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Photoelastic analysis of surface-cracked elements in presence of Hertzian contact and interposed fluid

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Abstract

Starting from Way's studies [6] in late 1935 a lot of work was made to investigate the influence of lubrication on contact fatigue surface crack propagation problems. A lot of numerical models can be found in literature; nevertheless an experimental evaluation of SIFs by considering the presence of the interposed fluid was never made. The present paper presents an experimental procedure modeling a contact problem of a disk with an surface-cracked semi-plane with interposed fluid: a photo elastic model with a sandwich design is proposed. The assembly realization is discussed in detail. Using a multi parametric approach experimental SIFs are obtained for different fluids. Results are reported and future work is proposed.

Keywords: pitting, fracture mechanics, photo elasticity, lubrication

1. Introduction

Fatigue propagation of cracks in hertzian contact stressed components is one of the more common cause of failure in gears, bearings, railway tracks. It's necessary to distinguish between two kinds of contact fatigue damage: edge-cracks (pitting) or sub-superficial ones (spalling). In both cases the damage causes part loss and consequent deterioration of the surfaces in contact. In literature isn't possible to find a uni-vocal nomenclature to distinguish these two phenomenons, which are indeed really different. For example, Tallian[1] define spalling macroscopic contact fatigue caused by the fatigue propagations of the cracks, and reserve the term pitting to surface damages with different causes. Kuhnell [2] define pitting the formation of small pits caused by superficial defects, and with spalling the formation of deep cavities caused by sub superficial defects. The lack of a uni-vocal nomenclature may be due to the small physical understanding of these phenomenons.

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Cracks can be originated by the cyclic contact loading or from defects as dents or scratches on the surface; they propagate with a characteristic inclination relative to the contact surface. When the cracks reach a critical length, they may bifurcate: in particular in gears and bearings, the cracks propagate reaching the surface and causing loss of material and the formation of a pit on the surface. Further details can be found in [3], [4] and [5].

In 1935 Way [6] showed as contact fatigue originated cracks may be reproduced in laboratory conditions. From that moment a great experimental work was developed, demonstrating that the propagation of those cracks happens only in presence of lubricant interposed between the crack faces. At this moment isn't readily understood how a crack can propagate in a compression stress field, because a crack closure would be expected. Three hypothesis were made to justify this behavior:

- the cracks propagation would be guided by the mode II of loading;
- the lubricant fluid would be forced into the crack by the load, thus generating a mode I opening of the crack;
- the lubricant would be entrapped into the crack, driven near the apex of the crack and subsequently pressurized with a critical opening near the tip.

In the past a lot of theoretical models of the phenomenon were developed to investigate those mechanisms. Keer and Bryant [7] developed a technique based on the distribution of the dislocations to represent a bi dimensional crack in a semi-space, and utilized it to study this problem, considering the first of the mechanisms proposed [8]. Murakami and Nemat-Nasser [9] developed another numerical technique called body force method permitting to evaluate three-dimensional cracks and utilized it for this problem. The results, obtained considering the second mechanism, give SIFs [1] that can lead to crack propagation ([10], [11] and [12]). Bower [13] utilized an extension of the dislocation method of Keer and Bryant and favored the third mechanism. There are some works that utilized FEM technique, like the one of Benuzzi [14], considering both the second and the third mechanism, or one of Chai [15], considering fluid entrapment.

Opposing to this great numerical work there isn't a work establishing some experimental results to understand which, if one, of those models is right or similar to reality. The aim of the present work thus is to develop a method on the basis of which experimental SIFs may be obtained, leading to results that have to be matched by the numerical methods.

2. Experimental set-up

As an example of edge-cracked element, a photo elastic model of a surface cracked plane in contact with a cylinder shown in Figure 1 is built. A similar approach can be found in [16], studying spalling kind problem and in [21] where a perpendicular edge-crack without fluid interaction is considered. Note that cylinder speed is considered low enough for quasi-static behavior.

As said, the model should be capable of reproducing the real stress field with fluid interaction. Using a model composed by a single layer of birefringent material a crack passing or not trough

[1] Stress intensification factors

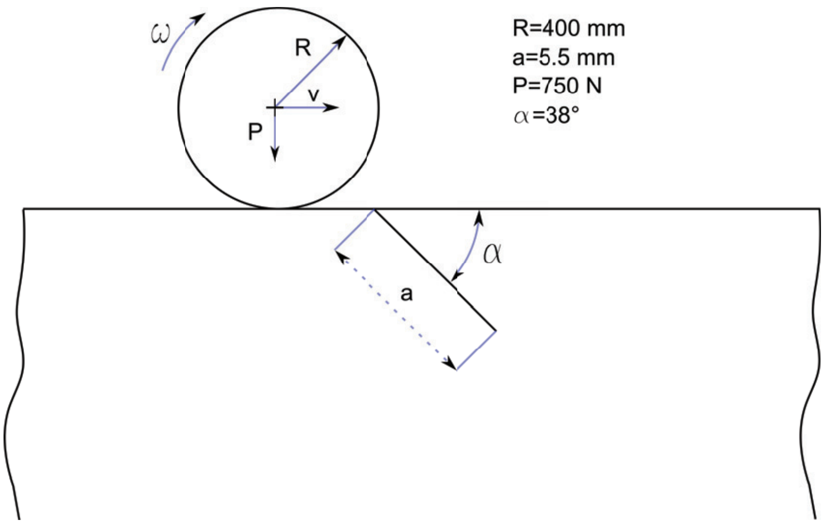

Figure 1: Quoted scheme of the problem. Speed is low enough for quasi-static behavior.

the width could be realized. Sadly both solutions would lead to wrong analysis: in the first case the fluid isn't correctly constrained, in the second the plane stress condition can't be achieved.

A sandwich approach can avoid this problem: the model reported in Figure 2 is composed by two layers of polymethacrylate, a non-birefringent material, and one, centered, of polycarbonate, strongly birefringent. The crack is passing through polycarbonate, and the sides lie into the polymethacrylate: observed condition is now of plane-stress and the fluid is correctly constrained on sides.

Theoretically the wheel width should be equal to the model's one, but this isn't permitted by the fluid containing surfaces. Model making requires a tie constrain between the different layers, simulating the behavior of a single material. This also requires the use of materials with a similar elastic behavior, as is for the two chosen. The tie constrain is realized using the Araldite 2028, an adhesive produced by Vantico, that can bond together the layers without compromising the photo elastic signal. It's an episodic resin polymerizing at ambient temperature. The gluing process need some attentions, reported here.

Cleaning - First is necessary to clean wheel surfaces to be glued, avoiding the use of degreasers as the acetone, which can destroy the photo elastic signal, dulling the surfaces.

Adhesive application - The two components of the adhesive are mixed by the provided dispenser. To avoid the formation of bubbles is necessary to use a brush, correctly distributing the glue on the surface. Without this attention, the increased width of adhesive layer can lead to viscoelastic behavior of the obtained model, while the bubbles lead to local distortion of the stress field.

Assembly - The surfaces spread of glue are now putted together and loaded with some weight. The polymerization time depends on ambient temperature; anyway the model was maintained under

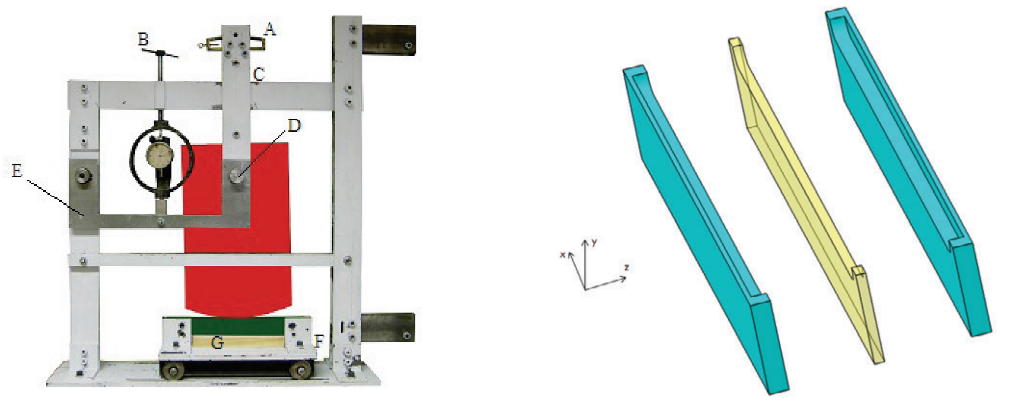

Figure 2: Experiment parts: the loading system (left), the sandwich project (right)

loading for twelve hours at least.

2.1. Crack

Once the sandwich model is obtained, it is necessary to realize the edge-crack. This is surely the most difficult part. Many attempts were made to realize a crack that was deep and sharp. In single layered models edge-cracks are usually realized hammering a razor blade into it. This lead to realistic cracks. In a sandwich model this approach can't be followed, because of the great difference in the crack propagation into different layers. Better results can be obtained penetrating the model with a hot blade. A pencil torch was utilized to warm the blade, pressed by hand against the model. The operation was repeated till a required depth was reached. Two kinds of blades were used: a Stanley one to begin the crack and a Ruffin Professional, sharper and longer, subsequently. The blades were cut at the desired width using water-jet technology: simple cutting isn't possible because of the bending of blades.

The last step is the finishing of the contact surface by sandpaper, removing also the distortion caused by the blade penetration.

2.2. Loading system

The loads were applied on the model using the experimental apparatus shown in Figure 2. The horizontal displacement was imposed to the semi-plane model: this simplifies considerably the experiment. The loading system design allows to impose a vertical load on the center of the cylinder, and to measure it by a dynamo-meter.

The tests considered two different fluids:

- Agip 46, $\nu = 46$ $[mm^2/s]$;
- Tellus oil 100 $\nu = 100$ $[mm^2/s]$.

Figure 3: Uncracked sandwich (left); photo elastic results for dry model (right).

3. Results

At first was tested the contact between the uncracked plane and the cylinder, thus verifying the correct behavior of the sandwich and so the correct gluing of surfaces. After the cracked model was studied. In Figure 4 are reported photo elastic results. To obtain numerical values of SIFs is necessary to use an extrapolation technique. A multi parametric method was used. This approach uses the fundamental photo elastic equation:

$$\frac{N f_\sigma}{t} = \sigma_1 - \sigma_2 \tag{1}$$

where N is the fringe order, f_σ the photo elastic constant of the polycarbonate, t the thickness of the model, σ_1 and σ_2 the plane stresses, and the well-known relation:

$$\sigma_{1,2} = \frac{\sigma_{xx} + \sigma_{yy}}{2} \pm \sqrt{\frac{\sigma_{xx} - \sigma_{yy}}{2} + \tau_{xy}^2} \tag{2}$$

to obtain a minimization problem of the reported functional g_m:

$$g_m = \left(\frac{\sigma_{xx} - \sigma_{yy}}{2}\right)^2 + \tau_{xy}^2 - \left(\frac{N f_\sigma}{t}\right)^2 \tag{3}$$

Further details can be found in reported references ([17], [20], [18], [19] and [22]).

The results are reported in Table 1. Values of K_I are every time negative: this can be justified by the distance of crack faces, which permits a negative mode I of propagation. The value is anyway increased by the interposition of the fluid: the distance between crack faces can't lead to an entrapment of the fluid. The forcing of the fluid seems to be the driving mechanism of crack propagation, leading to a small opening of the crack faces. A marked increment is present in the value of K_{II} when interposing the AGIP 46. Tellus oil, instead, show a value similar to the dry one[2]. This could be due to the cauterization of the crack face's surfaces (see conclusions), that may lead to a small penetration of the fluid, explaining also the small increment in K_I.

Results presented are greatly influenced by the quality of the crack tip; the analysis suffers of the hypothesis of singular stress field, condition that may not be achieved in this experiment.

[2] Variation may be caused by measuring errors, repeatability, etc.

	Dry	Agip 46	Tellus oil 100
K_I	-7	-5.5	-6.12
K_{II}	5	8.84	4.47
σ_{0x}	5.90	7.65	4.22
error	0.8	0.7	0.9

Table 1: Results obtained using multi parametric method with various fluids.

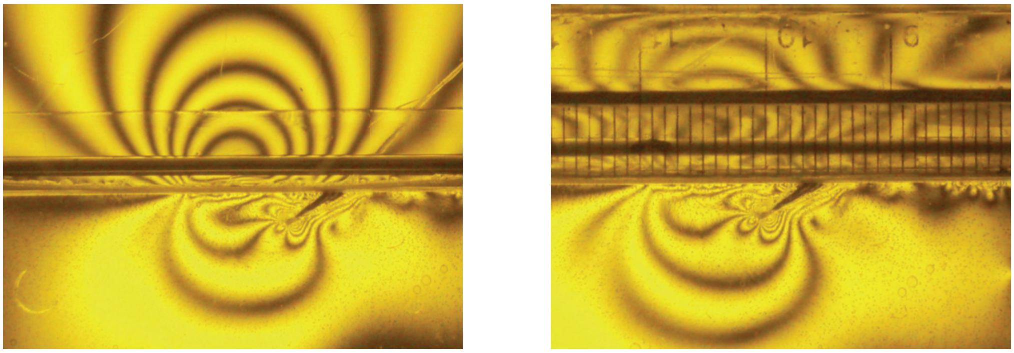

Figure 4: Photo elastic results: tellus oil 100 (left) and agip 46(right)

4. Conclusions

The approach presented is promising, considering that it led to the first SIFs experimentally obtained for a similar problem. The fluid-forced kind of mechanism is reported. This is strongly influenced by the morphology of the realized crack: a smaller crack may lead to fluid entrapment mechanism. The fluid interposition shown a correlation with K_{II}: the percent increasing in the second mode of loading can be important with some fluids. Nevertheless some imperfections need further work:

- the elevated temperature of the blade affected the finishing of crack face's surfaces, that look dark and cauterized, with unpredictable effects on the contact friction;
- multiple penetrations necessary to reach an acceptable depth of the crack affect the quality of the crack tip;
- the distance between crack faces may be unrealistic.

At this moment a five-layer sandwich is being studied: with some attentions this could lead to get over all of the limitations reported, also removing said uncertainties of the model.

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