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Safe choice of structural steels in a region of ultra-high number of load cycles

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Abstract
In this paper the authors introduce their own selected experimental results in the field of the investigation of fatigue resistance of structural steels. The experiments were carried out on the nine structural steels including high strength steels, DOMEX 700MC, HARDOX 400, HARDOX 450, 100Cr6 (UTS from 446 MPa to 2462 MPa) at high-frequency cyclic loading (f = 20 kHz, T = 20 ± 5 °C, R = -1) in the region of number cycles ranged from $N \approx 2\times10^6$ to $N \approx 2\times10^9$ cycles of loading. The continuous decrease of fatigue strength in dependence on the number of loading cycles was observed with the average value of ratio $\sigma_{a2\times10}{}^9/\ \sigma_{a2\times10}{}^6 = 0.69$.

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1. Introduction

Fatigue resistance of structural materials began to be experimentally studied at the beginning of the 19th century. The strain or stress vs. number of cycles (S-N, $\sigma_a = f(N)$) dependence including conventional fatigue limit usually referred to as $N = 2\times10^6 \div 10^7$ cycles (steels and cast irons) are the main parameters used at evaluation of fatigue resistance of structural materials. However, targeted research the fatigue fractures occur not only at low, high but also at ultra-high cycle region of loading.

Modern industry is focused on the increase of the performance of industrial equipment. This fact is connected with prolongation of fatigue life of individual parts of the equipment where, on the other hand, safety is the most important factor. With the aim to prolong the service life of parts was the fatigue resistance of structural steels in the region from $N \approx 1\times10^6$ cycles to $N \approx 1\times10^{10}$ cycles intensively studied during last years. In this region of ultra-high cycle loading are open questions about the influences of cyclic plasticity processes at very low loading amplitudes, surface and sub-surface fatigue crack initiation, micropurity, microstructural heterogeneity, inclusions, holes, shrinkages, pores, grain size, long grain boundaries and their effect on fatigue behaviour. Moreover, the fatigue limit existence and physical nature, shape of S-N, $\sigma_a = f(N)$ curve, type of loading and frequency influence are discussed intensively. Research in this field has shown that in structural materials (steels and cast irons) fatigue strength decrease continuously with increasing number of loading cycles even behind, in past sufficient, $N = 2\times10^6$ - 2×10^7 cycles. For this reason, is necessary to know values of fatigue strength in region of ultra-high number of cycles loading, if designing structural parts are intended to be cyclic loaded in this region (Bathias et al., 2004; Bathias et al., 1999, Bokůvka et al., 2002; Bokůvka et al., 2014; Nový et al., 2012; Chapetti, 2010).

The study of fatigue resistance of structural materials with the use of low-frequency loading (f = 10 - 200 Hz) in the region of ultra-high number of loading cycles is time consuming. Using of high-frequency, ultrasonic fatigue testing devices is therefore necessity. Time and economical effectiveness of the determination of the fatigue characteristics of structural materials is evident (Bokůvka et al., 2002; Bokůvka et al., 2014; Kazymyrovych et al., 2009; Stanzl-Tschegg, 1999; Trško et al., 2018, Höppel et al., 2010).

In this paper the authors introduce their own experimental results from the field of fatigue resistance of structural steels obtained in the region of ultra-high number of loading cycles.

2. Experimental

Experimental works, the quantitative chemical analysis, tensile tests, fatigue test were carried out on the nine structural steels incl. high strength steels (DOMEX 700MC, HARDOX 400, HARDOX 450, 100Cr6). Chemical analysis was performed with the help of emission spectrometry on an ICP (JY 385) emission spectrometer using a fast recording system Image. Tensile tests were carried out on a ZWICK Z050 testing machine at ambient temperature of T = 20 ± 5 °C, with the loading range in interval F = 0 – 20 kN and the strain velocity of $\dot{\varepsilon}_m = 10^{-3}\ s^{-1}$. Round cross-section specimens were used; the shape and dimensions of the test specimens met the requirements of EN 10002-1 standard (3 specimens were used). Fatigue tests were carried out at high-frequency sinusoidal cyclic tension-compression loading (f = 20 kHz, T = = 20 ± 5 °C, R = -1, cooled by distilled water with anticorrosive inhibitor) and with the use of ultrasonic fatigue testing device, see Fig. 1. Smooth round bar specimens (min. 10 pieces) shown in Fig. 2, with diameter of 4 mm, ground and polished by metallographic procedures were used for the fatigue tests (Trško et al., 2018). The investigated region of number of cycles ranged from $N \approx 2\times10^6$ to $N \approx 2\times10^9$ cycles of loading.

Fig. 1. Ultrasonic fatigue testing device for fatigue testing at f = 20 kHz

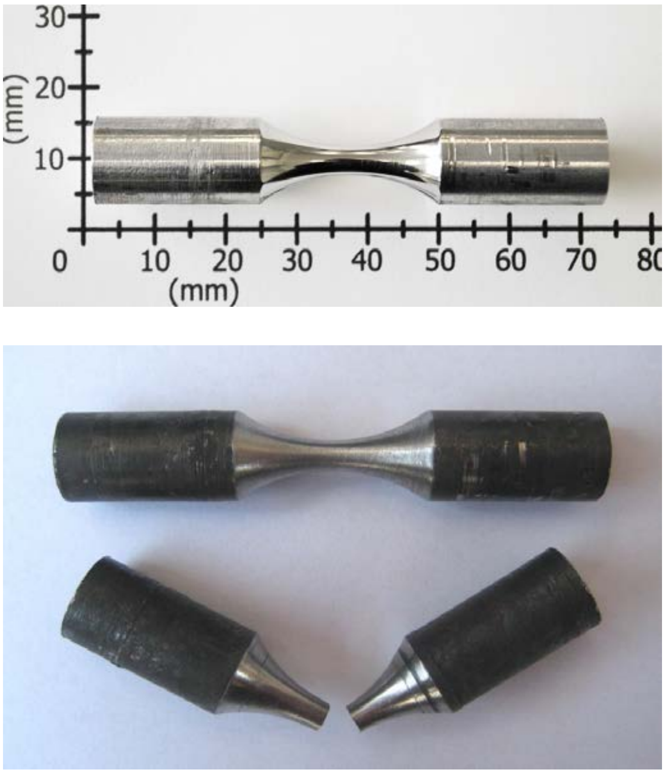

Fig. 2. Ultrasonic fatigue test specimen

3. Results and discussion

Summarize the analysis performed corrective actions can The results of quantitative chemical analysis (chemical composition), tensile tests (yield point in tension YS, YS0.2, ultimate tensile strength UTS, elongation A5, reduction of area Z and high-frequency fatigue tests ($\sigma_{a2\times10}{}^6$, $\sigma_{a2\times10}{}^9$, $\sigma_{a2\times10}{}^6$/Rm, $\sigma_{a2\times10}{}^9$/Rm, $\sigma_{a2\times10}{}^9/\sigma_{a2\times10}{}^6$) are shown in Table 1, 2, 3 and Fig. 3. The fatigue strength progressively declined in all tested steels.

Table 1. Chemical composition (in weight %) of tested structural steels

Steel	C	Mn	Si	N	Ti	Al	Mo	Cr	Ni	Cu	P	S	Nb	V	B
1	0.17	0.51	0.17	-	-	-	-	0.03	0.04	0.06	0.013	0.013	-	-	-
2	0.18	1.47	0.03	-	-	-	-	0.03	0.02	0.04	0.015	0.011	-	-	-
3	0.058	1.63	0.81	-	0.37	-	2.54	17.55	12.96	-	0.033	0.037	-	-	-
4	0.08	1.67	0.35	-	0.015	0.015	-	-	-	-	0.018	0.0037	0.06	0.014	
5	0.08	1.62	0.12	0.061	0.17	0.049	0.14	-	-	-	0.030	0.025	-	-	-
6	0.52	0.70	0.34	-	-	-	-	0.16	0.06	0.15	0.008	0.005	-	-	-
7	0.13	0.95	0.30	-	-	-	0.04	0.25	0.06	-	0.012	0.002	-	-	0.002
8	0.20	0.80	0.39	-	-	-	0.01	0.45	0.05	-	0.005	0.005	-	-	0.001
9	1.10	0.34	0.28	-	0.163	0.009	0.009	1.48	0.1	0.12	0.001	0.01	-	0.033	-

Table 2. Mechanical properties of tested structural steels

Steel	YS/YS0.2 [MPa]	UTS [MPa]	A_5 [%]	Z [%]
1	340	446	30.8	8.0
2	376	564	28.4	41.7
3	251	773	54.0	48.0
4	796	850	15.5	36.1
5	710	867	20	-
6	-	952	15.7	-
7	1226	1257	12.5	49.1
8	1425	1560	13.5	38.0
9	2276	2462	1.0	-

Table 3. Fatigue results of tested structural steels

Steel	$\sigma_{a2\times10^6}$ [MPa]	$\sigma_{a2\times10^9}$ [MPa]	Fatigue ratio $\sigma_{a2\times10^6}$/UTS	Fatigue ratio $\sigma_{a2\times10^9}$/UTS	Ratio $\sigma_{a2\times10^9}/\sigma_{a2\times10^6}$
1	285	201	0.63	0.45	0.70
2	352	210	0.62	0.37	0.59
3	408	288	0.52	0.37	0.70
4	425	265	0.50	0.31	0.62
5	390	288	0.44	0.33	0.73
6	548	350	0.57	0.36	0.63
7	500	352	0.39	0.28	0.70
8	551	400	0.35	0.25	0.72
9	891	741	0.36	0.30	0.83

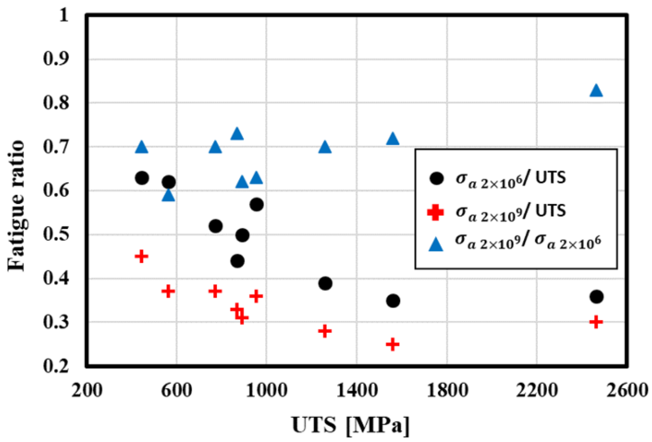

Fig. 1. Fatigue results $\sigma_{a2\times10^6}$ (●), $\sigma_{a2\times10^9}$ (+), $\sigma_{a2\times10^9}/\sigma_{a2\times10^6}$ (▲) vs. UTS of tested structural steels

The step-wise or duplex σ_a – N curves were not observed. The values $\sigma_{a2\times10^6}$ vs. $\sigma_{a2\times10^9}$ cycles of tested structural steels ranged from $\Delta\sigma_a$ = 84 MPa to $\Delta\sigma_a$ = 198 MPa. This fact is in a good agreement with works (Bokůvka et al., 2012; Bokůvka et al., 2014; Bathias et al., 2004; Ulewicz et al., 2013; Szataniak, 2016; Ulewicz et al., 2014).

where $\Delta\sigma_a$ is given from $\Delta\sigma_a$ = 20 MPa to $\Delta\sigma_a$ = 200 MPa. From the Tab. 3 is visible the influence of tested structural steel ultimate tensile strength UTS on the fatigue properties. The structural steel with high ultimate tensile strength UTS level exhibit the high values of $\sigma_{a2\times10^6}$ and $\sigma_{a2\times10^9}$; more precisely thresholds for fatigue crack initiation. In contrary the thresholds for cracks growth (defect tolerant approach) are decreased. The fatigue ratio is decreasing from 0.63 to 0.35 ($\sigma_{a2\times10^6}$), from 0.45 to 0.25 ($\sigma_{a2\times10^9}$), decreasing $\sigma_{a2\times10^6}$ vs. $\sigma_{a2\times10^9}$ with number of cycles increasing (N = 2×10^6 vs. N = 2×10^9 cycles of loading). The average value of ratio $\sigma_{a2\times10^9}/\sigma_{a2\times10^6}$ is about 0.69. Microstructural factors which improve resistance to fatigue crack growth do not necessarily guarantee improved resistance to crack initiation and philosophy of short cracks must be considered (Ritchie, 1981).

4. Conclusion

Based on the results of the fatigue tests it can be stated:

- in tested nine structural steels a continuous decrease of fatigue strength in dependence on the number of loading cycles was observable in the ultra-high region of loading cycles ($2\times10^6 < N < 2\times10^9$);
- the average value of ratio $\sigma_{a2\times10^9}/\sigma_{a2\times10^6}$ was 0.69;
- the values of conventional fatigue limit (usually referred to N = $2\times10^6 – 10^7$ cycles) are overestimated and, therefore, do not meet demands of safety of structural parts;
- these facts must be taken into consideration with reference to safety when designing structural parts in the ultra-high region of loading cycles.

Acknowledgements

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超高负载循环区域结构钢的安全选择

關鍵詞
结构钢
抗疲劳
超高周疲劳

摘要
在本文中，作者介绍了他们自己选择的结构钢抗疲劳性研究领域的实验结果。 实验在 9 种结构钢上进行，包括高强度钢，DOMEX 700MC，HARDOX 400，HARDOX 450,100Cr6（UTS 从 446 MPa 到 2462 MPa）在高频循环加载（f = 20kHz，T = 20±5℃，R = -1）在数周期范围内，从 N≈2×106 到 N≈2×109 个加载循环。 通过比率σa2×109 /σa2×106 = 0.69 的平均值观察到依赖于加载循环次数的疲劳强度的连续降低。