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ANALYSIS OF THE INFLUENCE OF INDENTATIONS ON CONTACT LIFE

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Applying the relation between stresses and contact fatigue as postulated by Ioannides & Harris, an investigation is carried out to determine the influence of dent geometry on contact life. This analysis is performed using line contact and point contact models. The stresses are calculated using a dry contact model and the elastic half-space assumption. Results from calculations using the line contact assumption are compared with the results of elliptical contact calculations, which model the dents more exactly. The difference in contact pressure between the line and point contact case is analysed in detail. The dent geometry has been obtained from an FEM analysis of an indentation process and the dent is scaled with respect to depth and width to obtain a family of dents. The FEM calculations were compared to experimentally obtained dent profiles. As was done previously for the line contact analysis, the influence of the residual stress field from the plastic indentation process was investigated for the calculated dent geometry (without scaling). The life reduction compared to the smooth contact case has been obtained for three different load cases for a large number of different dent sizes and dent slopes, employing the point contact analysis. The life reductions are compared to the results of an extended line contact analysis and the influence of the position of the dent on life reduction is investigated. This analysis is aimed at establishing the reduction of contact life caused by indentations stemming from handling damage and the overrolling of debris.

1 INTRODUCTION

Over the last decade, interest in the study of sub-contact size features on rolling contact performance has increased considerably. The majority of investigations has been experimental [10, 11, 17]. However, a number of theoretical investigations on micro EHL have been published in the literature on stationary line contacts, stationary point contacts [9, 13, 19] and transient line contacts [3, 4, 19, 20]. In most of these investigations the changes in pressure and film thickness have been studied. The influence of these pressure fluctuations on subsurface stresses and subsequently on contact fatigue life have been addressed in [5, 14, 18, 20, 21, 22]. With the introduction of the New Life Theory [6] a general relation between stress and risk of fatigue has become available which can be utilized for such a theoretical investigation. The introduction of powerful (and relatively cheap) computers and advanced solution methods has enabled a detailed theoretical study of the influence of sub-contact-size features [16]. In this paper the technique will be applied to study the influence of indentations on the performance of contacts. Obviously, engineering surfaces cannot be described as being mathematically smooth. Depending on the manufacturing process a certain surface topography (roughness) will be present. Additionally, the surface can exhibit manufacturing defects and indentations that stem from handling damage. Additional features like indentations from the overrolling of contaminant particles can be created during overrolling, depending in size and depth on the cleanliness of the lubricating medium. All of these features (roughness, defects and indentations) generally have a height (depth) which is comparable to or larger than the thickness of an EHL oil film (approximately 0.1 - 1.0 μm). Thus these features will change the contact conditions relative to the smooth surface conditions. Determining the geometry/topography of these features is relatively straightforward; however, the important question is: "To what extent does such a topography affect the contact performance?". There is no single answer to this question since the influence of the feature on the contact performance depends on the contact conditions. This work is aimed at investigating the influence on contact fatigue life, and relating it to both surface feature and contact conditions. More precisely, this paper focuses on indentations and other defects which have a ratio of length scale (width) to contact size (width) of 0.1 -1.0. In order to keep the complexity as low as possible when studying point contacts, stationary dry contact calculations are performed. The work can thus be regarded as an extension of the earlier line contact analysis of indentations [2, 14]. The dry contact analysis can be justified since the features of interest (indentations) have height dimensions which are one to two orders of magnitude larger than the lubricant film thickness. Thus omission of this thin lubricant film will not alter the subsurface stresses too much.

1.1 Notation

a	half-length of the contact ellipse (in y direction), [m]
b	half-width of the contact (ellipse) (in x direction), [m]
c	stress exponent
C	dynamic load capacity, [N]
dr	dent radius, in case of a model dent (eq. (3)) $dr = \lambda/4$, [m]
dV	infinitesimal volume, [m^3]
e	Weibull slope
E'	reduced elasticity modulus, $2/E' = (1-\nu_a^2)/E_a + (1-\nu_b^2)/E_b$
fx	scale factor for width of dents
fz	scale factor for depth of dents
h	depth exponent
l	grid level
L_s	relative life of smooth contact
L_d	relative life only accounting for dent geometry
L_r	relative life only accounting for residual stresses (Hertzian pressure)
$L_{r,d}$	relative life accounting for residual stresses and dent geometry
N	number of revolutions
p	pressure, [Pa]
p_h	Hertzian pressure, [Pa]
P	load, [N]
r	distance, $r = \sqrt{x^2+y^2}$, [m]
V_r	volume where risk > 0 ($\sigma > \sigma_u$), [m^3]
x, y, z	coordinates, [m]
z'	stress weighted average depth, [m]
$\mathcal{A}$	amplitude used to model scratch/dent, [m]
$\mathcal{D}$	height of model scratch/dent, [m]
$\mathcal{R}$	risk of fatigue
$\mathcal{R}_{l,s}$	risk of fatigue of smooth line contact
$\mathcal{R}_{l,d}$	risk of fatigue of dented line contact
$\mathcal{R}_{x,d}$	risk of fatigue of extended line contact
$\mathcal{R}_{p,s}$	risk of fatigue of smooth point contact
$\mathcal{R}_{p,d}$	risk of fatigue of dented point contact
$\mathcal{S}$	probability of survival
λ	wavelength used to model scratch/dent, [m]
σ	stress, [Pa]
σ_u	fatigue limit, [Pa]

2 THEORY

In this paper the relation between risk of fatigue and stress at a point is applied according to the New Life Theory [6]:

$$\ln(\frac{1}{\mathcal{S}}) \sim N^e \int_{V_r} \frac{(\sigma-\sigma_u)^c}{z'^h} dV \qquad (1)$$

where the integral is taken over the volume V_r where the stress exceeds the (local) fatigue limit of the material, $\sigma > \sigma_u$. In [15] it was explained why the coefficients e and h can be changed (see also [12]), and in this work $h = 0$ is used. The stress-fatigue function σ incorporates the influence of the hydrostatic stress [7]. The contact pressures are calculated using an elastic dry contact model based on [8] and described in detail in [16]. This means that the thickness of the lubricant film is assumed to be negligible compared to the overall deformations of the contacting surfaces. From a stress point of view it can be considered as a pessimistic approximation, or as a limit case for high loads and thin films. Shear forces at the surface are not taken into account, thus the influence of friction is neglected. If straightforward methods in the solution process such as matrix multiplication and Gauss-Seidel iteration or Newton-Raphson were used, the computer time required for a solution (especially of the elliptical contact) would be very long. Therefore, fast methods for the solution and the integration are applied [1, 16]. When these contact pressures are known the subsurface stress tensor can be calculated in each point, again using the fast integration. The stress tensor is then converted to a life estimate employing equation (1). Calculation of both the pressure distribution and the subsurface stresses in the elliptical contact, using a grid of 129 × 1153 points on the surface, consumed approximately 6 CPU hours on a Silicon Graphics SG240. The number of points (planes) in the z direction for the stress calculation is of the order of 50, with increasing stepsize with z.

3 FEM MODEL

The process of surface indentation was modelled using the general purpose finite element code ABAQUS. The code contains routines to model plasticity, large deformations and body contact. These features make the model ideally suited for the purpose of indentation analysis. The upper body was taken to be a 1 mm tungsten carbide ball, loaded in a series of steps up to a load of 450 N onto a flat steel body modelled as a square of 1.5 mm. The base of the lower body was simply supported whilst the top of the indenter was constrained to move vertically. Second order mesh refinement was used to provide high resolution in the contacting regions. The plastic deformation (the indent) and the residual stresses in this lower body (produced by the denting operation) were stored after the two bodies had been separated. The entire problem was modelled employing radial symmetry using 614 parabolic quadrilateral elements (see figure 1). The depth profile of the indentation is compared in figure 2a with a measured indent which was created using the same load conditions. From this figure it can be concluded that whereas the general geometry and width of the model indentation agree well with the experimental one, its depth is overestimated by 5 μm. This is probably due to the strain hardening taking place in reality which was not incorporated into the FEM model. Preliminary results from calculations employing strain hardening show that the predicted depth of the dent is reduced by

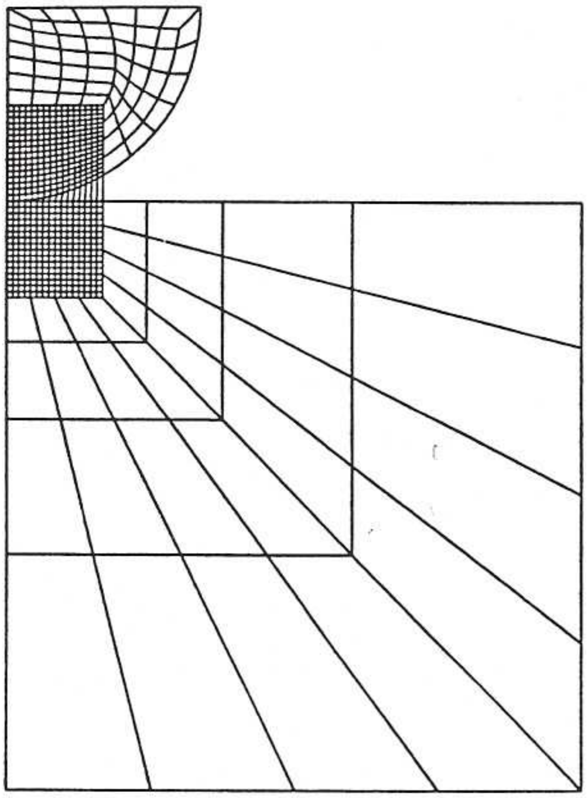

Figure 1 *FEM mesh used in indentation calculation.*

3 μm. Also, the height of the shoulders is reduced, whereas the actual width of the indentation remains unaltered.

The theoretical dent profile obtained from the FEM analysis is used in later sections to investigate the influence of the indentation geometry on the fatigue life. For this purpose the dent geometry was scaled. The influence on the fatigue life of the residual stress field obtained from the FEM calculation (figure 2b and 2c) is discussed in section 10.

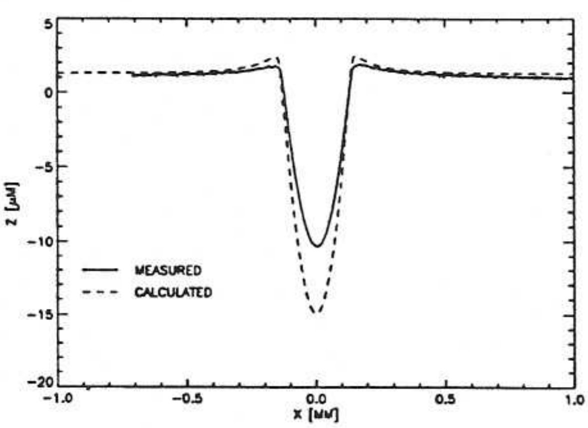

Figure 2a *Comparison of experimental and theoretical dent profile.*

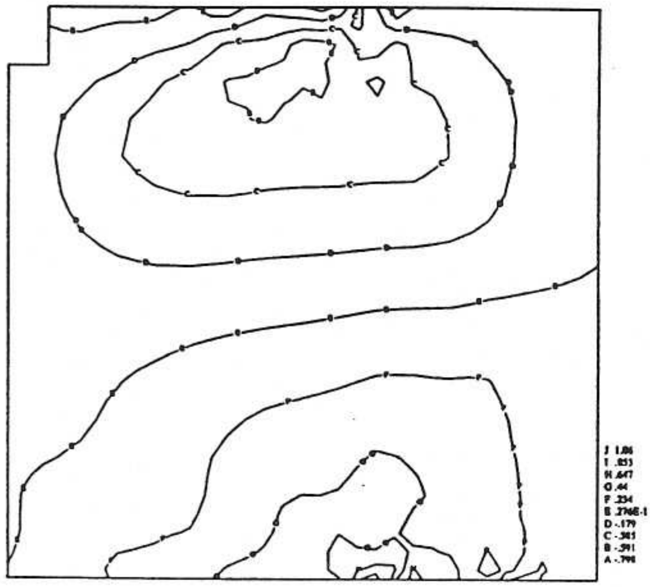

Figure 2b *Residual shear stress below indentation; shown is the central square of 0.25 mm.*

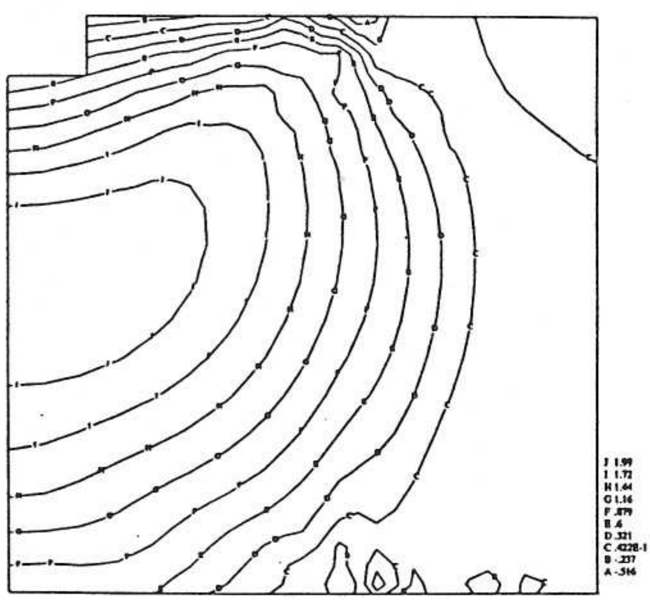

Figure 2c *Residual hydrostatic stress below indentation; shown is the central square of 0.25 mm.*

4 EXTENDED LINE CONTACT ANALYSIS

The line contact analysis carried out in earlier work has several limitations, which will be discussed:

- Dry contact analysis
- No friction
- No influence of residual stresses
- Stationary analysis
- Coarse approximation of circular indents

The influence of the dry contact assumption is relatively small as shown in [14], which also shows that the effect of the stationary analysis is small for centrally located dents as long as they are small compared to the contact dimension. Moreover, the influence of the residual stress fields as shown in [2] is relatively small. A systematic investigation into the effect of friction on contact life has yet to be carried out, but some hints are contained in [7]. This paper mainly studies the extension of the line contact problem to a point contact problem and its influence on contact life. The main shortcoming of the line contact analysis of the influence of indentations on contact life lies in the relative life reduction of indentations of different sizes. This can easily be explained theoretically: in the line contact analysis the pressures are governed by the local surface slopes. When an indent is scaled to half the size and depth, thereby retaining its original slopes, the associated subsurface stress field will remain identical, only it now occupies only 1/4 of the original volume. This is true under the assumption that the indentation is small compared to the Hertzian width, otherwise the local pressure will change due to the elliptical Hertzian pressure distribution. The effect of this reduction in volume can easily be counteracted by a slight increase in dent depth, increasing the dent slope and thus also the subsurface stresses. Because the exponent $c = 31/3$ (see equation (1)) of the stresses is large, the slope has only to increase by $4^{3/31} = 1.14$ to counteract the reduction in volume. Because of the non-linear influence of the fatigue limit, this slope multiplication factor is even smaller. In the next section the differences between the line and point contact problem will be treated extensively. As a result the theoretically predicted life reduction of small and relatively steep dents is dramatic. This is contrary to experimental observations which show that small dents have only a slight effect on contact performance. To overcome this deficiency in life predictions, the line contact analysis has to be extended.

A better approximation of the actual life reduction caused by a circular indentation can be obtained from the line contact analysis. Therefore, the circular dent is approximated by a rectangular shape and the dented line contact risk and the smooth line contact risk are added according to the ratio of dent versus contact size. The following equation calculates the risk of fatigue ($\mathcal{R}_{x,d}$) according to the extended line contact analysis (after [21]):

$$\mathcal{R}_{x,d} = \frac{\mathcal{R}_{p,s}}{\mathcal{R}_{l,s}}(\mathcal{R}_{l,s} + (\mathcal{R}_{l,d} - \mathcal{R}_{l,s})\frac{dr}{a}) \qquad (2)$$

This equation adds the difference between the dented line contact risk ($\mathcal{R}_{l,d}$) and the smooth line contact risk ($\mathcal{R}_{l,s}$) multiplied by the ratio of dent versus contact size in the (infinite) line contact direction to the smooth line contact risk, and multiplies the result by the ratio of smooth point contact risk ($\mathcal{R}_{p,s}$) and smooth line contact risk ($\mathcal{R}_{l,s}$). Calculations of the contact life based on this relationship are compared to the full point contact calculation in figure 3. Care was taken to ensure that both line and point contact calculations had the same number of points in the contact width direction, to ensure that similar numerical errors occur in both calculations.

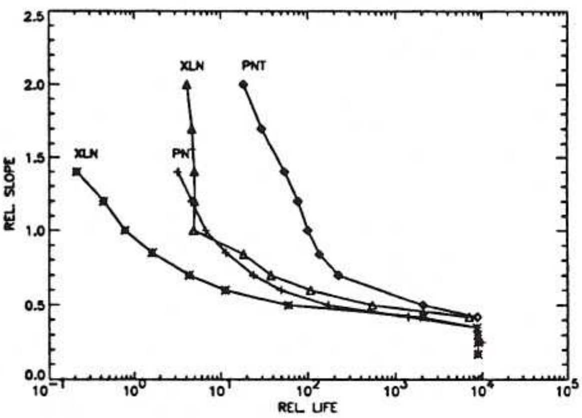

Figure 3 *Comparison of life reductions from the extended line contact analysis with full point contact calculations for two dents, $f_X = 0.50$ and $f_X = 1.0$, as a function of the relative slope f_Z/f_X. $p_h = 3.0$ GPa, $b = 0.3$ mm, $a/b = 8$, smooth contact life is* $0.8513\ 10^4$.

From this figure it can be concluded that equation (2) is not a good approximation of the point contact risk of fatigue. The predicted lives are too low, and, depending on the size and depth, the error in the predictions varies between zero and two orders of magnitude. Moreover, for different contact conditions (pressure, width and ellipticity ratio) the results can be very different. Compared to the full line contact predictions, however, the trend is in the right direction.

Since the approximations to the point contact calculations were not successful, it was decided that a full point contact analysis cannot be avoided and sections 6-9 present and discuss the results. The next section analyses the difference between the line and point contact problem.

5 DIFFERENCE BETWEEN LINE & POINT CONTACT PROBLEMS

In this section the pressure perturbations stemming from the indentations will be compared for the line and circular contact case. In order to keep numerical errors comparable in the two models the same number of points, 129 per contact dimension, was used. In the line contact case the dent is modelled as a transverse scratch by:

$$\mathcal{D}(x) = \mathcal{A}\ 10^{-10(x/\lambda)^2} \cos(\frac{2\pi x}{\lambda}) \quad (3)$$

In the circular contact model the dent is modelled in a circular symmetric way by:

$$\mathcal{D}(r) = \mathcal{A}\ 10^{-10(r/\lambda)^2} \cos(\frac{2\pi r}{\lambda}) \quad r = \sqrt{x^2+y^2} \quad (4)$$

In the comparison the contact pressure and contact width was fixed at 3.0 GPa and 0.3 mm respectively. The maximum pressure is given in figure 4 as a function of the dent amplitude $\mathcal{A}$ ranging from $\mathcal{A}$=-10 μm (true scratch/dent) to $\mathcal{A}$=+5 μm (true ridge/bump).

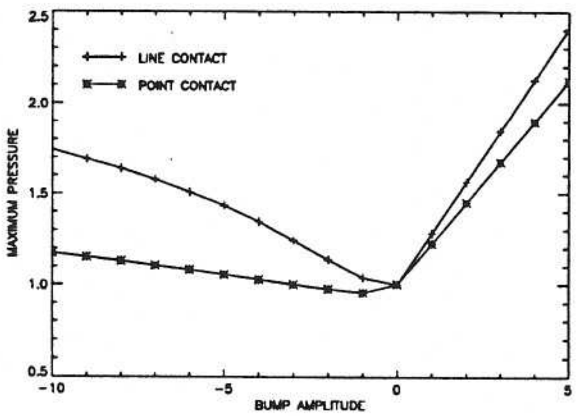

Figure 4 *Comparison of maximum pressure between dented line and point contact, as a function of the amplitude. $\mathcal{A}$ <0: dent, $\mathcal{A}$ >0: bump, p_h = 3.0 GPa, b = 0.3 mm, λ = 0.5 mm.*

Several aspects of this figure need explanation. The side of the diagram with $\mathcal{A}$ >0 shows a linear relation between the maximum pressure observed and the bump amplitude, which follows directly from the linear elastic equations. The values of the maximum pressure for the line and point contact differ by less than 20% and this difference can be attributed to the different contact problems studied (line versus point contact, transverse ridge versus circular bump). For amplitudes smaller than zero ($\mathcal{A}$ <0) two different features need an explanation: the non-linear increase of maximum pressure with amplitude and the large difference between line and point contact results. Let's start with the last point, the large difference in pressure increase, a factor of 4 from the point to the line contact. One has to realize that in these contact calculations, the load is kept constant. A dent will cause a large pressure drop in the central zone of the pressure distribution, but the affected area will be much smaller in the point contact situation, and as a result the pressure increase to ensure load balance will be smaller. The dent area in the line contact case is roughly 42 %, whereas in the point contact case it is only 17 %. Therefore the pressure increase is expected to be larger for the line contact case compared to the point contact case. Additionally the larger pressures in the point contact work on a larger area (proportional to the radius). Furthermore, a small pressure difference is expected anyway as was shown for the case where $\mathcal{A}$ >0. The second aspect, the non-linear behaviour is easily explained when realizing that the "cavitation condition" ($p \geq 0$) makes the problem nonlinear. For both the line and point contact the maximum pressure increases linearily from $\mathcal{A}$=-1.0 μm to -3.0 μm, then cavitation sets in and the problem becomes non-linear. Since the pressures in the contact centre cannot become negative, the overall pressure maximum increases more slowly. This non-linear effect will also occur for large positive values of $\mathcal{A}$, the actual value is determined by the Hertzian pressure, and the slope.

Having resolved the source of difference between the two models, we once again turn our attention towards the influence of indentations on the life of elliptical contacts.

6 MODEL VERIFICATION

In this section the influence of a transverse scratch on the life reduction of elliptical contacts with different ratios of the contact axes (a/b) is compared with the life reduction for a line contact with a scratch. The scratch was modelled theoretically in both the line and point contact analyses by equation (3). The results of this comparison are given in table 1. From this table it can be observed that the life reduction (dented life divided by smooth life) converges slowly to the line contact value. In all calculations the number of points in the contact width direction was fixed, as well as the actual width of the contact. The calculational parameters were: p_h = 3.0 GPa, b = 0.5 mm, the number of points in the contact width dimension (b) was 129, $\mathcal{A}$=-10 μm, λ=0.5 mm.

These results confirm that the life reduction caused by a transverse scratch of very slender elliptical contacts actually approaches the line contact value. A better agreement cannot be expected since even for very large ellipticity ratios the elliptical contact never becomes a true line contact.

Table 1 *Comparison of life reduction, scratched contact life divided by smooth contact life as a function of a/b. $a/b = 1$: circular contact, $a/b = \infty$: line contact.*

a/b	life red.
2.0	2.0 10^{-1}
5.0	1.8 10^{-1}
10.	9.6 10^{-2}
20.	6.1 10^{-2}
50.	4.0 10^{-2}
∞	1.7 10^{-2}

7 NUMERICAL PROBLEMS IN POINT CONTACT CALCULATIONS

The point contact calculations suffer from two different types of problems related to computer capacity and the stationary model. The first problem is simply a matter of computational power; it involves the number of gridpoints required to describe accurately the influence of an indentation. Ideally the total number of gridpoints should be large and proportional to the inverse of the size of the indentation, to ensure that the local stresses are correctly modelled. Unfortunately this is not possible, because of computing time restrictions, but an estimate of the error made (especially for the small dents) is given in table 2.

Table 2 *Comparison of life for two different dents (three different sizes) using a different number of gridpoints, p_h=3 GPa, b=0.3 mm, (constant number of points per unit contact size* **6 6 6**, *constant number of points per unit dent size* **5 6 7**. *The smooth contact life* = 0.8513 10^4, *the grid level* **l** *is given in bold face.*

fz/fx	fx	fx	fx
1.0	1.4	0.7	0.35
	6 0.247 10^1	**6** 0.221 10^2	**6** 0.507 10^3
	5 0.364 10^1	**6** 0.221 10^2	**7** 0.143 10^3
0.7	1.4	0.7	0.35
	6 0.793 10^1	**6** 0.681 10^2	**6** 0.854 10^3
	5 0.974 10^1	**6** 0.681 10^2	**7** 0.458 10^3

These dents are circular extensions from the dent obtained through the FEM analysis, and these circular dents will be used throughout the remaining sections. In this table the life reductions caused by two dents are compared for two different calculations. The first calculation uses a constant number of points for the entire contact, as was done to obtain the results described in the next section. The second calculation uses a constant number of points in the dent in order to approximate the local pressure (stress) variations with equal accuracy, irrespective of the dent/contact size ratio. In the table, the level **l** of the grid is given in bold, increasing **l** by one doubles the number of gridpoints in each direction, decreasing **l** by one halves the number of grid points. From this table it can be concluded that the life reduction predicted for the small dents ($f_X = 0.35$) is underestimated by a factor 3-4, compared to the large dents. The error in the life reduction of large dents is of the order of 50%. The nature of this error tends to underestimate the influence of small dents since there are insufficient gridpoints to capture the pressure and stress variations.

The second source of error mainly affects the large dents. Consider a large dent, which lies mainly outside the contact area. The static calculation will underestimate the influence of this dent due to the fact that it cannot look beyond its own contact area. As a result a large proportion of the dent will not contribute to the fatigue risk. Consequently, the true damaging potential of such a large dent can only be established in a transient overrolling simulation. Even the damaging potential of large dents that lie entirely within the contact region will be underestimated since the local pressures near the contact edge will be lower than the central ones. Also in this case a transient analysis is the only way to correctly model the true damaging potential. However, it was not possible to carry out these calculations because of computing time restrictions. In figure 5 a sequence of static contact lives is displayed with dents in different positions relative to the contact centre, to model the overrolling of indentations of different sizes. A realistic approximation of the risk of large dents should take this integration over space into account.

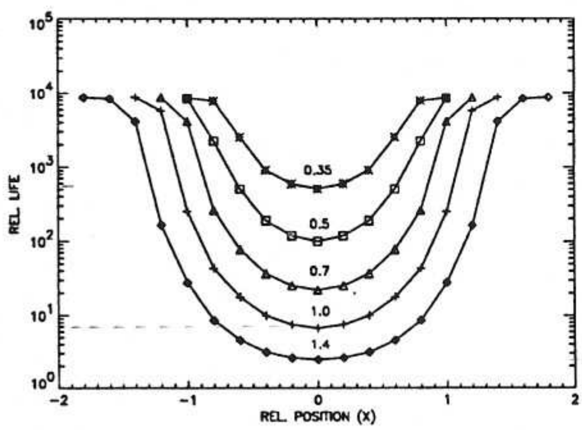

Figure 5 *Life reduction as a function of the dent position relative to the centre of the contact, for a set of dents ($f_X = f_Z$ =0.35, 0.50, 0.70, 1.0, 1.4). Contact conditions:* p_h = 3.0 *GPa*, b = 0.3 *mm, smooth contact life* = 0.8513 10^4.

It can be concluded from this figure that the volume affected by the larger dents extends beyond the actual contact area, and thus the influence will be underestimated when using the static analysis. In order to correctly predict the influence of the larger dents, a transient analysis like the one described for line contacts in [14] should be performed. As was shown there, the influence of the indent on life during an actual dry contact overrolling can be approxi-

mated by the influence of the static pressure distribution when the contact is situated centrally over the dent, provided that the size of the indent is small compared to the size of the contact and the indentation is relatively deep. In the same paper it was also shown that the difference in pressure profile for lubricated and dry contact conditions is relatively small for relatively thin lubricant films. Also, the influence on the fatigue life was shown to be minor.
Although similar comparisons cannot (yet) be performed for point contacts, it is expected that the line contact findings will carry over to the point contact conditions.

8 POINT CONTACT RESULTS

In this section the results of the full point contact calculation are presented. The contact has an ellipticity of 1:8. The numerically obtained indentation profile shown in figure 2a was converted to a rectangular mesh. This dent profile was used to generate the variety of dents used in this section. Therefore, the width was multiplied by a factor (f_X) whereas the depth was multiplied by a second factor (f_Z). For $f_X = f_Z = 1.0$ the original profile is thus obtained; for $f_X = f_Z = 0.5$ a dent half the size and half the depth of the original profile is obtained.

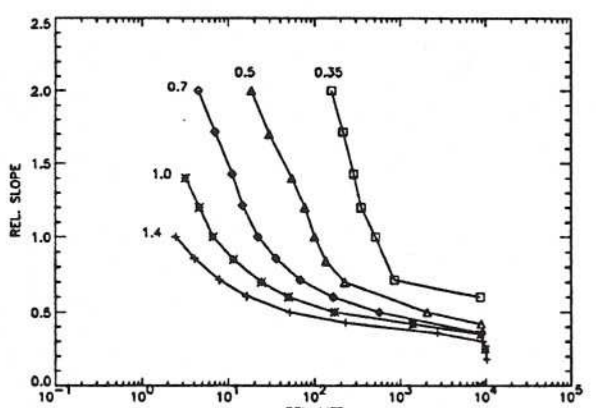

Figure 6 *Life reduction caused by dents as a function of the relative slope* (f_Z/f_X) *for different values of* f_X, $p_h = 3.0$ *GPa*, $b = 0.30$ *mm, smooth contact life is* $0.8513\ 10^4$.

The resulting dent was positioned in the centre of the contact ($x = 0, y = 0$) where it causes a maximum risk of fatigue (see figure 5). The life reduction factors presented in figures 6, 7 and 8 are displayed as life versus the ratio of f_Z and f_X (a slope factor) for three different load cases. Lines of different f_X values represent dents of different sizes. The original dent has a width of 0.3 mm and a depth of 18 μm. The vertical axis in these plots was chosen to represent the slope and not the physically more appealing dent depth. Plotting the results in a life versus dent depth graph causes all the lines to intersect, and thereby

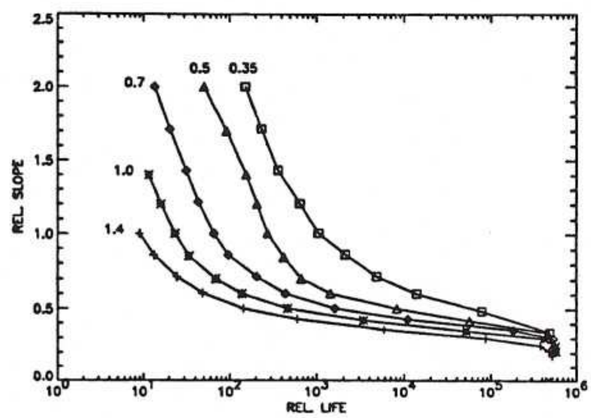

Figure 7 *Life reduction caused by dents as a function of the relative slope* (f_Z/f_X) *for different values of* f_X, $p_h = 2.5$ *GPa*, $b = 0.25$ *mm, smooth contact life is* $0.4802\ 10^6$.

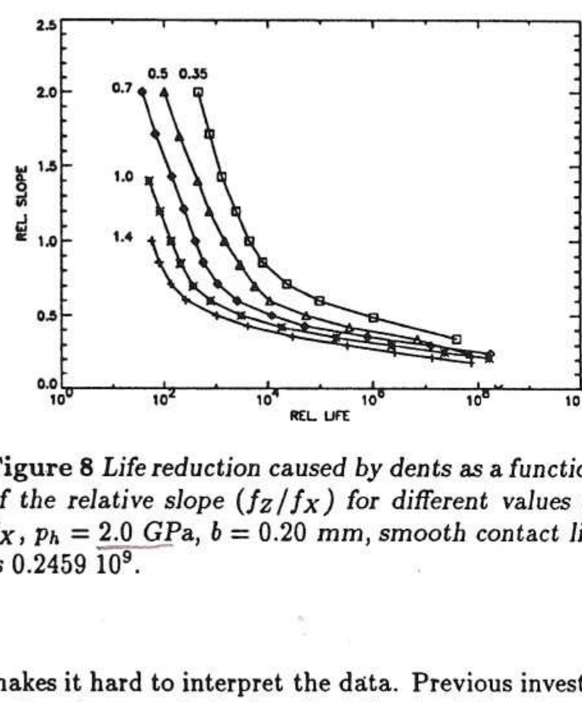

Figure 8 *Life reduction caused by dents as a function of the relative slope* (f_Z/f_X) *for different values of* f_X, $p_h = 2.0$ *GPa*, $b = 0.20$ *mm, smooth contact life is* $0.2459\ 10^9$.

makes it hard to interpret the data. Previous investigations have made it clear that the dent slope is one of the most important parameters determining the reduction in life. The results displayed in figures 6, 7 and 8 relate to contact life. Whenever the inner ring life is desired, the dented and smooth risks should be added according to the ratio of dented versus smooth area. Note the different scales on the life axis in the graphs. A number of conclusions can be drawn from the figures. First of all, the influence of small dents on contact life is considerably smaller than in the (extended) line contact calculations, which was the main reason for carrying out this analysis, especially in the 3 GPa case (figure 6). Secondly, for low loads (low pressure) even these small dents cause a considerable decrease in life. This implies that when the benefits of long life are sought by using low loads, the level of cleanliness in the application has to be high, and in general handling and mounting has to be performed carefully to avoid damage.

9 DISCUSSION OF THE POINT CONTACT RESULTS

The results presented in the point contact section cannot be interpreted as being generally valid. The results only apply to this particular choice of contact size, ellipticity ratio, pressure level and fatigue limit, and cannot be extrapolated to other types of contacts. Superimposed on these influences, the surface roughness left by the manufacturing process will affect contact performance in a certain manner. This influence can be neglected in the present analysis. As is obvious from the results of the previous section, the load (contact size and contact pressure) has a considerable effect on both the expected contact life and the expected life reduction due to indentations. For very high loads even relatively large indentations will hardly affect the performance, but for lightly loaded (long life) applications even a small indentation can significantly reduce the performance. As was argued before, it is not possible to give quantitative values for the life and life reduction without performing a specific calculation for the required contact load, size and ellipticity and indentation geometry and size.

10 RESIDUAL STRESSES

In this section, the influence of the residual stress field from the indentation process described in section 3, figures 2b and 2c, is studied. The effects on life from the geometry of the indentation and the residual stress field are studied separately. This work is an extension of the line contact work presented in [2] and the notation used is similar.

Table 3 *Influence of the created dent on contact life including the residual stress field, for three load cases. Case 1: $p_h = 3.0$ GPa, $b = 0.3$ mm, case 2: $p_h = 2.5$ GPa, $b = 0.25$ mm, case 3: $p_h = 2.0$ GPa, $b = 0.2$ mm.*

case	L_s	L_d	L_r	$L_{r,d}$
1	$0.85\ 10^4$	$0.67\ 10^1$	$0.14\ 10^2$	$0.81\ 10^1$
2	$0.48\ 10^6$	$0.23\ 10^2$	$0.12\ 10^3$	$0.38\ 10^2$
3	$0.25\ 10^9$	$0.14\ 10^3$	$0.17\ 10^4$	$0.23\ 10^3$

As in [2] where the influence of the residual stresses on the contact life was relatively benign, the influence of the residual stresses in the point contact case is also relatively small (see table 3). However, it is required to model the squashing of debris particles more accurately than is done by the simple indentor model described in this work. Also, it will become necessary to model the squashing of different size particles in order to obtain the correct dent geometries and residual stress fields, and coarse approximations through scaling as used in this work should be refined. Another feature that needs to be incorporated into such an extended study is the original (compressive) residual stress left in the material by the manufacturing process. This stress field and its interaction with the residual stresses from the indentation process is expected to have a significant effect on contact life. Only after such refinements may more definite conclusions regarding the influence of residual stresses around an indentation be drawn.

11 CONCLUSION

The current investigation was aimed at creating a model to predict the reduction in life caused by indentations in highly loaded contacts. As was discussed extensively, neither a line contact nor an extended line contact can achieve this goal, mainly because of the overestimation of the risk of fatigue of small indents. The difference between the line and point contact model is related to the maximum pressure, and can be explained from the constant load condition and the different geometry. The point contact calculation does achieve a more realistic risk prediction, also for small indentations. The main disadvantage lies in the amount of computing time required for a single calculation. The computer restrictions cause the risk of small dents to be underestimated, but an analysis of this error shows that it is not too large. The influence of large dents is underestimated for another reason: they lie partially outside the (high pressure region of) the Hertzian contact. A qualitative analysis has been performed which shows this behaviour but a quantitative measure cannot be given for the moment. In line with earlier results obtained for the line contact analysis, the influence of the residual stresses from the denting operation has only a small effect on life.

The results of this and other work will be combined to further (quantitatively) understand the damaging influence of indentations on rolling contact performance. A necessary extension of the present work involves the correct description of the dent creation process, modelling the squashing of debris particles more accurately to obtain the actual residual stress fields. Thus it will provide a thorough theoretical foundation for the investigation of the damaging effect which contaminated lubricants and handling damage have on rolling contact performance.

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