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THE APPEARANCE OF PITTING WEAR ON GEARS AND SOME OF THE FACTORS THAT INFLUENCE IT

Claudiu Ovidiu POPA, Simion HARAGÂŞ

Abstract: *This article aims to evoke some aspects of the fatigue cracks that have the consequence of pitting wear appearance on the spur gears. Different factors acting on the already propagated cracks and opened to the surface of the gear tooth will be considered. The result is the appearance of a pit. The stresses field corresponding to the contact between two cylinders that shape the contact between the teeth flanks was presented. A possible way of forming the cracks that start from the surface of the flanks is also presented.*
Key words: *pitting, fatigue crack, pits, gear, stresses field, rollers, lubricant, voids, inclusions.*

1. INTRODUCTION

Running out of gears can have a multitude of causes of a different nature. In a speed-load qualitative diagram (Fig. 1) it can be presented the areas in which the gears deteriorate [2].

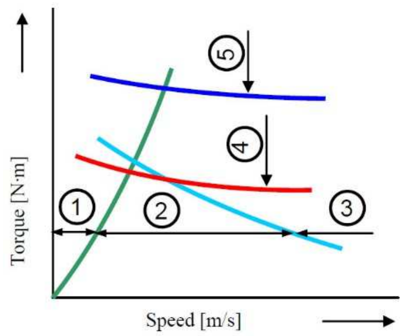


Fig. 1. Damage resulting in the dismantling of gears

In area 1, there is a predominant danger of abrasive wear, because the lubricant film does not provide a sufficient carrying capacity.

Zone 2 is the optimal operating range of a gear, provided that the lubricant is free of impurities and acids.

Zone 3 corresponds to high velocities, when it becomes predominantly the danger of abrasive wear, because of the high temperatures caused by the relative teeth slides, which result in decreased viscosity of the lubricant.

Zone 4 is the area of pits appearance and zone 5 of tooth breakage through fatigue.

2. THE PITTING WEAR

Pitting is a phenomenon of fatigue of the tooth flank material. It has been known since the 19^{th} century, the first major researches on the modeling of this phenomenon being carried out by Wöhler (1871).

Pitting is considered to be the leading cause of end use of gears, especially of those with low and medium hardness.

2.1 The appearance of cracks on the surface of the gear teeth

The pitting consists in the removal of fine splinters from the surface of the teeth flanks and the formation of small pits due to these detachments. The size of the surface of these pits, as well as their number, results in high values of deviation of the tooth flanks from the correct shape, as well as improper gearing, shocks and noise.

These pits can also initiate cracks, which can cause teeth breaking through fatigue. At the same time, the material resulting from the pitting phenomenon, being engaged by the lubricant, can cause a sharp abrasive wear on the flanks of the tooth.

Pitting is characteristic of some specific phenomena, which are not encountered in other types of fatigue applications, such as: presence of lubricant, abrasive wear, contact corrosion, superficial plastics deformations, thermal phenomena, etc.

The main factor causing cracks growth is the existence of tangential, superficial stresses produced by the normal force on the tooth and the frictional force between the flanks of the teeth in contact [3] [4] [5] [6].

There is also a decisive influence on the tensile stresses, as well as the action of the lubricant on the flanks of the cracks.

Pitting has two forms of manifestation [18]:

- early pitting;
- progressive pitting.

The incipient pitting occurs during the first period of operation ($N \approx 5 \cdot 10^4$ cycles) and is a consequence of processing defects. After $5 \cdot 10^4$ cycles, pitting development stops.

The progressive pitting is a typical phenomenon of fatigue, the first manifestations begin after a period of incubation (accumulation of destructive energy) of $5 \cdot 10^4 \ldots 5 \cdot 10^5$ cycles. The periods of explosion of the number of pinches follow periods of stagnation and accumulation of energy, followed by a new period of explosion of the number of pits. Typically, the period of stagnation of a contact element corresponds to a period of explosion of the number of pits on the other element [1] [17] [18].

Fig. 2, Fig. 3, Fig. 4 and Fig. 5 schematically illustrates how the pits are formed. The frictional force on the drive wheel is directed from the pitch circle to the tooth head and the tooth base, while the friction forces are directed towards the pitch circle (Fig. 2) [9] [11].

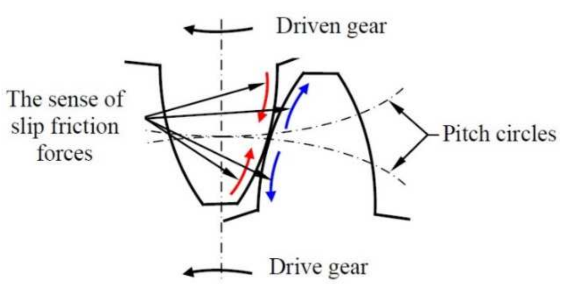


Fig. 2. The direction of the slip friction forces

As result of the repeated loading of the teeth flanks, at the drive gear appear cracks directed to the pitch circle and at the driven gear appear cracks oriented from the pitch circle (Fig. 3).

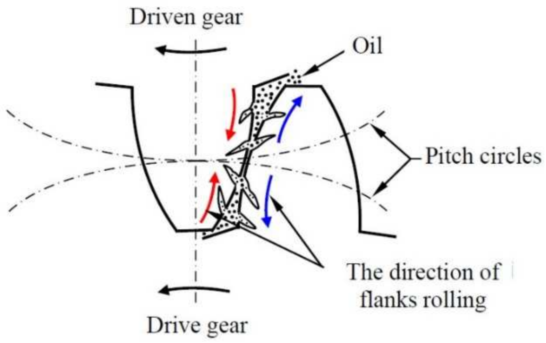


Fig. 3. The appearance of cracks on the surface of the teeth

2.2 Main cracks, secondary cracks

From Figure 4 it can be observed that after the occurrence of an initial crack, due to the repetition of the cyclical stress, it develops, increases its size, the oil enters the crack acting as a wedge, so that at some point there will be a detachment of the material from the surface of the pieces, resulting a small pit.

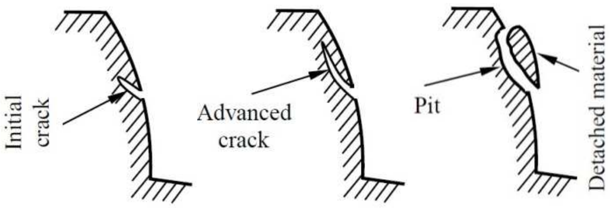


Fig. 4. The cracks growths on the teeth flanks

In Figure 5 (a and b), the inclination of a main crack, according to the direction of the sliding speed is shown. It can be seen that if the sliding speed (denoted in figure by the v_a) and the rolling speed (v_r) have the same sense, the crack angle is such that when the contact passes over the crack, the oil is sucked. Instead, when the two gears have different senses, the oil is pressed into the crack.

After the main crack is formed, the oil acts as a wedge, forces the flanks of the crack and thus produces a secondary cracks, perpendicular to the main crack. Then, when the hertzian contact is repeating over the main crack, the secondary cracks widen and extend until a small portion of the material is detached, so the pitting occurs [1] [9] [18].

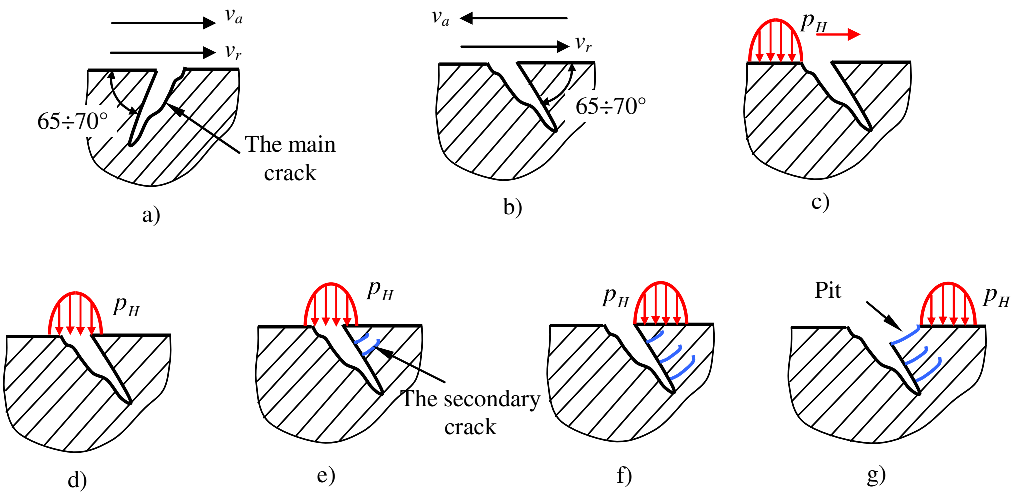


Fig. 5. The pitting mechanism, the main and the secondary cracks

Oil adhering to the surface of the teeth flanks and entering the already formed cracks, due to the direction of advance of the point of contact of these flanks, will be pressed into the cracks situated on the surface of the foot of the gear tooth, but will be expelled from the cracks situated on the surface of the head of the gear tooth.

From the above, it can be seen that the lubricant used is of major importance in the cracks growth and therefore in the occurrence of pitting, but the initiation of fatigue cracks may also occur in the absence of the lubricant.

2.3 Cracks initiated on the surface or substrate respectively

From the point of view of the main crack formation, there are two variants to explain this phenomenon, namely [1] [2] [18]:

a) The initial crack starts from the surface to the substrate.

The initiation point of the cracks is considered to be, on the one hand, the consequences of processing (surface microspheres due to the cutting and finishing process) and, on the other hand, the state of tensions.

Analysing the residual stresses on the flanks, Gapish (cited in [18]) observed that in the tooth head area (where the sliding and rolling speeds have the same senses) the three main stresses, in three orthogonal directions, are all of compression in time, while on the tooth base the two main stresses contained in the contact layer are compressive and the tension perpendicular to the contact surface is tensile (Fig. 6). As the tensile fatigue limit is significantly lower than the compressive fatigue limit, it results that the type of residual stress, after a direction perpendicular to the contact surface, may be the cause of cracks that would develop from the outside to the inside, and the pits could be placed predominantly on the foot of the tooth.

In the case of plastic gears, or in the case of the gear whose teeth have low stiffness, the pits no longer appear on the tooth foot, but move towards the head of the tooth, which obviously does not confirm previous assumptions from Gapish's experiences. However, the observations made here cannot be neglected in explaining the phenomenon of pitting.

b) The initial crack starts from the substrate and opens on the contact surface.

It is known that in the contact substrate at a certain depth ($0.786 \cdot b_H$ where b_H is the half-width of the Hertzian contact area, neglecting sliding, friction and lubrication), during the action of the normal stress, a maximum tangential stress occurs. By repetition, this stress causes a distortion of the molecular structure, which leads to the cracks initiation.

In favor of the occurrence of the cracks in the substrate also pleads the findings of Beching and Nichols (quoted in [13]), according to which the stress cone in the case of pure rolling (Fig. 7a) deforms, in case of sliding rolling, as in Figure 7b. The shape of the pits is very similar to the shape of this effort distribution.

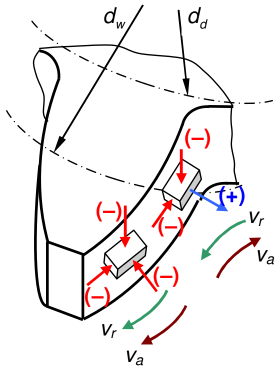
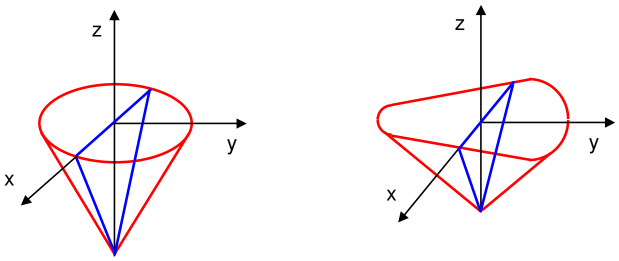


Fig. 6. The stresses distribution on the tooth flank



a) b)

Fig. 7. The deformed stresses cone

2.4. The stresses field in the case of two cylinders with parallel axes

Stresses field is very important in the occurrence of pitting on gear teeth. The contact between the flanks of the gear teeth can be replaced by the contact of two cylinders on their generators, and having the rays equal to the curvature radius of the involutes at the considered point.

The case of the contact of two radial cylinders with the parallel axes, of R_1 şi R_2 rays, the L length and a rectangular coordinate system XYZ is considered (Fig. 8).

Two cylinders with a limited length and the parallel axes are in contact before deformation on a line (the common generator). After applying the compressive forces distributed along the length of the cylinders, the linear initial tangent turns into a contact on a narrow band limited by two straight lines, the half-width of the contact area being determined by the equation (1).

$$b = 1.128 \cdot \sqrt{\eta q \frac{R_1 \cdot R_2}{R_2 \pm R_1}} \qquad (1)$$

where $\eta = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}$ is the elasticity coefficient of materials and q is the load per unit length of cylinder.

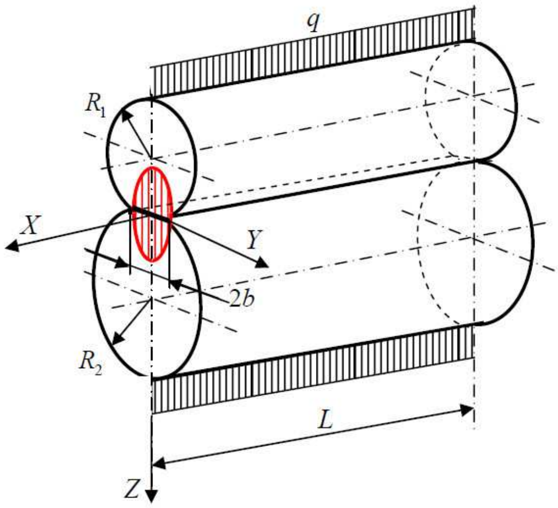


Fig. 8. Elastic contact on two-cylinder with parallel axes

If the materials of the cylinders in contact are identical and the Poisson coefficient is $\nu = 0.3$, it can be obtained:

- elasticity coefficient of materials:

$$\eta = \frac{1.82}{E} \qquad (2)$$

- the half-width of the contact band:

$$b = 1.522 \cdot \sqrt{\frac{q}{E} \cdot \frac{R_1 \cdot R_2}{R_2 \pm R_1}} \qquad (3)$$

- the maximum pressure value:

$$p_0 = 0.4180 \cdot \sqrt{q \cdot E \cdot \frac{R_2 \pm R_2}{R_1 \cdot R_2}} \qquad (4)$$

Two cylinders with a limited length and the parallel axes are in contact before deformation on a line (the common generator). After applying the compressive forces distributed along the length of the cylinders, the linear initial contact turns into a contact on a narrow band limited by two straight lines, the half-width of the contact area being determined by the relation (1).

The cylinder state tensions in the vicinity of the contact area can be considered as a limit of the stress state in the vicinity of the elliptical contact surface, when the ellipse axis becomes infinite.

The unitary stress σ_x at an arbitrary point of the plane perpendicular to the contact surface through its median line, i.e. through the large axis of the contour ellipse, is [14]:

$$\sigma_x = -p_0 \cdot 2\nu \cdot \left(\sqrt{1 + \left(\frac{z}{b}\right)^2} - \frac{z}{b} \right) \qquad (5)$$

Similarly, unitary efforts on the other directions are [14]:

$$\sigma_y = -p_0 \cdot \left[\frac{1+2\cdot\left(\frac{z}{b}\right)^2}{1+\left(\frac{z}{b}\right)^2} - 2\cdot\frac{z}{b} \right] \quad (6)$$

$$\sigma_z = -p_0 \Big/ \sqrt{1+\left(\frac{z}{b}\right)^2} \quad (7)$$

For $z = 0$, meaning for the points of the middle line of the contact strip we obtain:

$$\sigma_x = -2\cdot\nu\cdot p_0;\quad \sigma_y = -p_0;\quad \sigma_y = -p_0 \quad (8)$$

In Fig. 9, the principal unitary stresses on the middle line of the contact band are shown.

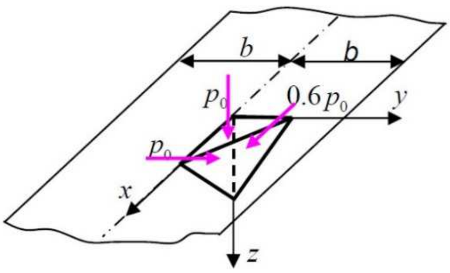


Fig. 9. The main unit efforts on the middle line of the contact strip

By studying the vicinity of the body contact area, it is assumed that the axis x is pointing along the line of contact on its middle line, the axis y is in the plane of the contact band, perpendicular to the middle line, and the axis z is perpendicular to the plane of the contact band and pointing towards the inside of the body.

Since the length of the cylinders in contact is assumed to be infinite, then the origin of the coordinates can coincide with any point on the middle line of the contact strip, so it can be said that the stresses state of the bodies in the case of the linear contact is constant along the contact band. Thus, the relationships that determine the components of the stresses field at some point of coordinates (x, y) are [14] [15]:

$$\sigma_x = -2\cdot\nu\cdot p_0\cdot\frac{z}{b}\cdot\left(\sqrt{\frac{b^2+t}{t}}-1\right) \quad (9)$$

$$\sigma_y = -p_0\cdot\frac{z}{b}\cdot\left[\sqrt{\frac{b^2+t}{t}}\cdot\left(2-\frac{b^2z^2}{t^2+b^2z^2}\right)-2\right] \quad (10)$$

$$\sigma_z = -p_0\cdot\frac{bz^3}{t^2+b^2z^2}\cdot\sqrt{\frac{b^2+t}{t}} \quad (11)$$

$$\tau_{yz} = \tau_{zy} = -p_0\cdot\frac{byz^2}{t^2+b^2z^2}\cdot\sqrt{\frac{t}{b^2+t}} \quad (12)$$

$$\tau_{xy} = \tau_{yx} = 0;\quad \tau_{zx} = \tau_{xz} = 0 \quad (13)$$

where t is the largest root of the equation:

$$\frac{y^2}{b^2+t}+\frac{z^2}{t} = 1 \quad (14)$$

Tangential stresses are also important. These tensions are determined by the main normal stresses and reach a maximum-maximum on the OZ axis at different depths below the contact surface; this is why they are also called main tangential stresses.

Of particular interest are the main tangential stresses located on the OZ axis under the contact surface at certain depths, the value of which can be determined by relations [15]:

$$\tau_{45(xy)} = \frac{\sigma_y-\sigma_x}{2};\quad \tau_{45(zy)} = \frac{\sigma_z-\sigma_y}{2};\quad \tau_{45(xz)} = \frac{\sigma_z-\sigma_x}{2} \quad (15)$$

and which are inclined by 45 degrees to the coordinates X and Y, Z and Y respectively Z and X (Fig. 9).

The greatest value of these values is the tension $\tau_{45(zy)} = 0.3\cdot\sigma_0$, located at the depth $z_{45} = 0.8\cdot b$ [15].

2.5 The influence of three-dimensional surface defects in sliding rolling contact

The three-dimensional defects of the materials from which the spur gears are made are considered to be inclusions and voids (cavities).

Tensions in the areas with structural discontinuities are higher than in other parts of the material, due to the fact that they can be considered as stress concentrators.

Cracks, voids, can act as areas of fatigue crack nucleation, especially if they are at the surface of the piece. Thus, smooth surfaces increase the duration of nucleation, while grooves, notches, decrease this duration. Dislocations may also cause fatigue cracks.

The effects of non-metallic inclusions and small defects are essential in dealing with the problem of small cracks.

Some researchers have shown that only oxide inclusions greater than 30 μm in diameter have to be taken into account in determining lifetime for, for example, bearing balls [10]. Insertions smaller than a threshold value or limit, do not affect fatigue strength of the material.

It has been found that oxides generate stretching stresses in the matrix surrounding inclusion, while sulfur inclusions rarely produce this. This explains why non-metallic inclusions of oxides are more harmful than sulfide inclusions.

The same inclusions can have different effects on fatigue resistance, depending on the direction of the load. Different influences of inclusions occur if the load produces tensile stresses in the longitudinal or transverse direction of the defect.

It has also been observed that the effect of inclusions may vary depending on where they are located in the depth of the gear tooth.

Many researchers (Murakami, Shiozawa, Toyoda, Watanabe, etc.) have found that the main parameters of nonmetallic inclusions affecting the life of a metallic element are the shape and size of inclusions, their degree of adhesion to the matrix of the substrate, the elastic constants of the matrix, respectively inclusions.

In the tests performed, it was found that the fatigue destruction was initiated in the area with inclusions from the substrate of the material [7] [8] [10] [16].

Murakami [10] proposed a method of estimating fatigue life based on Vickers hardness of the material and the maximum size of nonmetallic inclusions. The main hypothesis was that an inclusion in a certain area of the material could be replaced by a crack of the same size, positioned in a plane perpendicular to the maximum tensile tension.

Toyoda [16] showed that non-metallic inclusions in the tooth flank of the gear substrate tend to cause fatigue defects if the gears are made of cement steels. He proposed an empirical equation for determining lifetime fatigue, including Vickers hardness of the material, projection of the inclusion area on a plane perpendicular to the tension direction and residual strain.

In sliding rolling contacts of gears, bearings, cams, it has been found that cracks can be initiated both from the free surface of the workpiece and from the surface of holes beneath the free surface, or from the interface between an inclusion in the substrate and the material matrix.

Liu [8] considers, for the simplification of the problem, that both the voids and the inclusions are spherical and on the surface of the piece there is a hertzian contact pressure and a proportional tangential tension as a result of the action of the friction forces, the coefficient of proportionality being the friction coefficient, (Fig.10).

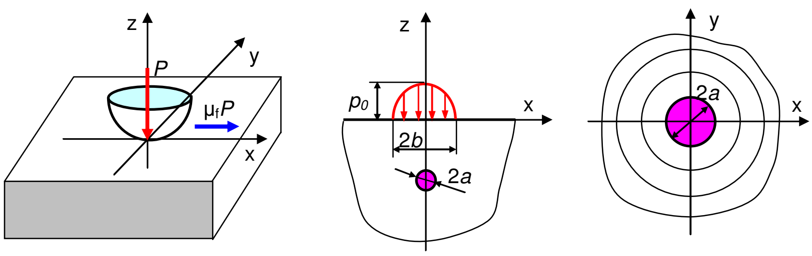


Fig. 10. The schematization of punctual hertzian contact in defective environments

2.6. The effect of rotation in the pitting appearance

From this point of view, Murakami [12], using a two-roller system between which there is a sliding rolling contact, carried out two series of experiments, summing up five tests on the fatigue phenomenon (Fig. 11).

Test 1 consists in the fact that when a crack is detected on the surface of the roller (gear tooth), the direction of rotation is reversed, keeping the role of the two leading (respectively driven) rollers unchanged.

Test 2 consists in the fact that when a crack is detected on the surface of the driven roller, the role of the two rollers (the driven gear becoming the driving gear) changes, and a number of rotation cycles are then performed.

Test 3 considers that after the crack appears on the rolled surface, the test continues to proceed without any change, watching the cracks evolution.

Tests 4 and 5 assume that during their performance, the rolls of the rollers driven with those of the leading rollers are reversed.

Several aspects have been identified, and briefly presented:

- in Test 1, if a crack of a predetermined size corresponding to a number of cycles has been found, the direction of rotation of the rollers has been reversed and the experiment continued. The initial crack ceases immediately to propagate. After a further number of rotations, the crack still did not grow, but new pits appeared on the rolled-up roll, but in the opposite direction to the original crack;
- in Test 2, when the preset size crack appeared, the rollers were changed and the experiment continued. The initial crack immediately ceased to propagate and did not increase even after further application of 1×10^6 cycles;
- in Test 3, the number of cycles in which an arrow-shaped crack appeared on the surface of the driven roller was followed;
- In Test 4, the number of cycles at which an arrow-shaped crack was transformed into a pit was followed;
- In Test 5 a surface defect of a morphology different from that of the arrow-shaped crack is found; even if a large number of cycles continue to apply, the surface defect does not turn into a pit, so the crack growth behavior is completely different in Test 5 versus 4;
- In the process of forming the surface-origin pit, the crack growth rate is low at the start of the crack growth process; after the crack has reached a certain size, a surface pit is formed at a high crack growth rate;

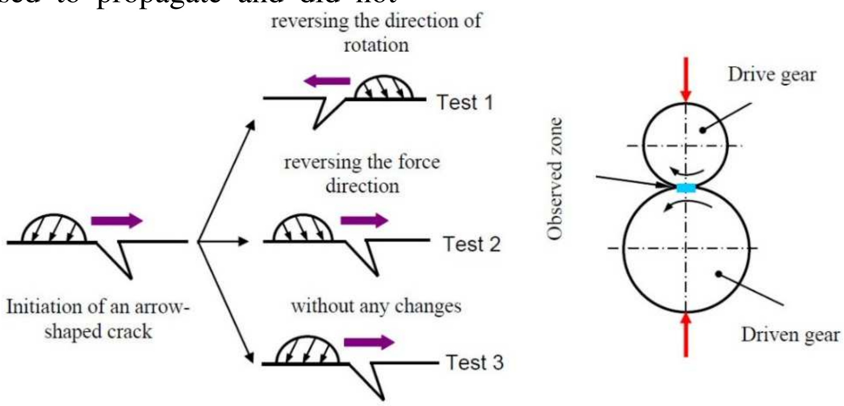


Fig. 11. The effect of the rotation direction and the role of the coupling elements

- even if there is a large crack in an arrow-head shape on the driven roller, inclined at a small angle to the surface and having a direction opposite to the direction of the load movement, it will grow hard;
- even if there is a large crack in the form of an arrow-head on the leading roll, inclined at a small angle to the surface and in the same direction as the direction of the load movement, it will grow hard;
- on the basis of experiments and theoretical studies, it can be said that the formation of the pit of origin at the surface requires not only the initiation of a fatigue crack but also its increase under the influence of oil pressure; thus Murakami [12] considers that the mechanism of formation of the pit with surface origin is the following: a small crack at the contact surface is initiated due to the local stresses, which increase according to the in plane growth mode (mode II) under cyclic stresses in the early stages of the process of fatigue. If the crack is on the ledge and inclined at a small angle to the surface, the crack forms a so-called arrow-head tip through the crack opening mode (mode I) due to the effect of the oil pressure, after the initial fissure developed by the plane mode has reached a certain size.

3. CONCLUSIONS

In this article, some aspects of fatigue cracking have been presented. The existence of early and progressive pits was highlighted, as well as the existence of primary and secondary fatigue cracks which interact with each other.

It was presented how cracks appear, depending on the friction forces and the role of the gear, as well as the influence of the lubricant, which leads to the crack opening, increasing it till to the detachment of material on the tooth surface. In this respect, we also considered the correlation between the direction of the incline of the crack and the sliding speed.

The two possible cases were presented, namely when the crack formed at the surface of the tooth, respectively in the substrate.

It has been shown that contact between the teeth flanks can be replaced by the contact between two cylinders having their rays equal to the curvature rays of the involute at the considered point and the stress field that appears in the contact area was established.

The influences of three-dimensional defects (voids, inclusions of different types) in pits appearance were presented. There were also considered some aspects regarding the direction of rotation and the role of gears in the appearance of the pitting wear. A possible way of forming the cracks that start from the surface of the teeth flanks was eventually presented.

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Apariţia pitingului la roţile dinţate şi factorii de influenţă

Articolul își propune să analizeze unele aspecte ale fisurilor de oboseală care au ca rezultat apariția uzurii la angrenaje. Vor fi luați în considerare diferiți factori care acționează asupra fisurilor deja propagate și care se vor deschide la suprafața dintelui. Rezultatul este apariţia unei gropiţe pe flancul dintelui. S-a prezentat starea de tensiuni care apare la contactul pe generatoare dintre doi cilindri care pot simula contactul dintre flancurile dinților roților dinţate. Se prezintă, de asemenea, o posibilă modalitate de formare a fisurilor care pleacă de la suprafaţa flancurilor.

Claudiu Ovidiu POPA Lecturer Ph.D., Technical University of Cluj-Napoca, Department of Mechanical System Engineering, Claudiu.Popa@omt.utcluj.ro, Office Phone 0264/401665.

Simion HARAGÂŞ Professor Ph.D., Department of Mechanical System Engineering, Technical University of Cluj-Napoca, Simion.Haragas@omt.utcluj.ro, Office Phone 0264/401665.