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FATIGUE STRENGTH TESTS OF LAYERED STEEL

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Abstract

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The work deals with original measurement of fatigue properties of formed layered steel material – damask steel. This is a material that exhibits a fine micro-structure as well as a regular composition of many material layers with complementary properties. The article experimentally verifies high-cycle fatigue properties of layered steel and evaluates them from the point of view of fatigue tests of conventional steel materials and a parallel application of a non-destructive – acoustic emission – testing. Finally, it discusses the influence of production on fatigue strength and the possibilities of using multi-layered steel materials in technological practice.
A serious result of this pilot experiment is the fact documented no only by the fractographic observation, but mainly by the AE records that the fatigue service life of this material is high if it its not stressed by tension approximating the yield point R_e. However, such stress is not common in practical use of tools made of damask steel and thus under common bending stress an exceptionally long service life of tools made of this type of material is demonstrable. The fact that damask steel behaves like a homogeneous material is mainly confirmed by the records of the AE signal at lower values of stress σ_a. When stressed by higher amplitudes of tension σ_a damask responds in AE records similarly to a laminate material that is stressed by bending.

damask steel, fatigue tests, crack propagation, non-destructive testing, acoustic emission

Damask steel

Damask steel is a material that exhibits a fine micro-structure as well as a regular composition of many material layers with complementary properties. In general, two types of a steel "semi-finished product" are used that are joined using the forge welding method, i.e. hot volume welding, and heat treated from the point of view of mechanical properties of the fine structure after forming. The material is completely compact without visible traces of delamination even in case of a significant degree of deformation as a consequence of general stress, i.e. when subjected to a static force.

The final cut that is led through the formed packet in a "suitable direction" and the micro-structural composition participate on the damask steel "pattern" after being chemically induced. Etching follows after grinding and polishing. Depth etching (with the use of an acid solution that dissolves individual steel components at a different rate) is manifested by the development of a three-dimensional relief that is characterized by the formation procedure of the layered material composition and the influence of the applied input materials.

The production is based on the selection of suitable steel. With an increasing content of alloying elements steel loses conditional weldability. Therefore, carbon steel is used for the conventional production method. Another parameter for material selection is the ability to join hard, high-carbon steel with considerable resistance to wear on the one hand and on the other hand soft, low-carbon steel with good toughness, i.e. with quasi-plastic properties. The aim is to obtain non-homogeneous material with a relatively regular structure by gradually folding steel plates and simultaneously forging them together. The resulting structure is influenced by the folding technique, the number of folds and their "design". The result is layered material combining properties of the used steel types. I.e. the use of carbon and tool steel will produce damask steel resistant to fragmentation with high resistance to wear at the same time.

Thanks to forming the new material will exceed the soft component in toughness and the properties of the original "hard" component will be changed by forging into an even higher cutting capability and resistance to wear (Čechlovský, 2012; Rudolf, 2010; Černý, 2010; Černý, 2011).

Material fatigue

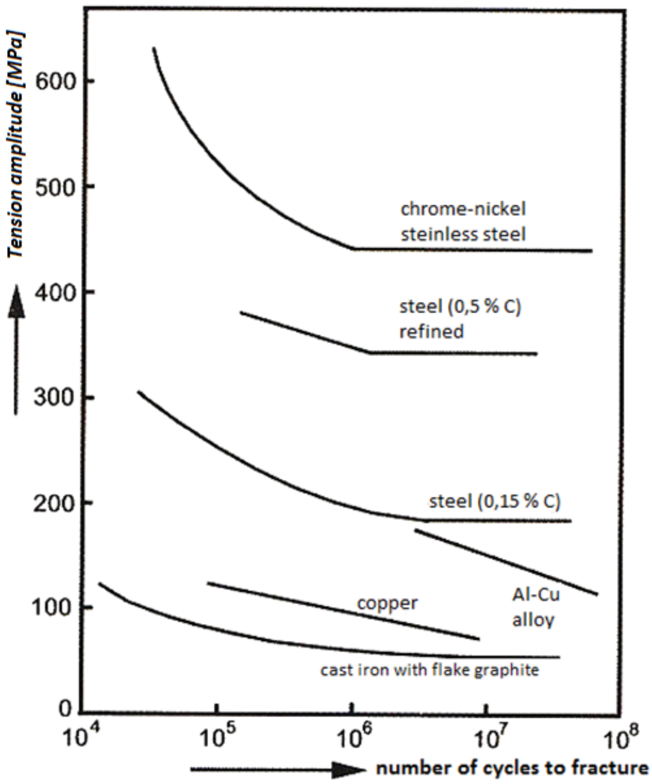
Cyclic quasi-dynamic stress leads to the occurrence of structural material failure, i.e. material fatigue with a growing number of cycles. This is manifested by final rupture of a part that is stressed this way even at lower tensile loads than is its strength characteristic derived from static loading. The reason is micro-deformation due to stress in the elastic range (also, tension concentrates in the area of micro-notches and around defects). In the pre-initiation period of fatigue cyclic deformation absorbs supplied energy within a non-identical movement of cyclic planes during relief. Thus, the surface relief gets gradually initiated and subsequently a fatigue micro-crack develops from intrusions. The failure of the body develops in three stages. The first one includes a change of mechanical properties of the material (occurrence of persistent glide bands, creation of a fatigue dislocation structure), the second one is the stage of initiation of a fatigue micro-crack, its growth and change of the propagation direction (its gradual orientation changes into a direction that is perpendicular to the external load). The final rupture of the material depends on the temperature, loading rate, the influence of external stress and fracture properties of the material. Fatigue can be classified with regard to the number of fatigue cycles until failure as - low-cycle fatigue (LC, up to 10^3 cycles) and high-cycle fatigue (HC, usually 10^4 to 10^6 cycles in steel; the stress is in the range under the yield point R_e).

The fatigue behaviour of material is influenced by the manner of loading, surface quality, size of the body, heat treatment (internal material tension), presence of notches (design, technological or structural notch). Therefore, test conditions need to be defined. What must be determined it is the test material type (product type, the same heat treatment, etc.) and the same test conditions (frequency, surface finish, type of loading cycles, external conditions).

The dependence of stress amplitude σ_a on the number of cycles N (in log) until material fracture is referred to as the Wöhler fatigue curve (also the S-N curve) (Fig. 1). It consists of the section of the fatigue time limit, which drops with the number of cycles, and the section belonging to the fatigue limit σ_c, where the fatigue stress theoretically does not change any more. The fatigue limit σ_c is a material characteristic. It can be defined as the maximum amplitude of stress at the "unlimited" number of cycles (Vojtěch, 2010; Pohoda, 2005).

Acoustic emission

In the course of material stress visually unperceivable changes occur in the structure. To verify these internal changes e.g. a non-destructive test method - acoustic emissions (AE) is used that



1: *Wöhler (S-N) curve of selected materials (Vojtěch, 2010)* can be combined in parallel with a destructive test. AE is getting more and more frequently used in industry for its unique ability to provide early warning signals of the occurrence of a failure. The development of a fatigue failure can be classified into unexpected failures (Mazal, 2006; Mazal, 2011).

Elastic waves are generated in a body e.g. due to dynamic relaxation of tension in the material (movement of dislocations, glides at edges, etc.). Within the AE method a transducer detects elastic waves, which are converted into an electric signal that is further evaluated. The process of occurrence and detection of an acoustic emission signal can be summarized in these primary stages: event in the place of source of the acoustic emission, propagation of tension waves towards the transducer, detection of waves by the transducer, transformation of the tension signal to an electric signal and its subsequent evaluation from the point of view of AE (Fig. 2).

Fractographic observations

Metallographic and fractographic macro- and micro-observations are used as a supplement of mechanical tests to verify the influence of the material structure and development of failure in the tested specimen. They are based of visual observation of a polished, etched specimen or the fracture surface after the test. A detailed check, evaluation of the basic structural phases and fracture mechanisms can be carried out with the use of both a light microscope (up to magnification of 1500x), and an electron screening microscope (SEM; up to the magnification of 20000x) (Dostál, 2011).

Experimental part

Practical use of cutting tools involves not only the regime of large (isolated) force actions (cutting, shearing, cleaving), but much more frequently a high number of cycles with low-load values. This load (high number of cycles) causes material fracture even though the conventional strength characteristic of the material R_m has not been exceeded. So the conclusion can be drawn that the service life of a component results from its resistance to high-cycle fatigue. A tool usually has the shape of a flat rectangular profile exposed to bending stress. Therefore, in the experiments alternate bending stress was selected.

The test objects for the fatigue strength test were made of a rod forging of damask steel. It was produced using the forge welding method. The input packet was composed of 17 layers (9 layers of steel 19 133 – Czech standard, layer thickness 6 mm, 8 layers of 80NiCr11 steel, thickness 1.2 mm). The packet was cut into 8 parts and folded 3 times and forged. This way damask steel with 136 layers was obtained. 15 test objects were made (5 mm × 12 mm × 80 mm). The production, hardening and tempering procedure are shown in Fig. 3.

For the HC fatigue tests a RUMUL Cracktronic electro-resonance pulsator was selected that makes it possible to load the tested object with alternate bending stress (Fig. 4).

On the tested specimen and on the clamping jaws AE DAKEL MIDI transducers with a preamplifier were attached (Fig. 4) and the obtained AE data were processed by a DAKEL Xedo measuring analyzer and the Xedo Deamon software application.

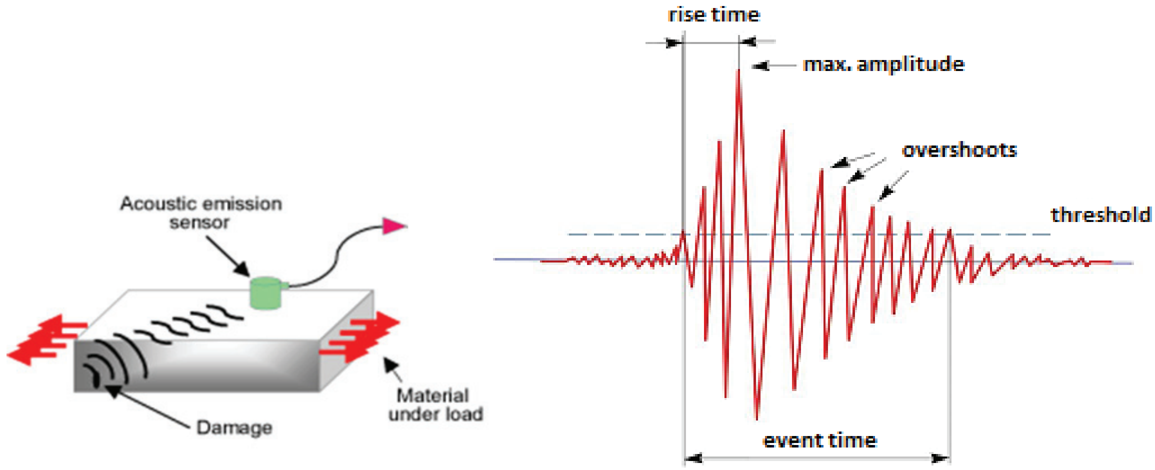
RESULTS OF THE HC TESTS

For the high-cycle fatigue test five sets of samples were used while each of them was subjected to a test at a predetermined load. The average results for individual stress levels are recorded in Tab. I.

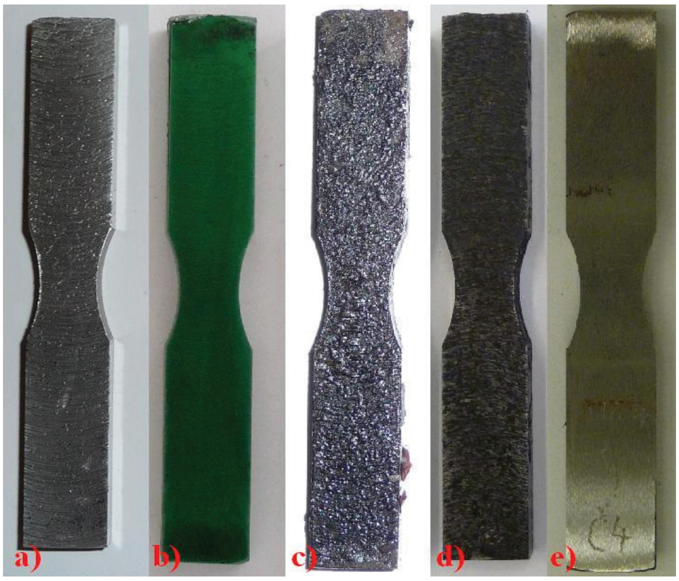
The basic Wöhler (S-N) dependence for the mean values of specimens of the five sets is shown in Fig. 5.

The final fracture of the fatigue test specimens was achieved in liquid N_2 (Fig. 6). The fracture surfaces were subjected to fractographic observation using a screening microscope (SEM). The obtained results are presented under the figures (Figs. 7 to 15).

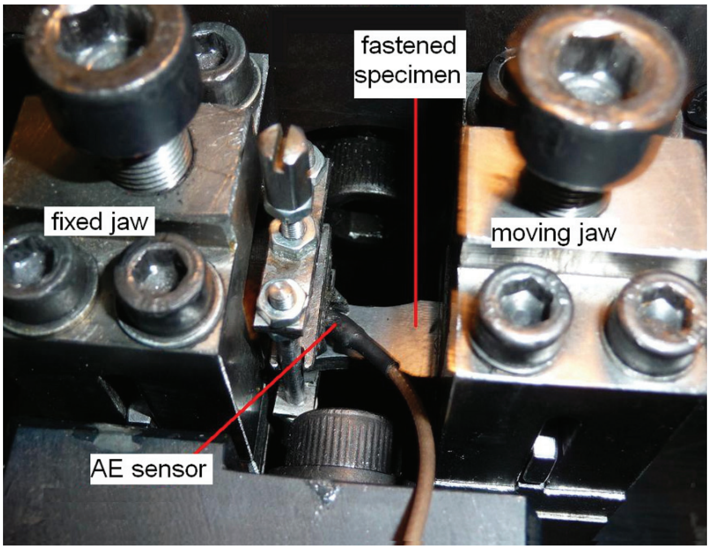
More detailed information about the processes going on in the material structure during the HC tests were obtained from the AE non-destructive



2: *Principle of detection and AE and representation of basic parameters (Vlašic, 2011)*



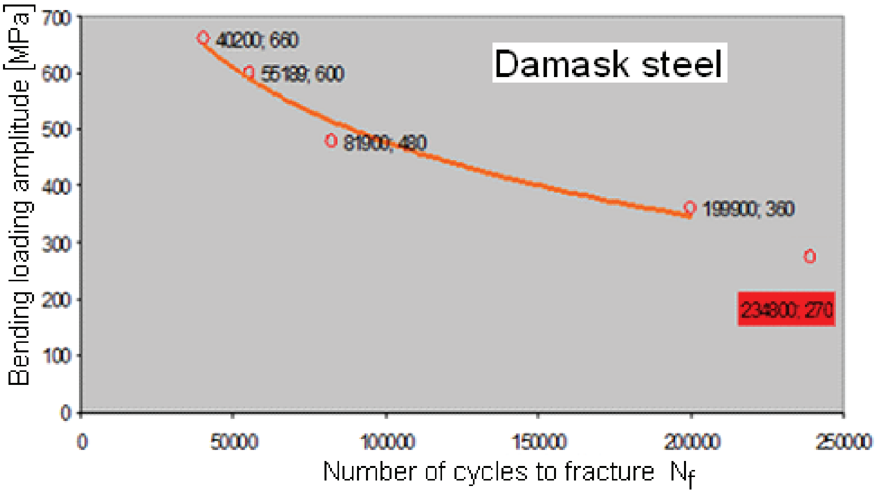
3: *Specimen for HC fatigue test – a) machining, b) the coating against surface decarburization during quenching, c) hardened from 900 ° C / oil, d) tempering 150 ° C (Jech, 1983), e) grinding (author)*
Note: *Steel 19 133 gives damask steel hardness and resistance to wear. To ensure toughness and resistance of the damask material to fragmentation 80NiCr11 steel was selected.*



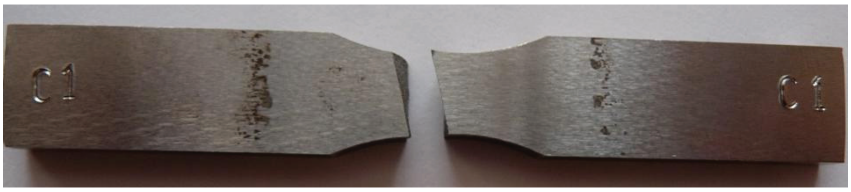
4: *Specimen in the clamping jaws with the AE sensor (author)*

I: *Results of high-cycle fatigue*

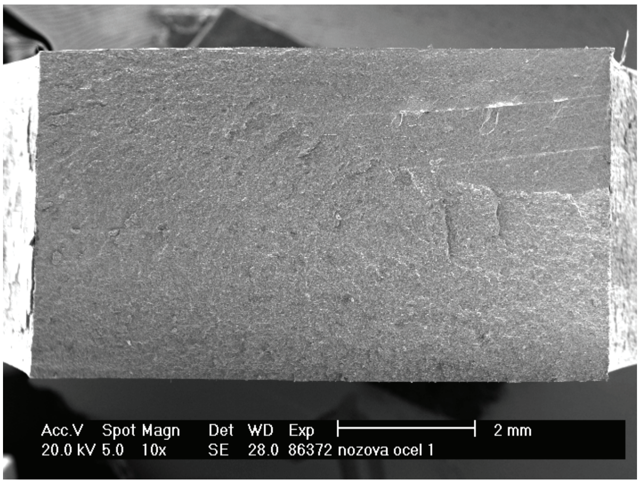
Number of specimen set	Selected loading		Starting frequency	Number of cycles
	Bending moment ± [Nm]	loading σ_a ± [MPa]	[Hz]	[–]
1	22	660	72.4	40200
2	20	600	72.1	55189
3	16	480	72.39	81900
4	12	360	72.21	199900
5	9	270	72.14	234800



5: *Wöhler (S-N) curve of tested Damask steel (author)*



6: *The test specimen after break in liquid nitrogen (author)*



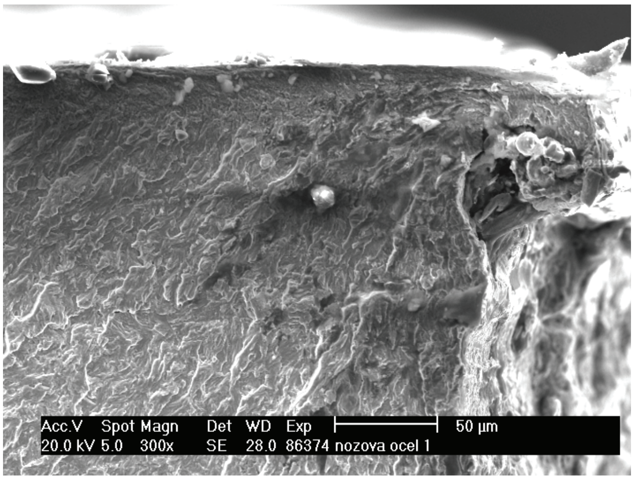
7: *Typical appearance of the fracture surface after break in N_2 (author)*

tests. Typical courses of the AE signal are shown in Figs. 16 to 20. AE count (emission count) is the number of times the acoustic emission signal exceeds a preset threshold during any selected portion of a test and RMS is time averaged AE signal, measured on a linear scale and reported in volts (intensity parameter of continuous emission).

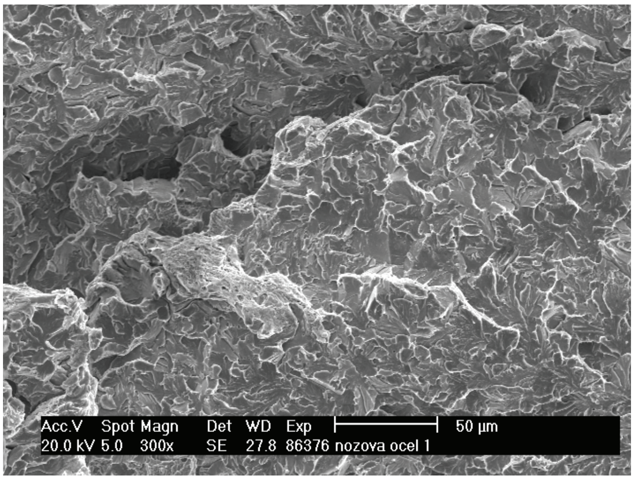
CONCLUSION

Under high-cycle fatigue, subjected to alternate bending stress (cyclic symmetrical loading) up to 600 MPa damask behaves like a homogeneous material! Also in this case the conventional stress saturation of material, compaction, was manifested. The fact that damask steel behaves like a homogeneous material is mainly confirmed by the records of the AE signal at lower values of stress σ_a (see Figs. 18 and 20). During the test acoustic activity can be observed in the initial stage of the cyclic loading, when the material gets compacted. When compaction has been achieved, the AE activity stops. An increase of both RMS and the number of acoustic event only appears at the end of stage I of the fatigue life and on transformation of the micro-crack into a central fatigue crack.

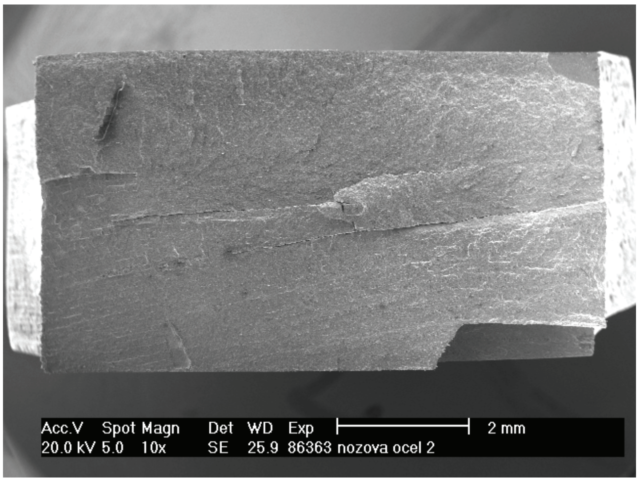
In specimens with a higher amplitude of the loading bending torque, when $\sigma_a < R_e$, the acoustic



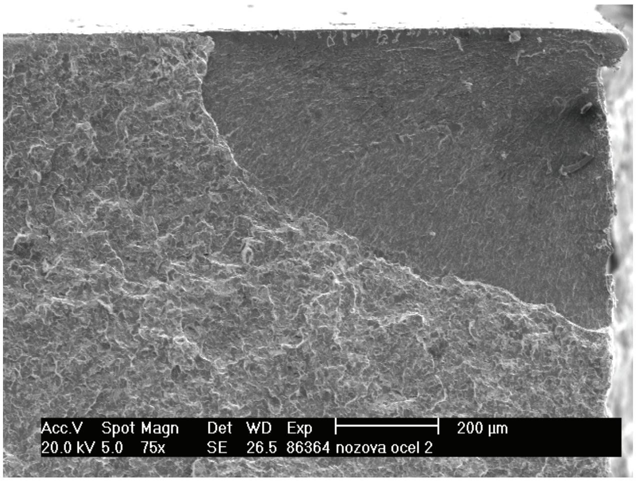
8: *The emergence of fatigue cracks on the inhomogeneity – inclusion (right) (author)*



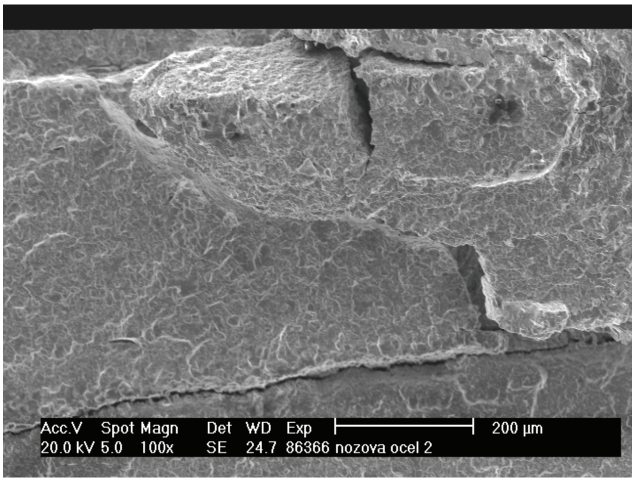
9: *Discontinuity in the layers weld and its influence on crack propagation (author)*



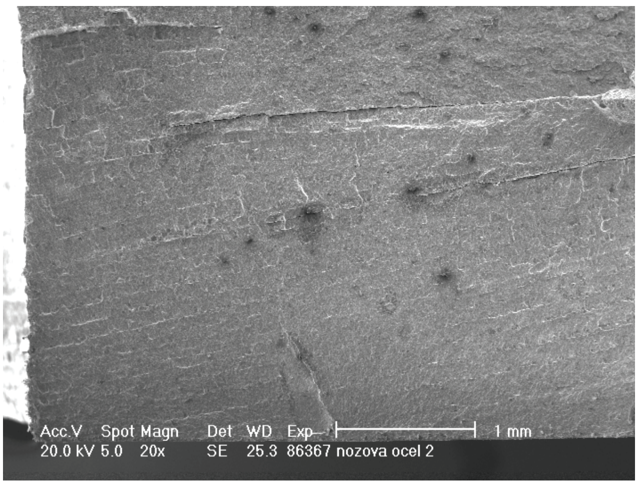
10: *Fracture surface with initiation place and influence of stress distortion (author)*



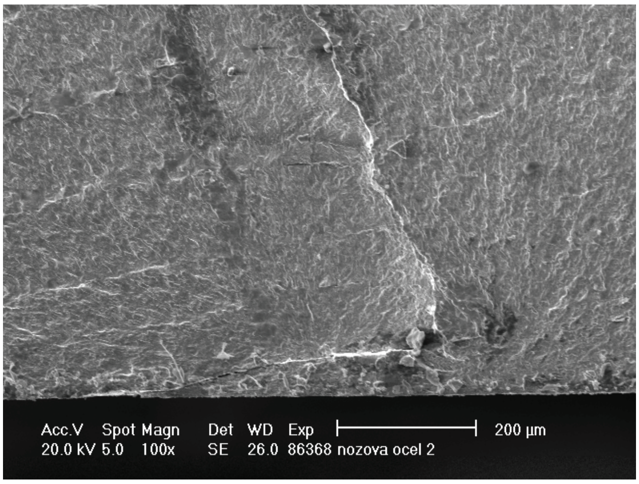
11: *The initial position (right) and the development of micro-cracks of veneer after sanding - significant inhomogeneity with metal bond, formation of relief on the surface of the sample (author)*



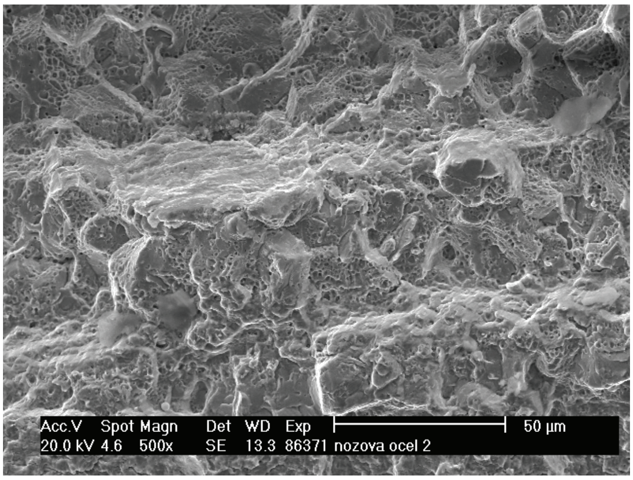
12: *Steps on the fracture surface cracks due to the transition to other levels caused by tension and material inhomogeneity (author)*



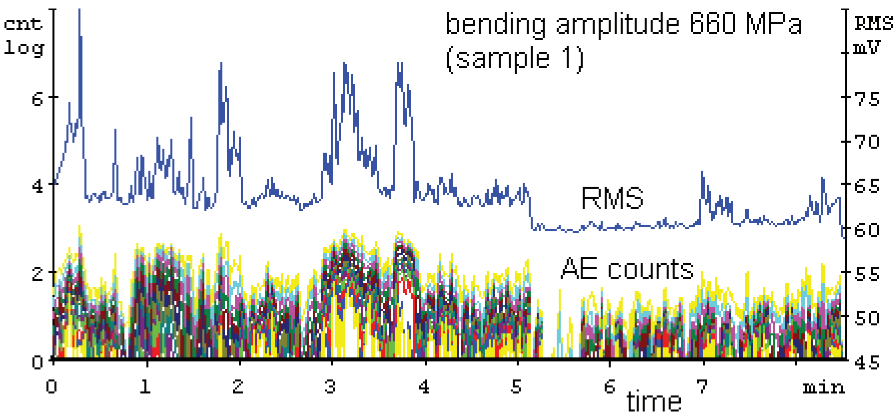
13: *Tracks "slip of" layers at a higher bending stress (author)*



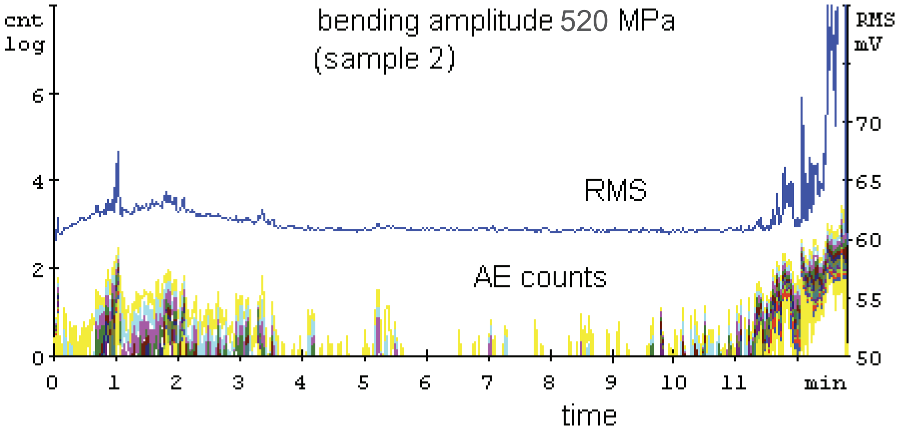
14: *Secondary fatigue microcracks in contact between two layers of steel (author)*



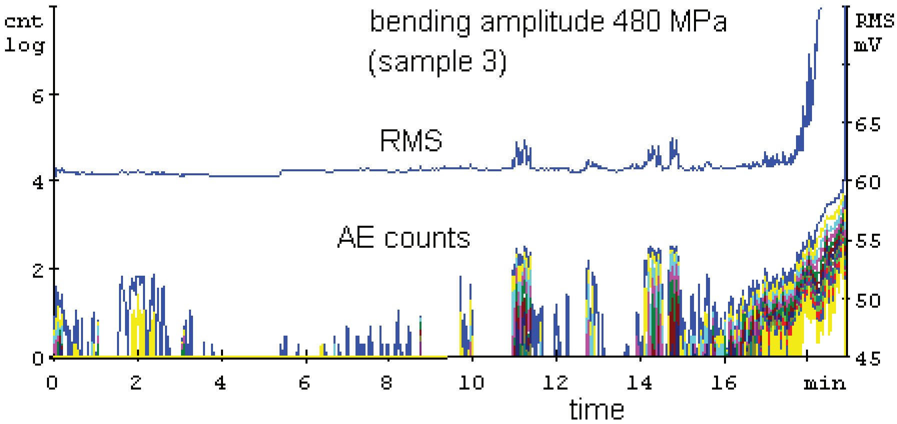
15: *Transition weld of "damask" creating "bridges" in the wrong smithery weld (author)*



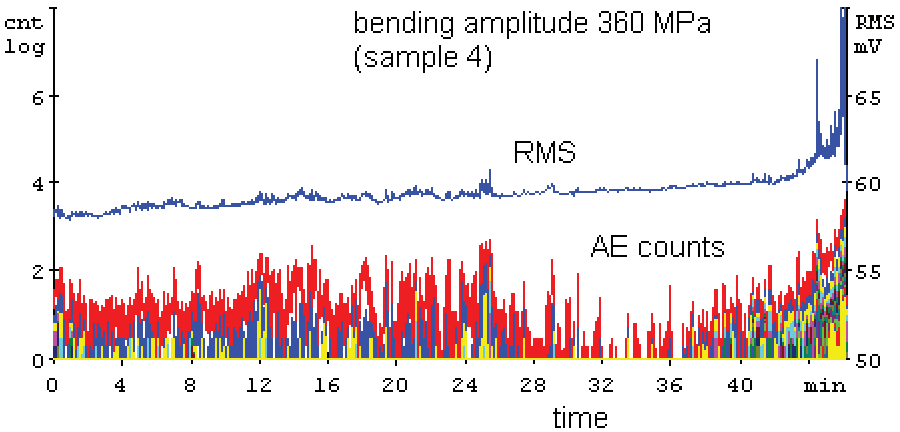
16: *AE signal at a high value of bending stress – acoustic response of micro-layers at the discontinuities in welds (author)*



17: *Example of AE signal from the sample with a lower micro-response (at lower bending stress during the test) (author)*

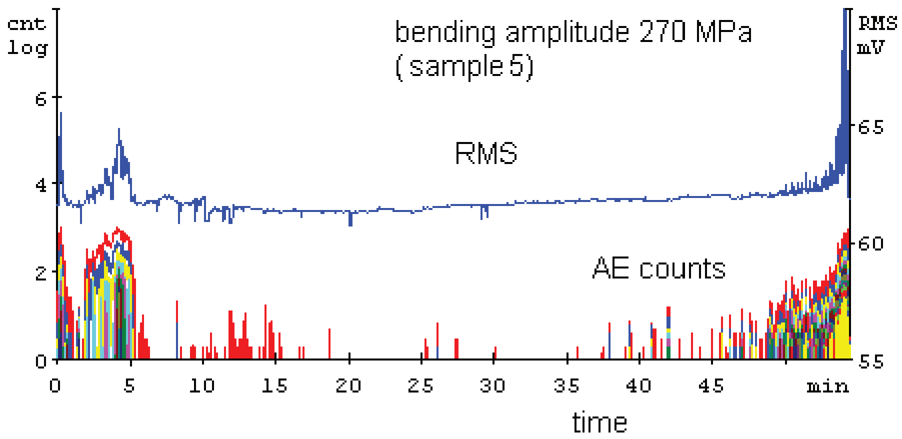


18: *Material of the sample according to AE behaves as a homogeneous (author)*



19: *Emissions waves when moving layers at low deformation (author)*

activity of compaction is superimposed by the manifestation of acoustic waves emitted during micro-friction between layers of the damask material. When stressed by higher amplitudes of tension σ_a damask responds in AE records similarly to a laminate material that is stressed by bending. Glides of sliding steel layers are manifested as a significant source of the wave activity (Fig. 16). The activity of events in case of poor-quality welding (forging) of the layers within the currently used and described production technology of damask steel is also characteristic. However, the activity is situated in other levels of events, which is also documented by the course and value of RMS (Fig. 19).



20: *The initial stabilization and initiation of microcracks at the end of the record (RMS and number of AE counts) on quality of material forming no obvious defects in the welds between the layers (author)*

A serious result of this pilot experiment is the fact documented no only by the fractographic observation, but mainly by the AE records that the fatigue service life of this material is high if it its not stressed by tension approximating the yield point R_e. However, such stress is not common in practical use of tools made of damask steel and thus under common bending stress an exceptionally long service life of tools made of this type of material is demonstrable. Strong points of cutting tools made of damask steel do not only include aesthetic appearance, but the significance of this material is mainly in the sphere of fatigue strength. Of course, what must be taken into account here is also the influence of the input steel, share of the damask production technology and the applied heat treatment. All this may lead to different results with regard to material properties (also the fatigue limit). From the point of view of verbally documented techniques of production of the original damask the behaviour of this steel type cannot be evaluated generally[1]. Therefore, the above mentioned findings concerning high-cycle fatigue cannot be applied timelessly, i.e. to damask steel in general (historical damask). The conclusions are only valid for materials produced with the use of the above mentioned technology. What remains doubtful is more widespread application of damask steel in the technical practice with regard to its convenient mechanical properties, but in parallel with regard to its high production costs (Černý, 2012).

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1 Forging through damask packets originally continued in steps in individual processed steel volumes. Damask was gradually produced in stages with several-year breaks between forming (the range of 10 to 18 years is mentioned in literature!) and consequential conservation of forgings with leather soaked in grease in the meantime. This production technique has its empirical origin. It can be seen in the discovered consequence of a heat activated action with time dependence. It is obvious that the diffusion theory (of oxygen, hydrogen, nitrogen, etc. as well as additional elements called alloying additions contained in the alloy) and the theory of interatomary links were completely unknown then. Forming of the most precious plates of damask steel using the above mentioned technique took several generations!

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