International Journal of Fatigue xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Frequency effect and influence of testing technique on the fatigue behaviour of quenched and tempered steel and aluminium alloy

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ARTICLE INFO

Article history:
Received 25 January 2016
Received in revised form 13 May 2016
Accepted 14 May 2016
Available online xxxx

Keywords:
Very high cycle fatigue
Frequency effect
Ultrasonic fatigue and conventional testing machines
50CrMo4
EN AW-5083

ABSTRACT

Influences of testing technique and frequency on the fatigue behaviour of 50CrMo4 and EN AW-5083 were investigated. To clarify the effect of test frequency on the fatigue behaviour, tests with 20 kHz and $f < 400$ Hz were performed. The frequency effect can be caused by temperature, environment and strain rate. For the aluminium alloy, the influence of environment is responsible for the dependence of fatigue lifetime on the frequency. The fatigue lifetime of the steel showed in both environments similar frequency dependency, i.e. the strain rate is assumed to be responsible for the differences in fatigue lifetime.

1. Introduction

Machinery and constructions in many industries are used up to a number of cycles more than $N = 10^8$. For materials with a face-centred cubic crystal lattice and high strength steels with body-centred cubic lattice, fatigue failures, even in the very high cycle fatigue (VHCF) regime of more than $N = 10^7$ load-cycles, were observed. Therefore, the classical definition of the endurance strength, e.g. at $N = 10^6$, cannot be used without further investigations [1]. For an economic and safe design of components in this cyclic range, the material and component behaviour must be taken into account.

Research up to the VHCF-regime depends on the testing machines, which allow fatigue tests in an acceptable time, Table 1. For investigations up to the VHCF-regime different testing strategies are developed, e.g. parallel testing of specimens or the testing at higher frequencies. In [2] the increase of frequency is described as the most often used method to reduce testing time. With regard to the results of fatigue tests, fatigue lifetime depends on the test frequency. This dependence is caused by the influence of strain rate, environment and heating of the specimen. As heating of specimens can be avoided by cooling the specimens or measuring in pulse-pause mode, strain rate and environment are responsible for the frequency dependence of fatigue lifetime.

Generally, metallic materials show in a range from 1 up to 1000 Hz no significant frequency influences on fatigue behaviour, when corrosion, high temperature and high plastic strains are avoided [3,4]. Partly aluminium alloys are influenced by frequencies in this range [5,6]. Besides conventional high frequency testing machines (resonant fatigue testing machine, servohydraulic testing machine) also ultrasonic fatigue testing machines with a testing frequency of about 20 kHz are used.

In recent decades, ultrasonic fatigue testing machines have been used more and more frequently in order to reduce the test time. Generally, investigations are not conducted parallel on conventional and ultrasonic testing machines. Results of different comparative investigations show that the test method and frequency has an influence on the fatigue life and fatigue strength. For example in [7–11], differences in the fatigue behaviour can be regarded for different metals like steel, aluminium, titanium and tantalum. Thereby, investigations at ultrasonic frequencies show a longer fatigue lifetime than tests on conventional testing machines. However, investigations of different aluminium alloys in [12–16] show no dependence of fatigue behaviour on the test method and frequency.

The reasons for the differences in fatigue lifetime are mainly described by two effects. For material with a face-centred cubic crystal lattices (e.g. austenitic steels and aluminium alloys), differences in the fatigue behaviour are explained by the influence of the environment. On the other side, differences in fatigue lifetime with increasing frequency for material with a body-centred cubic lattice

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http://dx.doi.org/10.1016/j.ijfatigue.2016.05.013
0142-1123/

Table 1
Overview of testing machines, frequency, control and time.

Testing machine	Frequency	Control	Time for $N = 10^9$
Resonant-spring testing machine	40 Hz	Strain	289 days
Resonant fatigue testing machine	150 Hz	Stress	77 days
Servohydraulic testing machine	400 Hz	Stress	29 days
Ultrasonic fatigue testing machine	20 kHz	Strain	0.6–6 days dep. on pauses

(e.g. quenched and tempered steel) are explained by the effect of strain rate. This is also described in [17], where the influence of strain rate in pure metals with a face-centred cubic crystal lattice or a body-centred cubic lattice under cyclic deformation, considering dislocation mechanism, was investigated. But current research shows no consistency, considering the different effects on the S–N curves.

In fatigue tests, for the aluminium alloy AlZnMgCu1.5 no significant influence of testing frequency could be noticed [12]. Fracture mechanic tests of the aluminium alloy show a lower threshold value and a higher crack propagation rate in laboratory air than in vacuum. The influence of the testing frequency of different aluminium cast alloys was investigated in [8,13]. Differences in the fatigue strength of investigations at low frequency $f = 75$ Hz and at 20 kHz are explained by the influence of environment. Investigations [8] on several cast aluminium alloys revealed that with higher yield strength, the influence of humidity on crack propagation increases. Therefore, the influence of testing frequency is hardly noticeable in some alloys, but very pronounced in other cast aluminium alloys. In [9], a concept was developed based on investigation from [18]. It describes the influence of frequency over the humidity, measured by partial pressure p of water vapour. Results in [8,9] show that by a change of quotient (p/f) over the relative humidity, a good agreement of investigation at different frequencies was observed.

Results of investigations on steel [10,11] show that with increasing testing frequency from $f = 10$ Hz or 400 Hz up to 20 kHz, the fatigue strength also increases. The changes that occur in the stress–strain behaviour under monotonic load at different strain rates are comparable to the deviations, observed in the fatigue test. As a possible cause of the deviations, it has been observed that the increase in strain rate leads to changes in the cyclic stress–strain behaviour, similar to those changes observed under monotonic load at different strain rates. It is assumed that increasing test frequency and strain rate increases fatigue strength.

In addition to these frequency dependent effects, the S–N curve can also be influenced by testing technique. In the following, the influences of testing technique and frequency on fatigue behaviour are discussed using the example of the steel 50CrMo4 with two strength levels, and the aluminium alloy EN AW-5083.

2. Materials, fatigue tests and specimens

2.1. Materials

Investigated materials are a quenched and tempered steel 50CrMo4 with tensile strength of $R_m = 919$ MPa and 1726 MPa, and an aluminium alloy EN AW-5083 with $R_m = 323$ MPa. Table 2 shows the chemical compositions and Table 3 the material properties.

The heat treatment of the lower strength steel was done inductive by an austenitizing temperature of 900 °C and at a tempering temperature of 650 °C. To achieve the strength of 919 MPa, an additional tempering at 625 °C for 5 h was used. The higher strength steel was austenitized at 850 °C and tempered at 340 °C for 1.5 h. The naturally hard aluminium alloy is used in condition H111 (annealed and slightly cold worked).

The microstructure of 50CrMo4 shows the typical quenched and tempered structure with prior austenite grain size of 7 μm for $R_m = 919$ MPa, and 15 μm for $R_m = 1726$ MPa. Both strengths show no globular oxide inclusions with a diameter >13 μm for an investigated surface of 270 mm^2. Sulfid inclusions with a length of 210–310 μm were found for the lower strength steel. The retained austenite content is ⩽3.8% for both strengths.

The microstructure of EN AW-5083 shows primary intermetallic particles of Al, Mn, Fe and Cr with a hardness of 560 HV2, and particles of Al, Mg, Si, Fe, Ca, Mn and Cr with a hardness of 90 HV2. Examinations of intermetallic particle sizes show a mean length of 4 μm and the maximum length of 45 μm for an investigated surface of 0.081 mm^2.

The cyclic material behaviour was determined with strain controlled tests at a frequency of $1 \leqslant f \leqslant 5$ Hz, according to [19]. For the description of cyclic σ-ε-curve, the Ramberg–Osgood equation [20]

$$\varepsilon_a = \varepsilon_{a,el} + \varepsilon_{a,pl} = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{\frac{1}{n'}} \quad (1)$$

Table 2
Chemical composition (wt.%) of the quenched and tempered steel 50CrMo4 and the aluminium alloy EN AW-5083.

	C	Si	Mn	P	S	Cr	Mo	Ni
50CrMo4, $R_m = 919$ MPa	0.528	0.250	0.694	<0.01	<0.01	1.06	0.185	0.027
50CrMo4, $R_m = 1726$ MPa	0.507	0.264	0.727	0.016	<0.01	1.09	0.189	0.030
	Si	Fe	Mn	Mg	Cr	Cu	Mo	Ni
EN AW-5083, $R_m = 323$ MPa	0.136	0.280	0.686	4.850	0.107	<0.01	<0.01	<0.01

Table 3
Mechanical properties of the quenched and tempered steel 50CrMo4 and the aluminium alloy EN AW-5083, mean values of three tests.

	R_m [MPa]	$R_{p0.2}$ [MPa]	A [%]	E [MPa]
50CrMo4	919	842	$A_{10} = 20.0$	205 750[a]
	1726[a]	1544[a]	$A_5 = 12.5$[a]	215 400[a]
EN AW-5083	323	195	$A_{10} = 16.0$	70 150

[a] Measurement on one sample.

Please cite this article in press as: Schneider N et al. Frequency effect and influence of testing technique on the fatigue behaviour of quenched and tempered steel and aluminium alloy. Int J Fatigue (2016), http://dx.doi.org/10.1016/j.ijfatigue.2016.05.013