum bolt have to be known. To determine the fatigue strength of aluminum bolts fatigue tests have been carried out on a high-frequency resonance test bench according to the DIN 969 staircase method up to a limit of 10^7 load cycles. The tested bolts were vertically installed and concentrically loaded. Despite of the relatively high testing frequency up to 170 Hz no significant temperature rise of the bolts was detected. A possible frequency influence on the test result was verified at random with test series at lower frequencies and could not be observed in the range of fatigue resistance.

The results of the fatigue test are represented in Fig. 3. The values of the stress amplitudes σ_{A50} at 10^7 cycles are referred to the thread minor diameter cross section and amount to 20 N/mm^2 to 33 N/mm^2. Because of the high notch effect of the thread no influence of the alloy type and the manufacturing sequence (FHT and FTR) could be observed [7].

The compared to steel bolts smaller cyclic strength of aluminum bolts can be compensated by their higher elasticity (lower Young's modulus), which reduces the additional bolt load in the jointed system.

Finally, heat-treated aluminum bolts showed a drop of the fatigue strength after 1000 h aging at 150 °C (see [6]). In this context the possible influence of aging on the fatigue strength of finally thread-rolled bolts was investigated. For this finally thread-rolled bolts were aged over a time period of 1000 h at a temperature of 150 °C and afterwards tested in a single-stage Woehler test at room temperature. The results are shown in Fig. 4. It shows that an additional temperature aging of 1000 h at 150 °C has no influence on the fatigue strength of finally thread-rolled aluminum bolts

3. Conclusions

Presently available series production part high strength aluminum bolts of the 6xxx-series and the 7xxx-series can achieve a tensile strength of 400 N/mm^2 to 550 N/mm^2 without problems. Because of the temperature dependent stability of aluminum alloys aging tests at temperatures of 120 °C and 150 °C over a time period

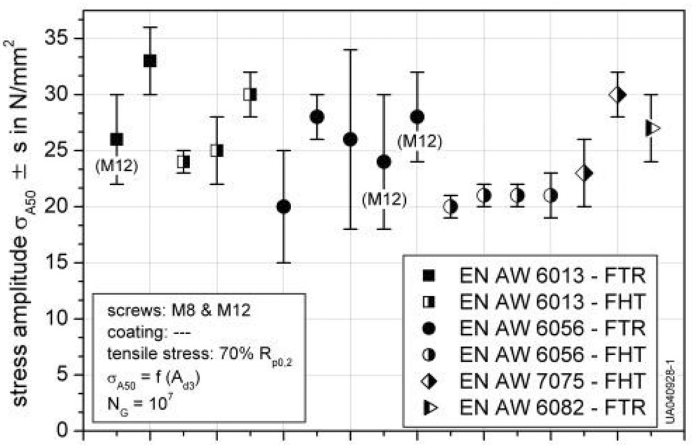

Fig. 3. Cyclic strength of aluminum bolts in the dimension M8 and M12 depending on the manufacturing sequence finally thread-rolled (FTR) and finally heat-treated (FHT) [7].

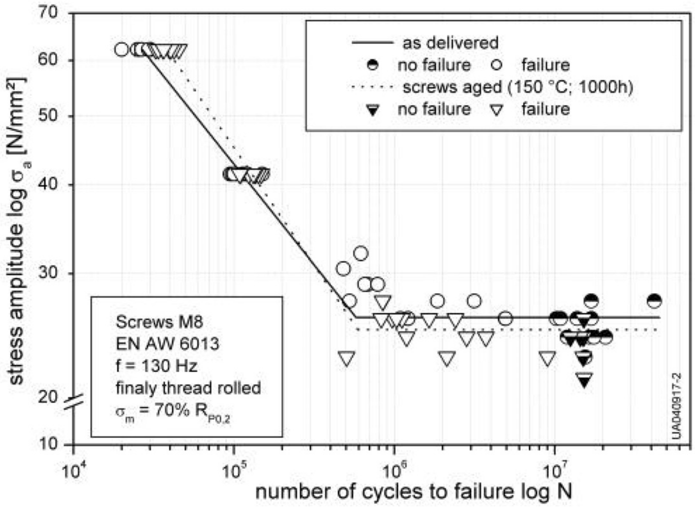

Fig. 4. Influence aging of 1000 h at 150 °C on the fatigue strength of finally thread-rolled bolts at RT.

of 4000 h have been carried out. Here especially bolts of alloy 7xxx showed a significant drop of the tensile strength. The fatigue strength at 10^7 cycles of the tested high strength aluminum bolts ranges from 20 N/mm^2 to 33 N/mm^2 and is significantly below the fatigue strength of steel bolts of the same dimension. A considerable increase of the fatigue strength due to a thread-forming process after heat treatment, such as with steel bolts could not be observed, although the final thread-forming process has a positive influence on fatigue strength of temperature-aged bolts.

Compared to steel bolts, the additional bolt load of aluminum bolts is reduced because of the higher elasticity as a result of the lower Young's modulus. With this effect the lower fatigue strength can be compensated for.

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