

Fatigue properties of the HSLA steel in high and ultra-high cycle region

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Abstract This work presents a study of the fatigue properties in the example of Swedish steel Hardox 400. Fatigue tests were carried out in the area of high and ultra-high cycle region. From the practical point of view the durability of some components in the automotive industry and similar technical applications such as special semitrailers ranges between 10^8 and 10^{10} cycles. But, only a few experimental results beyond 10^7 cycles are available now. The main objective of this research was to provide independent results to the company which uses Hardox steel in the construction of semitrailers. Selected mechanical and fatigue tests were carried out with the aim to study fatigue properties of Hardox steel. Based on the obtained experimental results the fatigue properties of this still not well recognized type of steel are discussed.

Key words – HSLA steels, Hardox 400; ultra-high-cycle fatigue; S–N curve

1. Introduction

Fatigue strength is the ability of material to resist the fatigue process. Attempts of metal fatigue rely on repeated burdening of the sample, causing alternating stress states. The variability of stress at the time τ is characterized by a frequency f , the size and type of stress and asymmetry coefficient of R cycle. Increased fatigue strength of material is gaining importance in solving the general problem of improving the reliability and durability of modern machines and structures. Analysis of causes of failures of machine elements and structures indicates that the majority of more than 90% of all cases is due to fatigue cracking. At the actual operation, the components and constructions are loaded mainly by repeating loading that could lead to the

ultimate state, fatigue fracture in the final consequence (RADEK N. 2012). If it is assumed that the construction material will be repeatedly cyclically loaded in the operation, then it will be necessary to determine very complex fatigue characteristics for the given operation conditions. It means to state experimentally the concrete values from the area of the low-cyclic, high-cyclic and ultra-high-cyclic fatigue for the construction material and by respecting of the philosophy of the admissible defects, also the values of fracture mechanics (TILLOVÁ E., CHALUPOVÁ M. 2009, MAZUR M., ULEWICZ R., BORKOWSKI S., NOVY F. 2012).

To determine the fatigue characteristics mentioned above experimentally, the normal frequencies are applied in the range from $f \approx 10$ Hz to $f \approx 200$ Hz, which is time demanding and expensive. This statement emphasizes the fact, that fatigue fractures occur even after a

billion cycles and more (KOSTER M. et.all 2010) and the stated, conventional criteria (BOKŮVKA O. et.all 2008) do not fulfill the requirements for the safety and evaluation of components and constructions endurance. Sakai T., Takeda M., Shiozava K., Ochi Y., Nakajima M., Nakamura T., Oguma N., Masuda S., Nishijima S., Tanaka Y., Naito T., Ueda H., Kikuchi M., Bathias C., Bonis J., Asami K., Hironaga M. stated f. e. the decreasing of the fatigue characteristics, dependence $\sigma_a = f(N)$ beyond conventional limit of cycles $N_f = 10^7$, first of in the high strength and surface hardened steels (for example Hardox steel) (SAKAI T. et.all 1999, MASUDA S. et.all 1986, NAITO T. et.all 1984, BATHIAS C., BONIS J. 1998, ASAMI K., HIRONAGA M. 1994). One of the possible directions is the application of experimental methods of high frequency cyclic loading to determination of the fatigue properties in construction materials. These experimental methods are progressive without question, with a wide future application, they are very time and economically effective (BOKUVKA O. et.all 2002, DORAZIL E. 1991). Economical factors are also very important for the producers of semi-trailers where we observe actions aimed at significant reduction in the weight of semitrailers by application of new steel grades, especially micro alloyed (HSLA- High Strength Low Alloy) of the structure: Ferritic, Ferritic-Pearlitic, ferRite-Bainitic, Bainitic and Bartenit Tempered. These group of steels bring specific combinations of mechanical parameters and abilities of dynamic reinforcement together with keeping the tendency to ductile fracture in a wide range of working temperatures (Hanus P., Konečný M. 2014).

2. Materials

The structural material, which is namely HSLA steel Hardox 400, was used for fatigue tests. The steel is produced by a Swedish metallurgic company SSAB. This steel is used for structural components of semi-trailers of tipper type by Wielton S.A. Company. Hardox 400 is an abrasion resistant steel with a nominal hardness of 400 HBW. Typical applications are components and structures subject to wear. Chemical composition and mechanical properties are shown in Table 1.

Table 1. Chemical composition (in wt.%) and mechanical properties, HSLA steel Hardox 400

Hardox 400								
C	Si	Mn	P	S	Cr	Ni	Mo	B
0.13	0.30	0.95	0.012	0.002	0.25	0.06	0.04	0.002
R_e [MPa]		R_m [MPa]		A5 [%]		HBW		
1150		1350		11		410		

The increase in the hardening of the steel causes the carbide forming elements (Cr, Mo) delaying tempering processes. For an intensification of the effect of chromium and molybdenum (such as Hardox steels) are used together. Moreover, the presence of molybdenum in the range of 0.25 ÷ 0.60% (for other types of steel Hardox) has a positive effect of secondary hardness and prevents irreversible temper brittleness at 250 ÷ 400 °C. The presence of molybdenum (min 0.20% Mo) is all the more important since chromium (like phosphorus and other trace additives) will increase the tendency to temper brittleness. Furthermore, nickel and manganese in the presence of chromium contribute to this process. The microstructure of Hardox steel is shown in Fig. 1.



Fig. 1. Microstructure of Hardox 400 steel

Metallographic analysis was carried out by means of an optical microscope NEOPHOT 32. As a result of the analysis of microstructure it was found that Hardox 400 steel has a structure of tempered Martensite. Steels that have been tested are characterized by coarsely acicular Martensitic structure.

3. Experimental procedure and result

Rotating bending, tension-compression and high frequency tension-compression loading were employed to investigate fatigue properties of Hardox 400, respectively. The loading system was rotating bending equipment operating at the frequency of 40 Hz. The stress ratio of $R = -1$ was chosen. Both experiments were performed at the ambient temperature. During the test the working part of the specimens was cooled by means of fans. To determine the material's fatigue strength 10 specimens of Hardox 400 steel underwent the high cycle fatigue test. Results of the comparative material were received from tests performed in identical conditions. The results obtained in a Wöhler curve are shown in Figure 2.

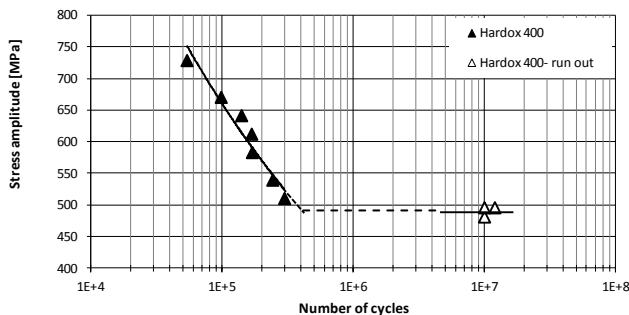


Fig. 2. Stress amplitude σ_a vs. number of cycles N for Hardox 400 steel (Rotoflex)

Next the fatigue tests of Hardox 400 were carried out using ultrasonic equipment for fatigue testing at the tension-compression loading. The sinusoidal loading with the frequency about 20 kHz and $R = -1$ was used. At high frequencies specimens were cooled by distilled water with anti-corrosive inhibitor. With this approach it is possible to reach the high and ultra-high cycle region ($N \approx 6 \times 10^6 \div N \approx 1 \times 10^{10}$ cycles) in times much quicker than the with use of conventional machines (NISHIJIMA K., KANAZAWA K. 1999; BATHIAS C. 2001).

Experimental material samples were made of fine-grained structural steel Hardox 400 according to the dimensions and shapes shown in Figure 3.

Methods of ultrasonic fatigue testing are described in detail by Salama and Lamerand (SALAMA K., LAMERAND R. K. 1982) according to the methods discussed in (PUŠKÁR A. 1997; NISHIJIMA S., KANAZAWA K. 1999, TRŠKO L. et all 2011.). The results obtained in a Wöhler curve are shown in Figure 4.

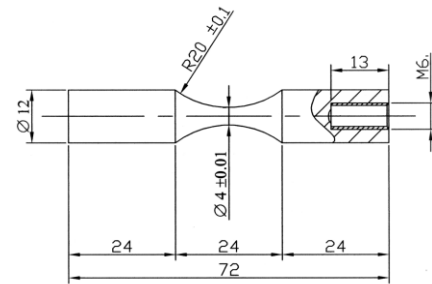


Fig. 3. Shape and geometry of the specimen used for fatigue tests at loading frequency of $f \approx 20$ kHz

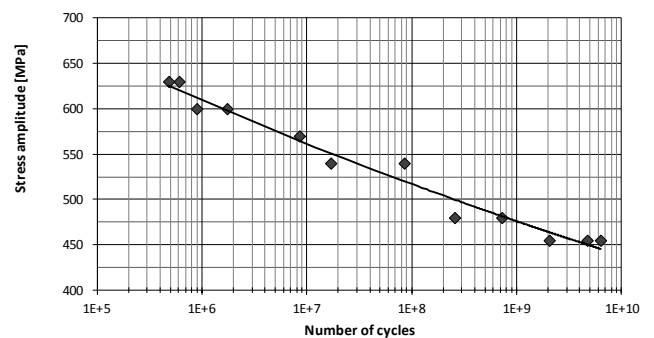


Fig. 4. Stress amplitude σ_a vs. number of cycles N for Hardox 400 steel ($f = 20$ kHz, $T = 20 \pm 10^\circ$ C, $R = -1$)

4. Discussion and conclusion

The research conducted to facilitate responses to constructors using Hardox steel, which is a safe operation life of structural elements made of steel Hardox in terms of fatigue wear. Research was conducted in the area of VC on rototflex and UHC at resonance fatigue testing machine KAUP-ZU. Results of HC and UHC fatigue tests are shown in Figs. 2 and 4. The continuous increase of lifetime was observed with decreasing stress amplitude. The fatigue properties of Hardox strongly depend on the Martensitic transformation conditions. The increase of the tensile strength is not accompanied by a corresponding increase of fatigue properties.

The test results (HC-rototflex) formed a curve (Fig. 2), which clearly shows that the stress amplitude σ_a decreases together with an increase in cycles number N beyond the conventional fatigue limit $N_c = 10^7$ cycles. Based on the obtained results the fatigue limits for Hardox 400 reached the level 490 MPa, stress amplitude decreases about $\Delta\sigma_a = 233$ MPa.

Examination of the specimens (UHC) which have been made from the material analyzed showed that the

decrease in amplitude of loads increases the number of cycles N . Stress amplitude at the level of 630 MPa caused the fractured specimens in two trials. These cracks were created at the number of cycles accordingly 600 and 400 thousand cycles. The lowest amplitude applied at 455 MPa resulted in cracks of three further specimens in the number of cycles above $N_f = 2 \times 10^9$.

Hardox research that has been carried out confirmed the need for experimental verification of new material groups in the actual conditions of use, before applying them to the elements of machine design.

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