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SIMULATION OF PITTING FORMATION IN GEARING

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Abstract: *In the presented article is presented a numerical simulation approach of pitting arise phenomena on the gear teeth. The basic assumption of the presented approach was that pitting (pits on the contact surfaces) is a result of fatigue crack propagation under (rolling) contact loading conditions. The solution approach consisted of numerical simulations of fatigue cracks growth in the FEM framework. Fatigue crack growth simulations are based on evaluation of the so called Paris law in conjunction with FEA of crack tip loading conditions and fracture criteria evaluation. Penetration of the fluid lubricant into fatigue (pitting) cracks is simulated using special cavity finite elements, which allow to introduce so called lubricant closure inside crack. A simplified distribution of residual stresses in the surface layers of teeth is included as well. The simulations were carried out under the commercial code ABAQUS CAE FEM programme which allows to develop in-house codes using the Python scripting language. Mentioned programme codes are the basis of all FEA including the simulation of the contact loading conditions and the incremental crack growth.*

Keywords: ***gears, pitting, FEM simulation, crack propagation.***

1. Introduction

Pitting is understood as fatigue damage of components caused by cyclic contact load, when material particles come off and shallow pits arise in contact surface. Pitting is most often related to damage of contact surface of gear teeth (Fig. 1), but it also occurs on working surface of rolling bearing or on heads of rails and railway's wheels. Pitting formation leads to degradation (in extreme case to loss) of functionality of afflicted device, to escalation of vibrations, noise and other negative effects. Therefore, appreciable attention is given to study of this damage with purpose of reducing or eliminating these negative effects.

Fig. 1: Pitting damage of real gear.

Physical fundamentals of pitting formation are so complex, that there are still being used special empirical relations for determination of lifetime (of for example gear sets), which require experimental data gained from tests carried out directly on gear sets in special test stands. These experiments are time-consuming and also costly.

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Many attempts to mathematical description of pitting wear were implemented in recent years. The basic assumption of these attempts is that initiation and fatigue crack propagation are in progress before pit rise. The results of experiments indicate that pitting cracks propagate from contact surface into material of surface layer at first and after cracks reach a specific deep, they curve and turned backward towards the surface. Finally, end-fracture results in detachment of a material particle, as a result of which the pit is originated.

Two main domains are discussed in conjunction with approaches to the numerical simulation of pitting damage rise process. The basic assumption of the first group is that a pressured fluid lubricant penetrates into cracks and influences its growth. This approach can be represented e.g. by Fajdiga et al. (2004), who simulate fatigue crack growth from a surface initial crack and contact loading approximated by pressure distribution corresponding to the EHD lubrication theory. In the second group of approaches other possible damage mechanisms of pitting rise are assumed. E.g. Ding et al. (2003) simulate pitting rise from subsurface initial cracks.

The presented article belongs to the first group of the above mentioned approaches. The fatigue crack growth is numerically simulated by finite element method. The crack growth starts from the surface initial crack. The contact conditions between real gear teeth near the pitting crack mouth are computed and the pressured fluid lubricant penetration into pitting crack is assumed.

2. Implemented phenomenological fatigue crack growth theories

The basic assumption of the presented crack growth simulations is validity of the small scale yielding (SSY) conditions. In another words, the initial cracks are so long that the material can be modelled as an isotropic continuum and a dimension of crack tip plastic zone is negligible compared to the total crack length.

Then the rate of fatigue cracks propagation can be described by phenomenological theory – the Paris law, which is usually expressed as a relation of crack growth rate against stress intensity factor amplitude. In the pitting crack simulations the crack growth predictions were based on the fracture mechanics criterion – J-integral. The application of J-integral criterion was enforced by nonlinear character of performed FE analyses (stress intensity factors are not supported), where the gear meshing has to be solved under large deformation condition. With respect to that, the modification of Paris law relation is required and consists in substitution of stress intensity factor amplitude by amplitude of J-integral (1).

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C(\Delta J)^m, \tag{1}$$

where C and m are material parameters and ΔJ is a J-integral amplitude.

The fatigue crack growth direction corresponds to the direction in which the maximum energy release rate is achieved. Under SSY conditions the criterion of maximum energy release rate is equal to maximal J-integral criterion and is equivalent to the maximal tangential stress criterion.

3. Experimental works

Experimental works were carried out at two basic levels. Firstly, simple so called CT test specimens were employed to provide data for validation of the crack growth prediction models under program ABAQUS and secondly, shortened fatigue tests of the real gearing were carried out using special testing machine (Niemann closed testing chain, Fig. 2 - Petr, K. 2010) to provide real pits shapes and gearing lifetime. More detailed information about used experimental equipment can be seen in the paper Jurenka (2011).

The both CT specimens and testing gears were manufactured from the 18CrNiMo7-6 material. After heat finishing (gears tempering and contact surfaces cementing into deep approximately 0.7 - 0.9 mm and hardening to final hardness approximately 58-60 HRC) the following characteristics of the material can be mentioned: Young's modulus 210 000 MPa, yield stress 1100 MPa, strength 1250 MPa. The estimated Paris law parameters are the following: C=1.42e-5 mm/[cycle.(N.mm)1.3] and m=1.3.

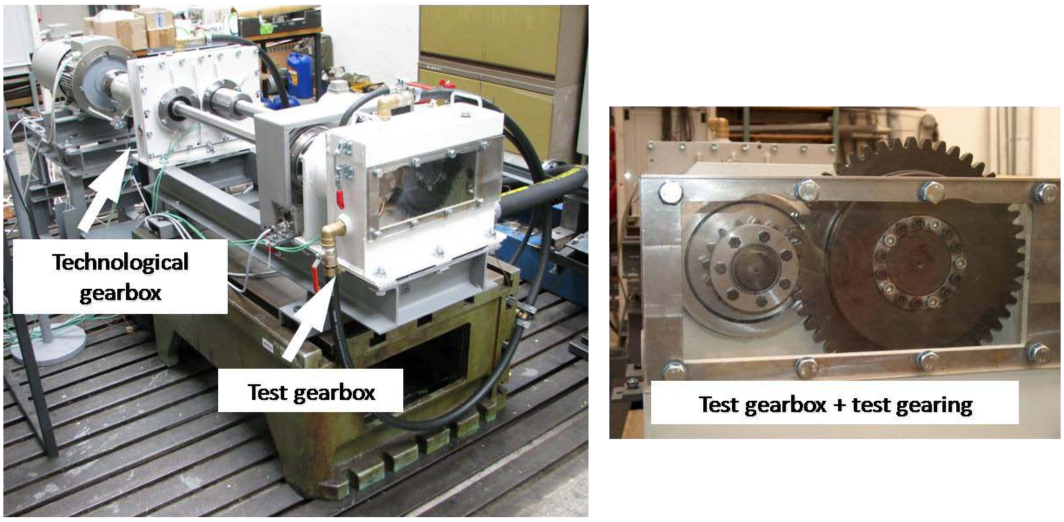

Fig. 2: Gear testing equipment (Petr, K. 2010).

Six tests were carried out. Digital pictures of teeth contact surfaces were made in the fixed time interval during the testing with time increment 2.5 hours. An example of time series of surface fatigue damage pictures is shown in the Fig. 3. Tested gearings were designed according to norm ISO 6336/1996 to limit durability approximately 30 hours under given loading conditions. Each test was stopped after formation of large pit or more smaller pits (maximal permissible pitting damage pollution of contact surface is 4%). The average life time of tested gearing was approximately 54 hours Fig. 4.

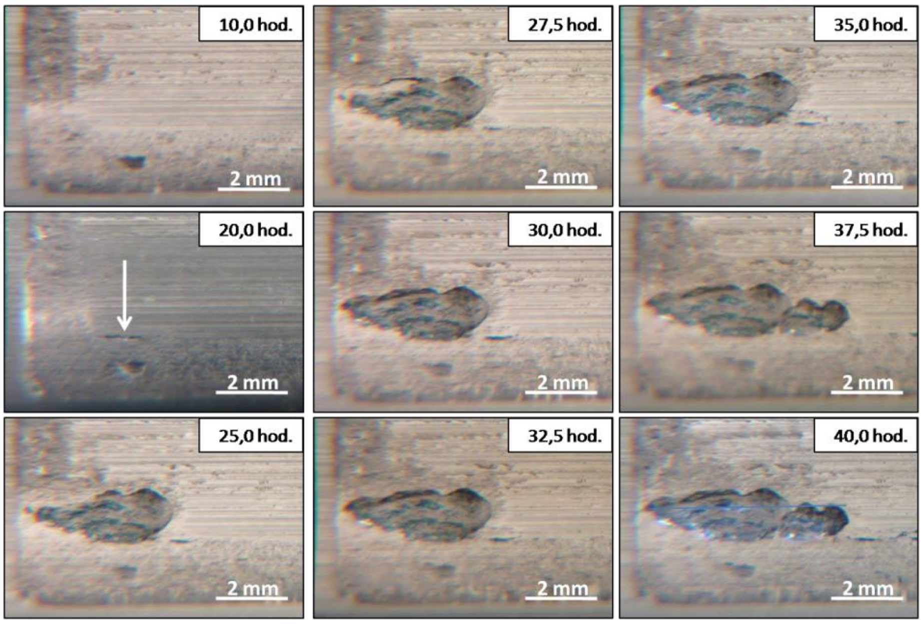

Fig. 3: Pitting damage formation during gears testing.

For providing more complete and accurate information about formation of observed pits, the detailed metallographic samples were created and analyzed. Material cuts were carried out through the biggest pits, and in the region of the tooth root, and region of the tooth head, of the pinion. The experimental tests results are shown in the Fig. 5, where the topology of four analyzed pits is displayed by the curved lines in context to the pinion tooth geometry. The direction of pitting crack initiation along the contact surface is shown by arrows.

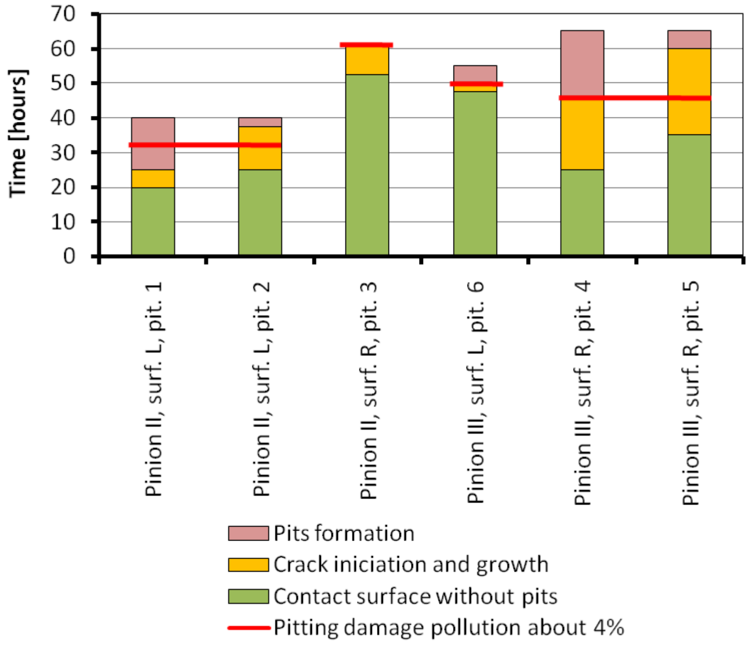

Fig. 4: Pitting damage formation during gears testing - gearing lifetime.

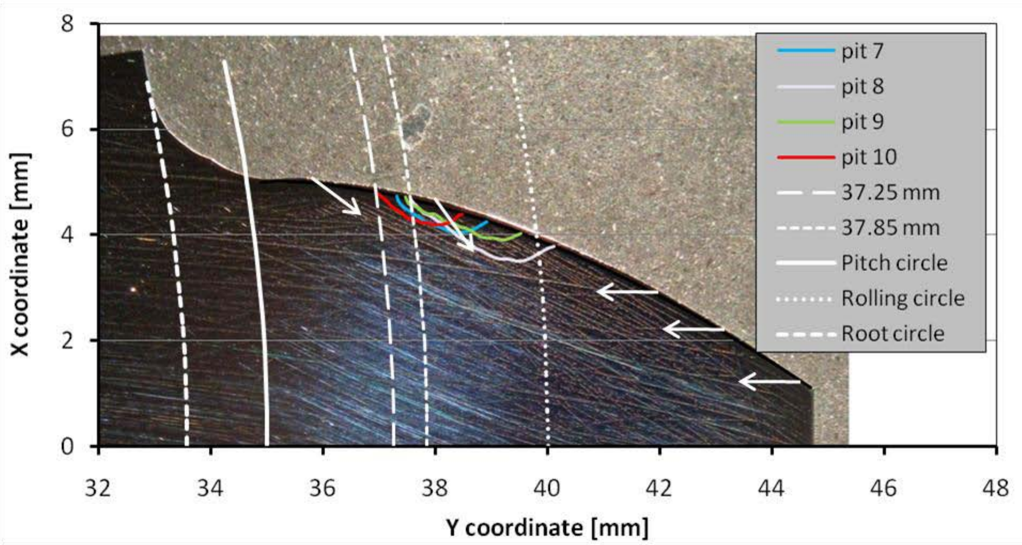

Fig. 5: Pitting damage formation during gears testing - pit topology and initial crack orientations (arrows) - metallographic sample.

According to presented pictures sequence in the Fig. 3 and pictures of metallographic samples, the probable process of pitting damage formation can be estimated:

- Pitting cracks start to propagate especially from the so called one tooth meshing contact area, thus the pitting damage is concentrated in this domain. In this domain the pitting cracks growth from tooth root to the tooth head.
- Relatively straight crack mouth could be a result of propagation of many short cracks in the critical domain of contact surface, from which the magistral crack is created subsequently. Presence of mentioned short cracks can lead to the creation of initial small pits in the critical region around the magistral crack mouth.
- The initial assumption, that the pits are created by fatigue crack growth, can be confirmed by the analysis of material particles, which were found in the oil tank. The dimensions and shape some of these particles correspond very well with formed pits (Fig. 6). So the pits were created by breaking off one or more relatively large material particles. This is in compliance with mentioned pictures sequence in the Fig. 3.

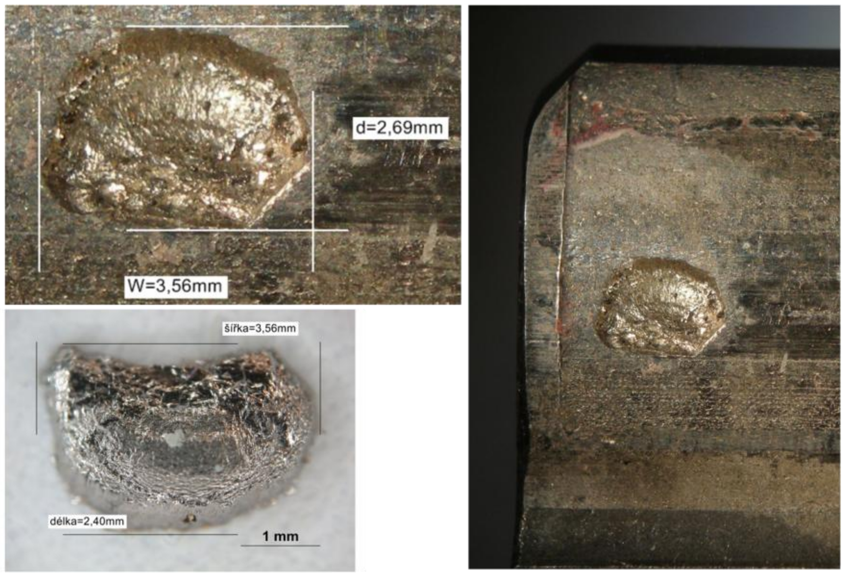

Fig. 6: Magistral pit and inverse material particle.

4. Pitting crack growth simulations

Simulations were performed under the commercial FEM code ABAQUS, which provides both computation tools for evaluation fracture mechanics criterion J-integral and Python language interface for in-house programme codes (developed at the Faculty of Mechanical Engineering CTU in Prague) submitting, which provide full automatic FE model creation and simulation control.

4.1. FE model and simulation flow

The numerical prediction of pitting formation presented in this article is based on the simulations of the gearing contact conditions, which induce boundary conditions for subsequent fatigue crack growth computational predictions. Basic mechanical quantities defining contact conditions are: contact pressure, shear stress, relative slip range and rate. Actually these quantities could be affected by both properties of fluid lubricant used and contact surface roughness. In the FE models the complex tribological relations (so called EHD lubrication conditions) are approximated by friction coefficient f, whose value can be in the range of 0.01-0.1 and special cavity model, which allows to include pressured fluid lubricant penetration into the pitting cracks. The residual pressure distribution in the subsurface layers was approximately estimated on the basis of experimental measurement using X-Ray diffraction. Linear elastic isotropic material model was assumed and all FE analyses are assumed as quasistatic and planar considering plane strain conditions.

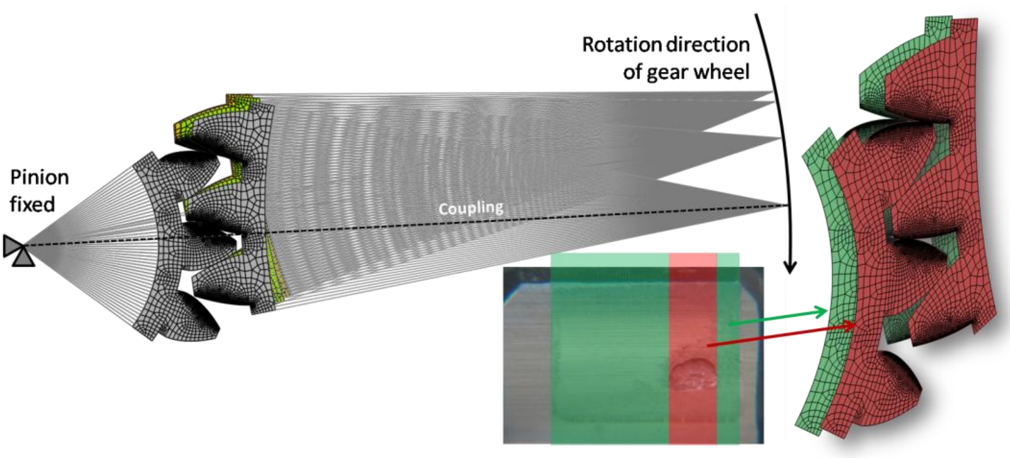

Fig. 7: The basic model concept.

The parametric FE model is conceived as the planar model, which combines two 2D models (one with pitting crack and one without) to simulate kvasi-3D contact conditions during gearing meshing. (Fig. 7).These two 2D models are merged in the gear ring regions and their thicknesses correspond to the thickness of cracked respectively non-cracked contact surface.

The initial crack is included in the FE model before the simulation start (Jurenka, 2011). Between modelled crack surfaces the special cavity finite elements (F2D2) are defined to simulate penetration of pressured lubricant into crack during gearing meshing. The law of mass flow q of pressure lubricant is defined by the simple relation:

$$q = C_v \Delta p \,, \tag{2}$$

where C_v is the viscous resistance coefficient and Δp is the pressure gradient. The value of C_v is approximately estimated using analytical equation for laminar flow into thin slot as:

$$\frac{q}{\rho} = \frac{b}{12 \cdot \eta} \frac{\Delta p}{l} h^3 \,, \tag{3}$$

where ρ is a lubricant density, b is a crack width, l is a crack length and h is a distance between crack surfaces. η is the dynamic viscosity of lubricant, which is a function of the pressure inside lubricant according to relation:

$$\eta = \eta_0 \cdot \exp(\alpha \cdot \bar{p}), \tag{4}$$

where η_0 is dynamic viscosity for 0 pressure, α is the piezo-coefficient of lubricant and $\bar{p}$ is a actual pressure inside lubricant. On the basis of comparison of relation (2) and (3) the relation for C_v estimation is given:

$$C_v = \frac{12 \cdot \eta \cdot l}{b \cdot h^3} \,, \tag{5}$$

Cavity volumes are defined between crack surfaces. These volumes correspond to the crack extension increments (Fig. 8). The mass flow between each two neighboring cavity volumes q_i (i = 1, ..., N, N is number of volumes, resp. crack extensions) is given by relation (2). In the cavity model the $\bar{p}$ corresponds to average pressure between neighboring cavity volumes, and the value of both $\bar{p}$ and Δp result from actual loading during gear meshing. The first cavity volume is connected with the contact surface and is pressured by actual contact pressure.

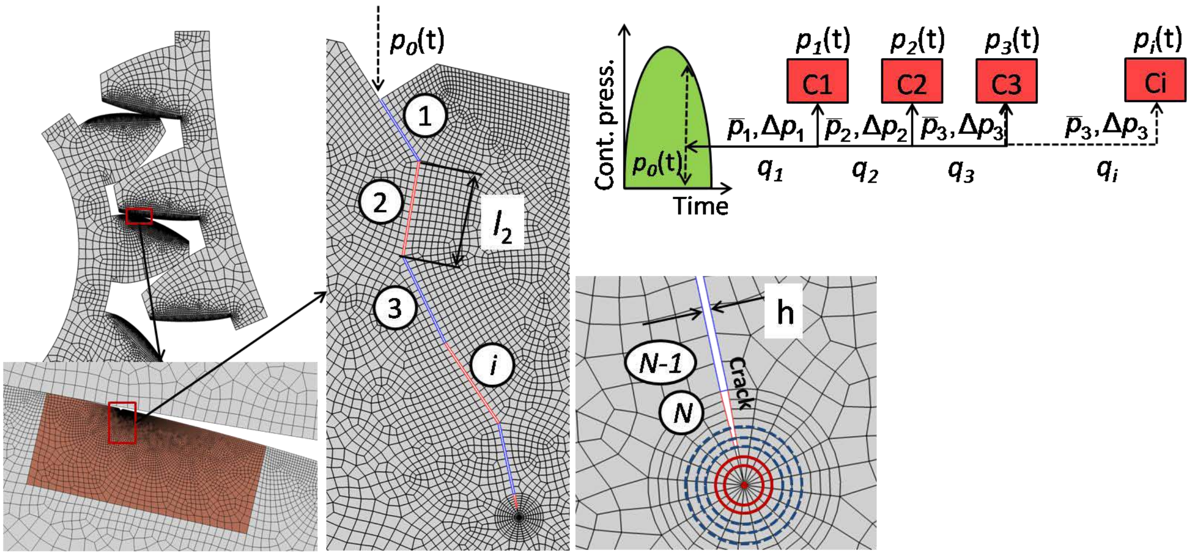

Fig. 8: The basic model concept.

In the FE model the residual stress distribution is defined as initial condition using several sublayers with constant residual pressure (Fig. 9). The distribution was approximately estimated on the basis of X-Ray diffraction residual stress measurement and theoretical knowledge (Neckář, F., 1991).

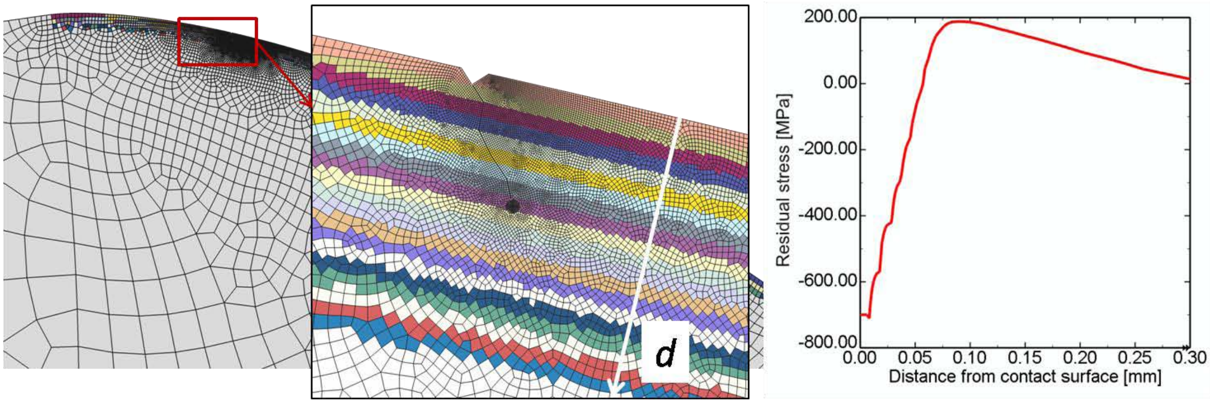

Fig. 9: Application of Residual stress distribution.

The basic scheme of simulation of pitting crack propagation is shown in the Fig. 9. In the first step the contact pressure distribution in the crack mouth is calculated. Subsequently the incremental crack growth is simulated in the loop as long as the final pit shape is achieved. In each computational iteration of the solution loop (item 2.1 in the Fig. 9) the J-integral is calculated in the several directions in front of the crack tip (Fig. 10). The probably crack extension direction is evaluated in the item 2.2 (Fig. 9) either as the direction, in which the maximum of J-integral was calculated (Španiel, M., 2008), or as an average direction calculated from all J-integral values bigger than the threshold value. It is assumed, that the crack can growth only if it is opened. Thus if the contact between crack surfaces arise (pressure in the cavity is not able to open crack), then the crack can not growth. In the last part of the solution loop (item 2.3, Fig. 10), the model crack is extended and FE model is modified.

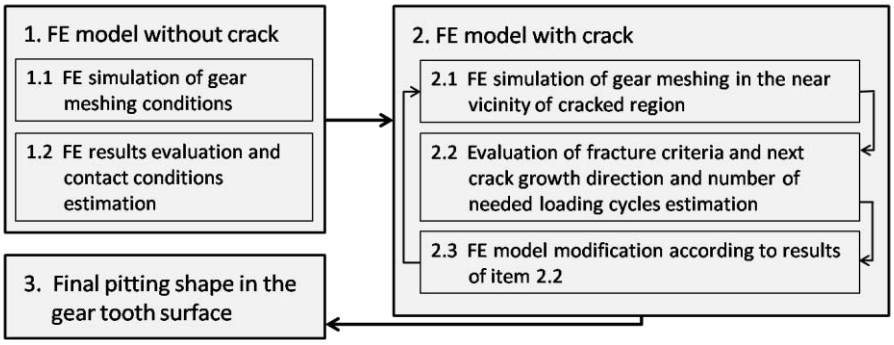

Fig. 10: Block schema of pitting simulation under ABAQUS.

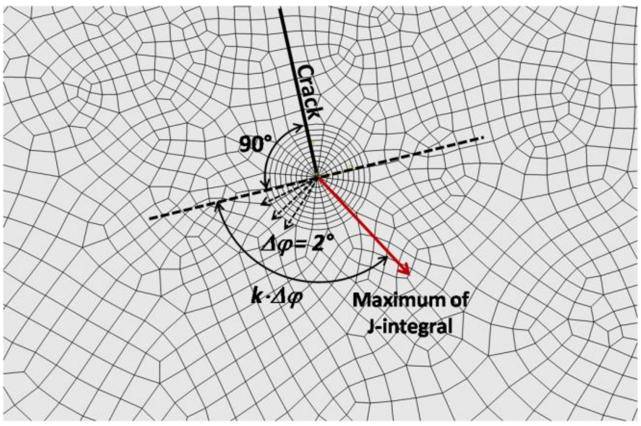

Fig. 11: Crack direction estimation.

With respect to the complex physical background leading to pitting formation, which can not be fully experimentally explained, the developed FE model was created in the relatively general form. This means, that they contains many parameters, which can be change independently and its influence on the pitting crack growth can be evaluated. The basic model parameters are listed in the Tab 1.

Tab. 1: The basic FE model parameters.

FEM model parameter	**Min value**	**Max value**
Friction coefficient on the teeth contact surfaces - f [-]	0,01	0,15
Friction coefficient between crack surfaces - f_c [-]	0,3	1
Initial crack length - a_{ini} [μm]	10	50
Initial crack angle between crack and contact surface - φ [°]	25	160
Crack extension increment length - l [μm]	10	50
Initial crack location on the contact surface (diameter of circle with center in the pinion axis) - ρ [mm]	37,25	37,85
Kinematic viscosity coefficient of fluid lubricant - υ [mm^2/s]	1	300
Dynamic viscosity coefficient of fluid lubricant - η_0 [MPa·s]	0,89e-9	0,27e-6
Piezo-coefficient of fluid lubricant - α [mm^2/N]	0,02	0,02
Density of fluid lubricant - ρ' [kg/m^3]	890	890
Initial crack surfaces distance - h [mm]	1e-6	1e-4

4.2. Results of simulations and discussion

The presented research of pitting damage phenomenon is based on both experimental results of real gearing tests and numerical simulations of pitting crack propagation under contact loading conditions. The main goal of performed numerical simulations is to provide information, which can confirm or confute above mentioned theory of pitting damage formation.

The simulated crack behavior (crack growth direction) is analyzed with respect to:

- The location of contact region between gear teeth according to the crack mouth,
- gearing meshing conditions,
- the stress field around the whole crack,
- the possibility of fluid lubrication penetration inside the crack,
- the J-integral values, and
- the residual stress distribution.

Numerical model is defined by many parameters, whose values can not be experimentally verified. The detailed sensitivity study of the influence of selected parameters on the pitting crack behavior has to be done. In the first stage the possibility of growth of initial pitting cracks is assessed.

In the presented simulation the following parameters were assumed (Tab. 2):

Tab. 2: Assumed FE model parameters.

FEM model parameter	**Value**
Friction coefficient on the teeth contact surfaces - f [-]	0,01
Friction coefficient between crack surfaces - f_c [-]	1
Initial crack length - a_{ini} [μm]	15
Initial crack angle between crack and contact surface - α [°]	30, 60, 90, 120, 150
Crack extension increment length - l [μm]	20
Initial crack location on the contact surface (diameter of circle with center in the pinion axis) - ρ [mm]	37,55
Dynamic viscous of fluid lubricant - η_0 [MPa·s]	0,89e-9 ÷ 0,27e-6
Initial crack surfaces distance - h [mm]	1,6e-4

The attention was focus on the initial stage of pitting cracks propagation in the presented article. With respect to the experimental observation the influent of small pits in the crack mouth region on the pitting crack growth was studied. The several basic configurations were assumed (Fig. 12). The initial small pit deeps were chosen as a) 0,001; b) 0,01; c) 0,03; d) 0,05 and e) 0,08 mm. The initial crack length was equal to 0,015 mm and the initial crack angle was 30° against to the contact surface.

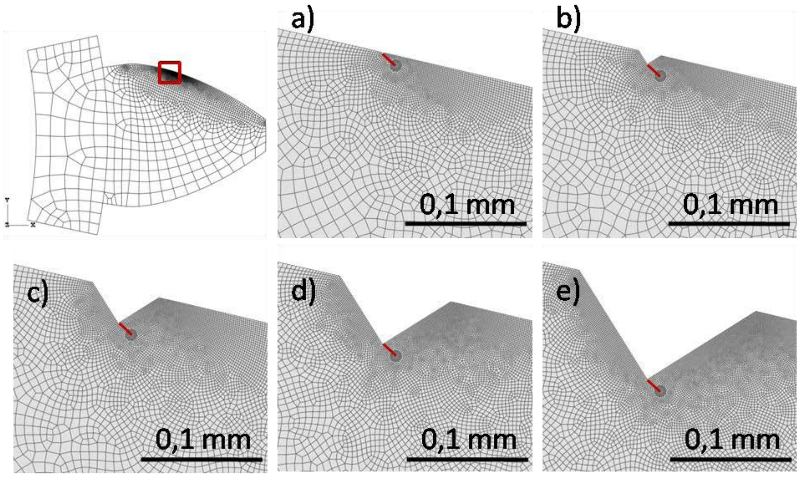

Fig. 12: Initial pitting cracks configuration.

The shape of pitting cracks after several simulation loops (several cracks extensions) with respect to the initial small pit dimension is shown in the Fig. 13. The initial configuration before the first simulation run is shown in the Fig. 12. The advance cavity model according to the Fig. 8 was used and residual stress was neglected. The model crack surface distance was 1,6e-4 mm.

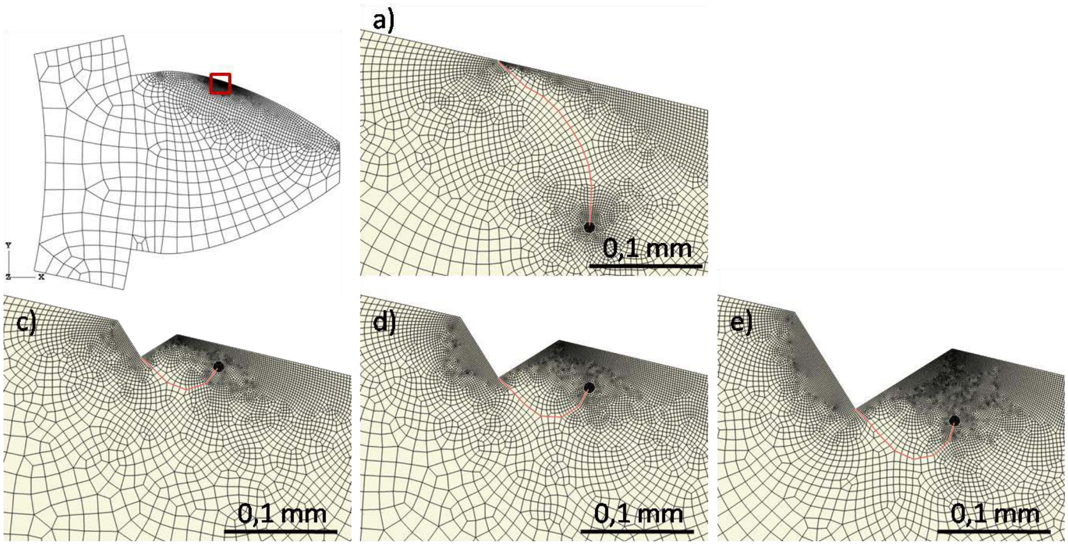

Fig. 13: Pitting cracks shapes.

The predicted lifetimes, resp. number of loading cycles needed to simulated cracks growth is for presented cracks listed in the Tab. 3. These results show, that it is possible to use the developed FE model to simulation of pitting damage formation. The mentioned results are in a relative good agreement with experimental data from qualitative point of view and it seams, that it is possible to validate FE model on the basis of sensitivity study of its parameters.

5. Conclusions

The achieved results show, that the chosen numerical approach to the simulation of pitting damage formation can be used. However the developed FE model is very complex due to credible description of physical background. Many parameters can be change and experimental verification of their values does not exist. From this point of view, the large sensitivity study of the most important parameters has to be done. On the basis such complex results, the FE model can be finally validate.

The main result and outputs of the above mentioned research are:

- The complex parametric FE model for pitting crack growth was created.
- The advance cavity model for simulation of penetration of pressured fluid lubricant into pitting cracks was introduced.
- The methodology for implementation of residual stress into subsurface layers of material was developed.
- The complex experimental tests of real gears were performed and evaluated.

In the future the attention will be focused on the extension of experimental base. Especially, on the validation of fatigue cracks growth under non-proportional mixed model loading conditions.

In the simulation domain, the large sensitivity study of FE model parameters will be carried out and the real heat treatment of contact surfaces will be simulated in the special program code SYSWELD to achieved more accurate information about residual stress distribution.

Tab. 3: Crack growth rate prediction.

Crack increments	a)			b)			d)			e)		
	J-int.	No. cycles	Time	J-int.	No. cycles	Time	J-int.	No. cycles	Time	J-int.	No. cycles	Time
	J [Nmm]	N []	t [h]	J [Nmm]	N []	t [hour	J [Nmm]	N []	t [hour	J [Nmm]	N []	t [hour
1	0.0139	3.65E+05	4.19	0.1441	1.75E+04	0.20	0.1713	1.40E+04	0.16	0.1758	1.35E+04	0.16
2	0.0437	8.24E+04	0.95	0.0797	3.77E+04	0.43	0.1239	2.13E+04	0.24	0.1334	1.93E+04	0.22
3	0.0771	3.94E+04	0.45	0.1366	1.87E+04	0.22	0.1160	2.32E+04	0.27	0.1001	2.81E+04	0.32
4	0.1103	2.47E+04	0.28	0.1497	1.66E+04	0.19	0.2374	9.14E+03	0.11	0.1984	1.15E+04	0.13
5	0.1388	1.84E+04	0.21	0.0720	4.30E+04	0.49	0.2607	8.09E+03	0.09	0.2763	7.50E+03	0.09
6	0.0600	5.46E+04	0.63				0.2076	1.09E+04	0.12	0.2722	7.65E+03	0.09
7	0.0563	5.93E+04	0.68							0.2109	1.07E+04	0.12
8	0.0729	4.24E+04	0.49									
9	0.0980	2.89E+04	0.33									
10	0.1398	1.82E+04	0.21									
suma		**7.33E+05**	**8.43**		**1.34E+05**	**1.54**		**8.65E+04**	**0.99**		**9.82E+04**	**1.13**

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