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Influence of cyclic stress wave form on the fatigue behavior of bolts

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Abstract: Bolted joints offer the great advantage of a non-destructive disassembly and can transfer higher loads than other detachable connections during operation. Therefore, bolted joints are one of the most commonly used joining methods in mechanical engineering and steel construction. In current guidelines the wave form and frequency of the load are neglected when estimating the fatigue strength. Even in rainflow counting the influence of load frequency and load wave form is also neglected. Although it is known from unnotched material samples that the wave form and frequency of the load have a measurable influence. In this study, bolts of size M10 are examined at different test frequencies and wave forms in the finite life range. The mean load is kept constant for all different wave forms during the tests. Each test is performed at a constant amplitude. For this purpose, a test setup was designed to perform fatigue tests with fluctuating axial load. It is shown that a long application time of the load shortens the fatigue life. In addition, the effective value of the load has an influence on the achievable service life. The greater the effective value of the load, the shorter the fatigue life.

Keywords: Constant amplitude, M10 fastener, fatigue life, frequency, VDI 2230

1 Introduction

Fastners, like bolts, have a wide range of applications. The aim of joining components is that they behave like a solid component without a parting line after the joining process Kampf (1997). Bolted joints account for 60-70% of all detachable joints in mechanical engineering Lori (2011). There are more than 2000 bolted connections in an automobile Wilke (2012). Volkswagen produces 29,000 cars per working day and requires for this more than 50 million threaded parts Kenzler (2010). These numbers illustrate the importance of bolted connections in technical products. The costs of bolt failures amount to more than 1 billion dollars Huang et al. (2009) per year. An evaluation of more than 200 cases of damage to bolts has shown that more than 68% of all bolt failures is caused by fatigue fracture Allianz-Versicherungs-Aktiengesellschaft (1984). Therefore, the fatigue resistant design of bolts is an important task. In Farahmand (2001) there are many examples of documented fatigue-related failures of bolted joints, e.g. water pipes and crude oil tanks. But also bolts of connecting rod bearings of reciprocating machines and bolts of slewing bearings of construction machinery and cranes are subjected to fatigue (Allianz-Versicherungs-Aktiengesellschaft (1984), Roth et al. (2022)).

One third of the load is transferred via the first thread that is screwed in Charlton (2011). In standard machine bolts, the greatest notch effect is present there and therefore this is also the usual point of fracture. Friction on the flanks has only a minor influence on the load distribution of the threads Seybold (2006).

Bolts are sharply notched components and due to the preload there is a high local mean stress Seybold (2006). Local plastic deformation occurs in the notch root due to the strong notch effect, so sufficient ductility of the bolt material is important to reduce stress peaks due to local plastification Illgner and Esser (2001). In consequence of the high notch effect, the fatigue strength is only about 10% of the static strength. In addition, the fatigue strength of steel bolts is almost independent of the strength class Seybold (2006).

The thread is usually rolled, because it's faster and more resource-efficient than cutting. Rolling can be done before or after heat treatment. If this is done after heat treatment there are induced residual stresses which enhance the lifetime. But also the rolling tools wear out faster. Due to this fact this type of bolts are more expensive. Usually, bolts in mechanical engineering are high preloaded (up to 90% of yield strength). At these high preloads the fatigue strength of bolts that are rolled after heat treatment is about 20 to 30% higher compared to bolts that are rolled before heat treatment Schneider (1992).

Even a ductile material has a brittle fatigue fracture, so there is no warning of a fracture if the crack is not visible. In ductile materials, the stress state in the crystal region also depends on the application time and not only on the magnitude of the load Lüpfert (1994). Thus, plastic deformation is a time dependent process Iida and Inoue (1972). With holding time, creep processes can develop better, therefore the material is damaged more than without holding time (Sautter (1971), Michler et al. (2017)). Damage processes such as flow, crack opening and crack propagation require a finite time Dünkel (1999). It follows that material properties are speed-dependent or depend on the excitation frequency (Takeo and Kiyoshi (1976), Schmidt and Paris (1973), Guennec et al. (2015)). Also Zhang et al. (1990) and Strizak et al. (2005) determined that the influence of frequency cannot be neglected, if it's below 1 Hz. Selines and Pelloux (1972) found out that there is a 4% increase in strength for triangle load compared to sine and 10% decrease in strength for rectangle load compared to sine for a ductile Al-Zn-Mg alloy. The influence of

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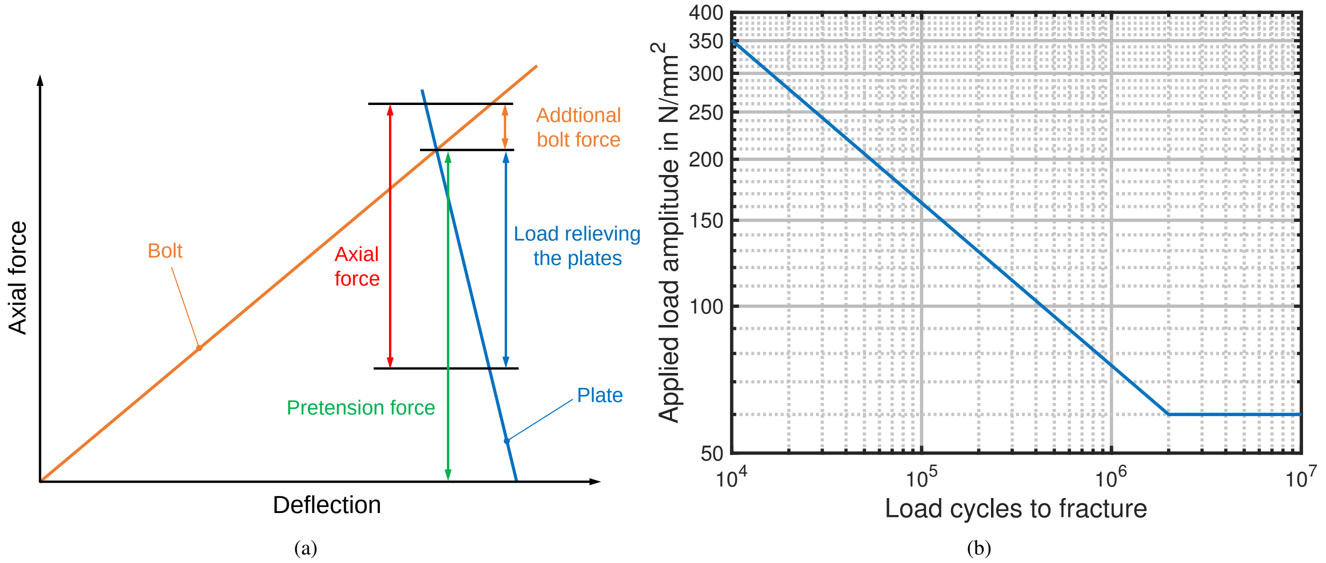


Fig. 1: (a) Joint diagramm of a concentrically clamped and concentrically loaded bolted joint, (b) Wöhler curve with 50% probability of survival for bolt size M10 according VDI 2230 Blatt 1

the test frequency on the fatigue on bolts is still an open question Marten (2009).
As a consequence to the preload force, the bolt forms a tensioned spring assembly with the plates. Because of the fact that the bolt has a higher resilience than the plate, an external axial force only acts to a small extent as an additional force on the bolt, see Fig. 1 (a). The largest proportion of an external axial force relieves the clamped plates.
VDI 2230 Blatt 1 is existing for decades and is frequently adapted to the current state of knowledge. This guideline has become the standard for the systematic calculation of bolted joints in mechanical and vehicle engineering. But, cycles to failure are mostly 2 to 4 times smaller than predicted by VDI 2230 Blatt 1 (Kremer (2005), Schäfer (2008)).
According to VDI 2230 Blatt 1 the calculation of the permanently transmissible amplitude $\sigma_{A,50}$ in N/mm^2 with 50% probability of survival is carried out with Eq. (1):

$$\sigma_{A,50} = \frac{d}{150} + 45. \tag{1}$$

In Eq. (1) d stands for the nominal diameter of the bolt in mm. For a finite life, between 10^4 till $2 \cdot 10^6$ load cycles, the number of load cycles until fracture $N_{VDI2230}$ for bolts rolled before heat treatment can be calculated using Eq. (2):

$$N_{VDI2230} = 2 \cdot 10^6 \left(\frac{\sigma_{A,50}}{\sigma_a}\right)^3, \tag{2}$$

with the applied stress amplitude σ_a. The resulting Wöhler curve from the Eq. (1) and (2) for a M10 bolt is shown in Fig. 1 (b). As can be seen in Eq. (1) and Eq. (2), the influence of load application time and load speed is not taken into account for calculation the fatigue strength of bolts. As already mentioned, an influence of the load application time and load speed on the fatigue life of metallic specimens was detected. The extent of these influences on bolts has not yet been investigated. Therefore, this study aims to clarify the extent of these influences on bolts.
In general, fatigue strength values scatter more than static strength values. The fatigue life of components is log-normally distributed, i.e. the logarithmic values of the achieved load cycles are normally distributed. Due to the fact that the load cycles to failure are log-normally distributed the fatigue life with 50% probability is calculated from the logarithmized lifetimes. Therefore, the standard deviation of the lifetimes is also specified logarithmized. In order to calculate the standard deviation of a sample in line with expectations in relation to the population, the sample standard deviation must be corrected using the method from Müller (2015).

2 Methods

In order to determine the influence of the load application time and load speed on the fatigue strength of bolts, tests with cyclic axial load were carried out. This chapter describes the test specimens and the experimental procedure.

2.1 Material

The sizes M8, M10 and M12 are most commonly used as fastening bolts. Due to the frequent use and the medium size of the three dimensions mentioned, bolts of size M10 were selected. All used bolts were manufactured according to DIN EN ISO 4017 and came from the same material and heat treatment batch. As already mentioned, the fatigue strength is almost independent of the

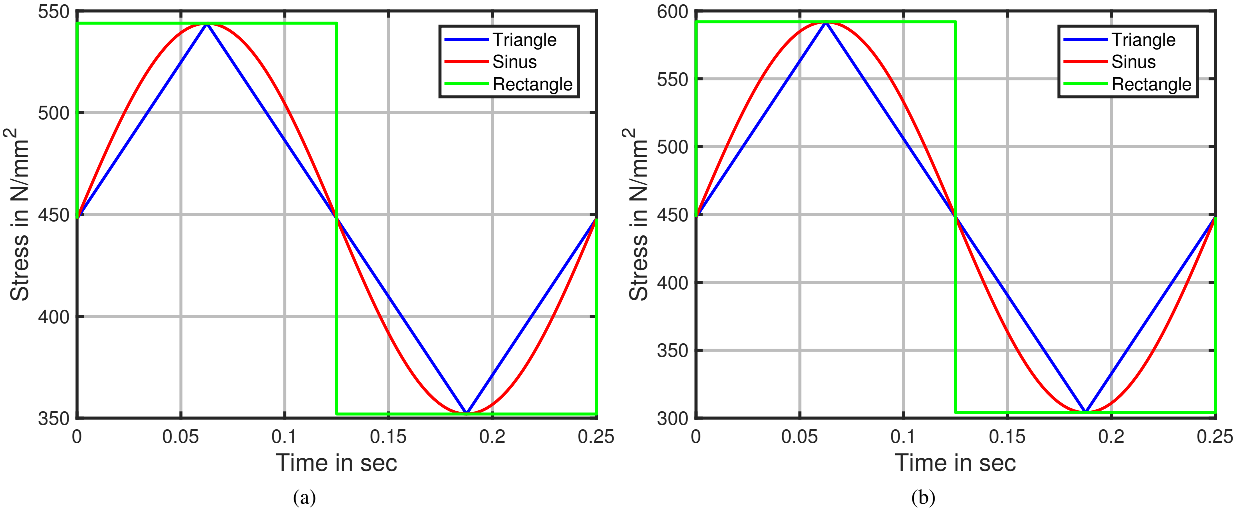


Fig. 2: (a) Wave form of the stress-time function for Amplitude of 96 N/mm^2 (b) Wave form of the stress-time function for Amplitude of 144 N/mm^2

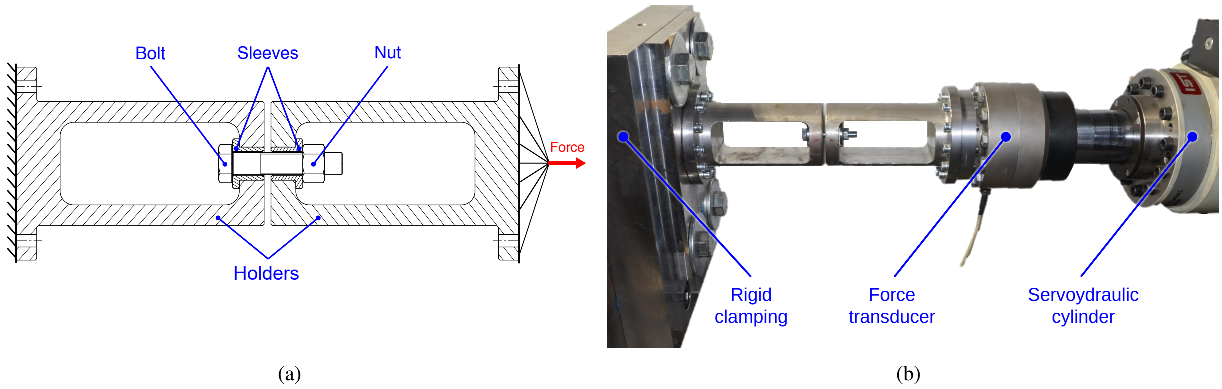
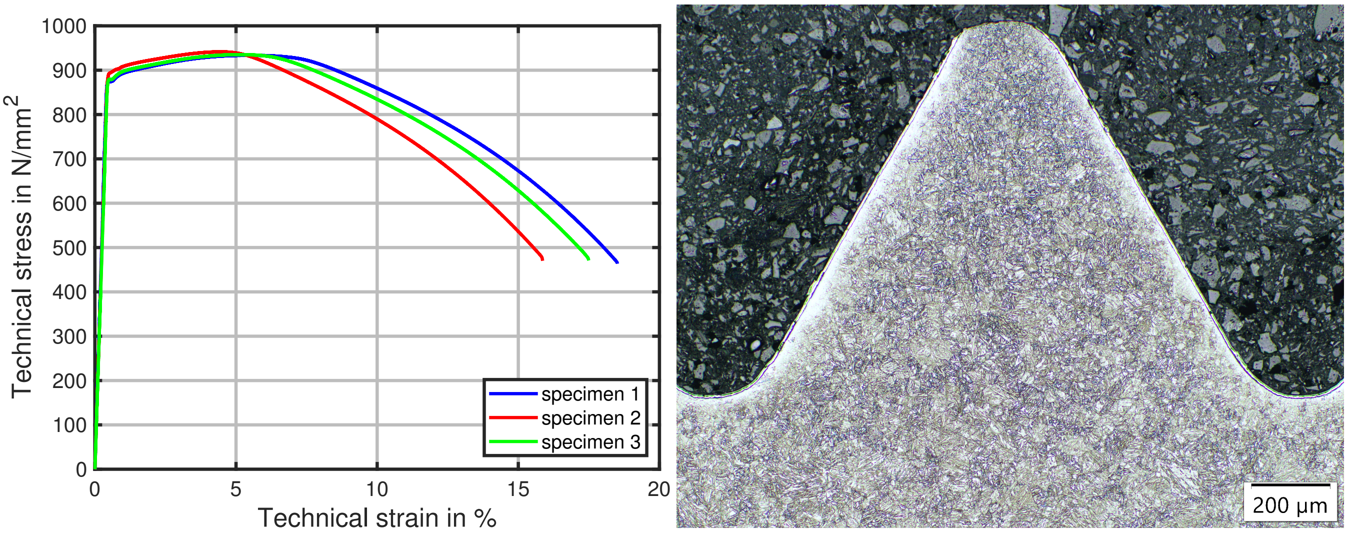


Fig. 3: (a) Cutting view of the holders with bolt and nut, (b) Holder connected to force transducer and hydraulic cylinder

strength class. Therefore, bolts with a length of 70 mm in strength class 8.8 were used. Strength class 8.8 indicates in a min. yield point of 640 N/mm^2 and a min. ultimate tensile stress of 800 N/mm^2. A M10 bolt has an equivalent stress area of 58 mm^2. For each test a new nut of size M10 and strength class 8 according to DIN EN ISO 4032 with galvanization was used.

2.2 Experiment

The preload is applied torsion-free according to DIN 969. If the bolts are tightened with torsional torque the torsional stress partially relaxes again after tightening Schneider (1992). As a result of the relaxation of the torsional stresses the bolt can absorb a higher axial force Alt et al. (2007), if they are tightened with torsional torque. The force transmission behavior, which was mentioned in Fig. 1 (a), is strongly influenced non-linear, if there is even a small unevenness of the jointed plates Buhr (2008). This does not happen if there is a gap between the two plates. As a result, the external force acts fully as an additional force on the bolt.
The mean load was selected according to the specification of DIN 969. This standard specifies the mean load to be 70% of the yield point of the bolt. The equivalent stress area and the strength class lead to a mean load of 25984 N. According to DIN 969, 1.6 times resp. 2.4 times the fatigue strength calculated with Eq. (1) were used as amplitudes. In Fig. 2 the nominal wave forms for both amplitudes are shown. So, the resulting stress ratios R are 0.65 resp. 0.51. Therefore, the stress ratios were in alternating tension for both test amplitudes.
To determine the influence of the signal wave form, the bolts were loaded with rectangular, triangular and sinusoidal loads at a frequency of 4 Hz. Eight bolts were tested per force amplitude in accordance with DIN 969 to reliably determine the scatter range in the finite life range. Tests were also carried out with sinusoidal loads at 0.4, 4 and 40 Hz. As with the variation of the stress wave form, eight bolts were also tested per force amplitude at each frequency.
For fatigue testing of bolts a holder was developed and manufactured. This holder fulfills the required geometric specifications acc. DIN 969. Due to replaceable sleeves the holder has the advantage that bolt sizes from M4 up to M16 are mountable. A cutting view of the holders with sleeves is shown in Fig. 3 (a). Also in this figure the bolt with corresponding nut to be tested can be seen.
The holder is connected to a servohydraulic cylinder from the manufacturer Instron with a maximum force of +/- 100 kN, which can be seen at right side of Fig. 3 (b). The cylinder is force-controlled by a MTS digital control system. Due to this the loading amplitude, mean value, frequency and wave form of the load signal can be set to any values in the limits of the hydraulic system.



(a) (b)

Fig. 4: (a) Stress-strain diagram for three tensile specimens, (b) Micrograph of one thread of the bolt

Mean load and force amplitude are applied by the testing machine. During the experiment the load and the displacement of the servohydraulic cylinder is measured. An experiment is completed when there is no reaction force measurable. This means the bolt fractured completely.

3 Results and Discussion

The manufacturer made the bolts out of 10B21 material according SAE J403. In Tab. 1 the results of a spark spectrometry analysis is shown. To characterize the strength of the material, tensile specimens of size A5x30 were made from the bolts according to DIN 50125. A tensile speed of 1 mm/min was used. The results of the tensile test are shown in Fig. 4 (a). As can be seen, the required values for yield strength (640 N/mm^2), ultimate tensile strength (800 N/mm^2) and elongation at break (12%) for strength class 8.8 according to DIN EN ISO 898-1 are met. In addition, quasi-static tensile tests were carried out on two whole bolts to determine the minimum breaking force. The breaking forces determined were 50.08 kN and 49.28 kN. Consequently, the minimum breaking force of 46.4 kN, for bolts of size M10 with strength class 8.8, according to DIN EN ISO 898-1 was fulfilled for both test specimens. Fig. 4 (b) shows the micrograph of one thread of the bolt. It can be seen that microstructure is completely martensitic. This fulfills the requirement of DIN EN ISO 898-1, which stipulates that 90% of the microstructure must be martensitic. In the micrograph the electrogalvanized surface of the bolt is also visible.

Because of the greatest notch effect in the first screwed-in thread all investigated bolts fractured at this position. As expected, an increasing effective value of the wave form leads to a shorter fatigue life, see Tab. 2. This effect can be observed for both test amplitudes. However, the percentage difference for the smaller amplitude between the rectangular signal and the sinusoidal signal is not as great as for the larger test amplitude.

Experimental lifetimes are between 5.2 and 8.4 times shorter than predicted by VDI 2230 Blatt 1. This is in line with the findings from the literature (e.g. Kremer (2005), Marten (2009) and Schäfer (2008)), where it was also found that VDI 2230 Blatt 1 is usually clearly on the unsafe side. In these studies, the experimentally determined lifetime is up to a factor of 5.0 shorter than estimated by the VDI 2230 Blatt 1.

The specification in DIN 969, which states that at least 8 tests per amplitude must be carried out, leads to statistically unreliable results. Therefore, as recommended by Müller (2015), a logarithmic normal distribution was assumed for the evaluation. The logarithmic standard deviations in this investigation (see Tab. 2 and Tab. 3) are smaller than usual compared to the literature. In the exemplary investigations of Kremer (2005) resp. Schäfer (2008) the mean logarithmic standard deviation were 0.095 resp. 0.171. The load wave forms with non-continuously differentiable curves are more difficult for the controller to adjust, i.e. the amplitude is subjected to fluctuations during the test run than with a sinusoidal load. As a result, the fluctuations of the amplitudes during the test run result in greater scatter in the lifetime. Nevertheless, the real amplitude was up to 6 N/mm^2 higher compared to the target amplitude. This occurred with the rectangular load with the higher amplitude.

A long application time (frequency of 0.4 Hz) ensures the shortest lifetime, see Tab. 3. If the application time is shortened, the achievable lifetime increases. This shows that the time-dependent effect of material fatigue also applies to bolts in the finite lifetime range. This effect can be seen particularly well at the lower amplitude. At the higher amplitude, this effect can only be seen up to 4 Hz. At 40 Hz, the effect of a longer lifetime cannot be detected due to the greater scattering at the higher amplitude. Another

Tab. 1: Spark spectrometry analysis of the M10 bolt, quantities are given in %

C	Si	Mn	P	S	Cr	Al	Cu	Ti	Sn	B
0.25	0.015	0.8	0.01	0.0066	0.032	0.028	0.007	0.028	0.002	<0.001

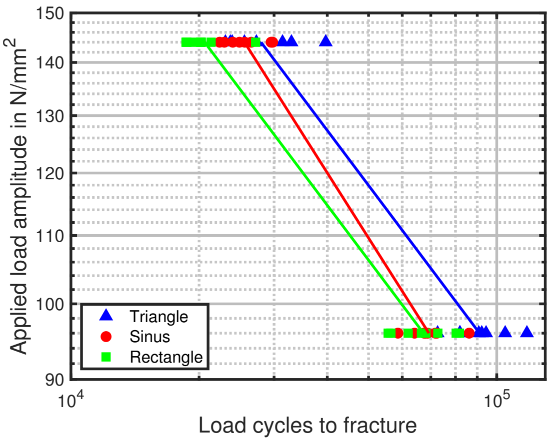
finding is that a longer application time results in a higher scattering of the lifetime. This can be seen in the comparison of the load cycles to fracture at 0.4 Hz vs. 4 Hz at both load amplitudes.
The experimental results with the achieved load cycles are also plotted in a Wöhler diagramm in Fig. 5. In this figure there are also shown the Wöhler curves with a 50% probability of survival.

Tab. 2: Experimental results for different wave forms

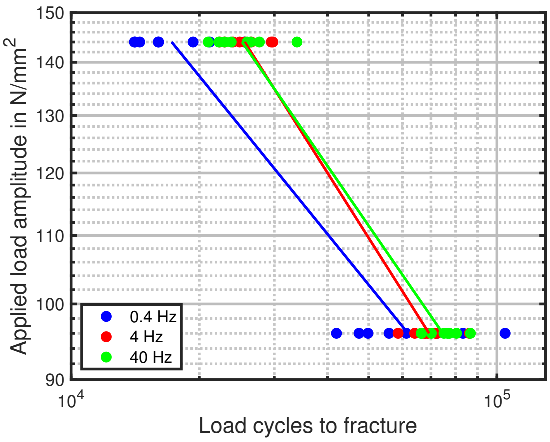
Amplitude in N/mm^2	Frequency in Hz	Waveform	N_{50}	$s_{log,50}$	$N_{VDI2230}$
96	4	Triangle	91106	0.0681	488281
		Sinus	69279	0.0498	
		Rectangle	67295	0.0659	
144	4	Triangle	27958	0.0869	144676
		Sinus	25563	0.0481	
		Rectangle	20608	0.0541	

Tab. 3: Experimental results for different load frequencies

Amplitude in N/mm^2	Frequency in Hz	Waveform	N_{50}	$s_{log,50}$	$N_{VDI2230}$
96	0.4	Sinus	61832	0.1389	488281
	4		69279	0.0498	
	40		74607	0.0419	
144	0.4	Sinus	17227	0.0979	144676
	4		25563	0.0481	
	40		25215	0.0684	



(a)



(b)

Fig. 5: (a) Experimental results for different wave forms (b) Experimental results for different load frequencies ; The Wöhler curves with a 50% probability of survival are also plotted

4 Summary

The fatigue behavior of M10 fasteners in the finite lifetime range was investigated with two different load amplitudes. The lifetime is influenced by the effective value of the load wave form. It was shown that with a lower effective value of the load the lifetime is increasing. Also, the application time, which is represented by the frequency of the load, causes an influence on the lifetime. The lifetime is decreasing when the frequency is decreasing. The guideline VDI 2230 Blatt 1 is on the unsafe side for the estimation of fatigue strength. This known observation was confirmed.
Further research should answer the question which of the parameter loading velocity or effective value of the load function has the biggest influence on the lifetime. This can be done with a sawtooth function of the load. This sawtooth must have an impulse rising edge, like the rectangular load function and has the same effective value like the used triangular load function. This load-time function can be used to differentiate whether the impulse load application at the same effective value like the symmetrical triangular load has an influence on the lifetime. Another lack of knowledge is how a high friction coefficient in the thread influences the lifetime.

Acknowledgment

We would like to sincerely thank Marco Wendler from IEST of TU Freiberg for performing spark spectrometry & micrographs and Gerd Schade from IWT of TU Freiberg for the tensile tests.

Appendix

In Tab. A.1 all individual achieved load cycles are summarized.

Tab. A.1: Summary of all individual achieved load cycles

Waveform	Triangle		Sinus		Rectangle		Sinus		Sinus	
Frequency in Hz	4		4		4		0.4		40	
Amplitude in N/mm^2	96	144	96	144	96	144	96	144	96	144
	104658	23057	67977	23996	56426	21340	41995	16052	80385	27685
	82009	25554	58598	22342	72723	18716	49799	21164	86630	33919
	117727	32950	64107	29768	55597	20197	83238	14133	76599	22236
	81878	27260	71740	29520	68158	20235	72315	14491	66501	26390
	94390	39660	86146	25598	61933	20192	104542	19345	77370	22938
	90750	31403	67531	22929	81725	18635	55815	14085	70151	23769
	72623	23678	68828	26511	66555	27154	61299	16022	66403	25900
	92223	23917	72340	24878	80299	19504	47449	25539	75088	20998

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