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## FRACTOGRAPHIC ANALYSIS OF HARDOX STEELS RESEARCH IN THE FIELD OF HIGH-CYCLE FATIGUE REGIME

The article presents preliminary fatigue tests results of two high-strength steels used in structural elements of trailers, wagons, farm devices, etc. Paper presents an analysis of fatigue test results of high-strength steels in the range from 10<sup>4</sup> to 10<sup>7</sup> numbers of cycles of applied load with a frequency of 40 Hz. Wöhler curve shows the results of the fatigue properties of steels Hardox 400 and Hardox 450, which are used in the construction of vehicles. Fatigue fractures were subjected to fractographic analysis in order to determine the mechanism of fatigue crack propagation.

**Keywords:** Fatigue crack, Wohler curve, high-strength steels, high cycle fatigue tests.

### 1. Introduction

Information about the fatigue strength of the material has become essential in solving the general problem of improving the reliability and durability of modern machines and constructions [1]. Demand for fatigue results of tested steel is reported by designers looking for new applications of high strength steel. Because manufacturers are interested in optimizing operational costs and increase of production, therefore, they pay attention to getting the greatest durability of produced objects. This is obtained by looking for new construction solutions of their products and application of appropriate materials (materials with appropriate properties). Material fatigue is a process of continuous accumulation of damages formed over a sufficiently long time. This process occurs due to variable mechanical stresses which cause nucleation and propagation of cracks, leading consequently to destruction of the material [2 - 4].

Extra high strength steels are used in structures such as truck chassis, cranes and excavators. In these applications, high strength steel is used in order to reduce weight while simultaneously increasing load capacity of the structure. According to the manufacturer information, Hardox steels are defined as "high-quality abrasion-resistant steels". They are characterized by high resistance to abrasive wear, the possibility of specialized machining tools, good weldability, excellent mechanical properties and resistance to impact loads. Hardox steels are produced in six types. Getting to know properties of the materials is meant to answer the question whether it is possible to substitute traditional

steel with high strength steel, resistant to wear and easily cold-shaped fine-grained steel. The article presents preliminary fatigue tests results of two constructional steel grades used in structural elements of trailers, wagons, farm devices, etc. [5 and 6].

### 2. Fatigue tests

Fatigue characteristics (dependence  $\sigma_a = f(N)$ ) of steel were determined at low testing frequency. The test was performed using the Rotoflex device which ensures loading specimens so that bending moment is constant over the entire working length of the specimen [7]. The correlations between stress amplitude per number of cycles until fracture (in S - N relation) and fatigue

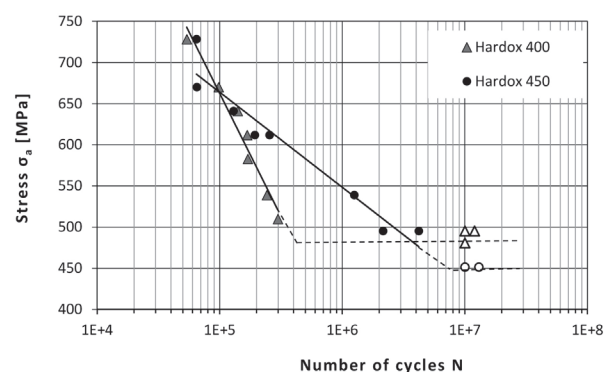


Fig. 1 Diagram of dependency between the stress amplitude and number of cycles of the tested steels

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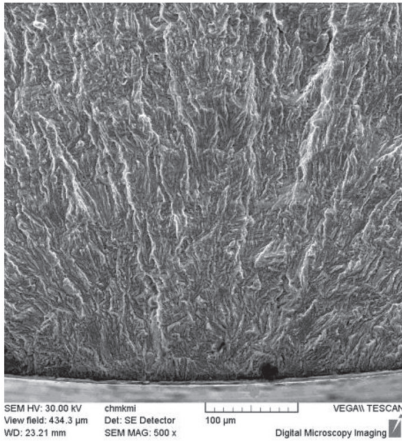


Fig. 2 Surface fatigue crack initiation for Hardox 400;  $\sigma_a = 330$  MPa,  $N = 1.55 \cdot 10^9$  number of cycles

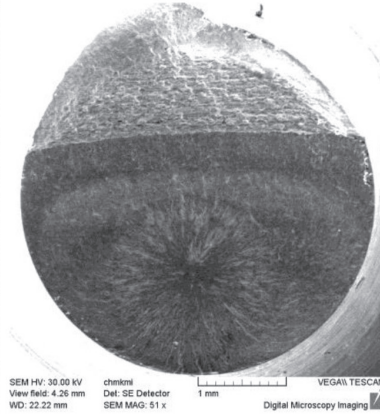


Fig. 3 Fatigue fracture Hardox 450 steel in the macro scale; subsurface fatigue crack initiation with structure "fish-eye";  $\sigma_a = 455$  MPa,  $N = 6.32 \cdot 10^9$  number of cycles

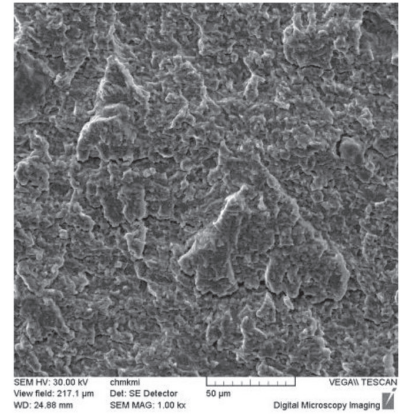


Fig. 4 Fatigue fracture surface, area of stable crack propagation for Hardox 450;  $\sigma_a = 524$  MPa,  $N = 1.5 \cdot 10^5$  number of cycles

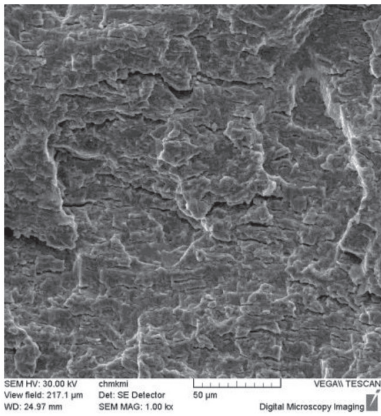


Fig. 5 Area of unstable fatigue crack growth before rupture area with a clear prevalence of large secondary cracks and striations; Hardox 450 steel  $\sigma_a = 524$  MPa,  $N = 1.5 \cdot 10^5$  number of cycles

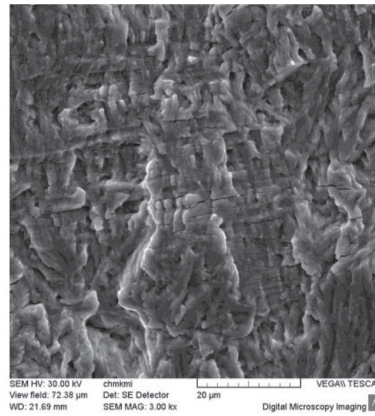


Fig. 6 Striations in the transcrystalline fatigue fracture of specimens Hardox 450 steel;  $\sigma_a = 600$  MPa,  $N = 1.74 \cdot 10^6$  number of cycles

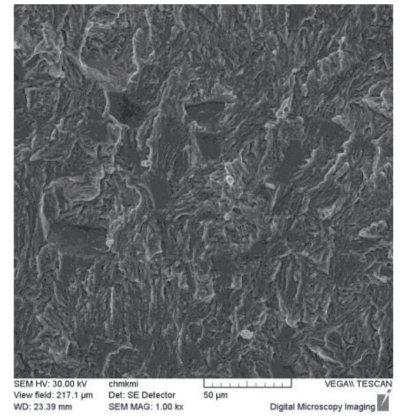


Fig. 7 Mixed character of trans- and intercrystalline fatigue fracture in fatigue failure of Hardox 450 steel;  $\sigma_a = 480$  MPa,  $N = 7.28 \cdot 10^8$  number of cycles

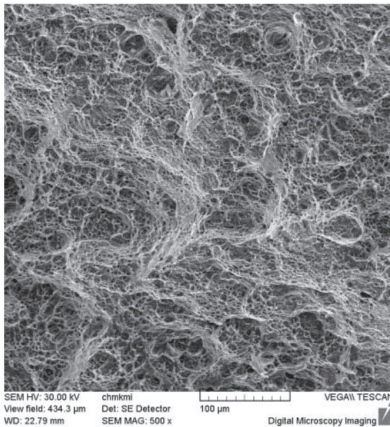


Fig. 8 Transcrystalline ductile fracture with dimple morphology in steel Hardox 400;  $\sigma_a = 330$  MPa,  $N = 1.55 \cdot 10^9$  number of cycles

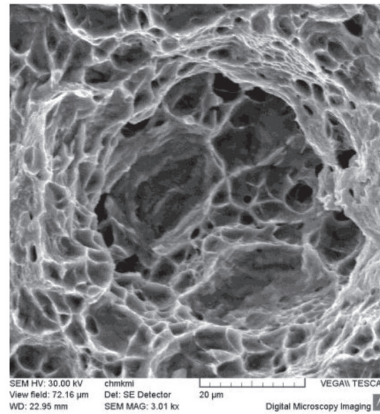


Fig. 9 Transcrystalline ductile fracture with dimple morphology in steel Hardox 400;  $\sigma_a = 330$  MPa,  $N = 1.55 \cdot 10^9$  number of cycles

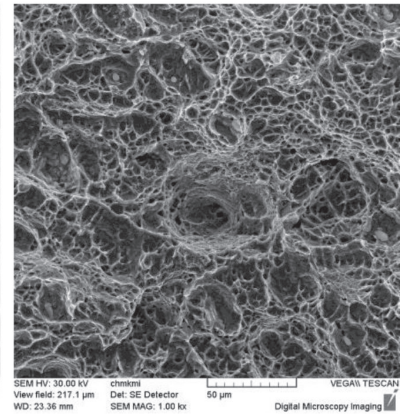


Fig. 10 Transcrystalline ductile fracture with dimple morphology in steel Hardox 450;  $\sigma_a = 480$  MPa,  $N = 7.24 \cdot 10^8$  number of cycles

resistance are the main parameters for assessment of fatigue properties of structural steel shown in Fig. 1. The shape of the curve is characteristic for the Wohler curve.

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 [8]. The tests results formed a dependency curve between the amplitude of applied stress and number of cycles to the specimen crack,  $\sigma_a = f(N)$  (Fig. 1). The tests results (for Hardox steels) formed a curve, which clearly shows that the stress amplitude  $\sigma_a$  decreases together with increase of cycles number  $N$  beyond conventional fatigue limit  $N_c = 10^7$  cycles. The fatigue study showed that in the case of Hardox 400, fatigue limit was 490 MPa. In the case of Hardox 450 steel the fatigue limit was 460 MPa, at the  $N = 10^7$  number of cycles. The results are close to each other, the difference is due to the higher strength and toughness properties of steel Hardox 450.

### 3. Fractographic analysis for the crack areas

In order to learn about the nature of fatigue process of the tested materials fractographic analysis for fatigue fractures was performed [9]. The tests were performed on a scanning electron microscope (SEM) Tescan II.

Test results for both materials Hardox 400 and 450 (Fig. 2) confirm the occurrence of only the surface fatigue crack initiation. Only two samples of steel Hardox 450 showed fatigue crack initiation point below the surface of the sample. In these cases, the fatigue fractures showed characteristic formations known in the literature by the term "fish eyes" (Fig. 3).

On the fatigue fracture surface of Hardox 450 specimens (Fig. 4) there are transcrystalline fatigue fractures of very fine particle morphology. In the area of unstable fatigue fracture just before rupture area there are many degrees of radial and secondary cracks (Fig. 5).

Transcrystalline fatigue fracture of tempering martensite was characterized for both analyzed Hardox steels. Analysis of both Hardox steels revealed transcrystalline fatigue failure of tempered

martensite occurring locally in the form of intercrystalline facets present on the surface (Fig. 7). A transcrystalline propagation mechanism was observed in the area of stable fatigue crack propagation, reflected by presence of striations (Fig. 6).

Areas of rupture for two tested materials are characterized by ductile fatigue fracture with dimple morphology (Figs. 8 - 10).

### 4. Conclusion

The research demonstrates the possibility of using fine-grained Hardox 400 and 450 steels in building of semi-trailers. The use of wear-resistant materials extends the life and also reduces the weight of a trailer thanks to thinner sheets used for the construction of trailers. One of the key parameters is to ensure uniformity of properties throughout the cross-section of the sheet.

Results of this study confirm the classic shape of the Wöhler curve (function of dependencies  $\sigma_a = f(N)$ ). The obtained graph clearly indicates the fatigue limit for all two tested materials. Fatigue tests for high cyclic fatigue, for tested high-strength steels showed a clear fatigue limit: in the case of Hardox 400,  $\sigma_c = 490$  MPa and  $\sigma_c = 460$  MPa in the case of steel Hardox 450.

The fractographic analysis showed that initiation of fatigue cracks was present on the surface of almost all specimens, which was also influenced by their loading. Only in the case of two specimens of Hardox 450, subsurface fatigue crack initiation was observed in the characteristic form of a "fish-eye" structure. However, it was impossible to determine the type of inclusions, which has an impact on the formation of the "fish-eye" structure. This was due to opening and closing of a fatigue crack in a very high number of cycles, which led to total fragmentation of particle inclusions.

In the case of Hardox steels, the share of intercrystalline fractures in the total fatigue fracture surface generally does not exceed 1%. Fatigue crack growth areas were characterized by striations that were oriented perpendicularly to the direction of fatigue crack propagation. The occurrence of fatigue striations is characteristic for the fatigue fracture of steels. Extending distances between individual striations can be observed on the fatigue fracture surface, running through the rupture area.

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