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SAFETY OF CONSTRUCTION COMPONENTS IN A VERY HIGH NUMBER OF LOAD CYCLES

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Abstract: Progressive, high-strength materials have an important position in the transport industry. In this industry, components are subject to high safety and reliability requirements because they often operate under long-term cyclic stress regimes. The paper presents results of fatigue resistance of high-strength materials such DOMEX 700MC, HARDOX 400, HARDOX 450, and INCONEL 718 (UTS from 850 to 1560 MPa) measured at high-frequency cyclic loading (f = 20 kHz, T = 20 ± 5 ° C, push-pull loading, cycle asymmetry parameter of R = -1) in the area from N = $2x10^6$ to N = $2x10^8$ cycles. Fatigue resistance showed a continuous decrease about average value $S_{a\ 2x10^8}/S_{a\ 2x10^6}$ = 19.1%.

Keywords: high-strength materials, fatigue resistance, push-pull loading, high-frequency, S – N curves

1. INTRODUCTION

Degradation fatigue mechanisms are dominant in the area of limit states of components and structures. More than 90% of all fractures are fracture caused by material fatigue. Targeted research, both theoretical and experimental, of low-cycle and high-cycle fatigue of materials, began in the mid-19th century. For the area of high cycle fatigue the fatigue limit S_c has been defined as the highest amplitude of fluctuating stress at a certain mean stress S_m which can material theoretically withstand for an infinite number of cycles. The infinite number of cycles was stated for steels from $N_c = 2.10^6$ to $N_c = 1.10^7$ cycles of loading. But the research institutes demonstrably noticed a decrease of material fatigue characteristics after mentioned number N_c of loading cycles. This fact was the reason for both theoretical and experimental research of fatigue degradation mechanisms in the field of very high cycle fatigue ($10^7 < N_c < 10^{10}$ cycles) at the end of the 20th century. There are studied the question about the physical nature of fatigue limit and the existence of fatigue limit, degradation fatigue mechanism when applying very low amplitudes of plastic deformation, growth of short fatigue cracks with extremely low rates role of inclusions, pores, long-grain boundaries, surface and subsurface fatigue cracks initiation, the shape of S_a – N curves (step-wise or duplex) and so on

(Bathias, 1999; Bathias and Paris, 2005; Bokůvka et al., 2002; Bokůvka et al., 2014, Hőppel et al., 2010; Chapetti, 2010; Kazymyrovich, 2009; Lukáš et al., 2011; Nový et al., 2007; Ritchie, 1981; Stanzl-Tschegg, 1999; Stanzl-Tschegg and Mayer, 2001; Vaško et al., 2017; Belan et al., 2019).

The specific problem of fatigue properties analysis after $N_c = 1.10^7$ cycles loading is, that it is very time-consuming which increases with the increasing number of loading cycles ($10^7 < N_c < 10^{10}$ cycles). The new experimental methods are developed in this period and the dominant position has methods based on high-frequency cyclic loading with working frequencies from f = 20 000 to 40 000 Hz where time-saving is significant. With using the testing device for high-frequency fatigue tests we can obtain fatigue characteristics of construction materials e.g. fatigue lifetime in the range of $N = 1.10^{4÷5}$ to 1.10^{10} cycles, rate of growth of long cracks from $d_a/d_N \approx 1.10^{-8}$ to 1.10^{-12} m. cycle^{-1}, threshold values K_{ath} for $d_a/d_N \approx 1.10^{-12}$ m. cycle^{-1} and dynamic modulus of elasticity E_D (Bathias, 2006; Trško, 2018).

The issue of fatigue damage to engineering materials, especially in the automotive industry, has undergone significant changes in the last decade. Car manufacturers are forced to constantly reduce the construction weight of cars and thereby reduce emissions, which has a positive impact on the environment. This is only possible with the use of progressive engineering materials and processing technologies, where the limits of material usability are shifted to the limit states. High-grade, low-alloy, high-strength steels and nickel superalloys with high Yield stress to Ultimate Tensile Stress (YS /UTS) ratio are very often used in the transport industry. With this in mind, they must meet increased safety and reliability requirements while respecting environmental and economic issues. Resistance to degradation fatigue processes is one of the most important requirements for these materials and is targeted experimentally (Skočovský et al., 2000).

In this work there are stated an experimental result from the field of study of fatigue life of structural steels DOMEX 700MC, HARDOX 400, HARDOX 450 and Ni-based superalloy INCONEL 718 obtained in the region of ultra-high number of cycles with using of high-frequency testing methods (push-pull loading with a cycle asymmetry parameter of R = -1).

2. EXPERIMENTAL MATERIALS AND METHODS

In this work, the fatigue lifetime of three structural steels and one Ni-based superalloy was experimentally studied. There were carried out the qualitative and quantitative chemical analysis, tensile tests and fatigue test. Chemical analysis was performed with the help of emission spectrometry on an ICP (JY 385) emission spectrometer using a fast recording system image. The chemical composition of experimental materials in wt.% are shown in Table 1.

Tensile tests were carried out on Zwick Z050 testing machine at the ambient temperature of T = 20 ± 5°C, with the loading range in interval F = 0 – 20 kN and strain velocity of $\acute{\varepsilon}_m = 10^{-3} s^{-1}$. Round cross-section specimens were used; the shape and dimensions of test specimens met the requirements of EN 10002-1 standard (3 specimens were used).

Fatigue tests were carried out at high-frequency sinusoidal symmetrical cyclic push-pull loading (f = 20 kHz, T = 20 ± 5°C, R = -1, cooled by distilled water with anti-corrosive inhibitor) and with use of high-frequency fatigue testing device, see Fig. 1. The high-frequency fatigue testing device consists of an ultrasonic generator, piezoelectric transducer, booster, exponential concentrator and test specimen. The electric power from the ultrasonic generator is transferred to mechanical vibration in the piezo-ceramic converter of the ultrasonic horn. This causes vibration at both ends of the specimen at the resonance frequency. The power is increased until the requested displacement amplitude is obtained (measured by deformation amplitude reader on the end of the specimen). A resonance fatigue testing device allows fatigue test to be performed with symmetrical push-pull loading (R = -1) at a frequency of f = 20 kHz in the temperature interval of T = 20 ± 5°C.

Table 1

The chemical composition of experimental materials in wt.%

Exp. Material	**C**	**Mn**	**Si**	**Ti**	**Al**	**Mo**	**Cr**	**Ni**	**Nb**	**V**	**B**
DOMEX 700MC	0.08	1.67	0.35	0.015	0.015	-	-	-	0.06	0.014	-
HARDOX 400	0.13	0.95	0.30	-	-	0.04	0.25	0.06	-	-	0.002
INCONEL 718	0.043	0.074	0.158	0.835	0.51	2.82	22.3	52.0	4.33	0.046	0.314
HARDOX 450	0.20	0.80	0.39	-	-	0.01	0.45	0.05	-	-	0.001

Source: Own measurements

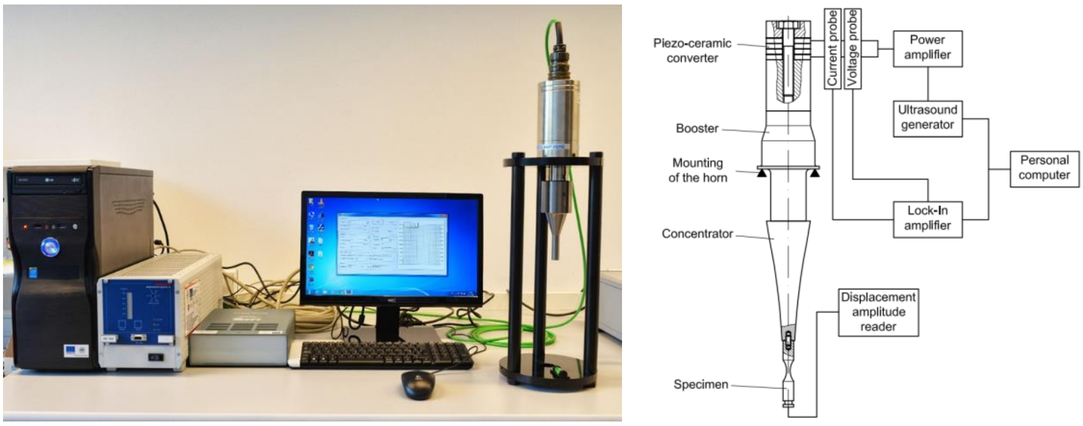

Fig. 1. High-frequency fatigue testing device including a schematic diagram of the construction

Smooth round bar specimens (min. 8 pieces) shown in Fig. 2, with a diameter of 4mm, ground and polished by metallographic procedures were used for the fatigue tests (Trško et al., 2018). The investigated region of the number of cycles ranged from $N \cong 2x10^6$ to $N \cong 2x10^8$ cycles of loading.

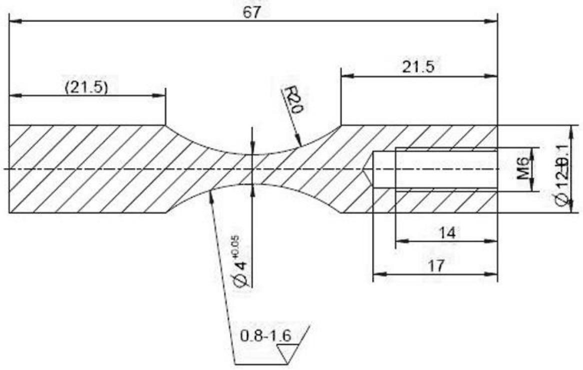

Fig. 2. Specimen shape and dimensions for high-frequency fatigue test

3. RESULTS AND DISCUSSION

The results obtained during an experimental works, qualitative and quantitative chemical analysis (chemical composition), tensile test (yield point of tension YS0.2, ultimate tensile strength UTS, elongation and reduction of area) and high-frequency fatigue tests in the region ranged from N = 2x10^6 to N = 2x10^8 cycles of loading ($S_{a\ 2x10^6}$, $S_{a\ 2x10^8}$, $S_{a\ 2x10^6}$/UTS, $S_{a\ 2x10^8}$/UTS and ratio $S_{a\ 2x10^8}/S_{a\ 2x10^6}$) are shown in Tables 1-3 and example of S-N curve results for INCONEL 718 in Fig. 3. In experiments were tested high-strength weldable steels DOMEX 700MC, HARDOX 400 and HARDOX 450 with increased yield strength YS0.2 (ratio YS0.2/UTS for DOMEX 700MC = 0.94, HARDOX 400 = 0.97 and HARDOX 450 = 0.91). These steels meet weldability conditions with carbon content up to C_{max} = 0.2% and carbon equivalent up to $C_E \leq 0.45$ (DOMEX 700MC C_E = 0.36, HARDOX 400 C_E = 0.35 and HARDOX 450 C_E = 0.42).

Table 2
Mechanical properties of experimental materials

Exp. Material	**YS0.2 [MPa]**	**UTS [MPa]**	**Elongation [%]**	**Reduction area [%]**	**YS0.2/UTS**
DOMEX 700MC	796	850	15.5	36.1	0.94
HARDOX 400	1226	1257	12.5	49.1	0.97
INCONEL 718	1034	1275	12.0	15.0	0.81
HARDOX 450	1425	1560	13.5	38.0	0.91

Source: Own study

For most applications, INCONEL 718 is specified as solution annealed and precipitation hardened (precipitation hardening, age hardening, and precipitation heat treatment are synonymous terms). INCONEL 718 is hardened by the precipitation of secondary phases (gamma prime and gamma double-prime) into the metal matrix. The precipitation of these Ni_3(Al, Ti, Nb) phases is induced by heat treating in the temperature range of 594 to 815°C. For this metallurgical reaction to properly take place, the ageing constituents (aluminium, titanium, niobium) must be in solution (dissolved in the matrix); if they are precipitated as some other phase or are combined in some other form, they will not precipitate correctly and the full strength of the alloy with not be realized.

Table 3
Stress amplitude S_a at various number of cycles to failure and its ratio to UTS

Exp. Material	**$S_{a\ 2x10^6}$ [MPa]**	**$S_{a\ 2x10^8}$ [MPa]**	**$S_{a\ 2x10^6}$ / UTS**	**$S_{a\ 2x10^8}$ / UTS**	**$S_{a\ 2x10^8}$ / $S_{a\ 2x10^6}$**
DOMEX 700MC	425	335	0.50	0.39	0.788
HARDOX 400	500	410	0.39	0.32	0.828
INCONEL 718	413	330	0.32	0.25	0.799
HARDOX 450	551	455	0.35	0.29	0.825

Source: Own study

If fatigue strength is of prime importance, INCONEL 718 forgings can be used in the annealed rather than the annealed and aged condition; ageing raises fatigue strength only slightly. Room-temperature high-frequency fatigue properties of annealed and aged INCONEL 718 specimens are in Fig. 3.

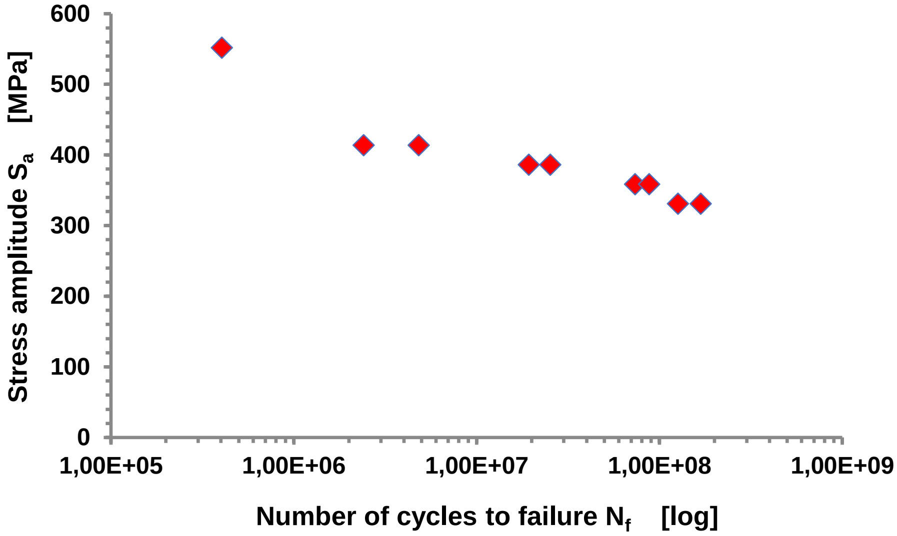

Fig. 3. The S – N curve at room-temperature high-frequency fatigue push-pull tests of annealed and aged INCONEL 718

Grain size is a major factor in the achievement of high fatigue strength. Its effect can be seen in Fig. 4. Our alloy was vacuum induction melted and vacuum arc remelted with conditions as follows: at 980°C/1 hr. and air-cooled then at 720°C/8 hrs. aged and cooled down with speed 50°C/hr. to 620°C held for 8 hrs. and then air-cooled. The average grain size was ASTM 12 (which corresponds from 4.2 to 5.9μm of grain size).

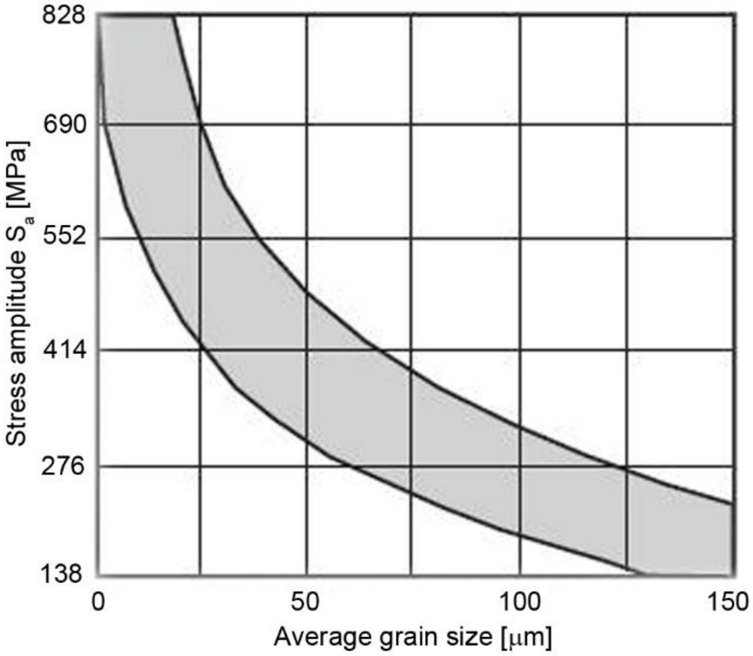

Fig. 4. Effect of grain size on endurance limit (10^8 cycles) of annealed and aged in accordance with the procedure described above of INCONEL 718

The fatigue lifetime, the stress amplitude Sa dependence from the number of cycles N decrease continuously in the tested region of loading cycles for all experimental materials. As an example, the stress amplitude Sa depends on the number of cycles N for the INCONEL 718, Fig. 3. The step-wise or duplex S – N curves were not observed. The values $S_{a\ 2x10^8}/S_{a\ 2x10^6}$ of tested structural materials ranged from ΔS_a = 83 MPa to ΔS_a = 96 MPa, the percentage decrease is from 17.5% to 21% (with an average value of 19%), see results in Table 4. This fact is in good agreement with works (Bathias, 1999; Bathias and Paris, 2005; Bokůvka et al., 2002; Bokůvka et al., 2014; Kazymyrovich, 2009; Stanzl-Tschegg and Mayer, 2001).

Table 4

Difference of stress amplitude ΔS_a and its percentage decreasing

Exp. Material	**$\Delta S_a = S_{a\ 2x10^6} - S_{a\ 2x10^8}$**	**Percentage decreasing**
DOMEX 700MC	90	21%
HARDOX 400	90	18%
INCONEL 718	83	20%
HARDOX 450	96	17.5%

Source: Own study

The facts mentioned above must be respected if we use these materials in the construction of parts and equipment and will be work in the ultra-high region of loading cycles. The authors have experimentally verified the effect of stress amplitude drop (ΔS_a, $\Delta S_{a\ 2x10^9}$ vs. $\Delta S_{a\ 2x10^6}$) on the design of components. Changes in design, shape and dimensions respecting safety and reliability were evident (Bokůvka et al., 2019; Faturík et al., 2014; Nový et al., 2016, Ulewicz and Mazur, 2013).

4. CONCLUSIONS

Based on the experimental work carried out in the field of fatigue resistance of high-strength steels and Ni-based superalloy it is possible to state:

- Fatigue resistance of structural materials, the dependence of stress amplitude S_a vs. the number of cycles N had a decreasing character over the entire tested area of the number of load cycles ($2x10^6 < N < 2x10^8$).
- No step–wise or duplex character of S – N dependence was observed in this area.
- The average percentage decrease of S_a in the given number of cycles ($2x10^6 < N < 2x10^8$) was 19.1%.
- Values determined at $2x10^6$ to $1x10^7$ of load cycles are overestimated and do not meet the reliability and safety criteria.
- The above-mentioned facts have to be respected in the design of components if their application in the area of the very high number of loading cycles is expected.

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