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The Fatigue Fracture Caused by a Random Operating Process

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Abstract The whole structures, mostly the structural nodes or elements work in time-varied stress instead of the static one. The stress concentrators are such changes of shape of mechanical part which evoke the changes of force flow. They influence the stress which loads this part. The risk of fatigue damage concerns structural components, structural knots and even whole structures subjected to random loading. This can initiate the accumulation of fatigue damage in critical points of the structure, growth and spreading of fatigue cracks and, eventually, fatigue fracture. Final failure of structural components may have fatal consequences. Damage and fatigue failure may occur due to a combination of cyclical stress and improper technology for producing a structural element, e.g. during welding. These failures are documented on the example of the holder of a crusher moving knife and of the turbine rotor shaft.

Keywords: *fatigue crack, fatigue damage, loading, stress concentration factor*

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1. Introduction

The whole structures, mostly the structural nodes or elements work in time-varied stress instead of the static one. Such kind of stress is caused by the operational stresses or the loading which is typically stochastic (a random). It is opposite to a deterministic processes which can be evaluated much easier and occur to a lesser extent. The detailed layout and classification of the oscillatory loading is given (Figure 1). Even the operational stress which is acting to a particular structural element may have a different composition and the character. There is also an example shown in Figure 1 of such operational stress with a specific composition. [1]

The single elements of the structure or the whole structural groups can be exposed to the different values of the number of load oscillations.

Therefore, the character of the stochastic process in time is random. It is called a random stress process where the deterministic argument is time. It follows that the random process of loading which was obtained using ESA (Experimental Stress Analysis) has to be computed properly for fatigue applications.

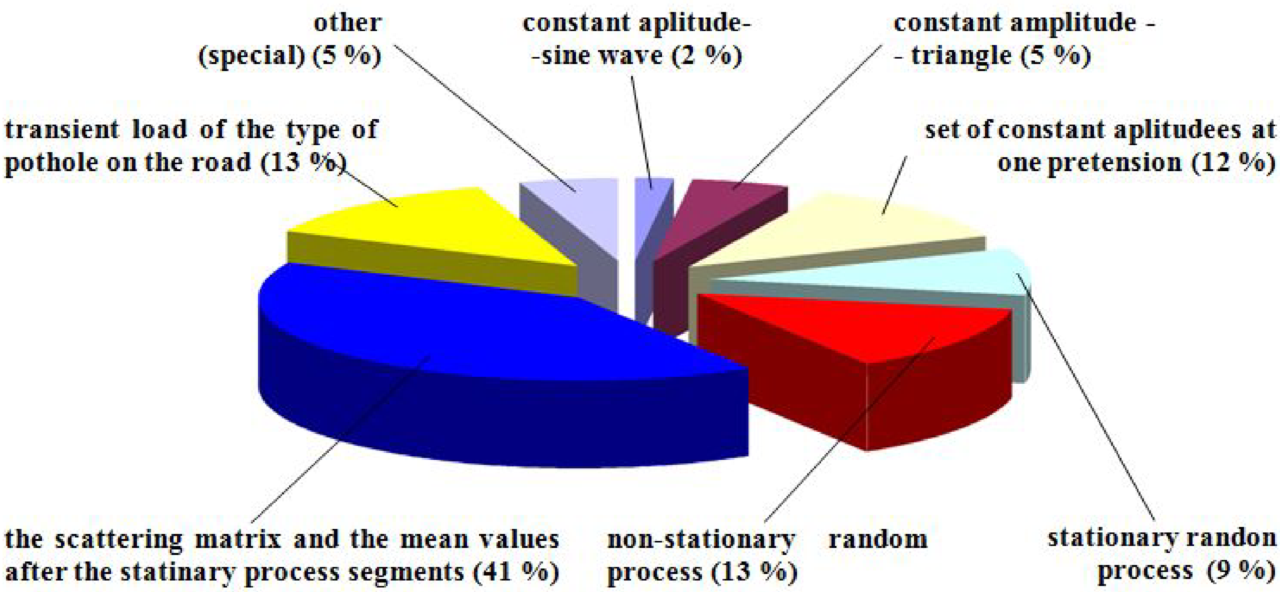

Figure 1. The relative share of the types of operating load

Actually there are two main types of evaluation of recorded data of the random process of loading and processing:

- the characteristics of correlation and spectral analysis;
- the characteristic of abundance method of parameters.

When it comes about the difficulty of processing, the weak stationary process is pretty bad process because of its characteristics. Most of its characteristics are unstable and depends on time. However the most difficult type of processing is the non-stationary process. Such process has all its characteristics unstable and also depends on time.

By subjecting a component or structure to the action of time-varying force or deformations of supercritical size, (the force or deformation which is causing a stress greater than the fatigue limit) there occurs a fracture process after some time. The fracture is the result of very difficult processes in a material structure. However, the maximum level of stress is (or can be) in a way that its static action tolerates the material without any breakage. The fatigue is type of the process where the permanent damage of the component with the fracture is. Of course, there can be the failure of the structure or its part before completing this process. In this case the fracture is called a fatigue fracture. Such fatigue character caused by the repeated dynamic stresses is a most operating fracture of real structures. Examples of these fractures are shown in Figure 2.

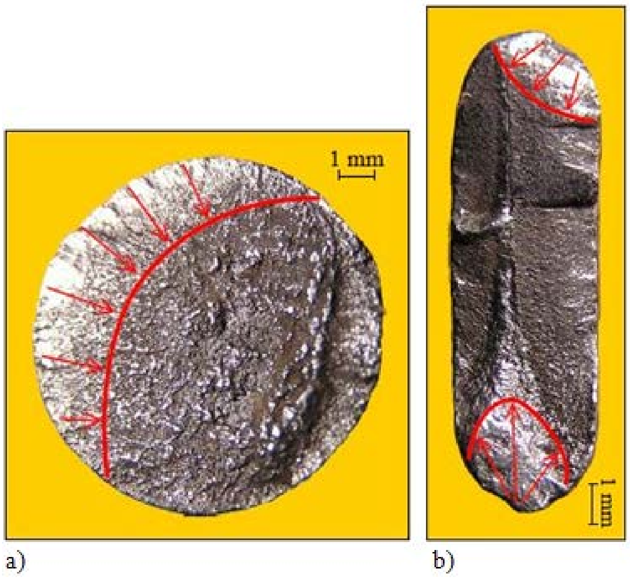

Figure 2. Typical surfaces of fatigue fractures caused by the real load

Figure 2 also shows the typical surfaces of fatigue fractures after the real loading process with the indicated directions of fatigue crack propagation. From the appearance of the fracture and also according the classification [2,3,4] it can be concluded that the fracture shown in Figure 2a) was probably caused by unilateral bend of the component at high nominal stress with its large local concentration. However, the fracture in Figure 2b) was probably caused by a non-symmetrical oblique bipolar bend of a high nominal stress of component with its small local concentration [5].

Due to reality that the fatigue (along with overload) and its consequence – the fatigue fracture is one of the main reasons of limited state of large structures, we can consider fatigue as a concept of limit states.

Mostly, there is irregular loading depending on time in practice so the source of the loading can be divided into:

- the static loading which is stable and it still present,
- the work loading which is not stable and depends on time and it is the result of operational stress of structural element,
- the vibration loading is type of cyclic loading with high frequency,
- the accidental loading which does not occur so often.

The work loading and also the vibration loading belong to cyclic type of loading which creates fatigue damage.

The fatigue fracture occurs suddenly, without any previous deformation of material. It is typical character of fatigue fractures.

2. The Mechanism of Fatigue Crack Propagation

The lifetime of the structure or fatigue strength depends on a way of propagation of fatigue crack. However the whole process (in case of sustained loading) ends with the fracture. The mechanism of fracture is the summary or the sequence of such mentioned effect. During the assessment process of structure there should be also taking into account the data of the origin and propagation of fatigue cracks by application of the mechanical fracture theory. The whole fatigue process of every component with the all conditions of loading can be divided in to a several phases:

- the phase of change of mechanical properties (I),
- the phase of crack initiation (II),
- the phase of crack propagation with two additional phases:
  - the phase of short crack propagation (III),
  - the phase of long crack propagation (IV),
- the phase of the final fatigue fracture (V).

The phases II, III, IV and V are shown in Figure 3.

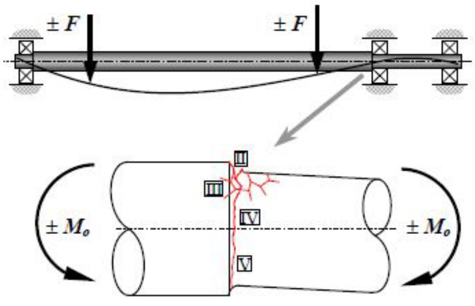

Figure 3. The phases of the fatigue process

There is a significant change of distribution and density of dislocations in a material that changes its mechanical properties. It is due to phases of mechanical properties where the initiation and accumulation of cyclic plastic defamation is. However, those irreversible changes occurring throughout the whole volume of sample.

In phase of crack initiation there is a concentration of stresses and deformations around the concentrators due to accumulation of cyclic plastic defamation. Finally it will create one or several micro-cracks. This process is limited only to a small volume of sample.

The phase of short crack propagation consists of micro-cracks of small length (0.5 to 1.0 or to 2.0 mm), with the suitable conditions for growing. Such cracks propagate crystallographically along the active sliding grooves of the grid in the plane of maximum shear stress. It is approximately at an angle of 45° to the direction of action of the cyclic tensile stress. The cracks are propagation in trans-granular way and it is questionable to use the linear elastic fracture mechanics in this phase.

There occur just one magistrate crack in phase of long crack propagation while the other cracks stopped growing. The crack is propagation upright in non- crystallographically way to the direction of main stress in way of trans-granular and less often inter-granular way. It is possible to use the linear elastic fracture mechanics in this phase. The propagation of long crack can be mathematically expressed using the parameters of fracture mechanics. However, there are many empirical relationships which are able to connect the velocity of fatigue crack propagation with the coefficient of the stress intensity K_a. Nowadays, the most commonly used law for such case is the Paris-Erdogan´s low which is described as:

$$dc/dN = A \cdot K_a^m, \tag{1}$$

where:
dc/dN is the velocity of fatigue crack propagation [m.cycle^{-1}],
N is the number of oscillations,
A, m are the parameters of equation (the materials constants experimentally determined),
K_a is the amplitude of the stress intensity coefficient [MPa.m^{½}].

The graphical representation of this dependence is illustrated by the kinetic diagram in Figure 4, where K_{ath} is the amplitude threshold of the stress intensity coefficient.

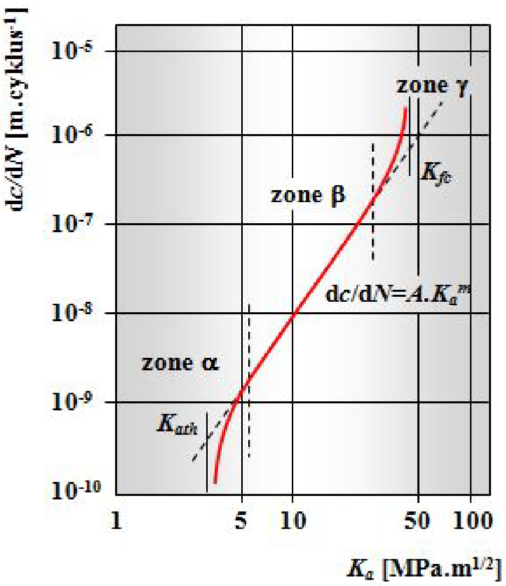

Figure 4. The kinetic diagram of fatigue damage

The K_{fc} is fatigue fracture tenacity in which the final fracture occurs and also to which the dc/dN curve is approaching asymptotically. The final phase of fatigue crack propagation is the final fatigue fracture. The magistrate crack propagation will increase the stress in a decreasing cross-sectional area. The final fatigue crack will occur in case that the upper loading cycle overload the critical level of stress of the remaining part of the cross-sectional area. Also the developed crack must reach the critical length at the same time. The critical crack length has a significant scatter because of changes in the material properties.

The final fracture process is mostly quick and brittle. However there can be a case when the final fracture has tough fracture character. The previous division of fatigue process into phases is the formal one which means that individual phases passing smoothly between themselves without any visible line.

3. The Failure of the Holder of a Crusher Moving Knife

The broken part of the holder of a crusher moving knife has character of damage due to stress concentration and fatigue fracture (Figure 5 and Figure 6). However the surface and subsurface stress concentrators are initiated places of fracture process.

According the visual survey, technical study of failure possibilities, the material analyses with a chemical composition and also according the influence of hardness and analyses of fracture areas and assessment of the technical condition but also according the maintenance reports and operational capability of the device we can conclude that crusher device was not designed correctly when it comes about the mounting the knife holder of body to a rotor. The welds create a number of concentrators. As the number of loading cycles exceeded the value of 2.10^6 cycles there occurred an increased loading of imperfect welding technology with the result of fracture process.

Figure 5. The overview of the failures part of the holder of knife

Figure 6. The shaft after the failure of the holder of a crusher moving knife

4. The Failure of the Turbine Rotor Shaft

The failure of cross-section of the turbine rotor shaft and its characteristics of fracture type shows the failure due to excessive cyclic loading caused by bending and torsion moment. Once the cross-section part was weak, there was an additional bend to break the rotor shaft in place. [6]

It was found from a detailed analysis of the fracture area (Figure 7 and Figure 8) that the place with the greatest depth of fatigue failure contains a crack in a circumferential direction. But this failure occurred due to imperfect technology which was used during the construction process of turbine rotor.

Figure 7. The fracture area of the broken part of the turbine shaft

Figure 8. The fracture area of the opposite broken part of the turbine shaft

According the fracture area analysis in term of failure mechanism we can conclude that there was not any shell structure of the crack propagation in critical cross-section of shaft found. However the fatigue fracture was non concentrically. From the detailed analysis of fracture area it is known that the place with the greatest depth of fatigue failure contains a crack in a circumferential direction. Its origin is not caused by loading but this failure occurred due to imperfect technology which was used during the construction process of turbine rotor. In case of variable loading process the mentioned crack could result into a surface first and then it could cause a sharp notch. Such notch is the main reason of the failure of the turbine rotor shaft.

Figure 7 shows the fracture area of broken part of turbine shaft. The fracture area exhibits the fatigue damage. On the left side of the figure there are macro-cracks under the surface of the shaft in the circumferential direction about 15 mm below the surface.

5. Conclusion

The analysis of the fatigue process belongs to a very difficult task which is involving a number of analyses associated with the result of experiments as well as numerical and analytical calculations.

The final damage of a material is the result of a complex process which involves a number of stages until fracture. There are various factors that affect the process. Depending upon the number of loading cycles, possible factors here are the preloading, time sequence of the cycles of various magnitudes and intervals, then the frequency and the speed of deformation changes, temperature, inner structure of the material, the shape of structural component etc. There have been a number of hypotheses as regards fatigue damage accumulation with respect to fatigue life prediction. The aim is to find such relationship which would fit for fatigue life during loading with higher number of cycles on the basis of results relevant for single-cycle tests. Hot spot stress depends upon the size of structural components or weld joints and upon the way these are being stressed. Hot spot stress implies increased stress due to some changes in bearing capacity of the cross-section of the structural component without any impact of local stress concentration factors which are caused by the shape of a weld joint or defects. The estimation of live necessarily requires the assessment of hot spot stress in the critical region of structural component or joint in which the occurrence of a crack is most probable.

Acknowledgements

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References

[1] M. Růžička, M. Hanke and M. Rost, *Dynamická pevnost a životnost*. 1. vydanie. ES ČVUT Praha, 1987. 212 s.

[2] F. Trebuňa and F. Šimčák, *Pružnosť, pevnosť a plastickosť v strojárstve*. 1. vydanie. Emilena Košice, 2005. 484 s. ISBN 80-8073-276-0.

[3] F. Trebuňa and F. Šimčák, *Odolnosť prvkov mechanických sústav*. Košice: Emilena, 2004. ISBN 80-8073-148-9.

[4] N. E. Dowling, *Mechanical Behavior of Materials*, Prentice Hall International Edition, 1993.

[5] O. Ostertag and P. Sivák, *Degradačné procesy a predikcia životnosti*. Typopress Košice, 2010. ISBN 978-80-553-0486-1.

[6] P. Trebuňa, M. Pástor, F. Trebuňa and F. Šimčák, *The analysis is of failure causes of the rotor shaft of steam turbines.* In. Metalurgija, 56, 2017, p.233-236.