

Model of Fatigue life Degradation of Crankshaft

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Abstract: - This article is dedicated to modeling and simulation of fatigue degradation of crankshaft. In this article is discussed model of crankshaft which is damaged during its service life. Specially authors consider in their work the fatigue damage influenced by the vibration during traffic. The fatigue damage is considerable problem in engineering and can cause catastrophic accidents, also this accidents can caused fatal injury of personnel. The crankshafts are subjected to the intensive multiaxial loading during its working life and crankshaft failure is much more frequent cause of the accident, during the engine service parts except cylinder rupture. Therefore great effort is devout to the fatigue resistance improvement and proper method of fatigue life modeling. In recent work, relatively new approach for fatigue crack modeling is discussed and its application on specific problem of crankshaft in four cylinder engine. Experimental part of this study is based on measurement of vibration on the crankshaft. The experimental device was used with down-scaled model of engine to reveal influence of vibration. The majority of fatigue crack models are working with predefined boundary length of crack. This length makes possible to distinguish between the different phases of crack growth, i.e. different crack growth mechanism. The method used in this work is based on another approach. The fatigue crack is simulated in this way: (1) the crack grew throughout the whole crankshaft volume controlled by nucleation mechanism, (2) by propagation mechanism. Thus two different fatigue curves are obtained and merged in one final fatigue curve. This method is in compliance with data obtained experimentally.

Key-Words: - Crankshaft, Simulation, FEM model, Fatigue, Modeling, Experimental study

1 Introduction

Currently, a large variety of engines is used in technical praxis. With exception of turbines a majority of engines is based on pistons which are moving under pressure forces. These pistons are sliding inside cylinders and these pistons are connected to the crankshaft. It can be said, that majority of combustion engines is an example of crank-mechanism. A crankshaft can be defined as a mechanical part, which is able to perform a conversion between reciprocating motion of piston and rotational motion. In the case of a reciprocating engine, crankshaft translates reciprocating motion caused by pressure forces of gas or steam, into rotational motion which caused spinning of wheels. Whereas in the case of a reciprocating compressor, the role is opposite, it converts the rotational motion into reciprocating motion. In order to do the conversion between two motions, the crankshaft has crank journal which is a part of a shaft or axle that rests on bearings. Usually an additional bearing surface is situated on the crankshaft ends. When we look on the Fig. 1, we can see all important parts of

mechanism. As the crankshaft undergoes a great deal of sideways load from each cylinder in a multi-cylinder engine (typically four or six), it must be supported by several such bearings, not just one at each end. A crankshaft is subjected to enormous stresses, potentially equivalent of several tones of force. The crankshaft is connected to the fly-wheel (used to smooth out shock and convert energy to torque), the engine block, using bearings on the main journals, and to the pistons via their respective con-rods. An engine loses up to 75% of its generated energy in the form of friction, noise and vibration in the crankcase and piston area.

It is typically connected to a flywheel to reduce the pulsation characteristic of the four-stroke cycle, and sometimes a torsional or vibrational damper at the opposite end, to reduce the torsional vibrations often caused along the length of the crankshaft by the cylinders farthest from the output end acting on the torsional elasticity of the metal. It is clear that the acting forces can cause considerable strain in these parts of engines. The experience of operating this device shows that the parts of crankshaft are often damaged despite that the acting load is deep

bellow the strength limits. Thus damage can be explained by materials fatigue [1-8]. The fatigue fracture was described by many authors, as cumulative process that occurs in mechanical parts which are subjected to cyclic forces whose size is smaller than materials ultimate strength or even bellow yield strength. From the microscopic point of view, the process of fatigue fracture can be explained using theory of dislocations.



Fig. 1 Crankshaft from four cylinder engine whose fatigue life is studied in article.

The dislocations are moving in material, which leads to formation of persistent slip bands. This persistent slip bands are nucleus of short cracks. Now, when first or nucleation phase of crack formation was described, we can start to describe growing phase. Crack growth phase starts, when the crack has reached some specific limit length. During this phase, the crack is growing to another specific length (or specific cross-section of component) and when that is achieved, the ultimate strength of material is exceeded the ductile failure of crankshaft occurs. Many authors with used of microscopic study made on mechanical parts destroyed due to fatigue, that the nucleation process starts on macroscopic and microscopic discontinuities at the size of crystalline grain. This theory was also confirmed by studies performed on laboratory samples. That is the reason why the surface treatment and heat treatment of the material are often used to increase the fatigue resistance of steel or other metallic alloys. Another approach in improvement of fatigue resistance of engineering components is based on the choice of appropriate shape and geometry of product with minimal influence of stress concentrators such as holes or sharp edges. Because this feature with strange

geometry, are common locations where the fatigue cracks often initiates. It is necessary all this these requirements to include in the final design of the product. Nowadays, many procedures are used to determine the fatigue resistance of machine parts. As can be seen from the geometry of the crankshaft is relatively complicated, but despite of these, it is possible to determine precisely the weak point of its geometry – critical cross-section. The analysis of forces that act on the crankshaft and other engine parts allowed describe the deformation of this structure. The crankshaft fatigue degradation cannot be described as a simple process caused by uniaxial loading. Crankshafts and other parts of engine are subjected to the bi-axial unless tri-axial loading. Therefore, it is necessary to predict fatigue life by particular methods. Many criteria are being used in technical praxis to determine fatigue life subjected to the multi-axial loading. These are the criteria proposed by these authors: McDiarmid, Matake, Kakun&Kawado, Gonçalves & Araujo & Mamiya or Papadopoulos criteria [5,7,8]. A large number of criteria are currently known, however, another approach has been chosen in this work. This article focuses on direct modeling of crack growth from a critical location, respectively several possible initiation sites that were identified based on stress-strain analysis of the crankshaft.

Simulation of fatigue degradation is still troublesome process and many engineers are often using empirical approach rather than an exact description based on understanding of physical patterns. Despite, the reality that fatigue prediction is nearly hundred and fifty years, the object of interest of many scientists. The first step to creating functional models of fatigue process was made by Paris in the sixties last century. Then Paris-Erdogan in their works are proposing to use the Irwin stress intensity factor or more precisely, its range to characterize the rate of crack advance per one cycle, da/dN . Thus, the single power law was proposed, so that the fatigue process can displayed in the da/dN -diagram. Since then, much effort was devout to understand more of fatigue process and Paris-Erdogan law and some its deviations were proposed, but we are still far from a complete understanding.

In recent work some modifications of Paris-Erdogan law were utilized to create model of crankshaft fatigue failure. This model also extensively used the finite element method for stress-strain analysis and the determination of stress intensity factor. The fatigue model is compared with some experiments.

2 Physical Theory of Damage Model

Process of growth of fatigue cracks in the mechanical can be described using new mathematical approach which was developed by Navarro [2,3,4]. These structures described in cited articles, of course, are of course significantly different in size than the objects studied in this work. This approach to the fatigue failure modeling combines in a specific way, model of initiation phase of fatigue process and with model of propagation phase. This model is fundamentally different from models of the same designation, by the fact, that the definition of boundary length of crack is not needed to distinguish between the two phases of crack growth. If the fatigue curve $\sigma-N$ is known, we can use this curve to determine curve $a-N_i$. From this new curve can be determined number of cycles needed for reaching of the crack length a . The fatigue curve $\sigma-N$ is shown in Fig. 2.

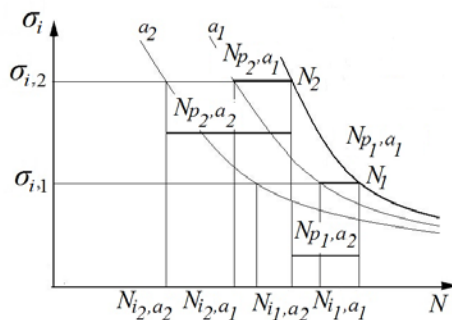


Fig. 2 The graph with fatigue curves which were used for final life reconstruction and represents relationship between number of cycle and fatigue crack length. These curves are based on $\sigma-N$ diagram.

From the analysis of forces acting on crankshaft, it is obvious that crankshaft is under multiaxial loading. In this case the curve $\sigma-N$ is expressed by parameters obtained from any multi-axial fatigue criteria. The cited authors assume that Papadopoulos or Fatemi-Socie criteria are suitable for this purpose, but a distinctly different nature of parts analyzed in this work requests the use of another criterion. Such criterion can be based on method proposed by Ellyin. This criterion has undergone some development and took its final forms in the publications [6,15]. This criterion is based on energetic approach, i.e this criterion is utilizing a sum of elastic and plastic terms of deformation energy as the damage parameter. The basic form of the criterion is:

$$\frac{\Delta W^t}{\rho_c} = \frac{\Delta W^p}{\rho_c} + \Delta W^{e+} = \kappa_E \cdot N^{w_E} + C_E \tag{1}$$

The parameters κ_E and w_E are material constants that can be set on uni-axial fatigue tests. The parameter C_E is the non-damaging elastic deformation energy, which is also determined from uni-axial fatigue tests in high cycle region.

The non-reversible dissipated energy in one cycle (i.e. energy dissipated in time stretch from t to $t + P$, where P is loading period) is calculated as an increase in plastic deformation energy:

$$\Delta W^p = \int_t^{t+P} \sigma_{ij} d\varepsilon_{ij}^p \tag{2}$$

Since the plastic term of deformation energy tends to be zero in high-cycle fatigue, the elastic term is added as well to include both potential categories. Here only the positive stresses and strains are evaluated, i.e. the loading phase that is opening crack. Thus, the equation by which is calculated energy increment in one cycle is:

$$\Delta W^{e+} = \int_t^{t+P} H(\sigma_i) H(d\varepsilon_i^e) \sigma_i d\varepsilon_i^e \tag{3}$$

wherever H is so called Heaviside function. This function is characterized by these typical properties:

$$\begin{aligned} H(x) &= 1 \quad \text{if } x \geq 0, \\ H(x) &= 0 \quad \text{if } x < 0. \end{aligned} \tag{4}$$

The parameter ρ_c is a factor of multi-axial constraint of system, which is defined to be

$$\rho_c = \left(1 + \nu_{eff} \right) \left[\frac{\max_i(\varepsilon_i(t_m))}{\max_{i,j}(\varepsilon_i(t_m) - \varepsilon_j(t_m))} \right] \tag{5}$$

Where, t_m is the time where a maximum value of the denominator is reached and ν_{eff} is effective Poisson's ratio, which can be obtained with the use of following formula:

$$\nu_{eff} = \nu_p - (\nu_p - \nu_e) \cdot \frac{\Delta \sigma_{eq}}{E} \cdot \Delta \varepsilon_{eq} \tag{6}$$

The fatigue criteria expressed by Eq. 1 can be used as damage parameter in calculation. If this criterion is used, so-called "nucleation life curves" can obtained in the form $\sigma_{eq} - N_i$ [10], see Fig. 2. The graph shown in Fig. 2 can be considered as

graphical representation of the cracks in the first phase of the crack initiation. These two initiations curves are drawn for two different lengths of crack – a_1 and a_2 . These curves correspond to the number of cycles required to reach crack length a_1 , a_2 , respectively for known equivalent damage energy in Ellyin criterion.

The fracture mechanics is used for calculation of the number of cycles needed to propagate a crack to length a_{FR} . The length a_{FR} is the crack length at the time of final rupture. The following equation expresses the number of cycles:

$$N_i(\sigma_{eq}, a) = N_{Total}(\sigma_{eq}) - \int_a^{a_{FR}} \frac{da}{C \Delta K^m} \quad (7)$$

The subscript *Total* in this equation means the total number of cycles to final rupture of specimen.. The subtrahend in this equation is obtained from Paris-Erdogan law. Limits of integral were determined from boundary condition and they are a – some crack length during fatigue process and a_{FR} – the length at the time of the final rupture.

Following phase of the crack propagation can be described by the curve $a-N_p$. The curve can be obtained by integration of growth law for any crack length to failure. Propagation stage of fatigue process can be described by the equation:

$$\frac{da}{dN} = C \left(\Delta K^m - \left(\Delta K_{th, Long} A^{\frac{KT}{1}} \right)^m \right) \quad (8)$$

where $\Delta K_{th, Long}$ is the growth threshold for long cracks. The KT is derived from the theoretical approximation of the Kitagawa–Takahashi diagram [17]. The parameter A is defined as:

$$A = \frac{a_0^{KT}}{a_0^{KT} + a_0^{KT} - d_0^{KT}} \quad (9)$$

a_0 is the El Haddad parameter [16] and d_0 is the average distance to the first microstructural barrier. El Haddad parameter can be defined with formula:

$$a_0 = \frac{1}{\pi} \left(\frac{K_{th, Long}}{\Delta \sigma_{FL}} \right)^2 \quad (10)$$

The parameter KT is working as power factor, and its purpose is to control the growth of threshold for long cracks ($\Delta K_{th, Long}$). The stress intensity factor $K_I(a)$ can be calculated from the following equation:

$$K_I = \sqrt{\frac{2}{\pi}} \int_0^a \frac{1}{\sqrt{S}} \left(1 + m_1 \frac{S}{a} + m_2 \left(\frac{S}{a} \right)^2 \right) \sigma(S) dS \quad (10)$$

where σ is the stress normal to the growth plane of the crack and S is coordinate running through the crack from the tip of crack to the surface. Both Parameters m_1 and m_2 are weight functions for edge and surface semi-elliptical cracks in flat plates and plates with corners. Parameters S and a are depending on the dimensions of the cross section of the specimen as well as on length of the crack. The complete fatigue life can be obtained by merging of $a-N_i$ curve (number of cycles to length) and $a-N_p$ curve (number of cycles to rupture). If the both curves are known, they can be merged. The merged curves can be used for description of the entire fatigue life of specimen.

3 Experimental Study

The experimental study present in our article includes two different parts. The first part is devoted to the determination of properties of crankshaft alloy. The second part is devoted to the experimental verification of the proposed model. The experiments from the first group were used to determine basic mechanical properties such as ultimate strength and yield strength. The material was alloy 42CrMo4 whose Yield strength is 900 MPa and ultimate strength 1300 MPa. These experiments also comprise determination of crack growth properties, i.e constants known from Paris-Erdogan law, C and m . The Elongation at failure $A = 14\%$ and elastic modulus 200360 MPa. The fatigue crack growth properties were determined measured according the ASTM E647, which is standard method proposed by ASTM. According to ASTM E647, it was used an eccentrically-loaded single edge crack tension specimen ESE and its dimensions are $w = 65$ mm and thickness $B = 5$ mm. With intent, to transform measured compliance data to crack growth rate data, the compliance crack length was adjusted after the test was completed to match visual measurements taken periodically throughout the test. The parameters C and m were determined as described above, and its value was $C = 3.79 \cdot e^{-8}$ and $m = 5.65$.

The crankshaft was tested using machine which simulates the working condition and loading in the engine. The machine is able to simulate the typical vibration in the engine, but this machine has also great limitation. The machine is unable to simulate the heat condition in working engine. Thus, the experiments were performed at room temperature. The characteristic frequency of noxiously vibrations is 70Hz. The loading forces are working

periodically on the crankshaft and the fatigue cracks occur in the region of crank journal, where the cross section is smallest. When we will look on the Fig. 3 we can see the part of the FEM model of the crankshaft. The figure is the representation of one quarter of the crankshaft with central pin cut off.

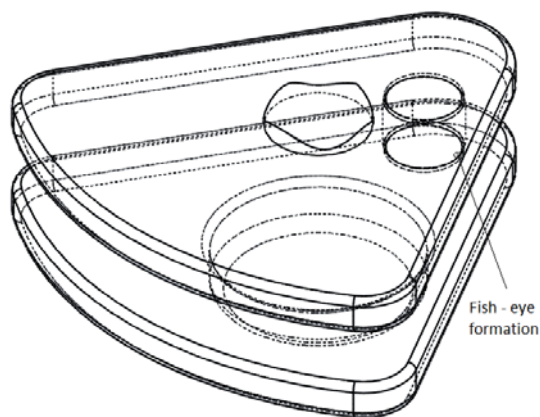


Fig. 3 The CAD model of the one quarter of the crankshaft with the crank journal and the lubrication groove. The fatigue crack initiate below the bottom of the lubrication. The elliptical crack initiated on the non-metallic inclusion.

The detail view of the crankshaft displays the part where the crank journal is located. The crank journal has lubricating groove and the fatigue crack initiate on the bottom of this groove. The fatigue crack initiate below the bottom of the lubrication. The elliptical crack initiated on the non-metallic inclusion. The crack is characterized by typical Fish-eye formation. This formation is in reality sub-surface crack which initiate on the non-metallic inclusion situated near the surface. These inclusions are working as local stress concentrators and also the area surroundings the inclusion is affected by hydrogen embrittlement. Typical sub-surface crack in the form of Fish-eye crack is shown on the Fig.4. The crack is characterized by typical Fish-eye formation. The diameter of the typical „dark area“ or fracture surface characterized by growth of crack affected hydrogen embrittlement has medium diameter 700 μm . The photography obtained by electron microscopy also contains the scale for comparison. When these imperfection (such as non-metallic inclusions) are situated deeper under the surface, the critical diameter necessary for the crack initiation is much higher, than in the case of inclusions situated near the surface, which is reason why the distant inclusion are not cause of fatigue fracture.

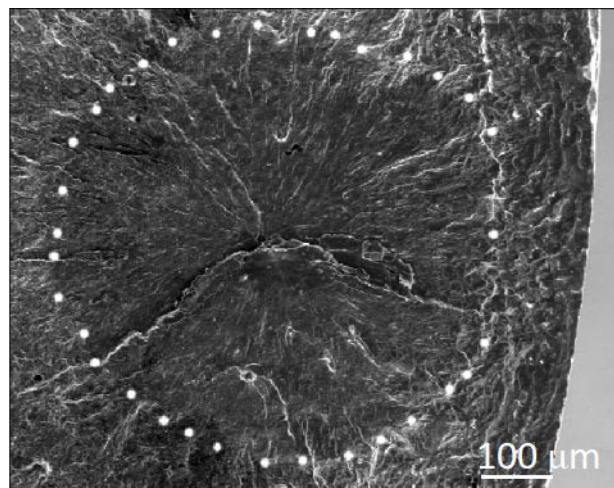


Fig. 4 The initiation site of the fatigue crack is represented by typical formation known as the Fish-eye crack. The medium diameter of the formation is 700 μm .

4 Simulation and Results

The necessary strain deformation analysis of the loaded crankshaft under working was obtained by the finite element analysis. For this analysis was used FEM software. 3D-models of crankshaft and crankshaft with crack were prepared using Autodesk Inventor software. Three dimensional models of crankshaft and crankshaft with growing crack were exported, meshed and solved to FEM software. The In the course of calculation, it was necessarily to ratiocinate an elastic-plastic model because in certain tests the yield stress is reached during the first loading cycle. For this reason, Ramberg–Osgood approximation was used to comprehend the fact, that some volume of crankshaft is loaded to the plastic deformation. The basic model predicts the semi-elliptical crack in the region of crank journal. In reality, the crack initiates not always on the surface, but below the surface because there are many non-metallic inclusions which are present as the result of imperfect heat treatment. These inclusions are the points in of maximal stress. The results of experiments and also the results of simulation are shown in Fig. 5. These experimental points are roughly correlates to the theoretical curve. Due the facts of subsurface initiation the model was improved for this case. Also the experimental points are divided into these two cases.

5 Conclusion

The region of crack initiation was determined by the analysis of stress-strain in the FEM model of the

crankshaft. The FEM model is used also for the determination of the stress state on the crack forehead. These values are used in the numerical simulation based on the equations described in the second paragraph. In reality, these stress values were established not from one FEM model, but from sequence of the FEM models which differ by the diameter of the crack, so different models corresponds to the growing diameter of the crack. Because first model was working only with cracks which initiated on the surface, the second model was prepared whose objective is to describe the case of subsurface crack. The fatigue curves which were determined according the method described in the second paragraph and two types FEM models (the surface crack and subsurface crack) are in relative agreement with results which were obtained by experimental study, see Fig. 5. The experimental points were labelled BS and OS. These abbreviations have these meanings: “below the surface” and “on the surface”.

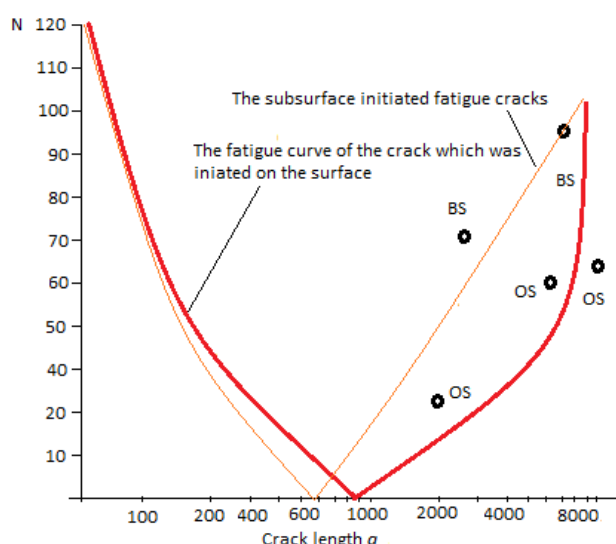


Fig. 5 The growth of crack through the crankshaft: (1) on the left side of graph is the curve which described the crack growing with initiation mechanism, (2) the right side of graph represent the crack the propagation phase of fatigue process. The number of cycles is in 10^4 of loading cycles.

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