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HIGH AND ULTRA – HIGH CYCLE FATIGUE OF C55 HIGH GRADE CARBON STEEL

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Abstract:
Article provides experimental results in the field of ultra-high cycle fatigue behaviour of C55 high grade carbon steel obtained at high-frequency loading (f ≈ 20 kHz, T = 20 ± 10 °C, R = -1). The results confirm a continuous decrease of fatigue lifetime beyond the conventional fatigue limit. Fatigue fracture surfaces were characterized by surface fatigue crack initiation in both high and ultra-high cycle region, what means that that influence of microstructure defects was not significant enough to cause the sub-surface crack initiation.

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High grade carbon steel, C55, ultra-high cycle fatigue, high-frequency loading, surface fatigue crack initiation

1. INTRODUCTION

Fatigue of structural materials is the dominant limiting state; more than 90 % of failures are caused by fatigue [1-4]. Fatigue failures can be observable in the low - cycle, high - cycle and also ultra - high cycle region. With the aim to extend the fatigue lifetime of machine components, the ultra - high cycle fatigue, at high - frequency loading (with the working frequencies about 20 kHz), is studied very intensively during last ten years [3,5-14]. In this work are stated experimental results from the field of ultra - high cycle fatigue of C55 high grade carbon steel obtained at high - frequency loading.

2. MATERIAL AND EXPERIMENTS

The C55 high grade carbon steel was used as an experimental material. This structural steel was heat treated by the procedure consisting of austenitization at 820 °C for 50 min, oil quenching and tempering for 90 min at 450 °C (cooled in calm air). Before the fatigue tests were carried out, other experimental works - quantitative chemical analysis, metallography analysis, tensile test and after fatigue tests fractography with using SEM, Tescan Vega microscope were conducted. The chemical composition and mechanical properties are given in Tab. 1. The microstructure of steel after the heat treatment is shown in Fig. 1 and it consists of tempered martensite.

Table 1. C55 high grade carbon steel, chemical composition (in weight %) and mechanical properties.

C	Mn	Si	Cu	Ni
0.52	0.70	0.34	0.15	0.06
Cr	P	S	UTS (MPa)	A (%)
0.16	0.008	0.005	952	15.7

The fatigue tests were realized by using methods presented in [3, 5, 13], at high – frequency sinusoidal cyclic tension-compression loading (testing frequency f ≈ 20 kHz, temperature T = 20 ± 10 °C, cooled by distilled water with anticorrosive inhibitors, coefficient of cycle asymmetry R = -1) and with use of the high frequency testing equipment KAUP-ŽU Žilina, SK. Smooth round bar specimens (10 pieces) with gage length diameter of 4 mm, polished by metallography procedures in the central gage length part, were used during the fatigue tests. The ultra-high cycle fatigue lifetime was investigated in the region from $N \approx 10^6$ cycles to $N \approx 10^9$ cycles of loading.

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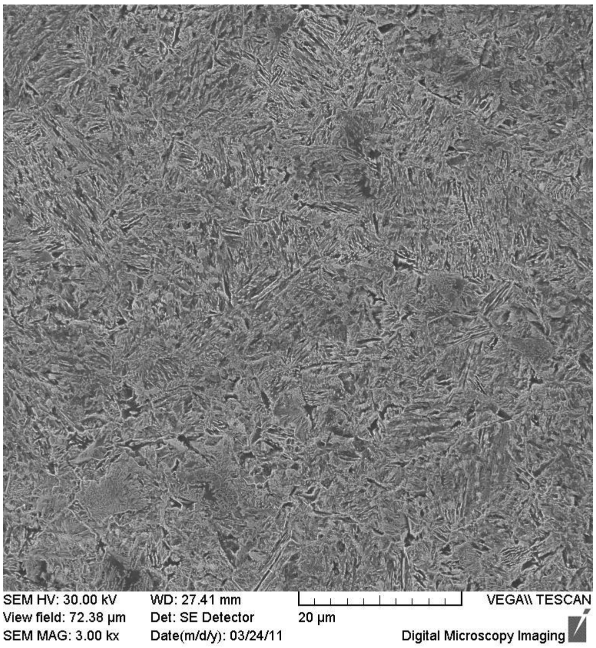

Fig. 1. Microstructure of high - grade carbon steel, SEM, (etched by Nital).

3. RESULTS AND DISCUSSION

Results of high – frequency cyclic loading, the dependence of stress amplitude vs. number of cycles, are shown for the high grade carbon steel in Fig. 2. Fatigue lifetime is characterized by a continuous decrease of fatigue life with increasing number of cycles over the whole region of fatigue loading.

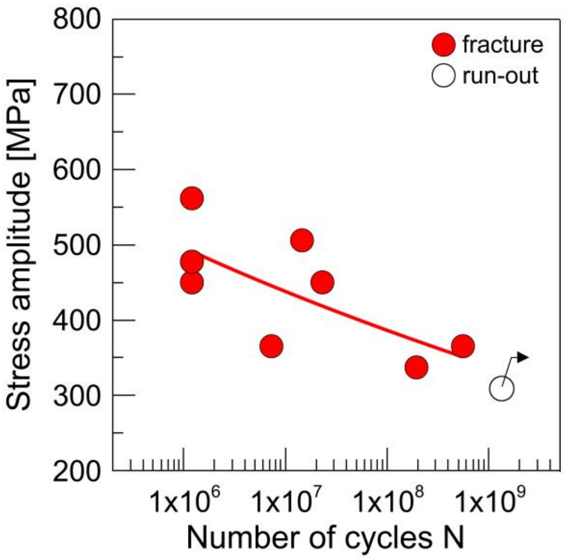

Fig. 2. S - N diagram, high grade carbon steel, high – frequency fatigue loading.

The loading stress range between high and ultra-high cycle fatigue loading $\Delta\sigma_a \approx 150$ MPa ($10^6 < N < 10^9$ cycles of loading) is comparable to results of authors of [8-14] which presented values from $\Delta\sigma_a \approx 20$ MPa to $\Delta\sigma_a \approx 200$ MPa (higher values were experimentally obtained for high strength steels or surface strain hardening steels). The surface fatigue crack initiation, Fig. 3 and Fig. 4, was observed even despite the fact that surface does not have a decisive role in starting of fatigue degradation mechanisms in the ultra – high cycle region (in the ultra-high cycle region the subsurface crack initiation is mainly observed, structural heterogeneity plays a very important role, "fish eyes" are created and as initiation places serve inclusions, microdefects, shrinkages, very small grains, long grain boundaries and so on [15-18]).

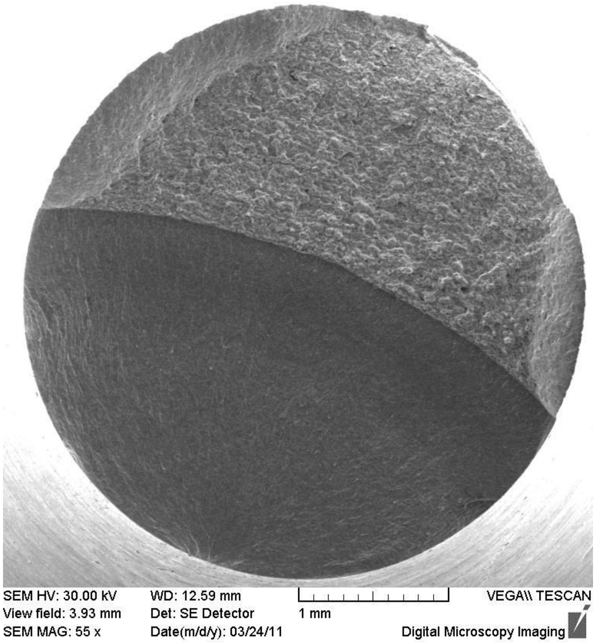

Fig. 3. Surface fatigue crack initiation $\sigma_a = 450$ MPa, $N = 2.3 \times 10^7$ cycles.

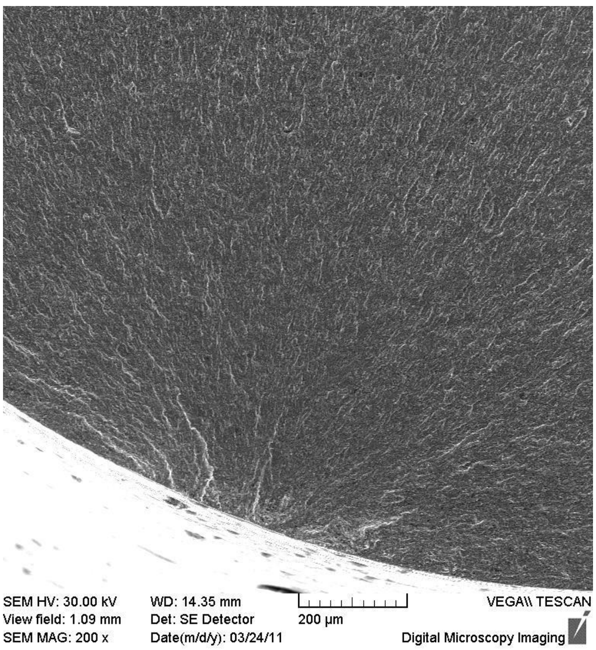

Fig. 4. Surface fatigue crack initiation detail $\sigma_a = 450$ MPa, $N = 2.3 \times 10^7$ cycles.

After the surface initiation, the crack grows under the stable conditions through a large part of the cross-section, what is shown in Fig. 5. When the cross-section becomes very weak, the crack passes from stable growth to unstable growth as can be observed in Fig. 6. For the remaining portion of the cross-section is characterized by the ductile fracture with dimple morphology (upper right-hand corner in Fig. 6) [17, 18].

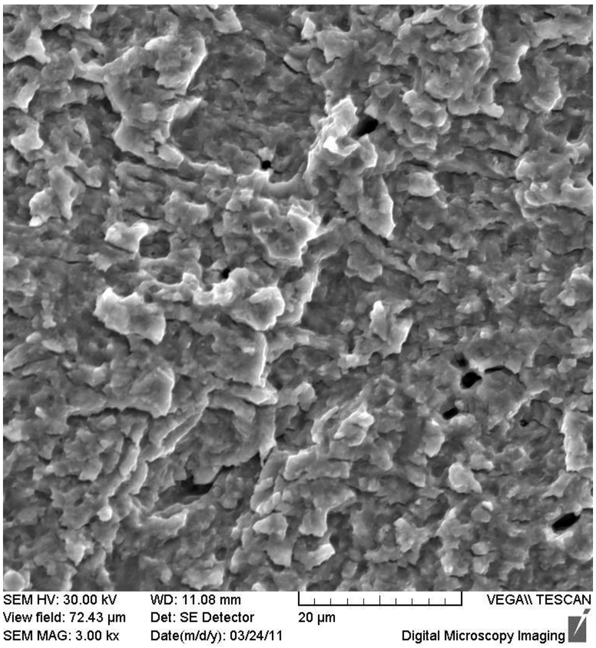

Fig. 5. Detail of stable crack growth, σ_a = 450 MPa, N = 2.3 x 10^7 cycles.

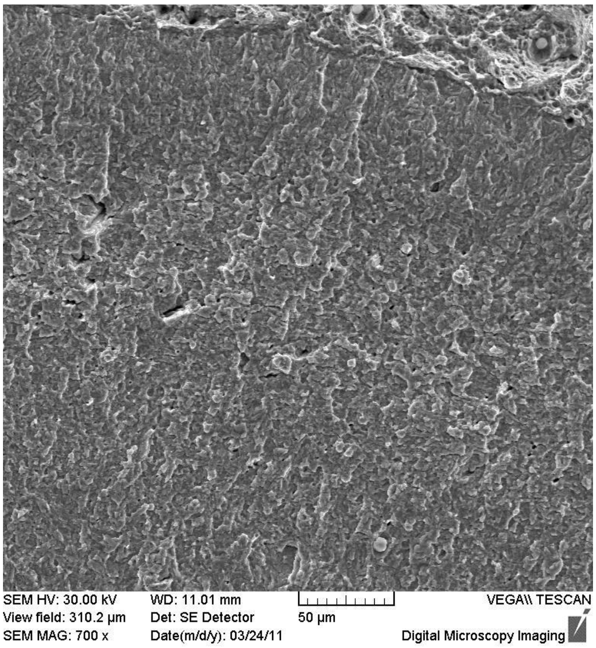

Fig. 6. Boundary between stable and unstable crack growth, σ_a = 450 MPa, N = 2.3 x 10^7 cycles.

4. CONCLUSIONS

With regards to obtained data the following conclusions can be drawn:

- the S-N curve has a fluently decreasing character in the whole studied region of loading cycles,
- the surface fatigue crack initiation in the ultra-high cycle region was observed only,
- the results about the fatigue limit, referred to number of cycles from N = 10^6 cycles to N = 10^7 cycles, are overestimated and do not fulfil the modern requirements for reliability and safety,
- the value of “fatigue limit” at N > 10^7 cycles (for steels and cast irons) can be determined only as conventional value related to specified number of cycles.

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