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ULTRA HIGH CYCLE FATIGUE OF MATERIALS

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ABSTRACT: *This contribution gives a summary review of fatigue behavior of several different structural materials in the ultra high cycle region (gigacycle fatigue). According to obtained data it is obvious, that fatigue strength continuously decreases with increasing number of cycles to failure and there is no "plateau" parallel with x-axis. It is obvious, that fatigue limit σ_C determined at $N = 10^6 \div 10^7$ cycles does not fulfill the requirements of safety and reliability of machine components and to design a component that will work in the ultra high cycle fatigue region requires complete information about fatigue behavior of used material.*
KEYWORDS: *structural materials, ultra high cycle region, fatigue behavior*

INTRODUCTION

Fatigue is a frequent cause of unexpected failures of machine components and constructions [1-4]. Fatigue life is an important characteristic of all engineering components and it is measured by a number of cycles it can withstand before fatigue failure takes place. Fatigue results significance is especially from safety, reliability, ecology and economical point of view. Based on the fatigue life concept, the mechanical fatigue can be sub-divided into three categories: low cycle fatigue (LCF) – up to $N = 10^5$ cycles to failure, high cycle fatigue (HCF) – between $N = 10^5$ and $N = 10^7$ cycles to failure and ultra high cycle fatigue (UHCF) – over $N = 10^7$ cycles to failure [5-7]. Nowadays the UHCF (gigacycle fatigue) constitutes one of the main design criteria for a number of applications, for example: gas turbine disks ($N = 10^{10}$ cycles), car engine cylinder heads and blocks ($N = 10^8$ cycles), ball bearings, high frequency drilling machines, diesel engines of ships and high speed trains ($N = 10^9$ cycles), etc [5]. Research of fatigue behavior of materials in the UHCF region is very intensive in the last two decades, mainly with the use of high frequency loading testing machines ($f \approx 20$ kHz), so there is a new amount of fatigue data available in the form of S – N ($\sigma_a = f(N_f)$) curves. Besides this fact, there are still opened questions about fatigue behavior of materials in the UHCF. Discussed are questions about behavior of dependence $\sigma_a = f(N_f)$, what is the physical basis of fatigue limit, if the fatigue limit really exists, what are the degradation mechanisms when applying very low values of plastic deformation, short crack growth at extremely low rate, the role of inclusions, pores, shrinkages, long grain boundaries and surface and subsurface fatigue crack initiation. Also the influence of frequency and type of loading behind so called basic number of cycles ($10^6 < N < 10^7$ cycles) in different structural materials is discussed [1, 3].

This work publishes authors own experimental results of several different structural materials and gives a short review about fatigue behavior of these materials in the UHCF region.

EXPERIMENTAL

For fatigue life behavior analysis, several different structural materials were selected: AISI 316Ti stainless steel [8], C55 high grade carbon steel [9], AW 7075 aluminium alloy [10], AZ31 magnesium alloy [11], Ti6Al4V titanium alloy [12], EN-GJS-1200-2 austempered ductile iron [13] and bearing steel 100Cr6 [14]. Mechanical properties are listed in Tab. 1. For S – N ($\sigma_a = f(N_f)$) curve estimation were performed fatigue tests with the use of methods by authors [1, 15] at high – frequency sinusoidal cyclic push - pull loading (testing frequency $f \approx 20$ kHz, temperature $T = 20 \pm 10$ °C, cooled by distilled water with anticorrosive inhibitors or by compressive air, coefficient of cycle asymmetry $R = -1$) and with use of high frequency testing equipment KAUP-ŽU Žilina, SK [1, 15]. Smooth round bar specimens (min. 10 specimens for each tested material) with 4 mm in diameter ground and polished by metallographic procedures in the gauge length were used during the fatigue tests. The investigated number of cycles was in the region from $N \approx 10^6$ cycles to $N \approx 10^{10}$ cycles of loading.

Tab. 1. Mechanical properties of selected materials for fatigue tests

Material	R_e (MPa)	R_m (MPa)	A (%)
AISI 316Ti	251	773	54
C55	593	952	15
AW 7075	482	578	5
AZ31	167	185	10
Ti6Al4V	873	953	13
EN-GJS-1200-2	864	1164	4
100Cr6	2276	2462	1

RESULTS AND DISCUSSION

Results of fatigue tests in the form of S – N ($\sigma_a = f(N_f)$) curves are plotted in Fig. 1. According to this figure it is obvious, that the fatigue strength continuously decreases with increasing number of cycles to fracture in the whole tested region of cycles (for example steel C55: σ_a = 496 MPa for $N_f = 10^6$ cycles and σ_a = 330 MPa for $N_f = 10^9$ cycles; for steel 100Cr6 σ_a = 866 MPa for $N_f = 10^6$ cycles and σ_a = 745 MPa for $N_f = 10^9$ cycles). The rate of decrease can be observed in Fig. 2, which represents the dependence of ratio $\sigma_a/\sigma_{a10}{}^6$ vs. number of cycles to failure. The lowest rate of decrease is observable for Ti6Al4V titanium alloy, the highest rate of decrease for EN-GJS-1200-2 austempered ductile iron. The AISI 316Ti stainless steel, C55 high grade carbon steel and AZ 31 magnesium alloy have very similar rate of fatigue life decrease.

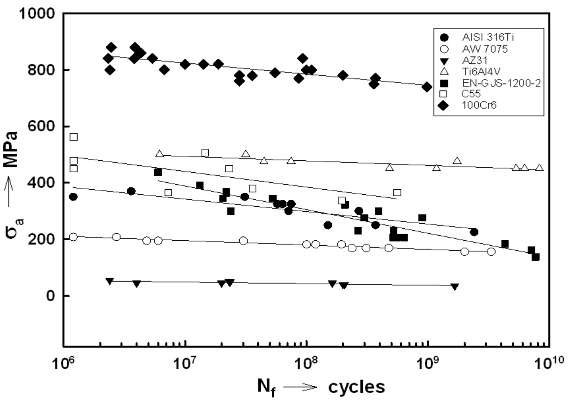

Fig. 1 S – N curves of selected materials

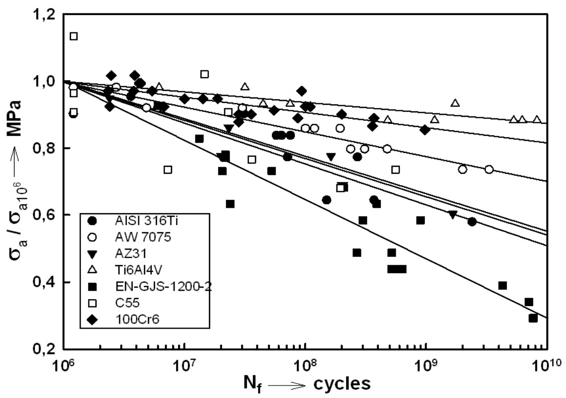

Fig. 2 Rate of fatigue life decrease

According to these results it is obvious, that there is no "plateau" parallel with the x-axis, and it can not be told, that there is constant amplitude of loading, under which the component can stand infinite number of cycles. The values of fatigue limit σ_C obtained at N = $10^6 \div 10^7$ cycles are overestimated and non – fulfill the demands of reliability and safety of machine components [16]. These facts can be shown for example at the steel C55 by comparison of N = 10^6 cycles vs. N = 10^9 cycles in the Smith diagram. Area of Smith diagram for steel C55 (Fig. 3) drown according to fatigue limit σ_C obtained at N = 10^6 cycles is much bigger, than the area of the diagram drown according to fatigue limit σ_C obtained at N = 10^9 cycles. Also, if we will obtain the fatigue limit σ_C from the tensile strength R_m according to approximate equations for fatigue limit evaluation at N = 10^7 cycles, for example: $\sigma_C = 0.5\ R_m$ (for steels with R_m < 1000 MPa) (1) [17], $\sigma_C = 0.5\ R_m \pm 70$ (for steels with R_m < 1100 MPa) (2) [18], $\sigma_C = 0.35\ R_m$ (for steels with R_m from 500 MPa to 1500 MPa) (3) [19], $\sigma_C = 0.32 R_m$ and $\sigma_c = 100 + 0.17\ R_m$ (4) [20] (for ductile irons with R_m < 900 MPa) (5) [21], we do not get full and reliable information about fatigue behavior of the material. For example, the steel C55 had R_m = 952 MPa, the fatigue limit at N = 10^7 cycles obtained by fatigue tests was σ_C = 440 MPa and according to listed equations it should be: σ_C = 476 MPa (1), σ_C = 476 MPa ± 70 MPa (2), σ_C = 333 MPa (3), σ_C = 304 MPa (4).

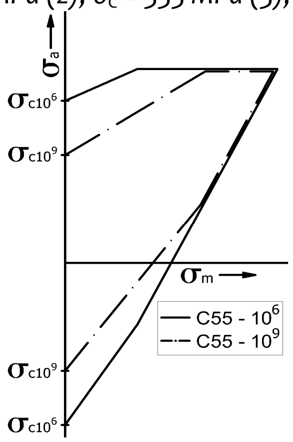

Fig. 3 Smith diagram for steel C55 drown for σ_C obtained at N = 10^6 and 10^9 cycles

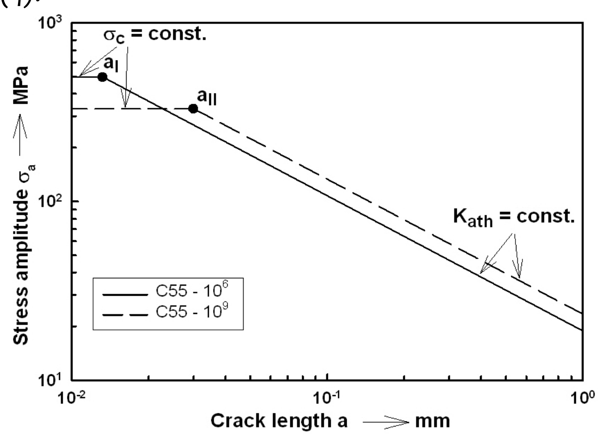

Fig. 4 Kitagawa – Takahashi diagram of steel C55 drown for N = 10^6 and 10^9 cycles

According to Kitagawa – Takahashi diagram for example at the steel C55 drown for N = 10^6 and 10^9 cycles (Fig. 4) it is obvious, that under cyclic loading with higher stress amplitude (K – T diagram for N = 10^6 cycles, intrinsic crack length a_I = 0.0132 mm) shorter cracks start to propagate then under cyclic *loading with lower stress amplitude (K – T diagram for N = 10^9 cycles, intrinsic crack length a_{II} = 0.0299 mm). Also the boundary between short and long crack is moving to bigger crack lengths with decrease of the loading amplitude [16].*

Many years ago it was reported that fatigue cracks initiation occurred from a small defects on the surface at high stress amplitude level and low number of cycles [22-24], but only in the last decade it was reported [25-28] that fatigue cracks starting from non-metallic inclusions in the subsurface zone of that at low stress amplitude level and ultra high number of cycles. This fact is observed mainly at high strength steels and surface hardened steels, see e. g. Fig.5 and Fig. 6, bearing steel 100Cr6 (R_m = 2462 MPa). Fatigue cracks were initiated from non-metallic inclusions (mainly TiN inclusions and with lower percent of occurrence also Al_2O_3 inclusions), inside the specimens. The TiN type inclusions have a very sharp shape and in the small localized area cause very high stress concentration with following fatigue crack initiation and propagation perpendicularly to the loading direction. Fatigue crack growth from the inside of defects (inclusions) can be assigned to the growth of microstructure short fatigue cracks (fish-eye area), whereby the later stage of crack growth is carried-out according to valid laws of long fatigue crack growth [1, 22]. In the case of low and middle strength steel, the fatigue cracks initiation is usually on the surface, see e. g. Fig. 7 and Fig. 8, steel C55 (R_m = 952 MPa). Subsurface fatigue crack initiation in the UHCF region is a microstructure related phenomenon which determines the fatigue lifetime, is associated with structural heterogeneities such as inclusions, microphores, microshrinkages, big and very small grains region and so on [14].

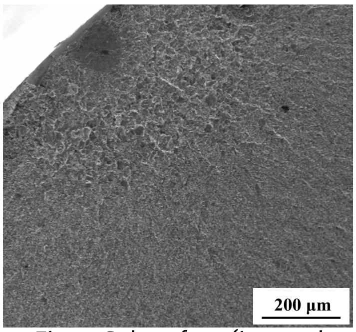

Fig. 5. Subsurface (internal defect-induced) fatigue crack initiation (REM), 100Cr6 bearing steel, push - pull loading, σ_a = 969 MPa, $N_f = 2.2 \times 10^7$ cycles

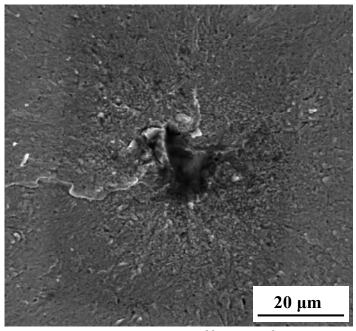

Fig. 6. Non-metallic inclusion located in the centre of the fish-eye(REM), 100Cr6 bearing steel, push-pull loading, σ_a = 780 MPa, $N_f = 3.6 \times 10^7$ cycles

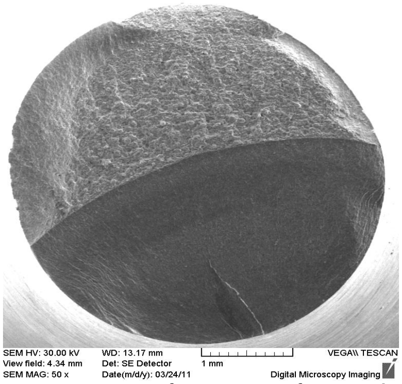

Fig. 7. Fatigue fracture surface with surface crack initiation (REM), C55 carbon steel, push – pull loading, σ_a = 450 MPa, $N_f = 2.3 \times 10^7$ cycles

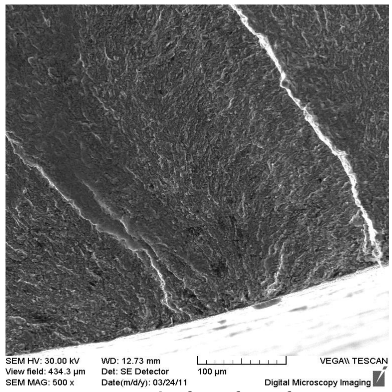

Fig. 8 Detail of surface fatigue crack initiation (REM), C55 carbon steel, push – pull loading, σ_a = 450 MPa, $N_f = 2.3 \times 10^7$ cycles

CONCLUSIONS

- *In all structural materials a continuous decrease of fatigue strength in dependence of cycles number to fracture is observable in the ultra high cycle region.*
- *From tested materials, the lowest rate of fatigue life decrease was observed for Ti6Al4V titanium alloy and the highest rate was observed for EN-GJS-1200-2 austempered ductile iron.*
- *The values of fatigue limit σ_C obtained at N = $10^6 \div 10^7$ number of cycles are overestimated and non – fulfill the demands of reliability and safety of machine components.*
- *Approximate equations for fatigue limit evaluation do not give correct information about fatigue life behavior of materials.*
- *The intrinsic crack length increases with decrease of loading amplitude and the boundary between short and long cracks moves to longer cracks also with decrease of loading amplitude.*
- *Subsurface fatigue crack initiation in the UHCF region induced from internal defects, mainly non-metallic inclusions occurs at high strength structural materials.*
- *Surface fatigue crack initiation was observed at the structural materials of lower strengths.*

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