ANALYSIS OF STRESS DISTRIBUTION IN COATED SUSBSTRATE SUBJECT TO CONTACT LOAD

Duarte E. N.
Universidade Federal de Uberlândia
ecioduarte@bol.com.br

Oliveira S. A. G.
Universidade Federal de Uberlândia
sgoulart@mecanica.ufu.br

Araujo C. A.
Universidade Federal de Uberlândia
cleudmar@mecanica.ufu.br

Abstract. To coat mechanical components, that will be subjected to contact load, has been a procedure aiming the reduction of the wearing in the substrate. However, these components can fail, generally, by: excessive plastic flow, fracture, or delamination of the coat from its substrate. In this work, perfect interface between layer and substrate was considered. It has been done a two-dimensional analysis, using finite element method, of the stress distribution arising when a plane coated body is subjected to a contact load by an elastic cylindrical indenter. Normal and tangential have been considered. Both, substrate and indenter were made of steel. Three different types of material were used as a coating: brass, ceramic and steel. The last one was used for validation. The results were used to investigate the influence of layer thickness in field stress, properties of the coating materials and the friction coefficient that acts between the indenter and coating. The results showed that there is an optimum thickness when the substrate is coated with ceramic. In this case, the substrate is more protected by the layer.

1. Introduction

The use of coatings on mechanical components to improve their performance has increased the interest in the study of this kind of problems. From disc drives in computer industry to human replacement organs, its applications has became very useful due to the new techniques developed over the last twenty years. Particularly, chemical vapour deposition (CVD) and physical vapour deposition (PVD), have made possible a control of parameters such as layer thickness and friction coefficient never seen before, Holmberg et al. (2002).

Some attempts to find the suitable method to study this problem have been proceeded. Matzbender and de With (1999, 2000a) performed an analysis about indentation and residual stresses. Oliveira and Bower (1996) have published an analysis of fracture and delamination in elastic thin coatings by an elastic cylindrical indenter. In the current work a finite element method was used to study this problem, considering normal and tangential forces and using three different materials as a coating: brass, ceramic and steel.

The aim of this paper is to use a computer model to calculate the stress distribution and to study the influence of material properties of the coating, friction coefficients and the layer thickness in elastic half-space (substrate) covered with a thin coating and subjected to a contact load applied by an elastic cylindrical indenter. Coulomb friction between the layer and the cylinder and a perfect interface between the layer and the substrate were assumed.

2. The finite element model

Figure 1 shows a schematic drawing of the problem that will be dealt with as well as the coordinate system. E_i and ν_i are the elastic constant of the materials. R is the radius of the indenter, h the thickness of the coating and a is the semi-width of contact between the cylinder and the coated solid. $p(x)$ and $q(x)$ are respectively the normal and tangential tractions distribution acting on the surface area.

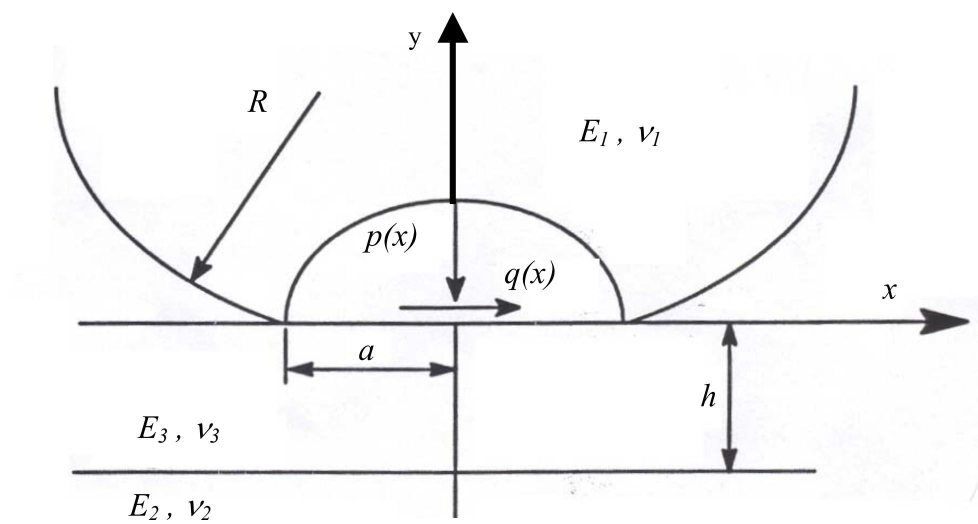

Figure 1 : Schematic presentation of the layered half-space subject to a contact load applied by an elastic cylindrical indenter. The indexes in Figure 1 above are: 1 for indenter, 2 for substrate and 3 for coating.

A bidimensional finite element model was used to calculate the first principal stresses that can be associated with the brittle type of failure and the von Mises equivalent stress associated with the beginning of plastic deformation. After analyzing the suitable mesh density in the neighborhood of the contact area, the model was discretized using a structured finite element mesh. In this area the elements size used were around 1/16 of the coating thickness. Figure 2 shows a detail of the mesh. PLANE 42 was used as a structural element and CONTA 172 and TARGE 169 were used as contact pair in ANSYS® 6.0. The area of the finite element model taken to describe the configuration of plane was 15x25 mm.

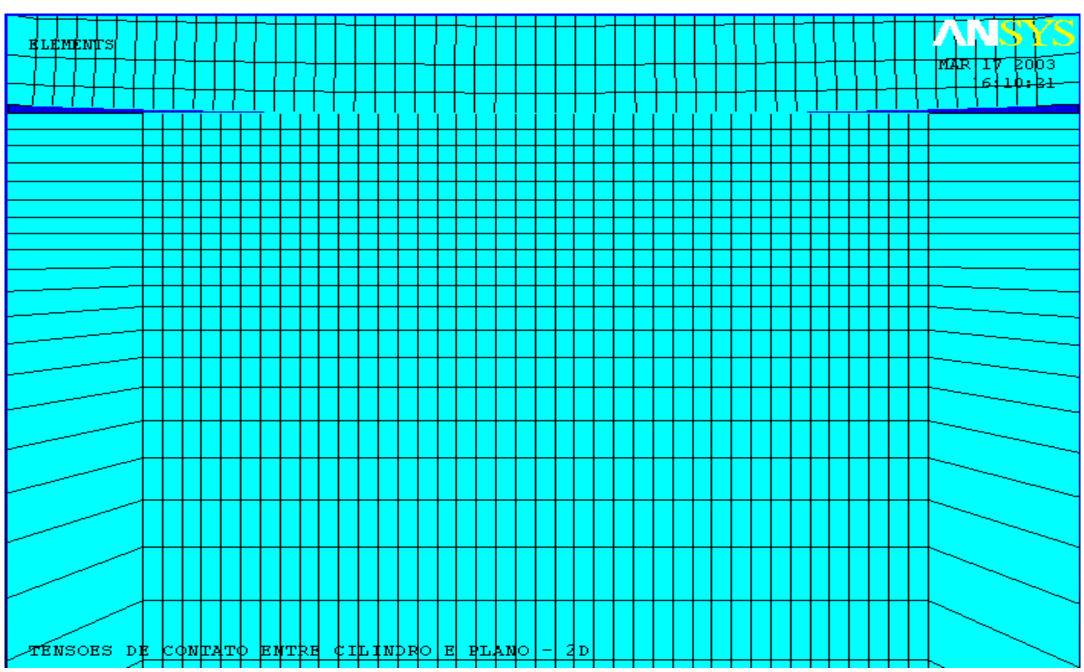

Figure 2 – Suitable mesh density around the contact area.

To simulate the contact conditions, some parameters were used in the calculations of the stress distributions. Since elastic behavior was assumed at all parts, the calculation was done using three load steps. In the first one, a control of motion of the target surface was performed, giving a very small displacement about 0.0005 mm, in order to avoid rigid body motion, during the contact analysis. It was solved and saved. In the second one, after deleting de small displacement given in the y axis, from the first load step, a 100 N normal load was applied on the highest point of the cylindrical indenter. It was solved and saved. In the last and the third one, the tangential force was applied at the same point. It was solved and saved again.

3. Parameters of the analysis

The analysis was done for seven different values of tangential force to simulate a change in the friction coefficient. The values used were: zero, 5 N, 10 N, 20 N, 30 N, 40 N and 50 N. In order to avoid rolling, a friction coefficient equal to 0.6 was used in the finite element code. The cylindrical indenter had 5mm radius, the material was steel, and we used three different layer materials: SIC, Brass and steel. The last one was done to better analyze the influence of the coatings and also for validation of the model.

Keeping the same tangential force (friction coefficient), in order to study the influence of the thickness of the layer, the problem was solved for seven different layer thicknesses: 0.032, 0.064, 0.096, 0.128, 0.160, 0.192 and 0.224 mm. Table 1 shows the mechanical properties assumed for the used materials.

Table 1: Mechanical properties for the used materials

Material	Poisson ratio (ν)	Young Modulus(E)
Steel	0.3	210 GPa
SiC	0.2	450 GPa
Brass	0.35	111 GPa

4. The Model validation

Some attempts to perform a suitable method to describe the stress field of thin hard coatings have been reported. And, the one of Oliveira and Bower (1996), was used to validate the current work.

In the Figure 3, the stresses σ_x and σ_y were mapped onto the OY axis shown in the y axis (see fig. 1), trough all the thickness of the layer, using the finite element model and the analytical solution by Oliveira and Bower(1996). This results are for a half-space covered with h/a=0.8127 for steel and $\mu = 0$.

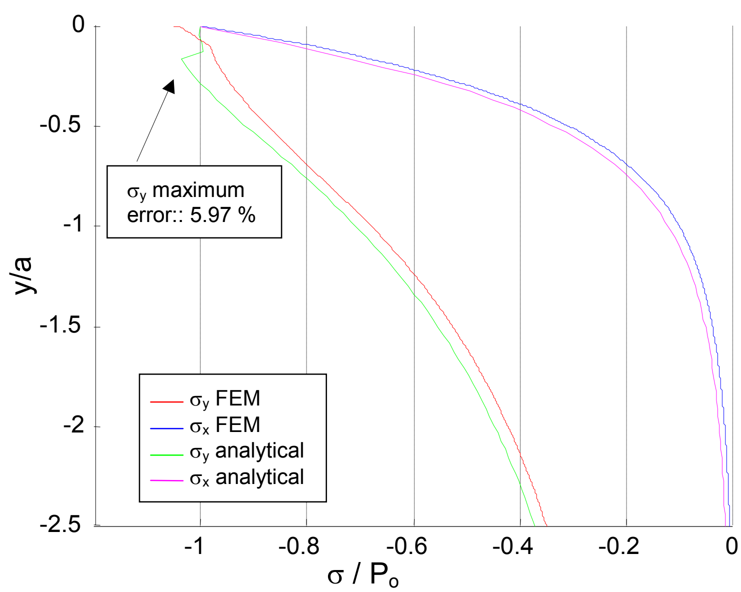

Figure 3: Stresses σ_x and σ_y in OY, using FEM and Oliveira and Bower (1996).

5. Results and discussion

5.1 The Influence of material properties in the field stress

The simulated first principal stress (σ_1) distribution in the contact surface are shown in Figure 4. These results of (σ_1/P_0) are for a normal force equal to 100 N and zero tangential force.

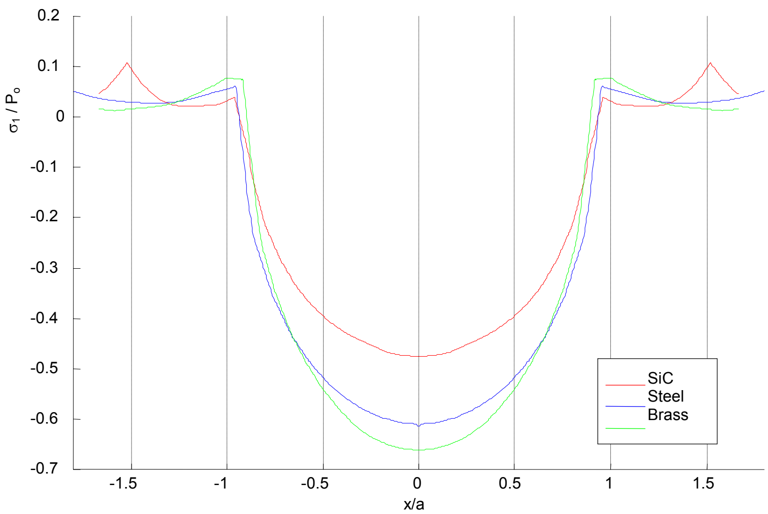

Figure 4 – First principal stress (σ_1) in the contact surface, using finite element model.

According to the results in figure 4, there is $\sigma_1 > 0$ for | x/a | = 1.5, when only compression force is applied by the cylindrical indenter. In terms of strain, the same behaviour was verified. This tribological behaviour has been investigated for some materials by Pintaúde (2002) and named "pilin-up". But, this term was used, for the first time, by Norbury and Samuel (1928) to name Brinnel hardness morfologies. It was verified that the values of σ_1 , in the region far from the indentation, goes to zero.

In Figure 5 a Vickers hardness impression by laser interferometry is shown. This empirical observation is mainly, according to results, for ceramic coatings. This suggests that the phenomenon depends on material properties.

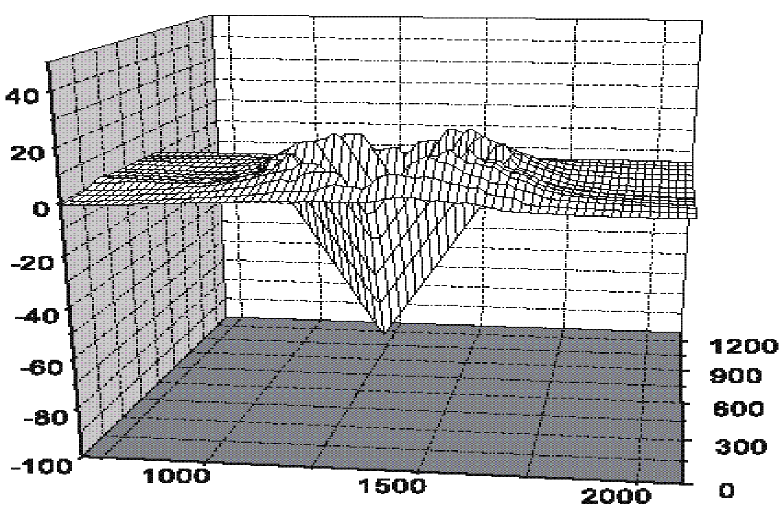

Figure 5 – Piling-up, according Pintaúde, G. (2002), for AISI 52100 steel, in Vickers hardness impression.

5.2 The Influence of layer thickness in the field stress

Figures 6 and 7 show the variation of the maximum values of the von Mises equivalent stresses (σ_{eqv}) and first principal stresses (σ_1) with the thickness of the coating (h/a), where a is the 0.07875mm to steel, 0.08625 mm to brass and 0.0720 to SiC). These results are for a constant value of friction coefficient, $\mu = 0.2$.

According Figure 6, for the brass coating, the values of von Mises equivalent stress are almost constant up to a thickness of h/a=1.39, and increases rapidly after that. Since in this case the mechanism of failure would be plastic deformation in the layer or substrate, the thickness of the layer needs to be chosen with care.

And, according to Figure 7, for the same value of h/a occurs the minimum value for σ_1 , for the SiC layer. In this case, the mechanism of failure in the layer could be brittle fracture and the value of the maximum traction stress is the one of interest.

Hence, for the cases analyzed, we can assume that there is an optimum thickness of coating that can better protect the component.

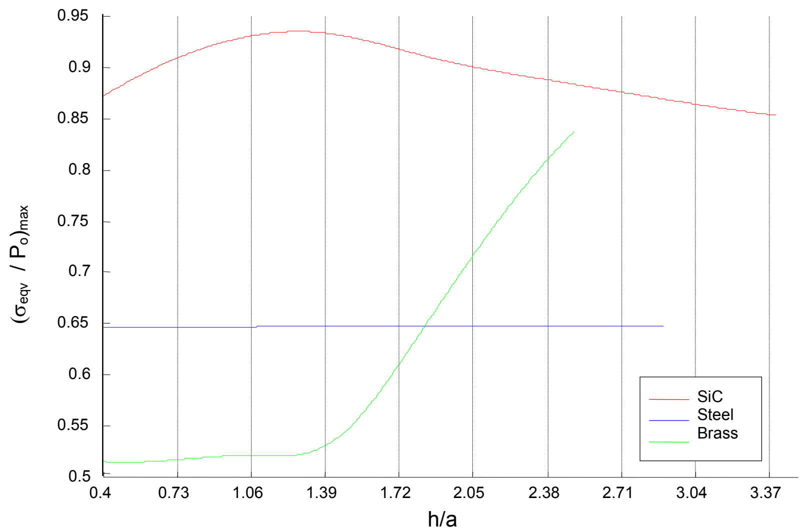

Figure 6 – Variation of the maximum values of von Mises equivalent stresses with thickness, for a constant value of $\mu = 0.2$.

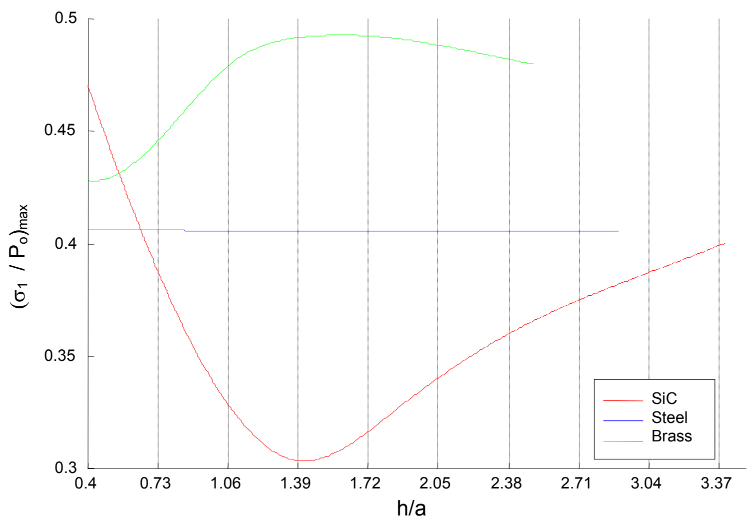

Figure 7 – Variation to the maximum values of first principal stress σ_1 with thickness, for a constant value of $\mu = 0.2$.

5.3 The influence in the field stress from friction coefficient

Figures 8 and 9 show the variation of the maximum values of the von Mises equivalent stresses (σ_{eqv}) and first principal stresses (σ_1) with the friction coefficient (μ), for a constant value of h/a = 0.8889 for SiC, 0.7420 for brass and 0.8127 for steel.

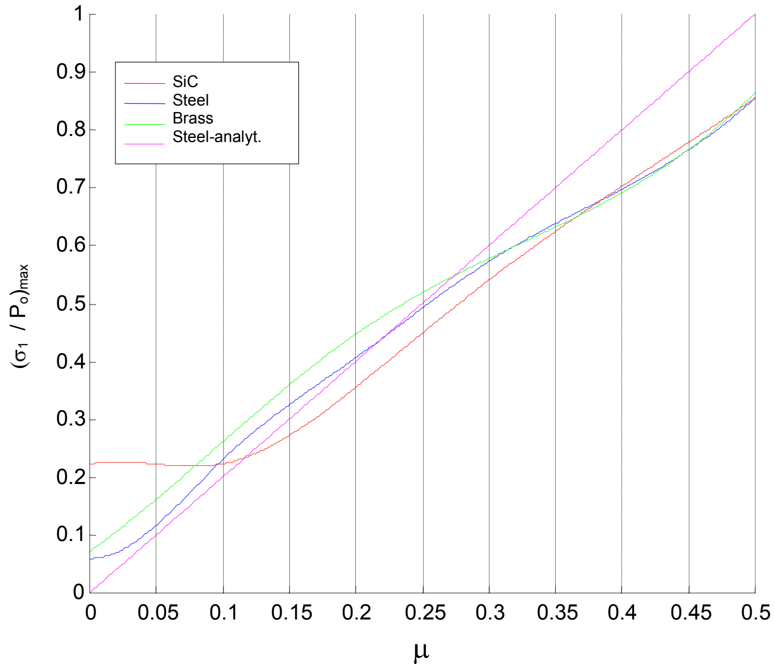

Figure 8 – Variation to the maximum values of first principal stress σ_1 with μ, for h/a constant.

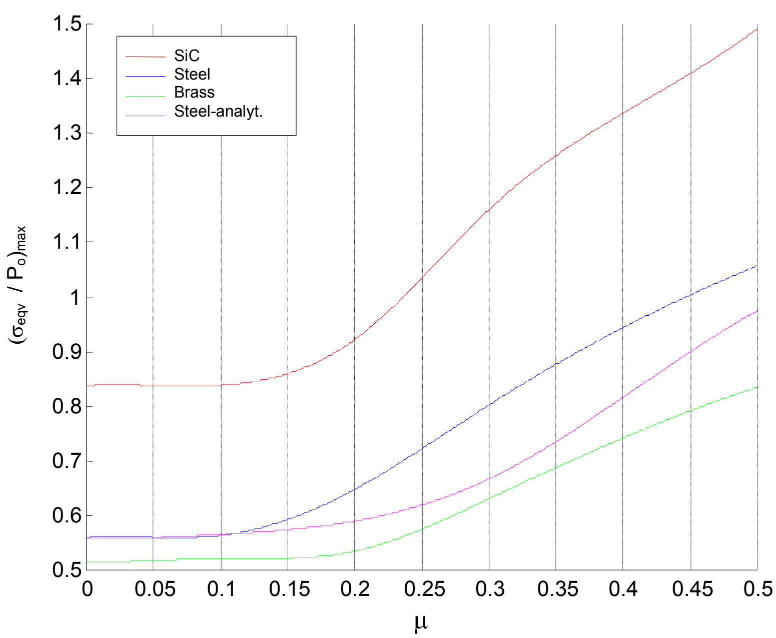

Figure 9 – Variation of the maximum values of von Mises equivalent stresses with μ, for h/a constant.

According Figure 8, for SiC with h/a = 0.8889, the first principal stress σ_1 increases significantly after μ= 0.15. Before this value, there are no sensitive changes in the value of σ_1. The highests values of σ_1 for SiC, when $\mu = 0.2$, always occur at the same region: contact surface. When the layer thickness is 0.064 mm, for values of μ between 0 and 0.50, the highest value of σ_1 for SiC occurs at the contact surface or at the interface between layer and substrate. For the other materials, the value of σ_1 increases almost linearly with friction. In this case, for $0.15 < \mu < 0.30$, the results for the first principal stress σ_1 increase linearly, for all coatings.

As can be seen in Figure 9, only after $\mu = 0.15$, the von Mises equivalent stresses begin to increase. Hence, for values of friction coefficient less than 0.15, there is little influence from tangential force in the von Mises equivalent stresses, for all different types of coatings and with h/a = 0.8889 for SiC and 0.7420 for brass. The highest value of von Mises equivalent stresses (σ_{eqv}) occurs at the interface between the layer and the substrate. However, it can also be observed the displacement of the peak in the σ_{eqv} into the interior of the layer when the layer thickness is increases, keeping μ constant and equal 0.2. When the layer thickness is constant and equal to 0.064 mm and the friction coefficient is increased from 0 to 0.50, the highest value of σ_{eqv} occurs at interface between the layer and the substrate or at the contact surface.

6. Conclusions

A FEM model to simulate contact load between a cylinder and a coated plane was designed and applied for different conditions. The stresses in the model were observed in the elastic region.

The validation done in the most critical region of the model shows reliable results. For this validation case, the greater discrepancy was around 6%.

When the friction coefficient is constant, the results show that we can find an optimum thickness, when the substrate is coated with ceramic. In this case, the substrate is more protected by the layer.

In the case of a substrate coated with brass, von Mises equivalent stresses have almost the same value if the layer thickness (h/a) is less than 1.39, for the specified conditions. The results show that there is an optimum thickness when the substrate is coated with ceramic. In this case, the substrate is more protected by the layer.

The influence from tangential force in the stresses field is weak, when the friction coefficient is less than 0.15 for of h/a = 0.8889 for SiC, 0.7420 for brass and 0.8127 for steel.

The maximum tensile stresses are located behind the contact at a distance of 0.5 to 1.0 times the half contact length (a) from the back edge of the contact, where the maximum value of first principal stress for the conditions studied in the current work occurs.

7. References

Holmberg, K, A. Laukkanen, H. Ronkainen, K. Wallin and S.Varjus, 2002, "Modelling Stresses and Fracture in Thin Coatings".6th International Tribology Conference – AUSTRIB '02.Perth, Australia.

Matzbender, J. and de With, G., 1999, "Sliding indentation, friction and fracture of a hybrid coating on glass", Wear, 236, 355-359.

Matzbender, J. and de With, G., 2000a, "Cracking and residual stress in hybrid coatings on float glass," Thin Solid Films, 359, 210--214.

Norbury, A L.; Samuel, T., 1928, "The recovery and sinking-in or piling-up of material in the Brinell test, and the effects of these factors on the correlation of the Brinell with certain other hardness tests", Journal of the Iron and Steel Institute, v. p. 673-87.

Oliveira, S. A G and Bower, A F., 1996, "An analysis of fracture and delamination in thin coatings subject to contact loading", Wear, 198, 15-32.

Pintaúde, G., 2002, "Análise dos regimes moderado e severo de desgaste abrasivo utilizando ensaios instrumentados de dureza". Escola politécnica da USP, Departamento de Engenharia Mecânica, São Paulo.