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FATIGUE LIFE OF HIGH STRENGTH STEEL FOR COLD FORMING

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The article presents the results of fatigue tests carried out on STRENX-type high-strength cold forming steel. For high-cycle fatigue tests carried out using low cycle loading frequencies of around 30 Hz, a ROTOFLEX machine was used. For ultra high-cycle tests, a KAUP-ZU testing machine was employed, which enables fatigue tests to be performed with symetric specimen loading (R = -1) and at a frequency of f ≈ 20 kHz. The relationships $\sigma_a = f(N)$ were determined experimentally in the high and ultra high-cycle region for STRENX high-strength steel. To determine the fatigue crack initiation mechanism, the fractographic analysis of fatigue fractures was made.

Key words: high strength steel, ultra-high-cycle fatigue, Wöhler curve, fractography

INTRODUCTION

Under the conditions of the operation of parts, as well as complete structures, failures occur within a range higher rather than that covered by the low and high-cycle regions [1]. This is one of the reasons for which research centres have placed in recent years particular emphasis on the determination of fatigue properties in high and ultra-high-cycle regions [2,3]. The adopted criteria (low-cycle and high-cycle fatigue < 10^7) do not meet the requirements for safe usage. The authors of research works [4,5] have found a decrease in fatigue characteristics (a drop in the stress amplitude σ_a with increasing number of cycles) beyond the conventional limit ($N_c = 10^7$), primarily for more resistant and surface-strengthened steel grades. The former findings and discussions on the safe stress and stable fatigue strength above the conventional number of cycles have been incomplete and inaccurate. This means that subjects, such as the behaviour of the relationship $\sigma_a = f(N)$ and the mechanisms of fatigue degradation beyond the conventional cycle limit, still remain open. In the case of some High Strength Steels (HSS), under axial tension-compression loading [6,7], the S-N curve is characterized by a continuous decrease of the load magnitude with increasing number of cycles.

The authors of published studies [8,9] present possible behaviours of the relationship $\sigma_a = f(N)$ above the conventional limit of material fatigue. In their publication [9], C. Bathias, I. Drouillac and P.L. Francois present three types of initiation of a fatigue crack, which may occur in cylindrical polished-surface specimen, depending on whether this is a low-cycle (10^4 cycles), high-cycle (10^6 cycles), or ultra-high-cycle (10^9 cycles) range. This is not, however, an iron rule. For cracks in a low-cycle range, initiation locations are often numerous and occur on the specimen surface; according to the widespread opinion, at 10^9 cycles the fatigue crack initiation is located under the specimen surface [9]. In her studies [10,11], Murakami and Nishijima have found that the initiation of a fatigue crack in high-strength steel occurs on the specimen surface at 10^6 cycles, and under the specimen surface at 10^8 cycles. These results were obtained from tests using a frequency of both 50 Hz and 20 kHz. Literature data [6] on ultra-high-cycle fatigue (UHCF) obtained above 10^7 cycles show that the classic Wöhler relationship has a dual behaviour (the Duplex S-N curve). This is associated with the point of fatigue crack initiation at a small number of cycles. In that case, the location of fatigue crack initiation is the surface, while at a high and ultra-high number of cycles, the fatigue crack initiation location should lie under the surface. However, the results obtained from tests for STRENX steel have shown that the location of crack initiation in the high and ultra-high-cycle region is the specimen surface. This is due to the fact that what we observe for high-strength steels is a continuous decrease in the load magnitude with increasing number of cycles, rather that the dual behaviour of the curve [12-14].

MATERIAL AND EXPERIMENTAL METHODS

Typical fine grained ferritic structure of cold forming STRENX high-strength steel is shown in Figure 1. The properties of the mechanically tested material are given in Table 1, while its chemical composition, in Table 2.

STRENX steel is characterized by a fine-grained ferritic microstructure with high amount of small cementitic (Fe_3C) particles and a few isolated titanium

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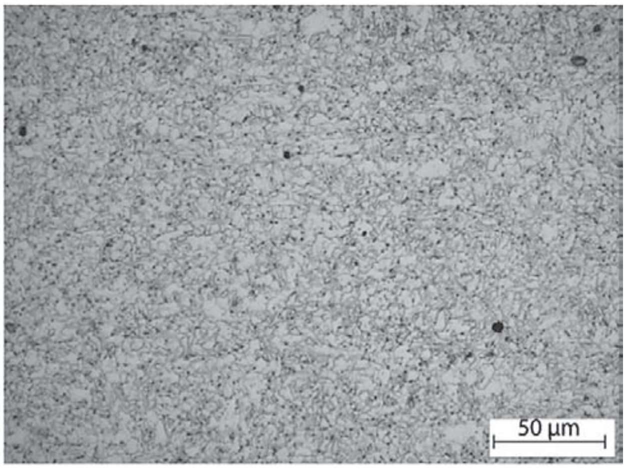

Figure 1 Typical ferritic structure of STRENX-type high-strength steel

Table 1 **Mechanical properties of STRENX steel**

Re / MPa	*Rm* / MPa	*A.5* / %	*Z* / %
796	850	15,5	36,1

Table 2 **Chemical composition of STRENX steel / wt. %**

C	Si	Mn	P	S
0,08	0,35	1,67	0,018	0,0037
Al	Nb	V	Ti	Al
0,015	0,06	0,014	0,015	0,015

nitride particles with a regular geometric shape. In the examined structure, sparse inclusions in the form of MnS particles were observed. The fatigue tests in the high-cycle region (VHCF) were carried out using a loading frequency of 30 Hz at an ambient temperature of 20 °C ± 10 °C. A ROTOFLEX testing machine was used in the tests. A schematic of the testing machine is shown in Figure 2.

A resonance machine enables an elastic-plastic strain to be induced in the smallest specimen cross-section. This is the location where the accumulation of fatigue damage occurs, which leads to a fatigue crack formation. A resonance fatigue testing machine (Figure 3) allows fatigue tests to be performed with symmetrical cyclic loading (R = - 1), at a frequency of f ≈ 20 kHz in the temperature interval of T = 20 ± 10 °C.

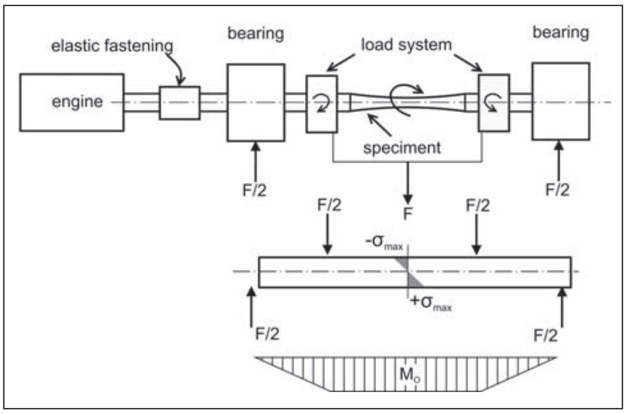

Figure 2 The ROTOFLEX testing machine used for rotary bending tests

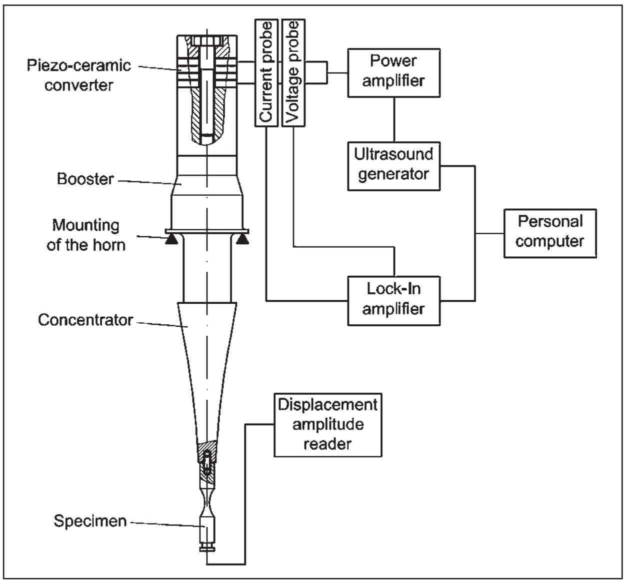

Figure 3 A schematic diagram of the design of the KAUP-ZU fatigue testing machine

RESULT AND DISCUSSION

During fatigue testing on the ROTOFLEX machine, the load cycle asymmetry factor was *R* = - 1, and the specimens were loaded at a frequency of 30 Hz at an ambient temperature of 20 °C ± 10 °C. The specimen working part was cooled during testing using fans. Based on the obtained results, the curve of the applied load amplitude versus the number of cycles (Figure 4) to specimen fracture, σ_a = f(N), was plotted. The experimentally determined Whöler curve shows a decrease in the magnitude of specimen fracture stress amplitude with the increase in the number of loading cycles up to the fatigue limit of this material (440 MPa). The results of the ultra-high-cycle fatigue tests carried out on the KAUP-ZU high-frequency fatigue testing machine are presented in Figure 5.

The load amplitude of steel fatigue testing decreased from s_a = 400 MPa (for N = 3,3 × 10^6 cycles and N = 8,1 × 10^6 cycles) to s_a = 240 MPa (for N = 4,1 × 10^9 cycles, N = 5,3 × 10^9 cycles and N = 8,9 × 10^9 cycles, which

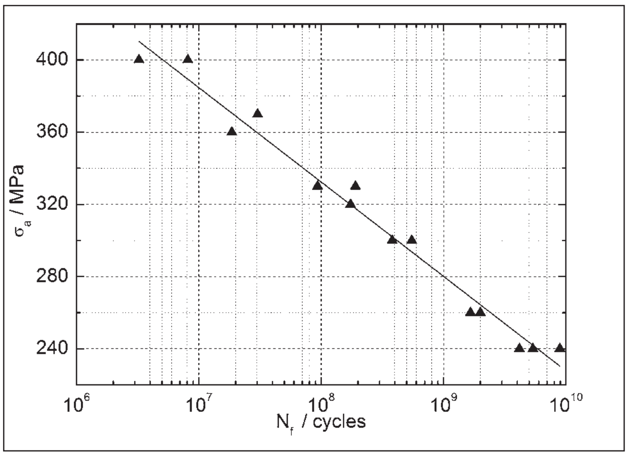

Figure 4 The fatigue life of STRENX steel; fatigue test, rotary bending in the high-cycle interval [f = 30 Hz, T = 20 °C ± 10 °C, R = -1]

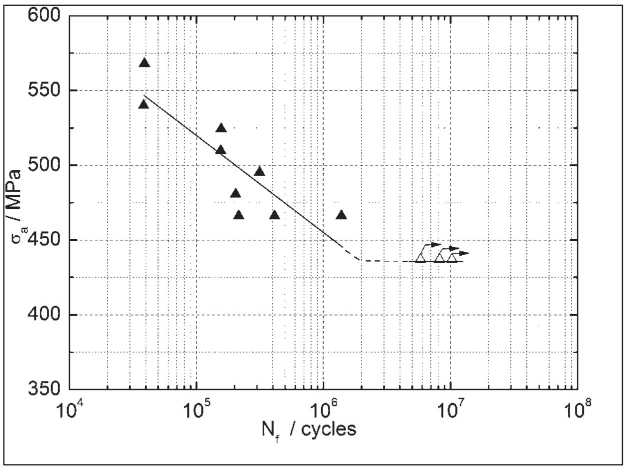

Figure 5 The fatigue life of STRENX steel; the fatigue test using high frequency push-pull loading [f = 20 kHz, T = 20 °C ± 10 °C, R = -1]

makes a difference in amplitude of $\Delta\sigma_a$ = 160 MPa. Based on the performed fractographic analysis of fatigue fractures it was found that the location of fatigue crack initiation was in all cases the specimen surface. The crack initiation location was dependent on the surface type (the degree of development of intrusions and extrusions on the surface), stress amplitude σ_a, as well as on the number of cycles to specimen failure, N. On the fatigue fracture surface of the specimen, there occurs a transcrystalline fracture of very fine morphology (Figure 6), which is characteristic for fine-grained steels.

In the region of unstable fatigue crack growth, before the final fracture region, distinctive radial steps and secondary cracks occur (Figure 7). The final fracture region is characterized by a ductile fracture with a dimple morphology (Figure 8).

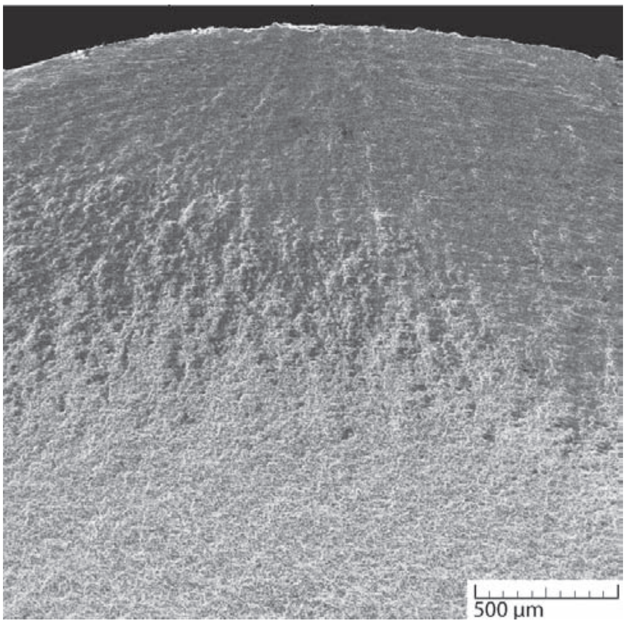

Figure 6 Surface fatigue crack initiation; σ_a = 360 MPa, N = 1,51 × 10^7 cycles

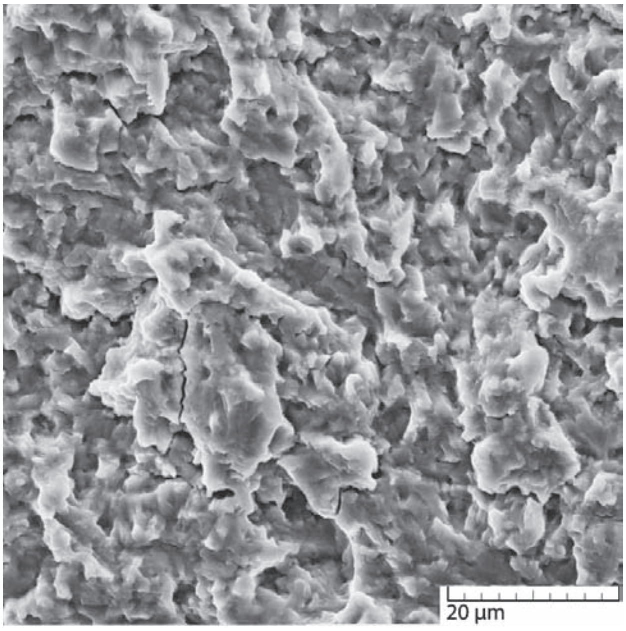

Figure 7 Fatigue fracture in the unstable fatigue crack growth region before the final fracture region with distinctly occurring characteristic steps, large secondary cracks and striation; σ_a = 360 MPa, N = 1,51 × 10^7 cycles

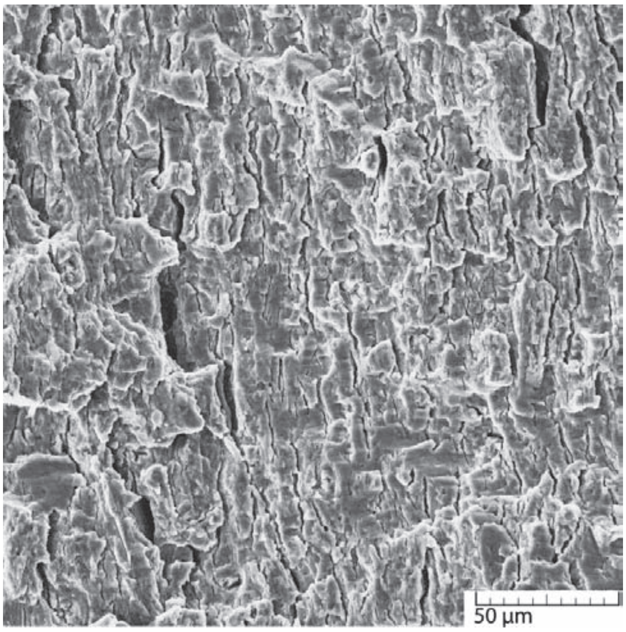

Figure 8 Fatigue fracture in the unstable crack growth region before the final fracture region with distinctly occurring characteristic steps, large secondary cracks and striation; σ_a = 360 MPa, N = 1,51 × 10^7 cycles

CONCLUSION

The results for the relationship σ_a = f(N) assume the classic shape of the Wöhler curve with a distinct fatigue limit. Determined from the experimental results, the curve shows a decrease in the magnitudes of stress amplitude σ_a with the increase in the number of load cycles N up to the fatigue fracture. The experimental tests carried out on the ROTOFLEX testing machine determined the relationship σ_a = f(N) in the high-cycle region. The difference in load amplitude amounted to

$\Delta\sigma_a$ = 131 MPa, for the number of cycles ranging from 3,8 × 10^4 to 1,0 × 10^7. The results of the tests on the KAUT-ZU testing machine in the region beyond the conventional fatigue limit confirmed a continuous decrease in σ_a stress amplitude with the increase in the number of cycles to specimen fatigue failure. The difference in fatigue test load amplitude amounted to $\Delta\sigma_a$ = 160 MPa, for the number of cycles ranging from 8,1 × 10^6 to 5,3 × 10^9.

The fatigue crack was initiated from the specimen surface. No preferred fatigue crack initiation locations were identified. The region of stable fatigue crack propagation has the nature of transcrystalline fatigue.

REFERENCES

[1] S. Stanzl-Tschegg, H. Meyer, Proceedings, International Conference on Fatigue in the Very High Cycle Regime Austria (2001). Stanzl-Tschegg S., Meyer H. (eds.) BOKU Variable Amplitude Loading in the Very High Cycle Regime,Vienna, pp. 371-378.

[2] F. Novy, M. Cincala, P. Kopas, O. Bokuvka, Mechanisms of high-strength structural materials fatigue failure in ultra-wide life region. Mater Sci. Eng. A 462 (2007), 189-192, DOI: 10.1016/j.msea.2006.03.147

[3] K. Shiozawa, L. Lu, S. Ishihara, S–N curve characteristics and subsurface crack initiation behaviour in ultra-long life fatigue of a high carbon–chromium bearing steel. Fatigue Fract. Eng. Mater. Struct. 24 (2001), 781-790, DOI: 10.1046/j.1460-2695.2001.00459.x.

[4] T. Sakai, M. Takeda, K. Shiozava, Y. Ochi, M. Nakajima, T. Nakamura, N. Oguma, Proceedings, International Fatigue Congress, Higher Education Press/EMAS, Beijing, China, 1999, Experimental Evidence of Duplex S–N Characteristics in Wide Life Region for High Strength Steels, pp. 573-578.

[5] C. Bathias, J. Bonis, Proceedings, 12th Bienniel Conference on Fracture, UK 14-18 September 1998, Effect on Inclusions on Gigacycle Fatigue of a Nickel Base Alloy, Fracture from Defects Vol. 1, pp. 321-332.

[6] I. Marines, G. Dominguez, G. Baudry, J.F. Vittori, S. Rathery, J.P. Doucet, C. Bathais, Ultrasonic Fatigue Tests on Bearing Steel AISI-SAE 52100 at Frequency of 20 and 30 kHz, International Journal of Fatigue, 25 (2003) 9-11, 1037-1046, DOI: 10.1016/S0142-1123(03) 0016-0.

[7] C.M. Sonsino, Course of SN-curves Especially in the High-Cycle Fatigue Regime with Regard to Component Design and Safety, International Journal of Fatigue 29 (2007), 2246-2258, DOI: 10.1016 /j.ijfatigue. 2006.11.015.

[8] Y. Murakami, T. Nomoto, T. Weda, Factors Influencing the Mechanism of Superlong Fatigue Failure in Steels, Fatigue & Fracture of Engineering Materials & Structures 22 (1999) 7, 581-590, DOI: 10.1046 /j.1460-2695.1999. 00187.x

[9] C. Bathias, I. Drouillac, P.L. Francois, How and Why the Fatigue S-N Curve Does Not Approach a Horizontal Asymptote, International Journal of Fatigue 23/1 (2001), 143-151.

[10] Y. Murakami, T. Nomoto, T. Weda, Factors Influencing the Mechanism of Superlong Fatigue Failure in Steels, Fatigue & Fracture of Engineering Materials & Structures 22/7 (1999), 581-590.

[11] K. Kanazawa, S. Nishijima, Fatigue Fracture of Low Alloy Steel at Ultra-High Cycle Regime under Elevated Temperature Conditions, Journal of the Society of Materials Science 46/12 (1997), 1396-1401.

[12] A. Vasko, L. Trsko, R. Konecna, Fatiuge behaviour of syntetic nodular cast irons, Metalurgija 54 (2015) 1, 19-22.

[13] J. Belan, High frequency fatigue test of in 718 alloy – microstructure and fractography evaluation, Metalurgija 54 (2015) 1, 59-62.

[14] R. Ulewicz, P. Szataniak, F. Novy, Fatigue properties of wear resistant martensitic steel, In: Metal 2014, 23rd International Conference on Metallurgy and Materials, Tanger, 2014, pp. 784-789.

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