A 3D surface coating model for predicting tribological behaviour

M. C. Dubourg, Y. Berthier

Coatings are increasingly used to improve the mechanical and tribological properties in applications that involve mechanical joints for which the tribological performance, particularly in terms of fretting wear and fretting fatigue is a limiting factor. Their selection is based mainly on "material parameters" obtained from microstructural characterization and hardness tests, whereas little account is taken of "mechanical parameters". A systematic procedure for the selection of viable coating combinations and their optimization is proposed here, based on an iterative process between experimental and theoretical approaches. A 3-D model of an elastic multilayered body in contact with a rigid ellipsoid has been developed. It is used as a tool to select and optimize coating combinations, i.e what coating properties and thickness are required in order to enhance the lifetime under contact conditions. This requires to understand damage mechanisms that may arise within the coatings and/or at interfaces, with the objective of designing optimal coating combinations to decrease detrimental stresses.

Parole chiave: tribologia, rivestimenti, modelli

INTRODUCTION

The use of coatings and/or surface treatments on first bodies in order to improve their tribological properties (friction, wear, corrosion, etc.) while conserving their volume characteristics has economic implications and is an area of fundamental research. The choice of coating is made as a function of the material's parameters, such as layer composition (metal, ceramic, polymeric, etc.), hardness, microstructure, coating technique, the measurement of the friction coefficient on different simulators, the type of use and associated degradations, and so forth. This selection is usually made empirically, without incorporating the contact's "mechanical" role and that of tribology. The need for specific models adapted to these particularities is crucial since they correspond to *geometric* conditions (size of the contact's area in comparison with the characteristic dimensions of the component or mechanism to be analyzed), *mechanical* conditions (steep gradients with time and space of stresses and strains), and *mathematic* conditions with the treatment of contact boundary conditions in unknown domains.

Implementing a systematic approach to selecting adequate coating combinations on substrate systems is based on an iterative method, alternating experiments with the measurement of design data (Young's modulus, Poisson's ratio....) related to the layers, modeling, tribological tests on simulators, and full scale tests. The model proposed privileges the analysis at the contact scale, placing the influence of the mechanism in parentheses, since it might be taken into account by other models (finite elements...). Thorough parametric analyses to achieve better understanding of the support and transmission of stresses through layers, the interactions between the layers (stacking of thin layers of different thicknesses, or coatings with graded mechanical properties) permit the selection of viable coating combinations and then their optimization by decreasing the detrimental stresses and thus minimizing the coating degradation by wear, spallation, failure....

M. C. Dubourg, Y. Berthier
Laboratoire de Mécanique des Contacts, INSA de Lyon, Villeurbanne, France

Paper presented at the 7th European Conference EUROMAT 2001, Rimini 10-14 June 2001, organised by AIM

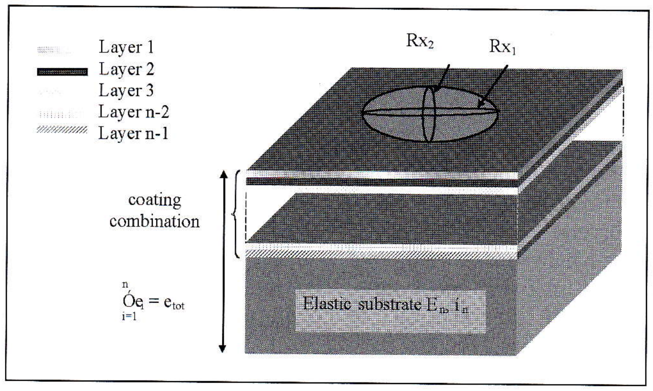

Fig. 1: Rigid ellipsoid in contact with elastic multilayered coatings bonded to elastic substrate.

Fig. 1: Ellissoide rigido in contatto con rivestimenti elastici pluristrato legati a substrato elastico.

NUMERICAL MODEL

This work began with the development of a 3-D multilayered model [1,2]. The most general case from the geometric standpoint is considered, the contact between a rigid ellipsoid and a parallelepipedic multilayered medium (Cf. Figure 1). Simplifying hypotheses were expressed. Each layer, m, of the coating combination is considered as perfectly isotropic, homogenous and of constant thickness e_m. Its behavior is linearly elastic, defined by a constant Young's Modulus E_m and Poisson's coefficient υ_m. The layers are perfectly bonded to adjoining layers, implying the continuity of strains at each interface. A normal load is imposed. Boundary conditions in terms of nil displacements or stresses can be considered at the lower surface of the multilayered coating, i.e. the substrate or layer n.

The approach used is semi-analytic and semi-numeric. It is based on the use of integral transformation methods and transfer matrices coupled with a Fast Fourier Transform algorithm to determine direct and inverse transformations. These methods make the model both fast and accurate, decisive when making parametric analyses at the localized scale of thin layers or that of graded coatings with mechanical

properties. Contact conditions (pressure distribution and contact patch) are determined by unilateral contact solution with friction. The interior stress field is then calculated.
Synthesis of the parametric studies carried out with this numeric tool has permitted improving phenomenological understanding of the mechanical behavior of multilayered coatings. The influence of "input parameters", mechanical properties (Young's modulus and Poisson's coefficient) and the thickness of the layers on the contact conditions between the contacting bodies, the support and transmission of stresses, especially at interfaces of adjoining layers, were analyzed in view to enhance the component life by minimizing the "output parameters", which are the potential degradation risks. These risks of cracking, delamination and resistance are controlled by tension, shear and yielding. These output parameters depend on three main effects:

- the effect of compression related to surface loading,
- the lateral effect related to the heterogeneity of the layers and the hypothesis of continuous deformations at the interface,
- the bending effect due to the indenting below the contact.

Thus the volume of material below the surface subjected to compressive stresses depends on the contact patch. The magnitude of the lateral effect corresponds to the difference in properties of two consecutive layers. It can lead to tensile stresses on the upper side of an interface in the case where the ratio of Young's moduli E_i/E_{i+1} of two consecutive layers is greater than 1. The flexion effect requires the conjunction of a ratio $E_i/E_{i+1} > 1$ and certain depths of the interface.
Therefore the behavior of multilayered coatings is studied as a function of:

- the contact conditions (contact pressure and surface area),
- the subsequent internal stresses,
- tensile and shear stresses at the interfaces of adjoining layers.

Their behavior is compared to that of a reference case, that of the uncoated substrate of identical total thickness. These points are illustrated by a few examples [1].
The variables used are:

P_o, A_o : maximum pressure and area of contact in case of multilayered coatings over a substrate,

P_{or}, A_{or} : maximal pressure and contact area in case of uncoated substrate, the reference case

$(\sigma^i_{11})^j_{max}$, $(\sigma^i_{22})^j_{max}$: maximum tensile stresses at interface j in layer i,

$(\sigma^i_{13})^j_{max}$, $(\sigma^i_{23})^j_{max}$: maximum shear stresses at interface j in layer i,

$(\sigma_{vmis})_{max}$, x_{3vmis} : maximum value of the equivalent Von Mises stress and corresponding depth (position according to x_3),

$\left(\sum_{j=1}^{i} e_j\right)$: total thickness of layers of the first to the inth layers, i.e. the thickness of interface i.

VARIATIONS OF CONTACT CONDITIONS

The parametric studies were carried out under normal imposed load. The variations in pressure distribution and contact patch are thus determined with respect to the properties and thicknesses of the layers. The results are presented in dimensionless form, with P_o normalized with respect to P_{or}, and the layer thickness normalized with respect to A_{or}. The total thickness of the substrate being great with respect to the

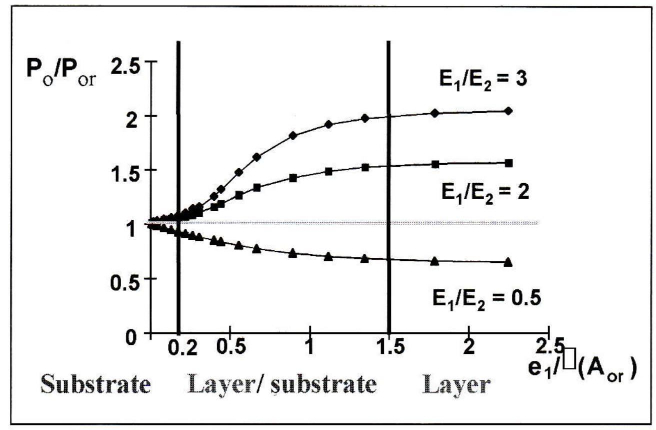

Fig. 2: Variations in normalized pressure with ratio $e_1/\sqrt{A_{or}}$ for a coating/substrate system.

Fig. 2: Variazioni della pressione normalizzata in funzione di $e_1/\sqrt{A_{or}}$ per un sistema rivestimento/substrato.

contact dimensions, P_{or} and A_{or} correspond to hertzian classical results.

Analysis of results for a two-layered medium

The thickness of the layers, generally qualified as thin or thick, must be defined in relation to the scale of the contact, as a function of the ratio of the normalized thickness of the layer over the half-width of the contact area (in 2-D) or the square root of the contact area (3-D) obtained in the reference case. This ratio governs the contact conditions. It defines three zones in which the pressure and the contact patch are governed respectively by the substrate, the multilayered entity and the first layer (Cf. Fig. 2). In the 2 extreme cases, Hertzian classical results give a good approximation, considering in the former case a medium with the substrate's mechanical properties and in the latter a medium with the first layer's mechanical properties.
Apart from these quantitative results, these curves also provide qualitative responses on the soundness of a treatment with respect to the role it must play, highlighting sometimes unforeseen secondary effects. Thus:

- a "thin" layer $e_1/\sqrt{A_{or}} < 0.2$ leads to no or only slight modifications of contact conditions, transmitting the same efforts as those to which the contact is subjected without treatment. Therefore the influence of the layer can only come into play with respect to surface properties (e.g., friction),
- a "stiff" layer on a more "compliant" and less resistant substrate and such as $0.2 < e_1/\sqrt{A_{or}} < 1.5$, is a combination frequently used to withstand for instance scratching by rough surfaces and debris. However, this combination may induce catastrophic failure as it concentrates the load. A drop of the contact patch accompanied with an increase in the peak contact pressure P_o are indeed obtained for an increase in E_1/E_2 ratio. This overload may be transmitted up to the layer interface and in the substrate and may generate a severest state of stress than those encountered in the uncoated case. Further the location of the maximum, if situated at the interface or within the layer, may be very detrimental, reducing instead of enhancing the lifetime.

Analysis of results in a three-layered medium

One way to overcome such problems is to consider a multilayerd coating combination to optimize the support and transmission of the load. The increasing range of possibilities provided by PVD and CVD coating techniques permit, for example, applying several successive layers in view to combining different properties: corrosion, fatigue, bonding, friction, etc. Therefore the layers and their thicknesses must be

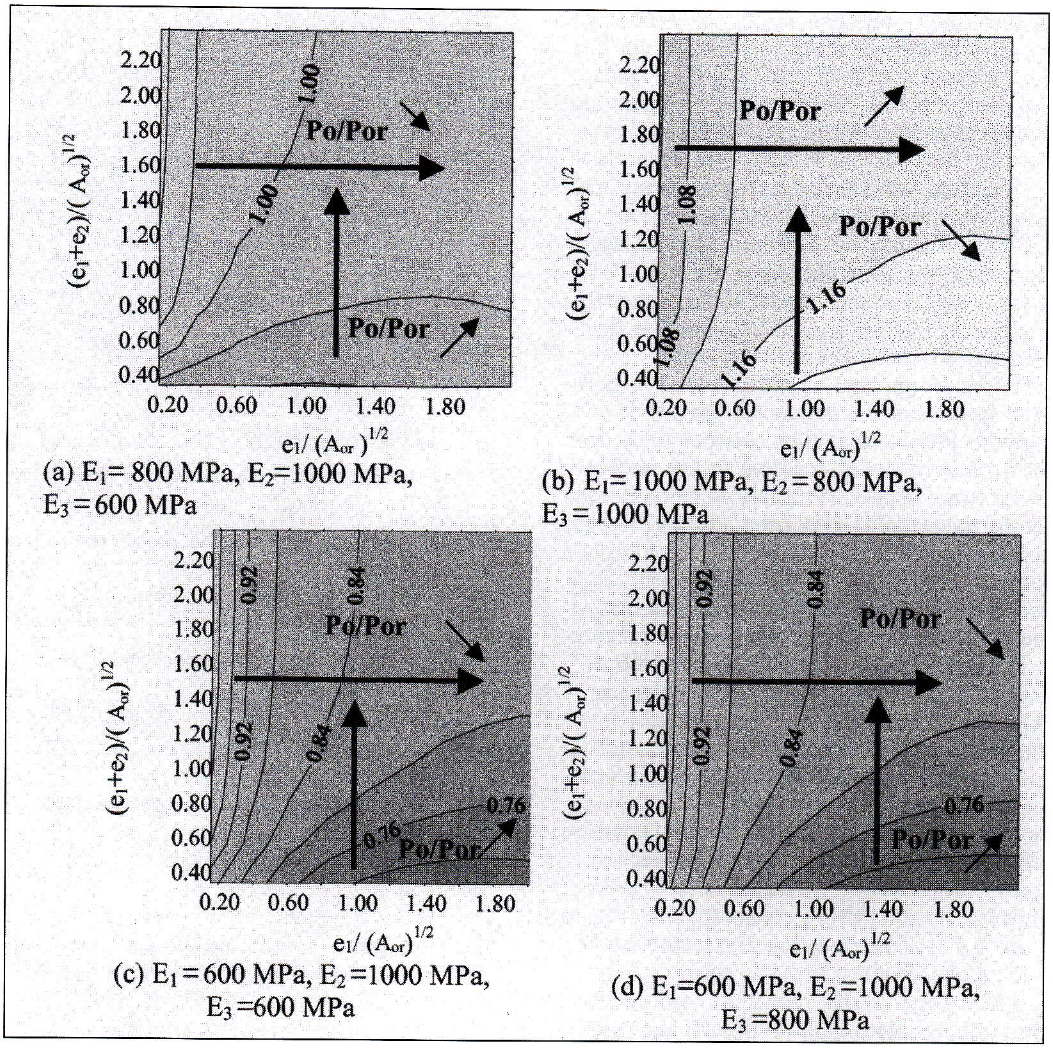

Fig.3: Variations of P_o/P_{or} with $e_1/(A_{or})^{1/2}$ and $(e_1+e_2)/(A_{or})^{1/2}$ for three-layered combinations. $e_1+e_2+e_3$ = 8 mm.

Fig. 3: Variazioni di P_o/P_{or} in funzione di $e_1/(A_{or})^{1/2}$ e $(e_1+e_2)/(A_{or})^{1/2}$ per diversi rivestimenti a tre strati. $e_1+e_2+e_3$ = 8 mm.

chosen, as must the order or sequence in which they are stacked. It is not a straight forward task and intuition alone can not give the answer.

To illustrate this, the behavior of a medium with a finite thickness, composed of three layers $(e_1+e_2+e_3)$=8 mm, is analyzed. The Young's Modulus for the single coating, the reference case, is 800MPa. The normalized representation of the results permits generalizing them to any configuration (thickness and properties of the layers). The variations P_o/P_{or} are shown in Fig.3 with $e_1/(A_{or})^{1/2}$ and $(e_1+e_2)/(A_{or})^{1/2}$. There are three possible ways of interpreting these variations:

- by imposing the global thickness of the treatments or layers, i.e. $(e_1+e_2)/(A_{or})^{1/2}$, with, logically, e_3 also fixed while modifying the relative thicknesses of layers 1 and 2. An increase of $e_1/(A_{or})^{1/2}$ implies a greater influence of layer 1 to the detriment of layer 2 on the system's behavior. The variations of P_o/P_{or} with $e_1/(A_{or})^{1/2}$ are governed by layer 1 Young modulus. Thus, for configurations (a), (c) and (d), E_1 being always smaller than at least one of the Young's moduli of layers 2 and 3, the increase of $e_1/(A_{or})^{1/2}$ causes the system softening, thus P_o/P_{or} decreases. The increase of this "compliance" is as great as the difference between E_1 and the other layer moduli. Viceversa, a stiffer layer stiffens the system.
- by imposing the thickness of the first layer $(e_1)/(A_{or})^{1/2}$ and by modifying the relative thicknesses of the two others: with $e_1/(A_{or})^{1/2}$ imposed, an increase of $(e_1+e_2)/(A_{or})^{1/2}$ corresponds to an increase of intermediate layer 2 concomitant with a decrease of the thickness of bottom layer 3. As a function of the value of its modulus in comparison with that of layers 1 and 3, increasing e_2 implies greater compliance (configuration (b)) or, on the contrary, increased stiffness (configurations (a), (c) and (d)). It should be noted that the weak influence of layer 3 on contact conditions is highlighted by comparing figures (c) and (d),
- by leaving the three parameters free.

Therefore the behavior of a three-layered system can be logically deduced from that observed for a two-layered one. The contact conditions mainly depend on the relative thicknesses and mechanical properties of the first layers which determine the system's overall stiffness and thus its behavior.

The transmission of the local loads of the first layer to the sub-layers and the substrate, with the hypothesis of perfect bonding at the interfaces, defines the stress and strain state in the coating. The correct matching of this state of stresses and deformations with the mechanical properties of the layers is the first step in choosing a surface treatment.

Here, we propose studying the internal stress fields in two and three-layered coating combinations. This study focuses on the analysis of tensile and shear stresses at interfaces in order to evaluate cracking and delamination risks under normal load.

ANALYSIS OF MAXIMAL TENSILE STRESSES

Tangential (σ_{13}, σ_{23}) and normal (σ_{33}) stresses are continuous at interfaces, whereas stresses σ_{11}, σ_{22} and σ_{12} are discontinuous. The discontinuity at i/i+1 interface is dependant on contact loading, the total thickness, the relative interface location with respect to the contact surface, the ratio E_i/E_{i+1}. These parameters interact to lead to a complex behavior resulting from three effects:

- a compressive effect connected to normal load: a compressive zone exists underneath the contact area,
- a lateral effect, linked to the mismatch between the values of the Young's moduli of two successive layers perfectly bonded. Since the strain behavior is imposed by one of the two joined layers, the compliance of the second may generate compressive and/or tensile stresses at the interface and in certain cases in all or part of the layer;
- a bending effect due to the indenting under the contact zone. Tensile and compressive stresses may indeed arise respectively at (i) and (i+1) interface sides for ratio E_i/E_{i+1} greater than 1, resulting in a bending phenomena, associated with cracking phenomena in the medium [2].

It is useful to analyze the tensile and compressive stresses at the interfaces as a function of their relative depths in order to evaluate potential cracking risks.

Influence of Young's moduli E_i and E_{i+1} at interface i

Study of interface 1

The variation of $(\sigma^1{}_{11})^1{}_{max}$ and $(\sigma^2{}_{11})^1{}_{max}$ with $(e_1)/(A_{or})^{1/2}$ are depicted in figure 4 for several ratios E_1/E_2 and having $Rx_1/Rx_2 = 0.18$ and $e/(A_{or})^{1/2} = 1.62$.

Behavior at the interface is the result of competition between the three effects mentioned above. It depends on the relative depth of the interface and the ratio of the Young's moduli of the three layers:

- for $e_1/(A_{or})^{1/2} < 0.1$, the interface is located in the compressive zone induced by the contact and is protected against any stress discontinuity whatever E_1/E_2 ratio,
- for $0.1 < e_1/(A_{or})^{1/2} < 0.4$, the depth of the relative interface increases and leaves the protection zone (compressive zone) generated by the contact. This thickening of layer 1 causes it to govern the strain at interface. Layer 1, the "master" layer with respect to "slave" layer 2, or vice-versa depending on their thicknesses, governs their common interface compliance. This results either in a compressive or, on the contrary, a tensile state of stress for the "slave" layer, depending on the relative properties of E_1 and E_2 (Cf. Figure 5). Thus, when "slave" layer 1 is stiffer than layer 2, interface 1 on layer 1 side is undergoing tensile stresses under the area of the contact. However, for ratios $E_1/E_2<1$, no tensile stress is obtained. These tensile stresses are potential harbingers of cracks near the interface.
- for $0.4<e_1/(A_{or})^{1/2}<0.7$, the position of the interface moves away from the contact's zone of influence: the tensile stresses at the interface decrease, as do effects 1, 2 and 3,
- for $0.7<e_1/(A_{or})^{1/2}$, the interface is outside the contact's zone of influence and tensile stress is no longer observed.

Study of interface 2

The elements of understanding obtained above for two-layered systems can be generalized for multilayered ones. By way of illustration, the variations for a two-layered system of stresses $(\sigma^1{}_{11})^1{}_{max}$ at interface 1 with $e_1/(A_{or})^{1/2}$ and the variations for a three-layered system of $(\sigma^2{}_{11})^2{}_{max}$ at interface 2 with $((e_1+e_2)/(A_{or})^{1/2})$, under identical loading conditions, are shown in Figure 6. Ratio E_1/E_2 of the two-layered system is 1000/600. Interface 2 of the three-layered one has identical 1000/600 sequence and layer 1 is such that E_1 is equal to 800 or 600 MPa. The different results obtained for a 2nd interface relative imposed depth correspond to different thicknesses of layers 1 and 2, i.e. different thickness combinations. The two-layered system is therefore the limiting case toward which the three-layered one tends when the layer 1 thickness becomes negligible.

Thus similar results in terms of tensile stress are obtained

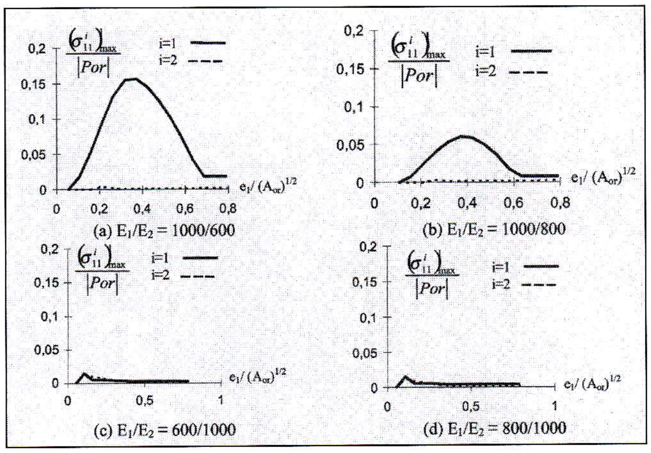

Fig. 4: Variation of tensile stresses for different ratios E_1/E_2 $(e/(Ar)^{1/2} = 1.62$, $Rx_1/Rx_2 = 0.18)$.

Fig. 4: Variazioni delle tensioni per diversi rapporti E_1/E_2 $(e/(Ar)^{1/2} = 1.62$, $Rx_1/Rx_2 = 0.18)$.

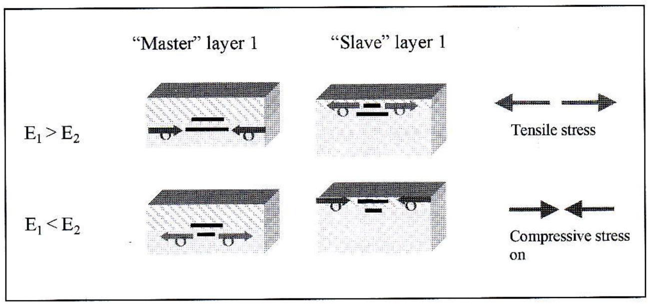

Fig. 5: Consequences for the interface of the "slave" layer conforming to the strain imposed by the "master" layer as a function of the relative properties of the 2 layers.

Fig. 5: Effetti sull'interfaccia dello strato "slave" prodotti dalla deformazione imposta dallo strato "master" in funzione delle proprietà relative dei due strati.

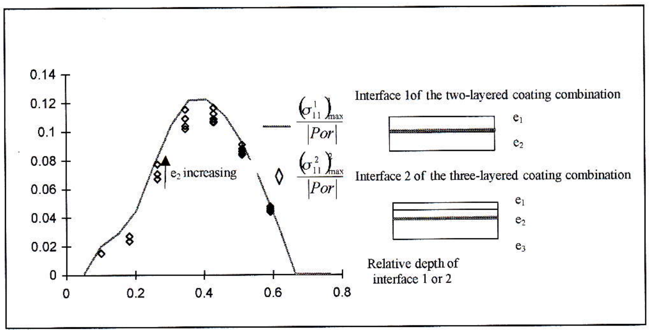

Fig.6: Peak tensile stress for sequence 1000/600. Three-layered: e_1 and e_2 variable for a given depth of interface 2 $(Rx_1/Rx_2 = 0.43$, $e/(Ar)^{1/2} = 0.776)$.

Fig. 6: Tensione massima per la sequenza 1000/600. Rivestimento a tre strati: e_1 e e_2 variabile per un dato spessore dell'interfaccia 2 $(Rx_1/Rx_2 = 0.43$, $e/(Ar)^{1/2} = 0.776)$.

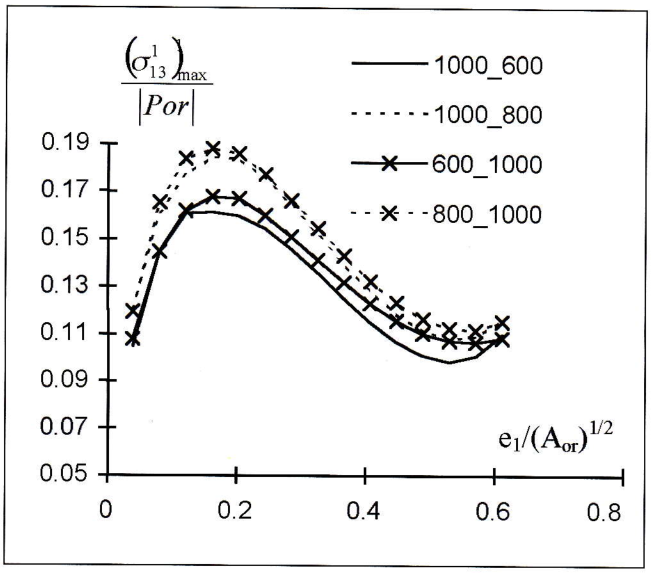

Fig.7: Variation of $(\sigma^1_{13})^1_{max}$ with $e_1/(A_{or})^{1/2}$ for ratios E_1/E_2 $(e/(A_{or})^{1/2}=0.77$, $Rx_1/Rx_2= 0.43)$.

Fig. 7: Variazione di $(\sigma^1_{13})^1_{max}$ in funzione di $e_1/(A_{or})^{1/2}$ per vari rapporti E_1/E_2 $(e/(A_{or})^{1/2}=0.77$, $Rx_1/Rx_2= 0.43)$.

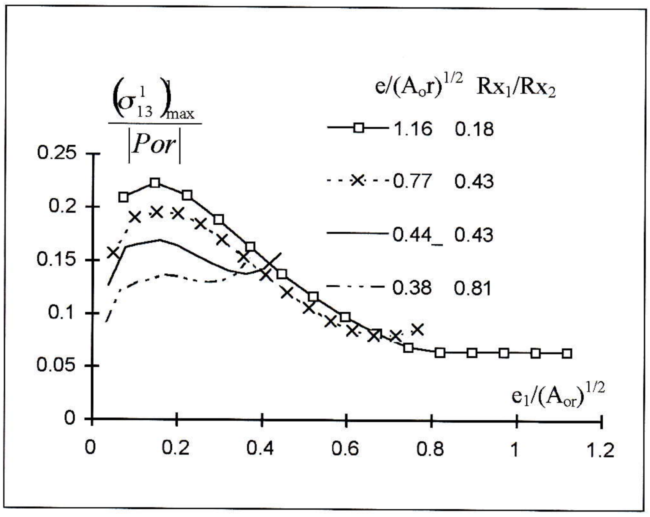

Fig.8: Variation of $(\sigma^1_{13})^1_{max}$ with $e_1/(A_{or})^{1/2}$ for several $e/(A_{or})^{1/2}$ ratios and Rx_1/Rx_2. $E_1/E_2=1000/600$.

Fig. 8: Variazione di $(\sigma^1_{13})^1_{max}$ in funzione di $e_1/(A_{or})^{1/2}$ per diversi rapporti $e/(A_{or})^{1/2}$ e Rx_1/Rx_2. $E_1/E_2=1000/600$.

for a relative depth of interface 1 of the two-layered system and interface 2 of the three-layered one, identical. Indeed, for low ratios $e_1/(A_{or})^{1/2}$ which modify contact conditions only slightly, almost identical local loads are transmitted to layer 2 by layer 1 of the three-layered system. The behavior at an interface i is therefore changed slightly by the existence of several layers between the surface of the contact and the interface studied. The behavior at an interface i mainly depends on its relative depth and the ratio of Young's moduli E_i/E_{i+1} of the bonded layers.

SHEAR STRESS ANALYSIS AT THE INTERFACE

The shear stresses at the interfaces are related to delamination risks. Perfect bonding conditions are assumed at the interfaces, which implies equality of shear stresses over the whole interface of joined layers i and i+1. Therefore these stresses are analyzed only in a layer at one interface.

E_i/E_{i+1} influence at interface i

Shear stresses $(\sigma^1_{13})^1_{max}$ are plotted at interface 1:
- in figure 7 for several E_1/E_2 ratios and an imposed loading condition,
- in figure 8, for an imposed 1000/600 E_1/E_2 ratio and several loading conditions defined by ratios $e/(A_{or})^{1/2}$ (variation of the total thickness of the system or the normal load on which A_{or} depends) and Rx_1/Rx_2 .

The variation of $(\sigma^1_{13})^1_{max}$ is general and depends on:
- the relative depth of the interface: the maximal value is reached whatever the loading condition for values ranging from 0.16 to $0.22(A_{or})^{1/2}$.
- the mechanical properties of each layer: the higher the mechanical properties of the layers, thus representative of hard coatings, the greater the level of shearing at the interface.
- the total relative thickness of the combination:
  - for $e/(A_{or})^{1/2}>0.44$, the finite dimension of the system does not modify the reduction of shear stress at the interface with an increase of $e_1/(A_{or})^{1/2}$,
  - for $e/(A_{or})^{1/2}< 0.44$, the interface is subjected to the joint influence of contact loading and the boundary conditions at the lower edge of the system, which offset the reduction $(\sigma^1_{13})^1_{max}$ with the increase of the relative depth of the interface.

As seen above for traction, these trends in behavior depend little on the existence of several layers between the surface and the interface studied, but essentially on the properties of its adjoining layers E_i/E_{i+1} and its relative depth (cf. Figure 9).

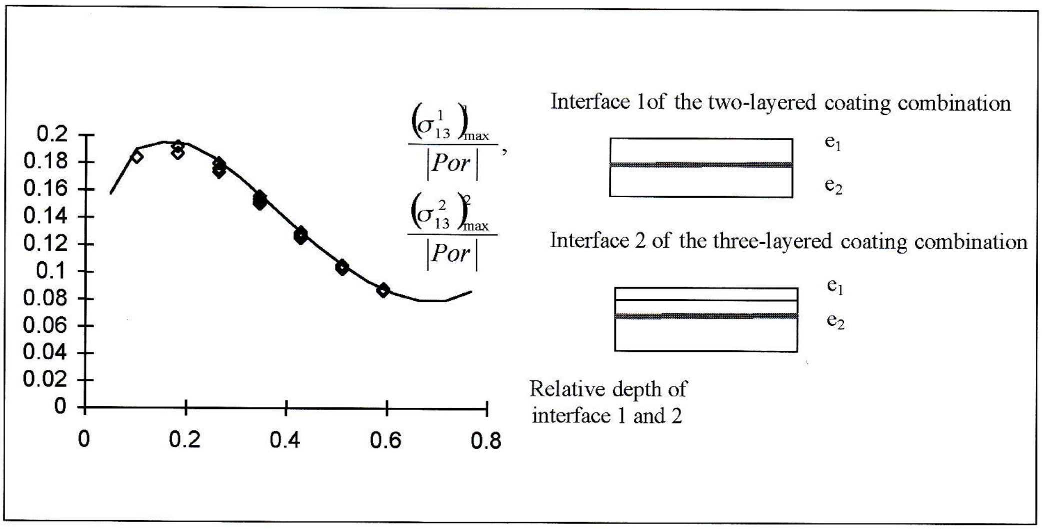

Fig. 9: Variation of maximal shear stress with the depth of interface 1 of two-layered and interface 2 of three-layered combinations. $(Ei/E_{i+1} = 1000/600$, $Rx_1/Rx_2 = 0.43$, $e/(A_{or})^{1/2}=0.77)$.

Fig. 9: Variazione della massima sollecitazione di taglio in funzione della profondità dell'interfaccia 1 per rivestimenti a due strati, e dell'interfaccia 2 per rivestimenti a tre strati. $(Ei/E_{i+1} = 1000/600$, $Rx_1/Rx_2 = 0.43$, $e/(A_{or})^{1/2}=0.77)$.

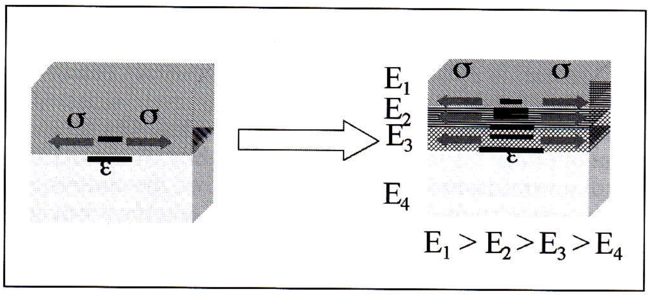

Fig. 10: Hard top layer applied on a substrate. A coating combination with intermediate layers to improve the support and transmission of the load.

Fig. 10: Strato superiore duro applicato ad un substrato. Una combinazione di rivestimento con strati intermedi per migliorare il supporto e la trasmissione del carico.

CONCLUSION

The use of complex surface treatments to improve the tribological performances of materials results in multilayered systems whose actual behavior is often unknown! The approach proposed here aims to provide a guide for selecting mechanically viable solutions before optimization. It incorporates the iterative use of experiments and modeling.
The results presented here were obtained by formulating simplified hypotheses: homogeneous, isotropic and elastic layers with perfect bonding at the interfaces. These necessarily simplified assumptions nonetheless permit progress in understanding coating combinations. On the basis of parametric studies carried out with the multilayered model developed, we propose several key points for establishing a solution:

- a multilayered system is one entity: local loads transmitted to the coatings and the internal stresses and deformations are interdependent elements of response;
- the need to reason in terms of relative layer thicknesses, defined with respect to the contact dimensions;
- the behavior of a multilayered system depends on three main effects whose result is a function of the relative thickness and nature of the layers. These are:
  - the effect of compression, related to the load on the surface,
  - the lateral effect, linked to the mismatch of the layer mechanical properties,
  - the bending effect, obtained at interface that fulfills 2 conditions: a ratio E_i/E_{i+1} greater than 1 and a depth situated outside the compressive zone induced by the contact.
- the dependence of contact conditions, peak contact pressure and contact patch dimensions with the relative thicknesses of the layers and their properties; in the case where several layers are applied, only the first modify contact conditions;
- identical, higher or smaller contact conditions can be obtained with respect to the uncoated reference case versus the coating combinations. The interior stresses within the sublayers and the substrate are accordingly determined. The choice of their mechanical properties and their relative thicknesses must take into account how the load is supported, transmitted, the points where the highest tensile, shear, Von Mises ...stresses occur with respect to sublayer interfaces with regards to the points that have to be optimized as a priority: to modify surface properties to improve the tribological behavior by getting a low, stable friction coefficient, to enhance the substrate's strength to fatigue, and so forth.
- tensile and shear stresses at the interfaces between layers mostly depend on the properties of the joined layers and the relative depth of the interface considered,
- the discontinuities of tensile stress on either side of an interface are as great as the difference between Young's moduli; minimizing them implies progressively adapting the difference of properties between a hard top layer and the substrate by stacking intermediate layers with graded properties (Cf ; Figure 10);
- a stiff layer applied on a more compliant layer leads to potential tensile stresses that must be minimized by modifying the relative thickness of this layer and the position of its interface.

On the basis of these elements, an initial well-considered choice of solutions (layers, thicknesses and stacking order) can be proposed theoretically for testing on other models (e;g. finite elements) at the scale of the mechanism or component, before progressing to the following step, using tribological test simulators.

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ABSTRACT

MODELLO 3D DI RIVESTIMENTI SUPERFICIALI PER LA PREVISIONE DEL COMPORTAMENTO TRIBOLOGICO

I rivestimenti sono sempre più usati per migliorare le proprietà meccaniche e tribologiche in applicazioni che prevedono giunti meccanici per i quali le prestazioni tribologiche, specialmente in termini di usura e fatica, rappresentano un fattore di limite. La loro scelta si basa principalmente su parametri dei materiali ottenuti dalle prove microstrutturali di durezza e di caratterizzazione, mentre si tiene poco conto dei parametri meccanici. Nella presente memoria viene proposta una procedura sistematica per la selezione delle possibili combinazioni di rivestimento e della loro ottimizzazione basata su un processo iterattivo fra metodi sperimentali e teorici. E' stato sviluppato un modello 3-D di un corpo elastico multistrato in contatto con un'elissoide rigida. Questo è stato utilizzato come strumento per la selezione e l'ottimizzazione di combinazioni di rivestimento, ad esempio quali proprietà e spessore di rivestimento siano necessari per aumentare la vita utile in determinate condizioni di contatto. Ciò richiede una comprensione dei meccanismi che determinano il danneggiamento che può insorgere all'interno dei rivestimenti e/o alle interfacce, con l'obiettivo di progettare combinazioni di rivestimento ottimali al fine di diminuire le sollecitazioni negative.
L'utilizzo di trattamenti superficiali complessi per migliorare le prestazioni tribologiche dei materiali porta infatti a sistemi pluristrato il cui comportamento è spesso sconosciuto.
I risultati presentati sono stati ottenuti formulando ipotesi semplificate: strati omogenei, isotropi ed elastici con bonding perfetto alle interfacce. Queste assunzioni necessariamente semplificate permettono tuttavia di compiere un pas-

so avanti nella comprensione delle combinazioni di ricopertura. In base agli studi parametrici effettuati con il modello multistrato sviluppato proponiamo diversi punti chiave per pervenire ad una soluzione:

- *Un sistema multistrato è un'unica entità: i carichi locali trasmessi ai rivestimenti e le sollecitazioni e deformazioni interne sono elementi interdipendenti.*
- *La necessità di ragionare in termini di spessori relativi dello strato, definiti con riferimento alle dimensioni del contatto.*
- *Il comportamento di un sistema multistrato dipende da tre effetti principali il cui risultato globale è funzione dello spessore relativo e della natura degli strati. Questi sono:*
  - *l'effetto di compressione, legato al carico esercitato sulla superficie,*
  - *l'effetto laterale, legato alla diversità delle proprietà meccaniche degli strati,*
  - *l'effetto di flessione, ottenuto alle interfacce che soddisfano alle 2 condizioni: un tasso E_i/E_{i+1} maggiore di 1 e una profondità al di fuori della zona di compressione indotta dal contatto.*
- *La dipendenza di condizioni di contatto, pressione massima di contatto e dimensioni della zona di contatto con i relativi spessori degli strati e delle loro proprietà; nel caso in cui più strati siano applicati, solo i primi modificano le condizioni del contatto.*
- *Con i rivestimenti si possono ottenere condizioni di contatto identiche, migliori o peggiori rispetto a campioni di riferimento non rivestiti. Si possono determinare quindi le sollecitazioni interne tra sottostrati e substrato. La scelta delle loro proprietà meccaniche e relativo spessore deve tener conto di come il carico viene sopportato, trasmesso e i punti in cui si determinano le maggiori sollecitazioni di tensione, di taglio, von Mises stresses relativamente alle interfacce del substrato nei confronti dei punti che devono essere ottimizzati come priorità: per modificare le proprietà superficiali, migliorare il comportamento tribologico ottenendo un coefficiente di attrito basso e stabile, per aumentare la resistenza del substrato a fatica e così via.*
- *Le sollecitazioni di taglio e tensione alle interfacce fra gli strati dipendono principalmente dalle proprietà degli strati una volta uniti e dalla profondità relativa dell'interfaccia in esame.*
- *Le discontinuità della tensione su qualsiasi lato di un'interfaccia sono maggiori quanto maggiore è la differenza fra i moduli di Young; la loro minimizzazione implica un progressivo adattamento della differenza delle proprietà fra uno strato superiore duro e il substrato mediante creazione di strati intermedi con le proprietà graduate (Cf. Figura 10).*
- *Uno strato rigido applicato sopra uno strato più morbido porta a potenziali tensioni che devono essere minimizzate modificando lo spessore relativo di questo strato e della posizione dell'interfaccia in questione.*

Sulla base di questi elementi, può essere proposta teoricamente una selezione di soluzioni iniziali ponderate (strato, spessore e ordine di impilamento) per effettuare prove su altri modelli (e.g. elementi finiti) alla scala dimensionale del meccanismo o componente, prima di procedere al passo successivo, cioè l'uso di simulatori in prove tribologiche.