ICMA 2021

1st International Conference on Micromachines and Applications

15–30 APRIL 2021 | ONLINE

micromachines MDPI

The internal cracks influence on the stress behavior of Al_2O_3 tribo-mechanical system under contact pressures

Corina Bîrleanu[1,*], Marius Pustan[1], and Florina Șerdean[1]

[1] Departament of Mechanical Systems Engineering, Micro and Nano Systems Laboratory, Technical University of Cluj-Napoca, Blv. Muncii 103-105, Cluj-Napoca, Romania

* Corresponding author: Corina.Barleanu@omt.utcluj.ro

MiNaS Micro-Nano Systems Laboratory

TECHNICAL UNIVERSITY OF CLUJ-NAPOCA, ROMANIA

Abstract:

This paper is based on the behavior of alumina ceramics in terms of stress and strain in the contact area and the tribological behavior of these materials. A mathematical concept of fracture the ceramic materials in which there are defects in the form of internal cracks has been developed.

A defect criterion has been formulated to allow the evaluation of the propagation of the semicircular crack which shapes the places where there are natural defects in the ceramic mass.

The model highlighted is the contact between two curved surfaces, specific to the ball-ring contact in the bearings. It has highlighted tensions stress and the stress factors, taking into account the coefficient of conformability and the influence of the friction effects. A large number of experimental tests were performed based on couple ball - bearing ring.

Key words: alumina; internal crack; stress , SIF, tribology

ICMA 2021

The internal cracks influence on the stress behavior of Al_2O_3 tribo-mechanical system under contact pressures

Outlines:

1. **Scope of paper**
2. **Theoretical aspects**
3. **Experimental characterizations**
4. **Results and discussions**
5. **Conclusions**

ICMA 2021

The scope of the research work:

- The main goal of the conducted research is to establish the quantitative connection between external forces, part geometry, including defect dimensions and ceramic material characteristics.
- Particularly, the customization of the concepts from fracture mechanics on a continuous ceramic medium in order to analyze the behavior at tribomechanical stresses of a ceramic bearing

ICMA 2021

Why alumina ceramic bearing?

Alumina ceramic is a kind of structural ceramics, with insulation resistance, voltage resistance, corrosion resistance, lower density, higher hardness, higher compressive strength, longer fatigue life, stable electrical performance characteristics.

Alumina bearings features:

low density, strong solidity, low friction coefficient, abrasion resistance, magnetic resistance, acid and alkali resistance, good resistance to wear and tear, electric insulation, self-lubrication.

Applications:

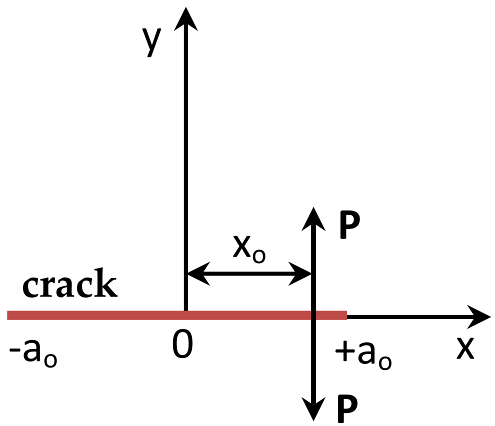
circulating pump bearings in central heating systems, washing machines and car cooling systems, food processing, vacuum applications, medical equipment, electronics applications, wet applications.

Theoretical aspects. Plane elastostatic problem of crack medium.

- the natural defect in the volume of technical ceramics is shaped in the form of a sphere, ellipsoid or a flat crack
- the cracks are defects with maximum severity, the stress estimates have a covering character
- **estimation** - relationship between the intensity of the stress, the geometry of the body and the defect and the stress intensity factor (SIF)

ICMA 2021

Stress intensity factor (SIF)



Irwin approximation

$$K_I = \frac{P}{\sqrt{\pi \cdot a_o}} \cdot \sqrt{\frac{a_o + x_o}{a_o - x_o}} = \frac{P}{\sqrt{\pi \cdot a_o}} \cdot G(x_o)$$

G(x$_o$) – Green function for SIF calculus for any normal distribution of forces on the flanks of crack

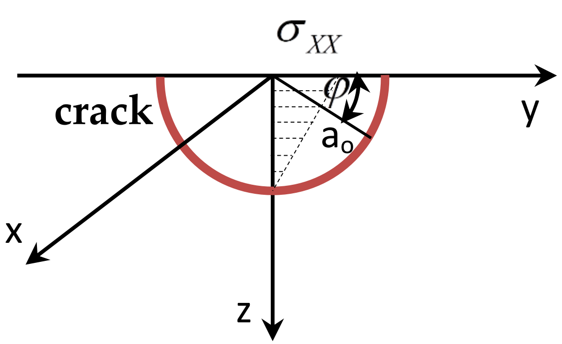
$$K_I = \frac{1}{\sqrt{\pi \cdot a_o}} \int_{-a_o}^{+a_0} p(x) \cdot G(x)\, dx$$

the validity of the Irwin approximation is for:

$$\frac{x_o}{a_o} = 0{,}1$$

ICMA 2021

Stress intensity factor (SIF) – semicircular crack



shapes the natural defect in the ceramic mass

constant normal stress: $\sigma_{xx}(z) = \sigma_K$

$$K_I^K(\varphi) = \frac{2}{\pi} \cdot \sigma_K \cdot \sqrt{\pi \cdot a_o} \cdot F_K(\varphi)$$

$$F_K(\varphi) = 1,211 - 0,186\sqrt{\sin\varphi}$$

variable normal stress: $\sigma_{xx}(z) = \sigma_I \left(1 - \frac{z}{a_o}\right)$

$$K_I^I(\varphi) = \frac{2}{\pi} \cdot \sigma_I \cdot \sqrt{\pi \cdot a_o} \cdot F_I(\varphi)$$

$$F_I(\varphi) = 1,031 - 0,186\sqrt{\sin\varphi} - 0,54\sin\varphi$$

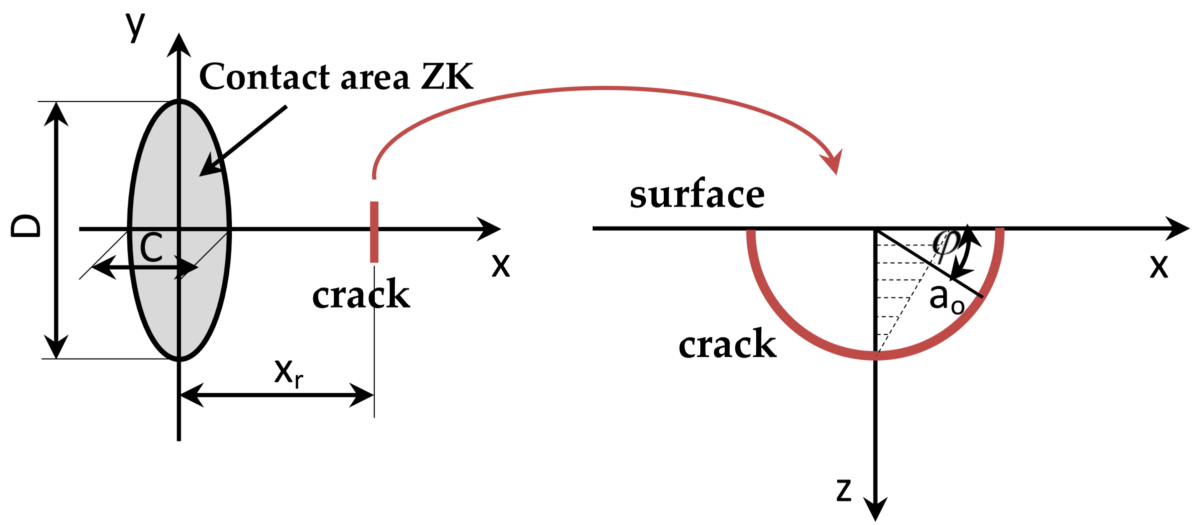
overlapping effects (stress): $\sigma_{xx}(z) = \sigma_K + \sigma_I z$

$$K_I(\varphi) = K_I^K + K_I^I(\varphi)$$

$$K_I^{mediu} = \frac{2}{\pi} \int_0^{\frac{\pi}{2}} \left[K_I^K(\varphi) + K_I^I(\varphi) \right] d\varphi$$

ICMA 2021

Modeling the defects distribution in technical ceramic mass

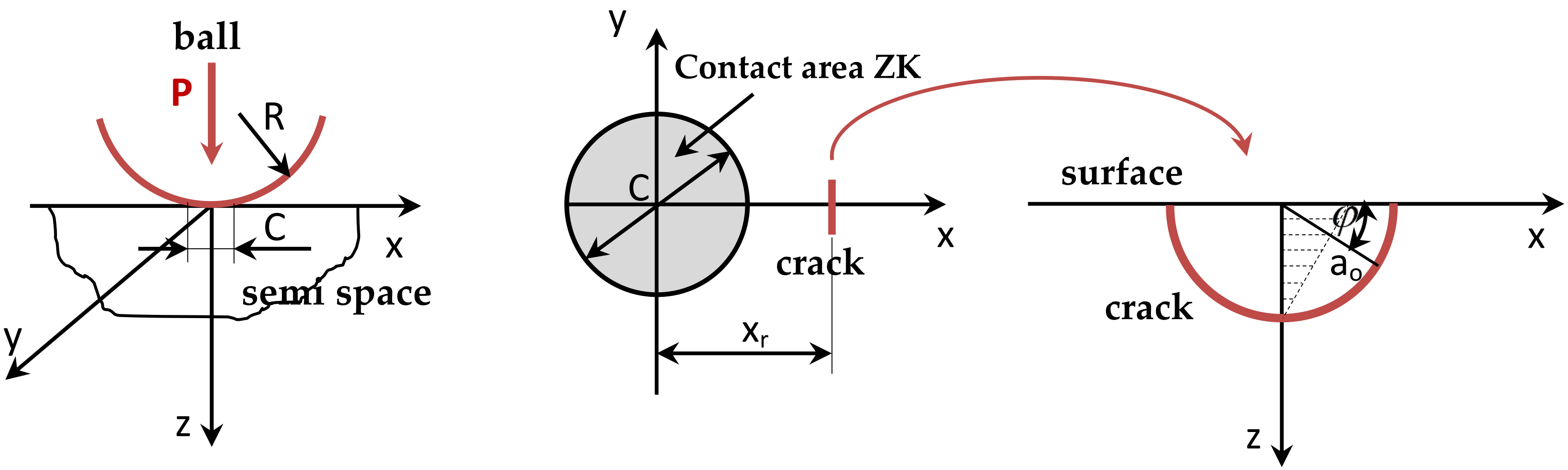


Normal and tangetial stress: $\sigma_{xx}(x_r, 0, z)$ *and* $\tau_{xz}(x_r, 0, z)$

$$\sigma_{ij}(x_o, y_o, z_o) = \int_{ZK} \left[\sigma(x,y) \cdot G_{ij}^{P}(x,y,x_o,y_o,z_o) + \tau(x,y) \cdot G_{ij}^{Q}(x,y,x_o,y_o,z_o)\right] dxdy$$

$$i, j = x, y, z \quad P = normal\ \ force, \quad Q = tangential\ \ force$$

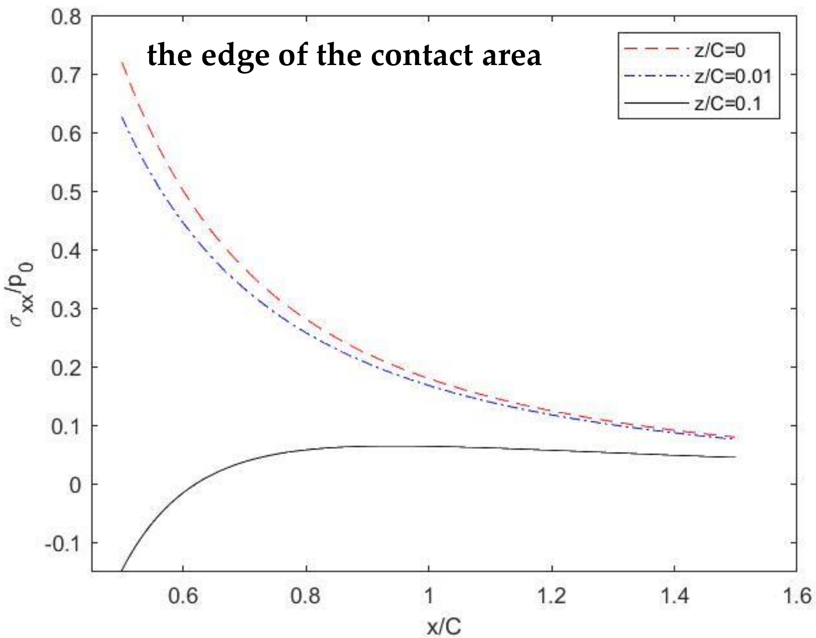
Static contact ball- plate



$$\frac{\sigma_{xx}}{p_o}=\frac{1}{3\cdot\left(\frac{x}{C}\right)^2}\left[(1-2\nu)\cdot\left(1-\frac{\frac{z}{C}}{\sqrt{\left(\frac{x}{C}\right)^2+\left(\frac{z}{C}\right)^2}}\right)-\frac{3\cdot\frac{z}{C}\cdot\left(\frac{x}{C}\right)^4}{\left(\sqrt{\left(\frac{x}{C}\right)^2+\left(\frac{z}{C}\right)^2}\right)^5}\right]$$

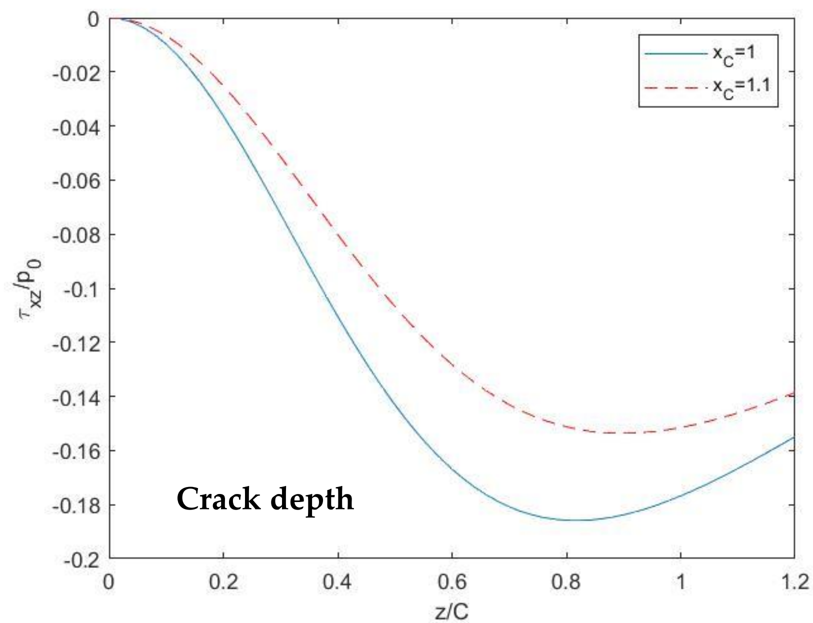
For alumina Al_2O_3, E =380 GPa, ν=0,23, $\frac{x}{C}=(1,2)$ *and* $\frac{z}{C}=0;\ 0,1;\ 0,01$ from literature

Normal stress area in Al_2O_3 semi space



Tangential stress area in alumina Al_2O_3 semi space

$$\frac{\tau_{xz}}{p_o} = \frac{1}{\left(\frac{x}{C}\right)^2} \cdot \frac{\left(\frac{z}{C}\right)^2 \cdot \left(\frac{x}{C}\right)^3}{\left(\sqrt{\left(\frac{x}{C}\right)^2 + \left(\frac{z}{C}\right)^2}\right)^5} \qquad \frac{z}{C} = (0,1) \; and \; \frac{x}{C} = 1;1{,}1$$



Stress intensity factor (SIF) in Al_2O_3 semi space

based on the relationships presented before for $\varphi = 0^o, have\ z = 0, y = a_o, x = x_r$

$$K_I = \frac{P\cdot(1-2\nu)}{\pi^2 C^2}\sqrt{\pi\cdot a_o}\left[C_1(\varphi)+C_2(\varphi)\right]\frac{\left(\frac{x}{C}\right)^2-\left(\frac{a_o}{C}\right)^2}{\left[\left(\frac{x}{C}\right)^2+\left(\frac{a_o}{C}\right)^2\right]^2}$$

$for\ \varphi = 90^o, have\ z = \frac{a_o}{2}, y = 0, x = x_r$

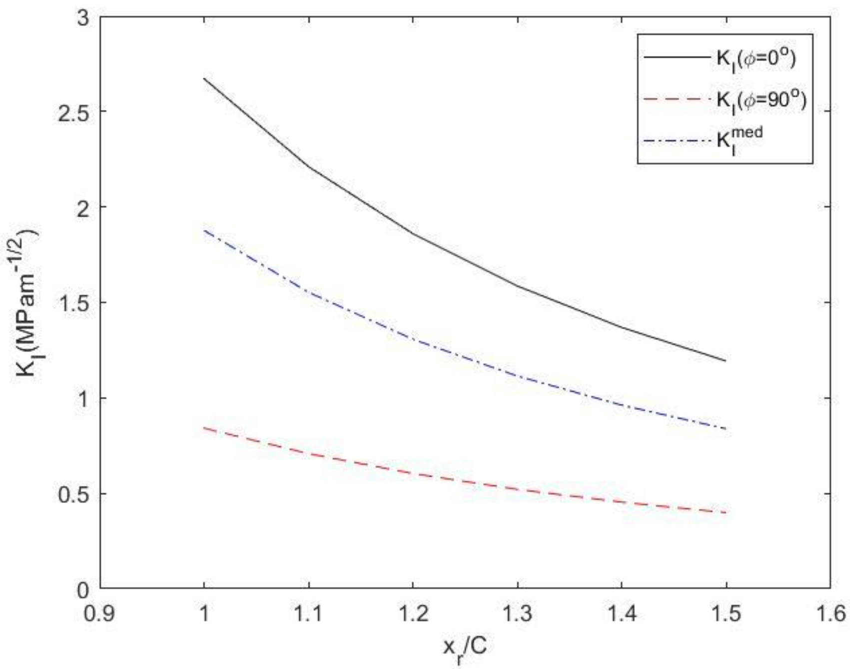
$$K_I = \frac{P\cdot\sqrt{\pi\cdot a_o}}{\pi}\left[C_1(\varphi)+C_2(\varphi)\right]\left\{\frac{1}{C^2}\cdot\frac{1-2\nu}{\left(\frac{x}{C}\right)^2}\left[1-\frac{\frac{a_o}{2C}}{\sqrt{\left(\frac{x}{C}\right)^2+\left(\frac{a_o}{2C}\right)^2}}\right]-\frac{3C^2\cdot\frac{a_o}{2}\cdot\left(\frac{x}{C}\right)^2}{\left(\sqrt{\left(\frac{x}{C}\right)^2+\left(\frac{a_o}{2C}\right)^2}\right)^5\cdot C^5}\right\}$$

$for\ z = 0, y = a_o$

$$K_I^{med} = \frac{4}{\pi^2}\sqrt{\pi\cdot a_o}\left[I_1+I_2\right]\cdot\frac{P}{2\pi}\cdot(1-2\nu)\frac{\left(\frac{x}{C}\right)^2-\left(\frac{a_o}{C}\right)^2}{\left[\left(\frac{x}{C}\right)^2+\left(\frac{a_o}{C}\right)^2\right]^2}\cdot\frac{1}{C^2}$$

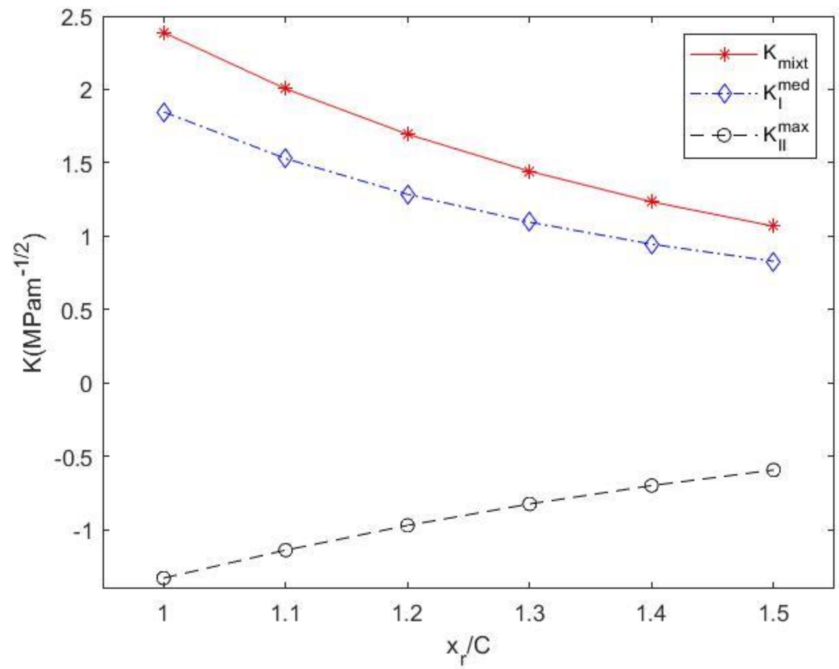
$$I_1 = 1{,}211\cdot\frac{\pi}{2}-1{,}86\int_0^{\frac{\pi}{2}}\sqrt{sin\,\varphi}\,d\varphi; \quad I_2 = 1{,}031\cdot\frac{\pi}{2}-0{,}186\int_0^{\frac{\pi}{2}}\sqrt{sin\,\varphi}\,d\varphi-0.54$$

Stress intensity factor (SIF) in Al_2O_3 semi space



R = 2,5 mm
P = 2820 N
C = 297 μm
p_o = 15,2 GPa
a_o = 15 μm

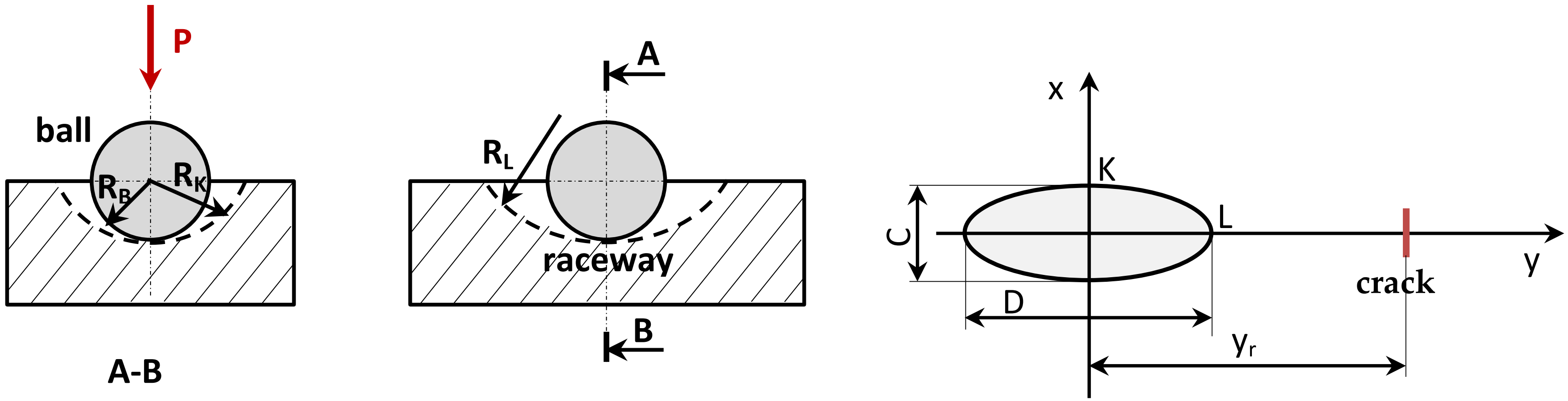
Stress intensity factor (SIF) in Al_2O_3 semi space for compound stress



R = 2,5 mm
P = 2820 N
C = 297 μm
p_o = 15,2 GPa
a_o = 15 μm

ICMA 2021

Modeling the contact between curved surfaces (contact in the bearing)



R_B – ball radius, [mm]; R_K – raceway radius, [mm]; R_L – outer ring bearing radius, [mm]; P – normal force, [N]

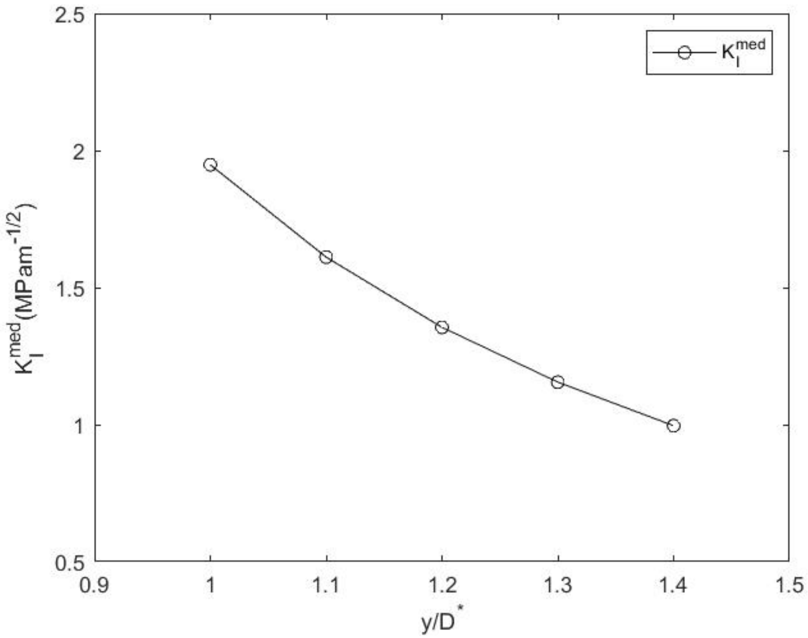
Assumptions:

- to use Hertz's method in the contact situation of curved surfaces in the same direction, the accuracy of the solution depends on the analytical description of h.
- h - distance on the z axis between the two bodies in contact
- for small contact areas compared to the radii of curvature it was determined that the considered error is ~7%
- the basic parameter in the design of the bearings is the conformability coefficient $S = \frac{R_K}{R_B}$
- In this work, $R_L = 10 \cdot R_B$

ICMA 2021

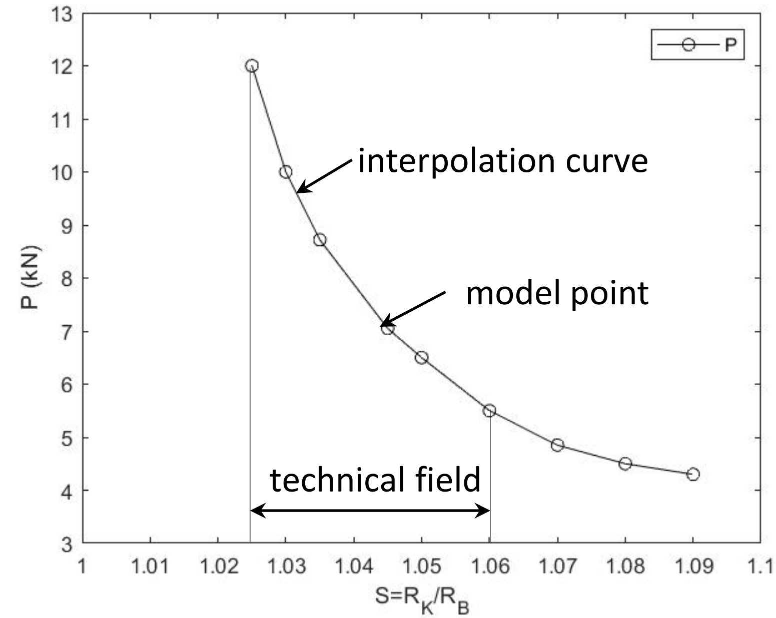
Stress intensity factor (SIF) depending on $\frac{y_r}{D^*}$

D^* - semi major axis of elliptical contact area



$R_K = 3{,}17$ mm
$R_B = 3{,}336$ mm
$R_L = 23$ mm
$P = 9000$ N
$a_o = 15$ μm

$$\frac{y_r}{D^*} = (1;1{,}1;1{,}2;1{,}3;1{,}4)$$

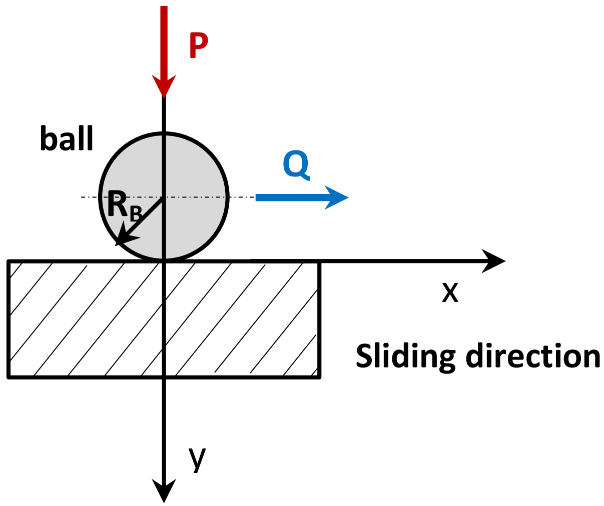


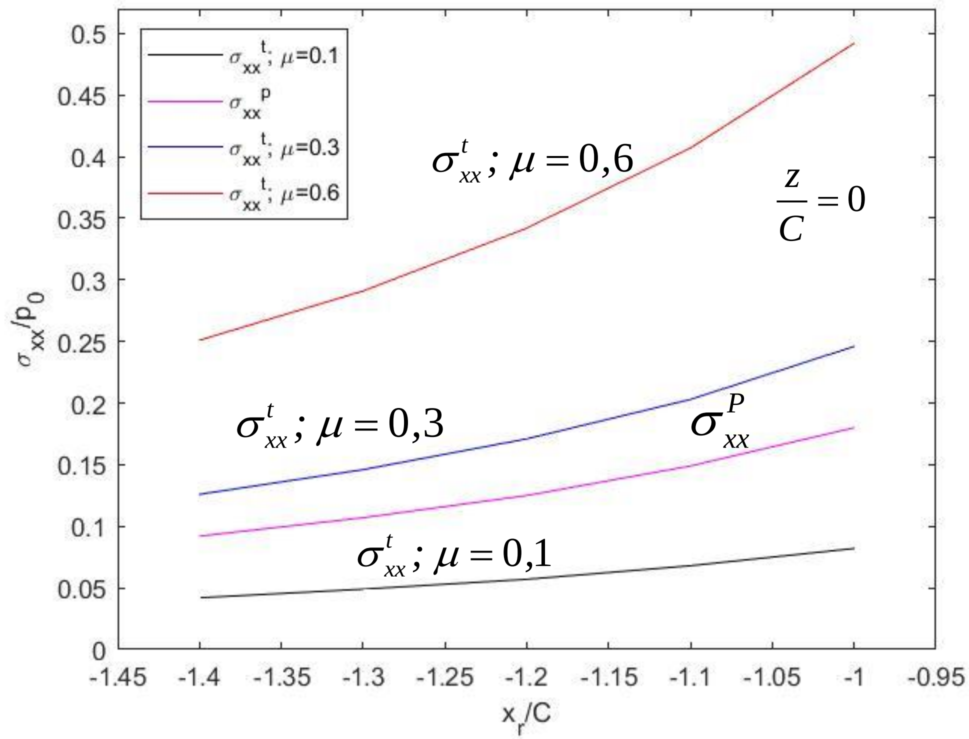
Variation of P depending on conformability coefficient *S* to achieve a value for

$$K_I^{med} = 2\ MPam^{-1/2}$$

If in the ball plate system we also consider the presence of the sliding contact given by a force Q = μ·P, μ - friction coefficient, the total stress will be the sum between the normal and the tangential one :

$$\sigma_{inner}^{total} = \sigma_{xx}^{P} + \sigma_{xx}^{t} \text{ and } \sigma_{xx}^{t} \text{- based on tangential stress}$$

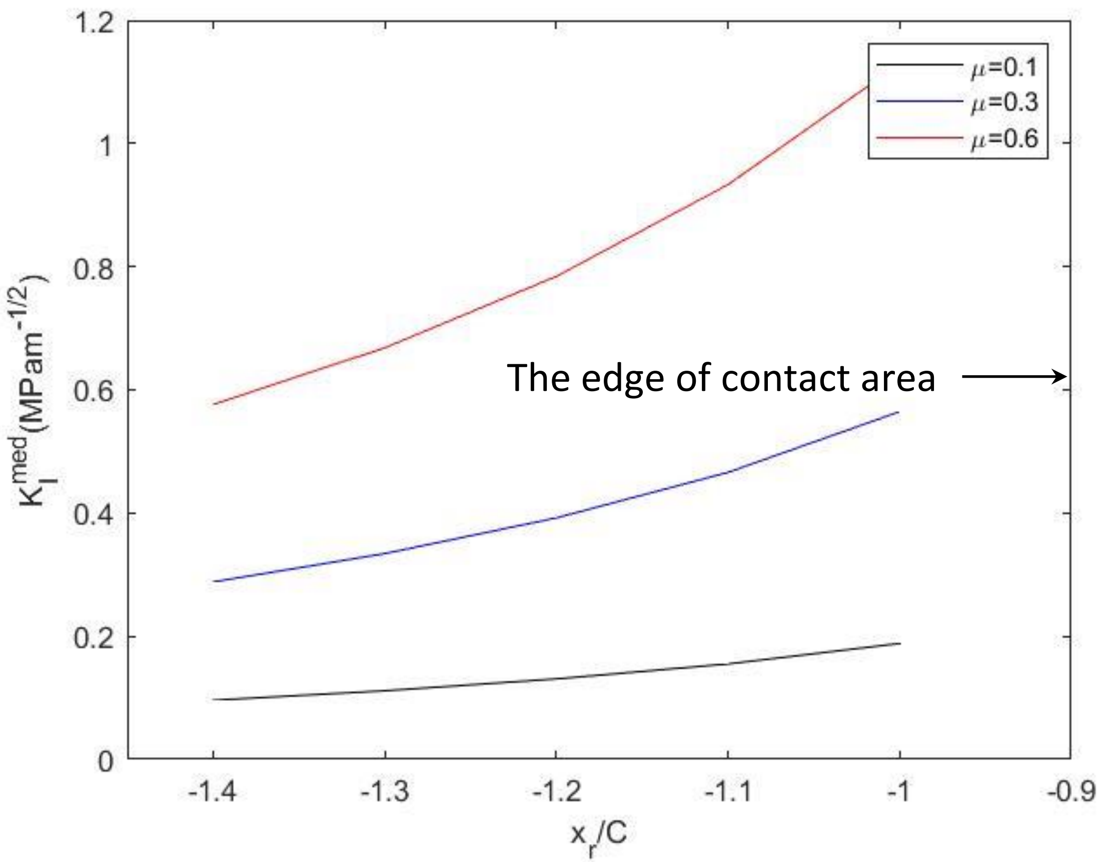




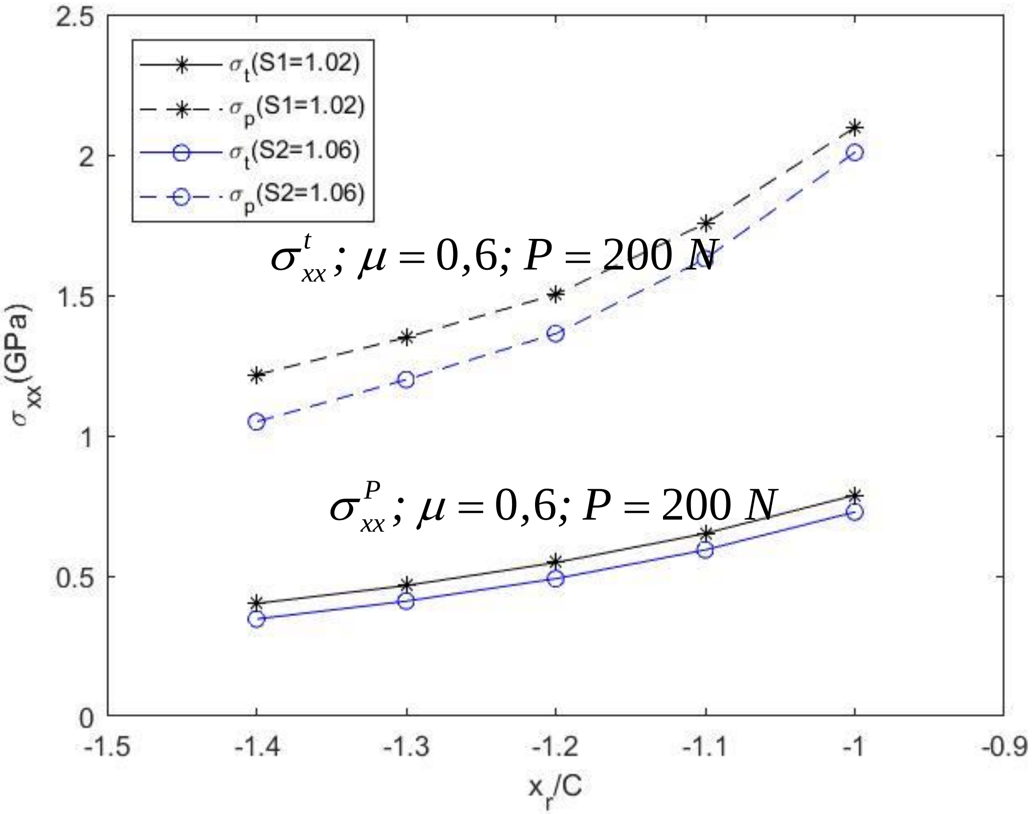
Specification: all values for the friction coefficients were determined experimentally on the Three Pins tribometer for the coupling of alumina / alumina material in dry friction conditions, in water and in mineral oil.

ICMA 2021

In the situation where the surface crack develops in depth under the influence of the presence of the sliding force and different friction conditions, K_I^{med} is represented in the figure below.



Taking into account the overlapping effects and the influence of the conformability coefficient *S* in micro-slip conditions, the results are presented in the graph below



Results and Discussion

- the theoretical and practical approach of the complete ceramic bearing is complex and interdisciplinary
- the mechanical stresses in the contact area are higher especially in the lack of lubrication, which justifies the application of ceramic bearings compared to metal ones
- the individual contact problems of the ceramic media with cracks were approached and a mathematical concept of breaking was developed for them
- the types of stress and the stress intensity factors were determined in the assumption of the elastic behavior of the ceramic body before breaking
- it went from linear crack to semi-circular crack that shapes the places with natural defects in the ceramic mass
- the contact between two curved surfaces characteristic of the ball - bearing ring contact was modeled

- the stress field and the stress intensity factors were studied on this model, taking into account the conformability coefficient and the fact that we cannot eliminate the influence of friction effects.
- from a tribological point of view, the friction coefficients on the three-pins tribometer were determined in different states of dry lubrication, water and mineral oil.

Conclusions

- over 30 tests were performed for each case in order to establish the formation of cracks depending on the normal force applied
- 99.7% alumina balls with diameters between 4.5 mm and 12.7 mm were used and ceramic rings were made to ensure a coefficient of conformability of 1.02 and 1.06.
- the paper will be extended by verifying the experimental results as well as the model proposed by finite element method
- from a tribological point of view, the experimental study will be extended by determining the wear on the Amsler tribometer and highlighting the traces of wear by SEM images.

ICMA 2021