Daniel Varecha - Slavomir Hrcek - Otakar Bokuvka - Frantisek Novy - Libor Trsko - Ruzica Nikolic - Michal Jambor

FATIGUE SAFETY COEFFICIENTS FOR ULTRA - HIGH REGION OF LOAD CYCLES

In this paper the authors introduce results from the field of the fatigue safety of selected steels in the region of ultra - high number of loading cycles. The fatigue tests were carried out at high frequency tension - compression loading (f = 20 kHz, T = 20 ± 5°, R = -1) in the region from N = 10^6 to N = 10^9 cycles. The fatigue safety coefficients were calculated by four methods (Goodman, Gerber, ASME elliptic and Soderberg). The percentage reduction of the fatigue safety coefficients (N = 10^9 vs. N = 10^6 cycles) was at Goodman, 7.99 ÷ 10.83 %, Gerber, 5.27 ÷ 8.26 %, ASME, 1.89 ÷ 6.42 % and Soderberg, 6.51 ÷ 10.25 %.

Keywords: *structural steels, ultra - high cycles fatigue, safety coefficients*

1   Introduction

Fatigue is the dominant degradation mechanism during the operation of components and mechanical constructions. More than 90 % of all the fractures are caused by fatigue of the applied material. Targeted research, both theoretical and experimental, of the low - cycle and high - cycle fatigue of structural steels, began in the mid - 19th century. For the area of the high cycle fatigue, the fatigue limit σ_c was defined as the largest fluctuating stress at certain mean stress σ_m that the structural steel withstands for an infinite number of cycles. For steels, the so - called basic number of cycles N_c, in the range from $N_c = 10^6$ to 10^7 cycles, was recommended for an infinite number of cycles. However, research institutes have demonstrably noticed that fractures caused by fatigue occur in structural steels far beyond the so - called basic number $N_c = 10^7$ cycles. Conclusions on the safe loading and permanent fatigue strength beyond this cycle limit are inaccurate and incomplete. In view of this fact, at the end of the 20th century, both theoretical and experimental research of ultra - high - cycle fatigue, in the range from N = 10^7 to N = 10^{10} loading cycles, began. Questions are being verified, such as what is the course of dependence $\sigma_a = f(N)$, the physical nature of the fatigue limit σ_c, the existence of the fatigue limit, degradation fatigue mechanisms at very low values of the plastic deformation amplitude, propagation of short fatigue cracks at extremely low rates, the role of inclusions, long grain boundaries, pores, surface and subsurface initiation of fatigue cracks, etc. after the so - called basic number $N_c = 10^7$ load cycles in structural steels. The course of the dependence $\sigma_a = f(N)$, including the step - wise or duplex curves with a "plato" is discussed [1-7]. High - graded steels of medium and high strengths are

used in various industries. They have a specific place in the field of rails, tires, wings and hull transport. With regard to this state area of application, these steels are required to have a long service life and high reliability and safety, [8]. Determining the fatigue safety factor is important both from a theoretical point of view and from a practical point of view [9-13]. In this paper the authors introduce their own results from the field of the fatigue safety of selected steels in the region of ultra - high number of loading cycles.

2   Experimental

Experimental works, the qualitative and quantitative chemical analysis, tensile tests, fatigue test and the fatigue coefficient k_u calculations, were carried out on eight structural steels including high strength steels (DOMEX 700MC, HARDOX 400, HARDOX 450). Chemical analysis was performed with help of the 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 rate of $\dot{\varepsilon}_m = 10^{-3} s^{-1}$. The round cross - section specimens were used, the shape and dimension of specimens have met requirements of the EN 10002 - 1 standard (3 specimens for each steel were used). The 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 use of the ultrasonic fatigue testing device. Smooth round bar specimens (minimum 10 pieces) with diameter of 4 mm, ground and polished by metallographic procedures, were used for the fatigue test [14-15]. The investigated

Daniel Varecha[1,*], Slavomir Hrcek[1], Otakar Bokuvka[1], Frantisek Novy[1], Libor Trsko[2], Ruzica Nikolic[2], Michal Jambor[3]
[1]Faculty of Mechanical Engineering, University of Zilina, Slovak Republic
[2]Research Centre, University of Zilina, Slovak Republic
[3]Institute of Physics of Materials, Brno, Czech Republic
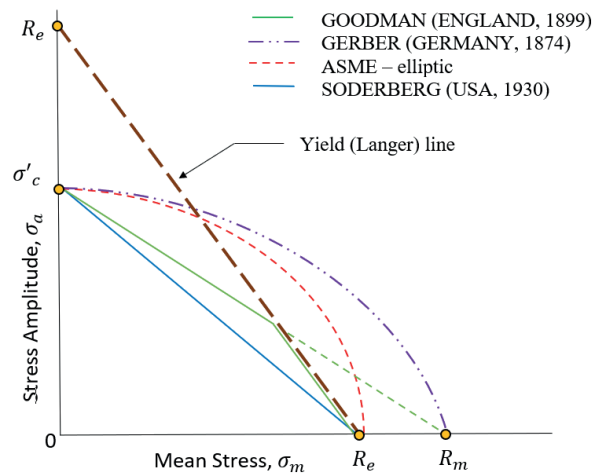*E-mail of corresponding author: daniel.varecha@fstroj.uniza.sk

Figure 1 $\sigma_a = f(\sigma_m)$ [12]

Table 1 *Mechanical properties of tested structural steels*

Steel	R_e (MPa)	R_m (MPa)	σ_a, 10^6 (MPa)	σ_a, 10^9 (MPa)
1	340	446	285	201
2	376	564	352	210
3	251	773	408	288
4	796	850	425	265
5	710	867	390	288
6	750	952	548	350
7	1226	1257	500	352
8	1425	1560	551	400

Table 2 *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

region of number of cycles ranged from N ≈ 10^6 to 10^9 cycles of loading.

The fatigue safety coefficient was calculated with regard to work [12], Figure 1, with the using equations: (1) Goodman, (2) Gerber, (3) ASME and (4) Soderberg.

$$k_u = \frac{1}{\frac{\sigma_a}{\sigma'_c} + \frac{\sigma_m}{R_m}}, \tag{1}$$

$$k_u = \frac{1}{2}\left(\frac{R_m}{\sigma_m}\right)^2 \frac{\sigma_a}{\sigma'_c}\left[-1 + \sqrt{1 + \left(\frac{2 \cdot \sigma_m \cdot \sigma'_c}{R_m \cdot \sigma_a}\right)}\right], \tag{2}$$

$$k_u = \sqrt{\frac{1}{\left(\frac{\sigma_a}{\sigma'_c}\right)^2 + \left(\frac{\sigma_m}{R_e}\right)^2}}, \tag{3}$$

$$k_u = \frac{1}{\left(\frac{\sigma_a}{\sigma'_c}\right) + \left(\frac{\sigma_m}{R_e}\right)}, \tag{4}$$

where:
σ_a is the stress amplitude,
σ_m is the mean stress,
σ'_c is the fatigue limit,
R_m is the ultimate tensile strength,
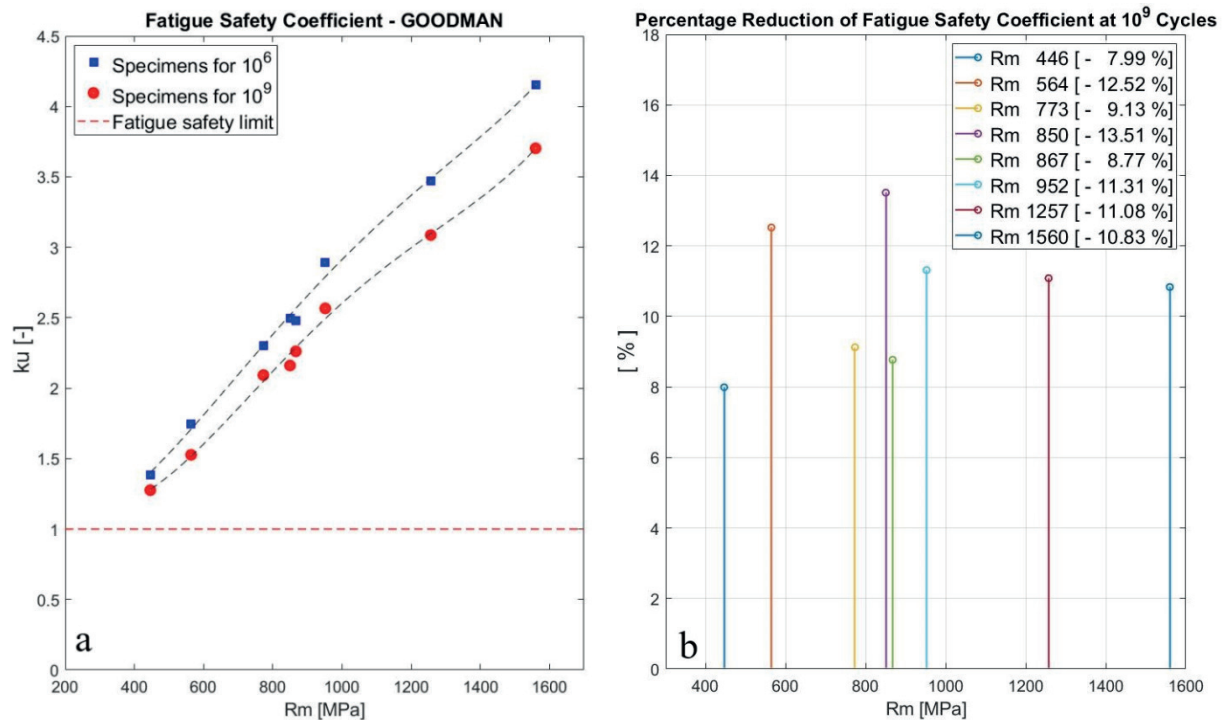R_e is the yield point.

Figure 2 *Fatigue safety coefficient k_u (a) and percentage reduction of k_u (b) - Goodman*

Table 3 *Specimens for the safety coefficient k_u for Goodman*

Specimens	1	2	3	4	5	6	7	8
k_u for 10^6	1.39	1.75	2.3	2.5	2.48	2.89	3.47	4.15
k_u for 10^9	1.27	1.53	2.09	2.16	2.26	2.57	3.08	3.70
% Reduction k_u	- 7.99	- 12.52	- 9.13	- 13.51	- 8.77	- 11.31	- 11.08	- 10.83

Application of the above described experimental work was executed on a screw joint, which is, during the operation, loaded by a cyclic stress in superposition with the preload. The material parameters of the screw were taken from Table 1, where values of R_e and R_m of experimental materials are given.

3 Results and discussion

Results of qualitative and quantitative chemical analysis (chemical composition), tensile tests (ultimate tensile strength R_m, yield point R_e) and high - frequency fatigue tests $(\sigma_a, 10^6, \sigma_a, 10^9)$, are shown in Tables 1 and 2, respectively. Results of the fatigue safety coefficient k_u calculations are shown in Figures 2 to 5 and also in Tables 3 to 6.

Material fatigue tests have demonstrably confirmed a continuous decrease in fatigue strength in the investigated range of the number of the loading cycles. The step - wise or duplex $\sigma_a = f(N)$ curves were not observed. The observed values of $\Delta\sigma_a$ ranged from $\Delta\sigma_a = 84$ MPa to $\Delta\sigma_a = 198$ MPa. Values $\Delta\sigma_a$ in the region of the ultra - high number of loading cycles for steels range from $\Delta\sigma_a = 20$ MPa to $\Delta\sigma_a = 200$ MPa. Higher values of $\Delta\sigma_a$ were exhibited by the structural steels of higher strength, what is related to their higher sensitivity to both surface and internal defects (micro - impurity, microstructural heterogeneity, pores, grain size, inclusions). These statements are in accordance with the works of the authors [1-7, 9].

It is clear from results (Figures 2 to 5, Tables 3 to 6) that Goodman and Soderberg methods are suitable methods (criteria) for evaluation of the fatigue safety of selected structural steels in the region of the high number of cycles. The Soderberg criterion checks the occurrence of any deformation. Lower values of k_u ensure that no fatigue failure or accidents would occur during the considered ultra - high number of load cycles. The Goodman criterion is very strict, but it is one of the best known criteria that allows for a simple analytical solution of fatigue tasks. The American Society of Mechanical Engineers (ASME) has addressed the issue of fatigue safety, which is a more conservative criterion but does not have sufficient margin to determine the fatigue safety coefficient for an ultra - high number $N = 10^9$ of cycles. The Gerber criterion seems to be the least suitable, because approaching the limit state of fatigue safety and at an ultra - high number of cycles fatigue fracture accidents can occur [9-13].
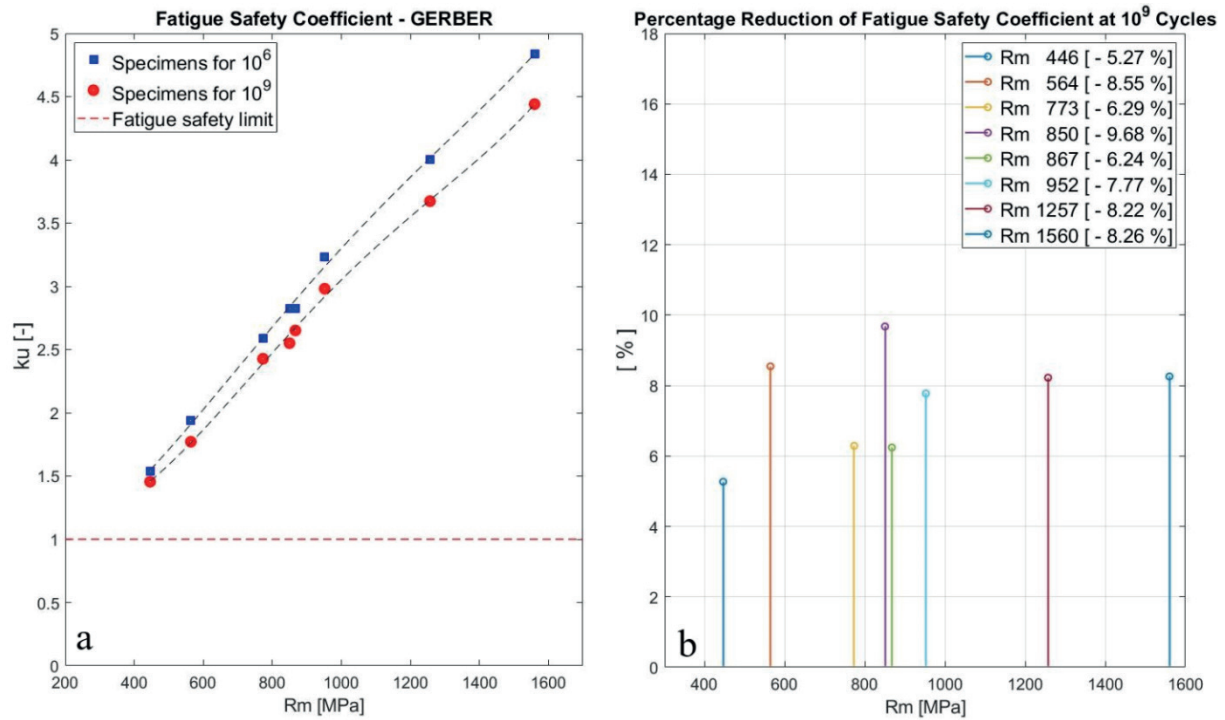
Figure 3 *Fatigue safety coefficient k_u (a) and percentage reduction of k_u (b) - Gerber*

Table 4 *Specimens for the safety coefficient k_u for Gerber*

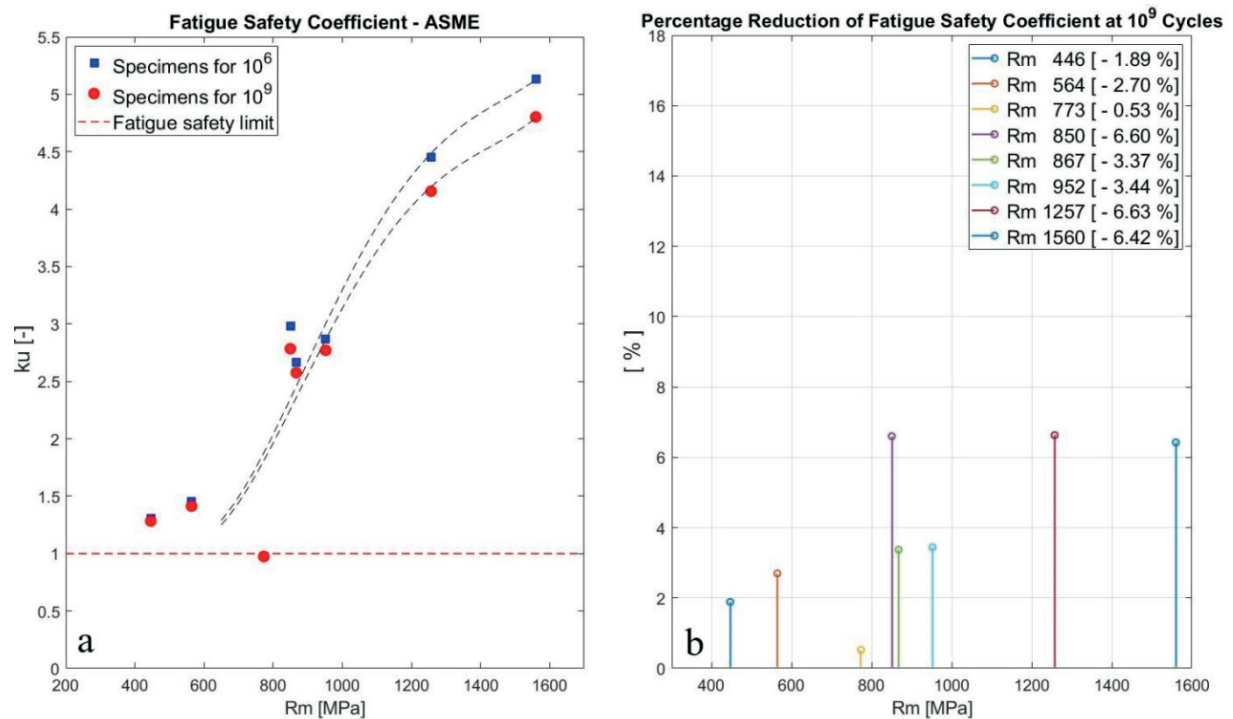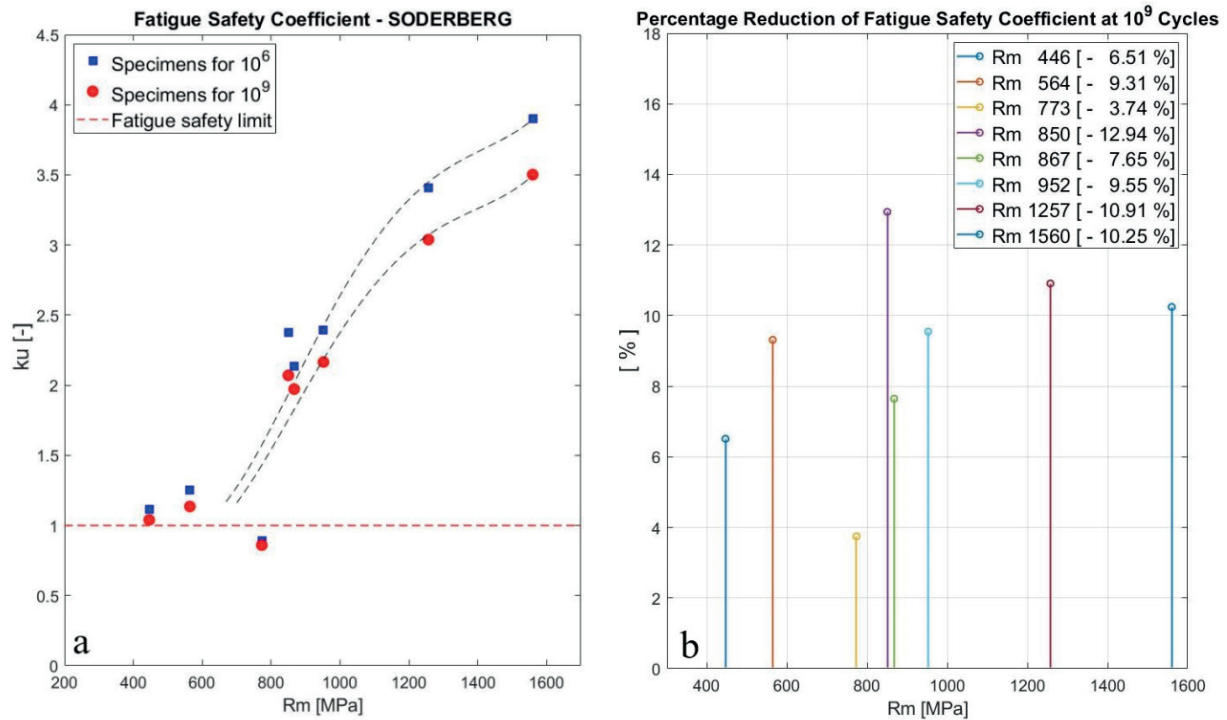| Specimens	1	2	3	4	5	6	7	8
k_u for 10^6	1.54	1.94	2.59	2.82	2.82	3.23	4.0	4.84
k_u for 10^9	1.45	1.77	2.43	2.55	2.65	2.98	3.67	4.44
% Reduction k_u	- 5.27	- 8.55	- 6.29	- 9.68	- 6.24	- 7.77	- 8.22	- 8.26

Figure 4 *Fatigue safety coefficient k_u (a) and percentage reduction of k_u (b) - ASME*

Table 5 *Specimens for the safety coefficient k_u for ASME*

Specimens	1	2	3	4	5	6	7	8
k_u pre 10^6	1.31	1.45	0.98	2.98	2.67	2.87	4.45	5.13
k_u pre 10^9	1.28	1.41	0.97	2.78	2.58	2.77	4.16	4.80
% Reduction k_u	- 1.89	- 2.7	- 0.53	- 6.60	- 3.37	- 3.44	- 6.63	- 6.42

Figure 5 *Fatigue safety coefficient k_u (a) and percentage reduction of k_u (b) - Soderberg*

Table 6 *Specimens for the safety coefficient k_u for Soderberg*

Specimens	1	2	3	4	5	6	7	8
k_u for 10^6	1.11	1.25	0.89	2.38	2.14	2.39	3.41	3.90
k_u for 10^9	1.04	1.14	0.86	2.07	1.97	2.17	3.04	3.5
% Reduction k_u	- 6.51	- 9.31	- 3.74	- 12.94	- 7.65	- 9.55	- 10.91	- 10.25

4   Conclusions

Taking into account the performed experimental work, the following can be stated:

- Dependence $\sigma_a = f(N)$ shows a decreasing character after the so - called basic number of cycles $N_c = 10^6$ to 10^7 cycles.
- The obtained values of the fatigue limit σ_c at the so - called basic number of cycles are overestimated.
- Determining the fatigue safety coefficient beyond the so - called basic number of cycles N_c is therefore desirable.
- These facts must be respected in a qualified choice of structural steel if the component or equipment will work in real operation in the region of ultra - high numbers of load cycles.

References

[1] BATHIAS, C. There is no infinite fatigue life in metallic materials. *Fatigue and Fracture of Engineering Materials and Structures* [online]. 1999, **22**(7), p. 559-565. ISSN 1460-2695. Available from: https://doi.org/10.1046/j.1460-2695.1999.00183.x

[2] BATHIAS, C., PARIS, P. C. *Gigacycle fatigue in mechanical practice*. New York, NY: Marcel Dekker, 1999. ISBN 0-8247-2313-9.

[3] BELAN, J., KUCHARIKOVA, L., TILLOVA, E., CHALUPOVA, M. Three-point bending fatigue test of TiAl6V4 titanium alloy at room temperature. *Advances in Materials Science and Engineering* [online]. 2019, 2842416. ISSN 1687-8434, eISSN 1687-8442. Available from: https://doi.org/10.1155/2019/2842416

[4] BOKUVKA, O., NICOLETTO, G., KUNZ, L., PALCEK, P., CHALUPOVA, M. *Low and high frequency fatigue testing*. Zilina, Slovakia: EDIS, University of Zilina, 2002. ISBN 80-8070-011-7.

[5] BOKUVKA, O., NICOLETTO, G., GUAGLIANO, M., KUNZ, L., PALCEK, P., NOVY, F., CHALUPOVA, M. *Fatigue of materials at low and high frequency loading*. Zilina, Slovakia: EDIS, University of Zilina, 2014. ISBN 978-80-554-0857-6.

[6] KAZYMYROVICH, V. Very high cycle fatigue of engineering materials - a literature review. Karlstad: Karlstad University, 2009. ISSN 1403-8099, ISBN 978-91-7063-246-4.

[7] VASKO, A., BELAN, J., KUCHARIKOVA, L., TILLOVA, E. Low and high frequency fatigue tests of nodular cast irons. *Metalurgija - Metallurgy*. 2017, **56**(1-2), p. 25-28. ISSN 0543-5846.

[8] SKOCOVSKY, P., PALCEK, P., KONECNA, R., VARKOLY, L. *Structural materials* (in Slovak). Zilina, Slovakia: EDIS, University of Zilina, 2000. ISBN: 80-7100-608-4.

[9] NOVY, F., ULEWICZ, R., BOKUVKA, O., TRSKO, L., LAGO, J. Reliability and safety of structural elements in the gigacycle region of loading. *Communications - Scientific Letters of the University of Zilina* [online]. 2016, **18**(3), p. 83-87. ISSN 1335-4205, eISSN 2585-7878. Available from: http://komunikacie.uniza.sk/index.php/communications/article/view/315

[10] BOKUVKA, O., JAMBOR, M., HRCEK, S., STEININGER, J., NOVY, F., TRSKO, L. Design of shaft respecting the fatigue limit for ultra-high number of cycles. *Periodica Polytechnica Transportation Engineering*. 2019, **47**(1), p. 6 -12. ISSN 0303-7800, eISSN 1587-3811. Available from: https://doi.org/10.3311/PPtr.11562

[11] FATURIK, L., HRCEK, S., TRSKO, L., BOKUVKA, O. Comparison of structural design in high and ultra-high cycle fatigue region. *Transactions of FAMENA*. 2014, **38**(4), p. 1-12. ISSN 1333-1124.

[12] BUDYNAS, R. G., NISBETT, J. K., SHIGLEY, J. E. *Shigley's mechanical engineering design*. New York: McGraw-Hill, 2011. ISBN 978-0-07-339820-4.

[13] GUJAR, R. A., BHASKAR, S. V. Shaft design under fatigue loading by using modified goodman method. *International Journal of Engineering Research and Applications*. 2013, **3**(4), p. 1061-1066. ISSN 2248-9622.

[14] TRSKO, L., NOVY, F., BOKUVKA, O., JAMBOR, M. Ultrasonic fatigue testing in the tension-compression mode. *Journal of Visualized Experiments* [online]. 2018, **133**, 57007. eISSN 1940-087X. Available from: https://doi.org/10.3791/57007

[15] BATHIAS, C. Piezoelectric fatigue testing machines and devices. *International Journal of Fatigue* [online]. 2006, **28**, p. 1438-1445. ISSN 0142-1123. Available from: https://doi.org/10.1016/j.ijfatigue.2005.09.020