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ABOUT THE CONNECTION BETWEEN THE CHARACTERISTICS OF THE LCF AND FCG

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ABSTRACT

Characteristics determined for low cycle fatigue, high cycle fatigue or fatigue crack growth are different. The question arises, whether common mechanical and microstructural features can be found or not in this narrow field of loading types, based on which relationship between the materials constants can be assumed. The paper introduces the similarity of the stress and strain state, furthermore the dislocation structure having been developed during low cycle fatigue and fatigue crack growth. This can form a basis for the establishment of a connection between the material characteristics determined during the above mentioned two types of testing. The validity of the hypothesis has been illustrated here by comparing the test results determined for different material grades, steels (micro-alloyed and thermomechanically treated steels) and aluminium alloys (groups of different microstructure).

KEYWORDS

Low cycle fatigue (LCF), fatigue crack growth (FCG), Manson-Coffin equation, Paris-Erdogan law

INTRODUCTION

The behaviour and the properties of the different materials are determined by the quality of materials (chemical composition, type of atomic bonding, spatial arrangement of atoms, micro- and macrostructure), furthermore the stress state, the strain rate and the temperature. Due to the great variety of these influencing factors we do not have a general model for describing the behaviour of materials, thus we have to use several material constant to be able to characterise it. Even if we consider the fatigue loading of the possible loading conditions we have to determine more material constants to be able to provide sufficient data for sizing and control.

We determine different properties in case of low cycle fatigue, high cycle fatigue, and fatigue crack growth rate measurements. We can ask if there are common mechanical or microstructural properties – at such a relatively small area – that could be taken as a basis in order to build a connection between the materials constants.

The aim of this paper is to introduce the similarity of the mechanical stress state and the dislocation structure in case of low cycle fatigue (LCF) and fatigue crack growth (FCG) which can be the basis of the connection of the determined constants. The assumption is supported by the results measured and analysed on the same steel and aluminium grades. Micro-alloyed and thermomechanically treated steels and aluminium alloys with different microstructure were used for the investigation.

COMPARISON AND SIMILARITY OF THE MECHANICAL STRESS STATE AND THE DISLOCATION STRUCTURE

Comparison of the mechanical stress state

In case of low cycle fatigue the load of the specimen is so large that the whole volume of measuring part of the specimen will suffer plastic deformation during the first half of the loading cycle. At the majority of the experiments the controlled parameter is the total strain amplitude and its time variation generally follows a sinus or a triangle function. Since the connection between the stress and strain is not linear in the region of plastic deformation, in case of total strain controlled low cycle fatigue the time dependence of the stress is influenced by the material, as well.

Figure 1 shows the time variation of the strain amplitude and the stress amplitude in case of low cycle fatigue with a saturated strain amplitude of $\varepsilon_a = \pm 1\%$. The difference is can be seen well. If the measuring part of the specimen is cylindrical with a uniaxial apprehension the same axial stress raises in each point of the cross section analysed.

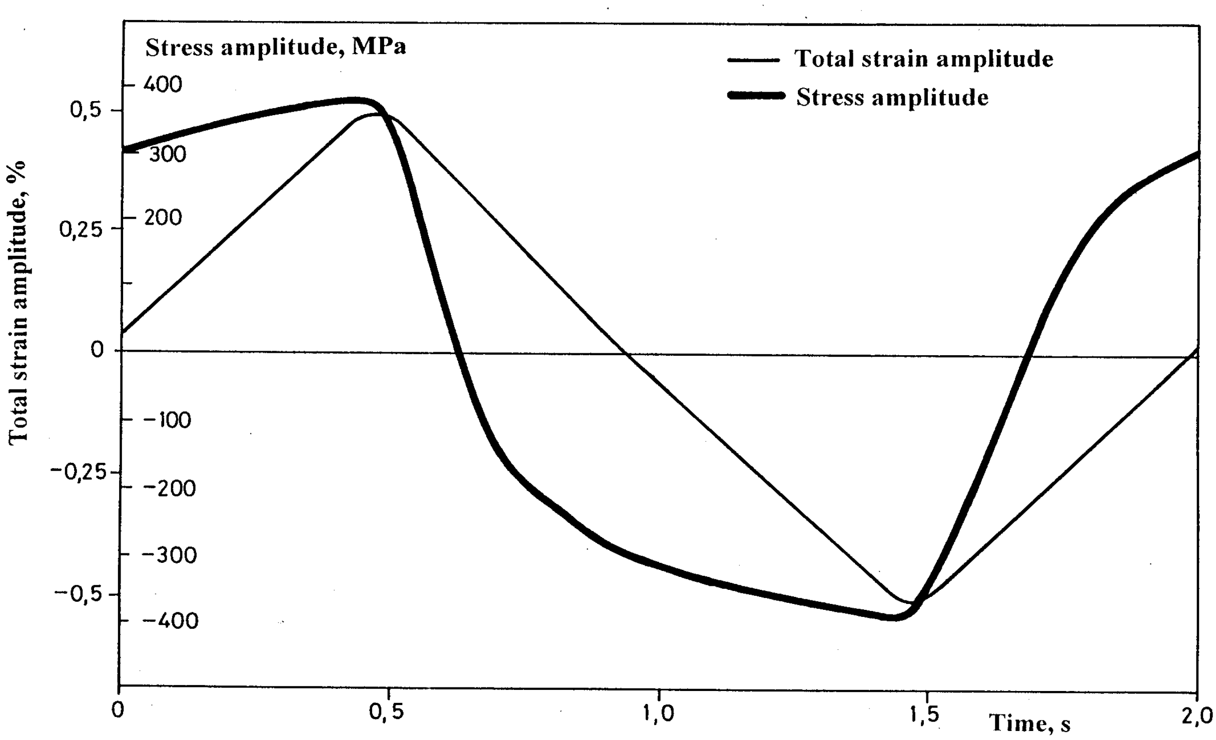

Figure 1: Time variation of the total strain amplitude and the stress amplitude in case of low cycle fatigue

Measuring the fatigue crack growth rate a plastic zone is forming at the crack tip during the first tensile cycle. The maximum size of the plastic zone (w) depends on the yield stress of the material (σ_0) and the stress intensity factor (K_I). Supposing an ideally elastic-plastic material and maximal loading the stress distribution in *y* direction in the function of the distance from the crack tip is going to form as shown in Figure 2 a). The maximum stress in the plastic zone is equal to the yield strength ($\sigma_y = \sigma_0$). Decreasing the load the stress distribution will change. When the load is zero again the stress distribution in *y* direction ahead of the crack tip is as shown in Figure 2 b), which demonstrates the reversed plastic zone, too.This means that a compressive stress arises in the plastic zone. Repeating the loading up (Figure 2 c)) and down the stress will be similar as experienced during low cycle fatigue.

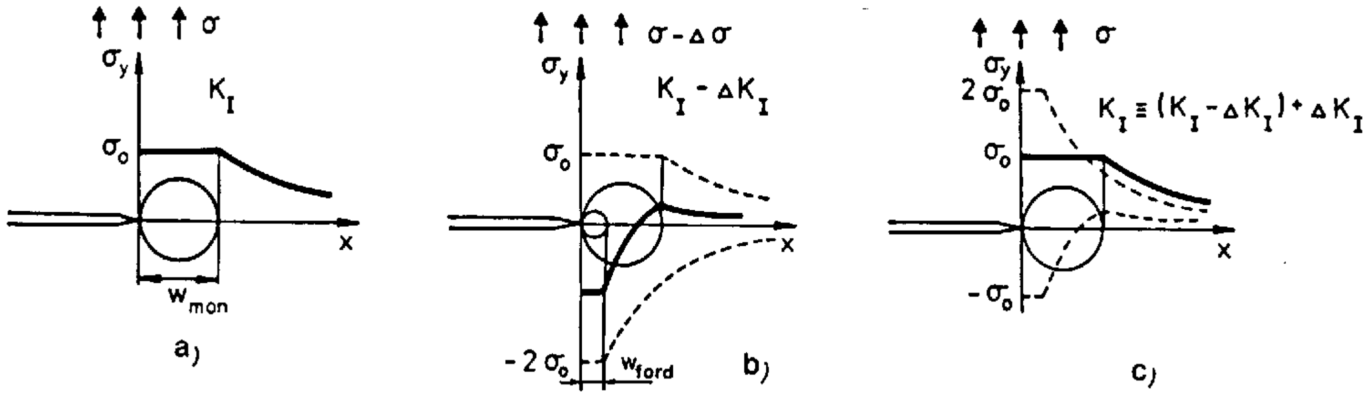

Figure 2: Stress distribution at the crack tip of the fatigue specimen

Comparison of the dislocation structure

Mild metals and alloys close to the equilibrium state can be characterized by a relatively small dislocation density ($10^{11} - 10^{13}$ m^{-2}) and a homogeneous dislocation distribution [1]. Under the influence of low cycle fatigue the dislocation density is growing and the dislocation distribution becomes heterogeneous even in the first cycle. At the early stage the edge dislocations, dislocation loops and dipoles, the labouring dislocation parts form uncondensed, blurred cell walls. With increasing number of cycles the number of multipoles and the dislocation density of the walls increases, the cell walls and the matrix will become more and more separated [1, 2]. At the beginning the cell size decreases with increasing the cycle number and after the dislocation density becomes stable the cell size will not change significantly. The orientation difference of the matrix crystal planes at the two sides of the cell-walls is increasing continuously during the entire fatigue process. The size of the cell is inversely proportional to the strain amplitude [7, 8].

In case of fatigue crack growth, a very large local plastic deformation will develop in front of the crack in the plastic zone, although its measure is different in the different points of the zone. Due to the large plastic deformation a cell structure will form [5, 6, 7]. In the crack vicinity the size of the cells is very small, while increasing the distance away from the crack their size is increasing. As well, the orientation difference of the planes of the neighbouring cells is the biggest near by the crack and getting more and more away the orientation difference is decreasing [8].

Based on these facts we can establish that the dislocation structure developing during low cycle fatigue is very similar to that which forms around the crack vicinity during fatigue crack growth.

INVESTIGATIONS AND RESULTS

For the experiments different micro-alloyed (37C, KL7D, DX52) and thermomechanically treated (X80TM, QStE690TM, StE690) steel grades (own tests and [9]) and aluminium alloys (AlMg3, AlMg5, AlMg5.1Mn, AlMg4.5Mn, 7075-T6) with different microstructure (own tests and [10], [11], [12]) were used. The chemical compositions of the examined materials are summarised in Table 1 and Table 2, the mechanical properties are listed in Table 3.

Low cycle fatigue tests have been executed in air, at room temperature, with total strain amplitude-control. The change of deformation was measured by a caliper, the time dependence of the load was a sinusoidal feature. The fatigue asymmetry factor was R = -1, the cycle number until failure was chosen at the 25% decreasing of the maximum tensile load. During the measurement the maximum values of the total strain and stress amplitudes and the hysteresis loop were recorded.

TABLE 1

CHEMICAL COMPOSITION OF THE TESTED STEELS, IN WT %

Material grade	C	Si	Mn	P	S	Al	Nb	V	Cr	Mo
37C	0.15	0.38	0.89	0.029	0.016	0.016	0.021	0.023	-	-
KL7D (1)	0.17	0.24	1.31	0.020	0.036	0.049	-	0.01	0.11	0.02
DX52 (2)	≤0.18	0.15-0.20	≤1.50	≤0.030	≤0.035	-	-	0.02-0.06	≤0.25	-
X80TM (3)	0.077	0.30	1.84	0.012	0.002	0.036	0.046	-	-	-
QStE690TM_FCG	0.08	0.29	1.75	0.011	0.002	0.041	0.04	0.061	0.037	0.32
StE690_LCF	0.15	0.53	0.87	0.011	0.004	0.038	-	-	0.63	0.22

(1) Ni = 0.08%, Ti = 0.0017%, Cu = 0.26%.

(2) Cu ≤ 0.30%.

(3) Ti = 0.018%, N = 0.005%.

TABLE 2

CHEMICAL COMPOSITION OF THE INVESTIGATED ALUMINIUM ALLOYS, IN WT %

Material grade	Si	Cu	Fe	Mn	Mg	Ti	Cr	Zr	Zn	Pb
AlMg3 (1)	0.179	0.022	0.310	0.2770	2.950	0.040	0.0430	0.0012	0.044	0.009
AlMg5_FCG	0.31	0.01	0.32	0.45	5.20	0.020	0.1	0.01	-	-
AlMg5.1Mn_LCF	<0.40	<0.10	<0.40	0.75	5.1	0.20	0.12	-	0.25	-
AlMg4.5Mn_FCG	0.21	0.01	0.27	0.77	4.53	0.015	0.1	0.03	-	-
AlMg4.5Mn_LCF	0.19	0.026	0.30	0.72	4.82	0.01	0.096	-	0.085	-
7075-T6_FCG	0.15	1.59	0.35	0.005	2.70	-	0.19	-	5.70	-
7075-T6_LCF	<0.4	1.2-2.0	<0.50	<0.30	2.1-2.9	<0.20	0.18-0.35	-	5.1-6.1	-

(1) Bi = 0.0150%, Be = 0.0018%, Al = 96.1170%.

TABLE 3

MECHANICAL PROPERTIES OF THE INVESTIGATED MATERIALS

Material grade	Yield strength R_y, N/mm^2	Tensile strength R_m, N/mm^2	Elongation A_5 %	Reduction of area Z %	Source
37C	269	405	33.5	63.5	own experiments
KL7D	392	535	≥19.0	-	own experiments
DX52	396	543	25.0	71.0	own experiments
X80TM	540	625	25.1	73.1	own experiments
QStE690TM_FCG	768	854	20.0	-	own experiments
StE690_LCF	743	885	-	57	[9]
AlMg3	127.7	217.9	27.0	-	[10]
AlMg5_FCG	185	288	14.5	-	[10]
AlMg5.1Mn_LCF	235	400	-	34.6	[12]
AlMg4.5Mn_FCG	230	296	18.0	-	[10]
AlMg4.5Mn_LCF	226	348	17.0	22.5	[12]
7075-T6_FCG	533	594	9.2	-	[11]
7075-T6_LCF	470	580	-	33.0	[12]

The results were evaluated by classical methods. The exponent ant the constant of the Manson-Coffin equation were determined by the following expression:

$$\varepsilon_{ap} = \varepsilon_f' N_t^c \tag{1}$$

where ε_{ap} is the plastic strain amplitude, N_t is the cycle number until failure, ε_f' and c are material constants. The calculated parameters, the material constants (c), for the different tested steel grades and aluminium alloys are listed in Table 4.

TABLE 4
PARAMETERS OF THE MANSON-COFFIN AND THE PARIS-ERDOGAN EQUATION

Material grade	Manson-Coffin equation, c	Paris-Erdogan equation, n	
		average	standard deviation
37C	-0.287	3.44	0.311
KL7D	-0.498	3.36	0.381
DX52	-0.784	3.11	0.140
X80TM	-0.478	2.49	0.561
QStE690TM_FCG	-	2.39	0.498
StE690_LCF	-0.659	-	-
AlMg3	-0.787	3.37	0.503
AlMg5_FCG	-	3.71	0.405
AlMg5.1Mn_LCF	-0.655	-	-
AlMg4.5Mn_FCG	-	3.57	0.444
AlMg4.5Mn_LCF	-0.755	-	-
7075-T6_FCG	-	2.13	-
7075-T6_LCF	-0.987	-	-

The fatigue crack growth rate measurements were made on compact tension (CT) and three point bending (TPB) specimens, in air, at room temperature, with a sinusoidal loading function and stress ratio of R = 0,1. The crack size was determined by optical method and using the compliance method. From the collected data and results of the fatigue crack growth measurements the exponent and the constant of the Paris-Erdogan equation have been determined:

$$\frac{da}{dN} = C\Delta K^n, \qquad (2)$$

where da/dN is the fatigue crack growth rate, ΔK is the stress intensity factor range, C and n are material constants. In each case first we calculated the related part of the kinetic diagram of the fatigue crack growth (da/dN-ΔK diagram), then we determined the two material constants (C and n) with linear regression. From these results we calculated the average of the data measured on 5-26 specimens. The average and standard deviation values of the exponent are also listed in Table 4.

EVALUATION OF THE RESULTS

In our earlier works we showed that there is a correlation between the two parameters of both the Manson-Coffin and the Paris-Erdogan equation [13], therefore it is sufficient to study the relationship of the two exponents (c and n). Figure 3 shows the relation of these material constants.

Despite of the relatively few measurement data we can establish that there is an admissible connection between the exponents of the Manson-Coffin law characterising low cycle fatigue and the Paris-Erdogan equation describing fatigue crack growth.

The connection among the steel groups of different microstructure is different, which is demonstrated by the example of some micro-alloyed steels (37C, KL7D, DX52) and two grades of thermomechanically treated steels (X80TM, QStE690TM/StE690). The connection among the aluminium alloy groups of different microstructure is different, too, which is demonstrated by the example of some alloys (AlMg3, AlMg5.1Mn/AlMg5, AlMg4.5Mn) and one other alloy (7076-T6).

Comparison of the various material grades (e.g. micro-alloyed steels – aluminium alloys, or micro-alloyed steels – stainless steels) requires further investigations.

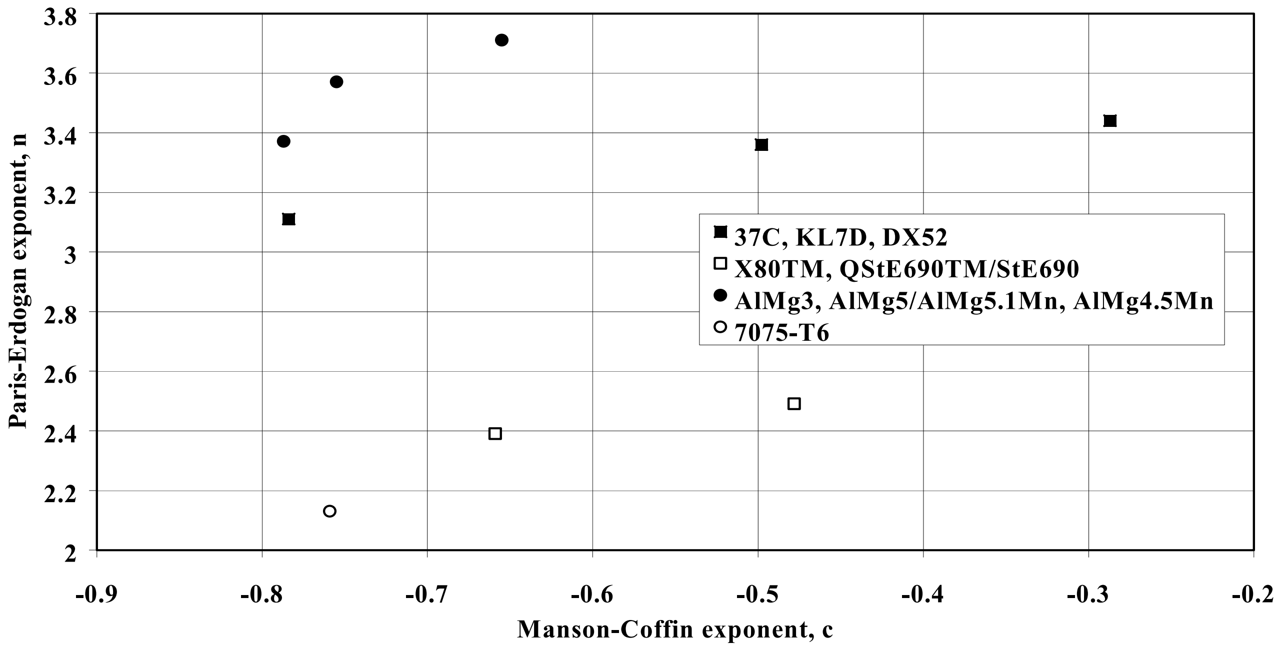

Figure 3: Connection between the exponents of Manson-Coffin and Paris-Erdogan equations

SUMMARY

Based on theoretical considerations and experiments the following establishments can be made. In the plastic zone in front of the crack tip the time dependence of the stress is similar in case of low cycle fatigue (LCF) and fatigue crack growth (FCG). The cyclic plastic deformation results in near the same cell type of dislocation structure. There is a connection between the exponents of the Manson-Coffin equation and the Paris-Erdogan law. The connection has been shown for different grades of steels and aluminium alloys.

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