# Contact area and maximum equivalent stress in elastic spherical contact with thin hard coating 

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#### Abstract

A finite element analysis was used in order to investigate the elastic contact of a sphere with a thin hard coating compressed by a rigid flat. A proper normalization of the dimensional contact parameters, such as the contact area, load, interference and maximum equivalent von Mises stresses in the coating and in the substrate was used to obtain a universal model of the elastic contact. This model provides empirical relations between these contact parameters for a wide range of mechanical and geometrical properties, which are different from the classical Hertz solution for a homogeneous sphere compressed by a rigid flat. The model also introduces a new approach for calculating the limit of elasticity in the coated system. © 2015 Elsevier Ltd. All rights reserved.


## 1. Introduction

Hard coatings can enhance tribological performance of mechanical components in contact and relative sliding and are used in many applications [1,2]. In spite of their wide use the thicknesses of these coatings for best performance are still selected mainly by a trial and error approach. This is due to the lack of a universal model for predicting an optimal coating thickness that is based on a scientific theory.

A contact model for a single coated sphere provides physical insights on the coating effect and can be a first step towards modeling the contact of coated rough surfaces in the same way the Hertz model for a homogenous sphere [3] was extended in the GW [4] model for contacting surfaces.

In Refs. [5-7] the finite element method (FEM) was used to study various aspects of an elastic contact between a coated sphere and a rigid flat. Ref. [5] deals with finding the terminus of elasticity for thin hard coatings on a softer substrate. The critical parameters at yield inception and the location of the onset of plasticity were found to depend on the thickness of the coating and on the mechanical properties of the substrate and coating material. An optimal thickness that gives the highest resistance to plasticity was found and it also depended on the mechanical properties of the coated sphere. A range of coating thicknesses was found for which, the coated sphere has poor resistance to plasticity compared to uncoated sphere. This detrimental range of

[^0]thicknesses was studied and characterized in Ref. [6]. In Ref. [7] a special normalization approach was described, which enabled a universal model for the load-displacement relation in an elastic coated spherical contact as well as a definition of an effective modulus of elasticity which, unlike in previously published studies, was load independent. The present study complements Ref. [7] in that it provides the relation between the interference or load and the contact area as well as the maximum equivalent von Mises stresses in both the coating and the substrate.

The contact area in a coated spherical contact has a major influence on wear, friction, adhesion, heat and electrical conductivity etc. The intensity and distribution of the stresses in a coated spherical contact is also important in regard with possible failure modes. The effect of coating on the size of the contact area (or equivalently the contact radius) and on the stresses has been dealt with in the literature by several investigators [8-22]. However, a universal model for the relation between the contact area, maximum von Mises stresses and other contact parameters in a coated spherical contact is still missing. Moreover, the majority of the studies published in the literature concern indentation of a coated deformable flat by a rigid spherical indenter. The indentation method is used mainly to characterize mechanical properties of coatings. In the present study we are interested in the behavior of an elastically loaded coated sphere where the mechanical properties of the coating are already known. It should be noted here that, for good tribological design of coated surfaces one should avoid asperities indentation and strive for asperities flattening that is associated with mild adhesive friction and wear.

Ref. [8] from 1972 and Ref. [9] from 1976 seem to be the pioneering studies of spherical coated contact. In [8] an approximate

|  | lature |
| :---: | :---: |
| A | contact area |
| E | Young's modulus |
| P | load |
| R | radius of the spherical substrate (inner radius of the coating) |
| $R^{\prime}$ | radius of the coated system, $R+t$ |
| Xi | coordinate system, centered in the center of the contact area, as represented in Fig. 1 |
| $Y$ | yield stress |
| $a$ | contact radius |
| $t$ | coating thickness |
| $z$ | vertical distance from the center of the contact area |
| $\alpha$ | power, Eq. (10) |

## $\beta$

$\nu$
$\omega$
$\sigma_{e q}$
slope parameter, Eq. (14)
Poisson's ratio
interference
equivalent von Mises stress
subscripts
co coating
su substrate
$t$ transition
VMmax maximum von Mises stress
VMmax_c maximum von Mises stress in the coating
VMmax_s maximum von Mises stress in the substrate
method was presented for the contact analysis of a multilayer medium consisting of one or two layers bonded to an elastic halfspace under impact and indentation loading by a parabolic punch. It was shown that the contact pressure distribution deviates from the corresponding homogeneous Hertz solution. In [9] the problem of elastic spherical contact area for a sphere indenting coated substrates was investigated. The results were presented in a dimensionless form and suggested that the contact area is affected by the elastic moduli ratio $E_{c o} / E_{s u}$, where $E_{c o}$ and $E_{s u}$ are the elasticity moduli of the coating and the substrate materials, respectively. Komvopoulos [10] used FEM to solve the elastic plastic contact problem of a coated half space indented by a rigid sphere and presented solutions for the contact pressure, subsurface stresses and growth of the plastic zone. Among other results, it was shown that for hard coatings with $E_{c o} / E_{s u}>1$, the contact area decreases with increasing coating thickness at a given indentation depth (interference). The author explained this behavior by higher resistance to deformation provided by the thicker hard coating. Ref. [11] presents a numerical 3D spherical contact model between elastic multilayered flat and a rigid sphere. It was found that with a hard coating the contact area at a given interference is smaller compared to the uncoated case. This contact area further decreases with increasing moduli ratio $E_{c o} / E_{s u}$. The opposite was observed for soft coatings with $E_{c o} / E_{s u}<1$ where the contact area was larger compared to the uncoated case. A discontinuity of stresses at the interface and an increase of von Mises stresses in the substrate for stiffer coating of medium thickness were also reported. Hence, increased risk for delamination. These results were also found in the flattening case, which is similar to the model in this paper, reported in Refs. [5,6]. In Ref. [12] the model of [8] was extended to provide the contact area radius for a rigid sphere in contact with an elastic layer over a flat rigid substrate. This model is limited to cases of extremely soft coatings such as elastomers. Liu et al. [13,14] extended the Hertz theory [3] to the case of coated bodies. These studies present a numerical treatment for a case of a rigid indenter in contact with a coated flat. It is reported, that like in the previous studies i.e. [8,12], the contact area radius depends on the Young's moduli ratio. It was shown that the size of the contact area, for given interference and coating thickness, decreases with increasing Young's moduli ratio. Ref. [15] presents theoretical and experimental results of indentation into a 3-layer material in the presence of adhesion. The size of the contact area was found to differ from the solution for uncoated case. In Ref. [16] a model for the spherical indentation of an elastic-plastic coating was presented. The model provides a relation between the contact area radius and the applied normal load. The model was compared with experimental results for soft compliant coatings on a much stiffer substrate. It was found
that the soft coatings increase the contact radius compared to an uncoated case. In a recent paper [17] the contact between a rigid ball and an elastic coated solid is studied. The effect of coating thickness on the stress field is numerically investigated. Among other results, it was found that hard coatings cause more concentrated contact pressure distribution, which means smaller contact radius. The same conclusion regarding the effect of stiffer coatings on the contact area size was reported in [18]. Eid et al. [19] developed a finite element elastic plastic model for a layered hemisphere in contact with a rigid flat in the presence of adhesion. Results were presented for a gold sphere coated with ruthenium (hard coating). It was reported that the contact radius increased with decreasing coating thicknesses at a given interference. Djabella and Arnell [20] used finite element analysis to investigate the contact stresses due to a combined normal and tangential loading of a coating/substrate system with hard coating on a softer substrate. It was shown that these stresses are function of the coating thickness and Young's moduli ratio. Also, it was reported that relatively thin coatings increase the stresses at the interface and hence, increase the risk of delamination. In Ref. [21] Holmberg et al. used FEM to investigate the contact stresses in a scratch test where a spherical indenter scratches TiN coated steel surfaces to study the generation of cracks. In [22] a numerical calculation of the stress distribution in a coated half space indented by a rigid sphere is presented. Two possible locations where high tensile stresses may occur were found. These locations are on the outer surface of the coating outside the contact area or at the substrate/coating interface. It was found that increasing in coating thickness or moduli ratio $E_{c o} / E_{s u}$ was accompanied by an increase of the tensile stresses at the interface.

In this study the concept of normalization by the transition values will be demonstrated on the maximum von Mises stresses within the coating or the substrate. Thus, a universal relation between the maximum stresses and the interference could be established as a function of the geometrical and mechanical properties of the coated sphere. This relation will provide a method for calculating the critical contact parameters (at yield inception) for a wide range of coated systems.

The present study forms an important addition to the results presented in Refs. [5-7] towards a complete model for an elastic coated spherical contact.

## 2. Theoretical background

Fig. 1 schematically presents a coated sphere system before loading (a) and in contact after loading (b) with a rigid flat. It

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