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# **Simulation of hard particle impact on a Ti-6Al-4V substrate coated by a W film produced by magnetron sputtering**

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## **Abstract**

Large amount of dust can be ingested into the engines of aircraft and helicopters in sandy fields. Any ingested particles through the compressor impact the airfoil surface causing progressive erosion of the blades. To protect compressor components from erosion, thin films have been developed. Studies have shown that W base coatings produced by PVD deposition, can be a good solution to protect Ti-6Al-4V blades. We have simulated the impact of sand particles in order to optimize such coatings. Our first aim is to know whether the loading could be described by a quasistatic approach or needed a complete dynamic calculation. It is made for wide range of radii of particles supposed to be spheres and of impact velocities. To be representative of experimental conditions, the dynamic character cannot be ignored. Explicit finite element simulations give rise to the amplitude of the stresses inside all the components (particle, coating, substrate). During impact time, depending on the initial particles velocities, on the depths of the layer and on the sphere radii, the stresses inside the sphere can increase faster than in the layer and than in the substrate. They also reach locally the limit of rupture. So the particle might break before the stresses become critical in the other components. Our second aim is the improvement of the model by taking into account the initial compressive residual stress field in the coating.

# 1 Introduction

The phenomenon of erosion due to impact of sand particles is not well understood. It occurs on Ti-6Al-4V helicopter turbine blades in desert during the taking off and the landing. This problem has been largely studied, first in substrate materials<sup>1,2</sup>, second in thin films<sup>3,4,5</sup>, in order to reveal parameters which influence the decrease of damages.

Many studies focalise on impact and show different degrees of damage in accordance with impact loading<sup>6,7,8</sup>. The target response depends strongly on its mechanical behaviour and also on all the characteristics of the particle (shape, size, velocity and mechanical behaviour). The presence of the layer and the incident kinetic energy of the particle affect the contact. So, the quasi-static approach of Hertz is limited.

Numerical studies allow a complete description of impact loading and give rise to the influence of the three protagonists: the substrate, the layer and the particle.

## 2 Contact definition

According to the Hertz's quasi-static theory<sup>9</sup> (see appendix A), and applying the elastic law of Stephenson and Nichols<sup>10</sup> the conditions of contact can be determined. In this case, the depth of the film is compared with the area of contact between the particle and the layer supposed to be an infinite half space.

Due to the large range of particle size (diameter between 50 and 600  $\mu\text{m}$ ) and velocity (between 50 and 300 m/s) to be investigated, the results show that the contact is managed either by the film either by both the film and the substrate. Figure 1 shows that for a particle of diameter 50  $\mu\text{m}$  the film has a great influence on the contact in the explored range of velocity. For a particle of diameter 600  $\mu\text{m}$ , the film influence is lower.

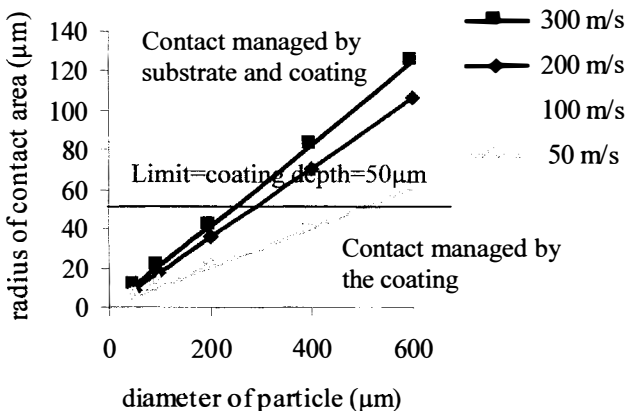


Figure 1: Rate of contact

Then, the influence of substrate properties, on the contact area, is unknown when coating and substrate managed the contact. So, the analytical methods appear insufficient. Consequently, we model an axisymmetric elastic impact using an explicit finite element code. The aims are: (1) the comparison of the contact geometry determined by the numerical method with the contact estimated by the Hertz's quasi-static theory, (2) the occurrence of dynamic effects, (3) the efficiency of the film, (4) the study of the distribution and the orientation of local principal stresses, (5) the evaluation of the residual stresses influence on the impact loading.

### 3 Dynamical aspects

According to the work of Johnson<sup>9</sup> when the impact velocity is less than 0.1 m/s the impact is elastic. For velocity ranging from 0.1 to 100 m/s the quasi-static theory can be applied. If the velocity is higher than 100 m/s, the impact can not be considered as quasi-static anymore.

In order to confirm such results, we evaluate the stresses reached under the contact and the radius of the contact area both by the Hertz's theory (see appendix A) and using the explicit finite element model for a substrate of tungsten or for a substrate of Ti-6Al-4V.

For Ti-6Al-4V, figures 2 and 3 show that the curves of contact radius or stresses obtained by explicit finite element calculation have the same evolution than the Hertz's curves when the impact velocity is less than 100 m/s. When the impact velocity raises, the difference between the two curves increases. The same results are observed for an impact on tungsten substrate.

So the description of the impact in a dynamical approach seems necessary.

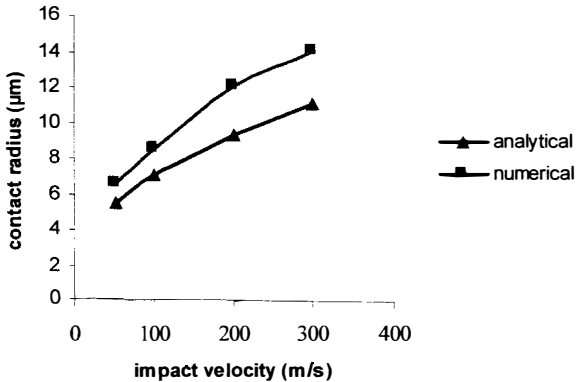


Figure 2: Evolution of the contact radius with the impact velocity, for a Ti-6Al-4V substrate, and a particle of diameter 50 µm.

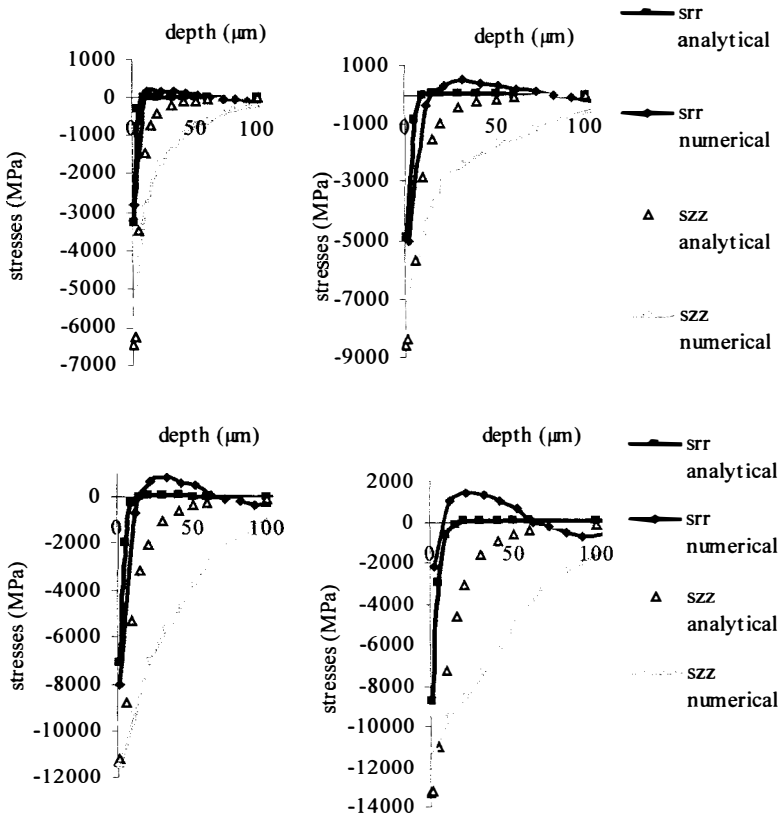


Figure 3: Evolution of the stresses, under the contact zone, with the depth, substrate of Ti-6Al-4V, particle of diameter 50μm, impact velocities of: a) 50 m/s, b) 100 m/s, c) 200 m/s, d) 300 m/s.

#### 4 Influence of the coating

In order to determine the influence of the coating, calculations of impact are made for a substrate and for a coated substrate. We consider that a coating is efficient when it minimises the level of stresses reached inside the substrate. As Fischer-Cripps<sup>11,12</sup>, the local principal stresses are studied (stresses noted  $\sigma_1$ ,  $\sigma_2$ ,  $\sigma_3$ , with  $\sigma_3 \geq \sigma_2 \geq \sigma_1$ ). Moreover, during the impact we observe the evolution of the stress field. And, the influence of the coating is described by the values of  $\sigma_3$  (figure 4) and by the difference  $\sigma_3 - \sigma_1$ .

When the kinetic energy of impact is low (cases a1 and a2 figure 4), the stresses in the substrate are reduced thanks to the coating. We can notice that: in the case a1) area influenced by the impact in the substrate is 100

$\mu\text{m}$  deep, in the case a2) the impact effect is localised in the coating depth and the substrate is protected.

When the kinetic energy of impact is high (cases b1 and b2 figure 4), the influence of the presence of the coating is lower. The stresses reached in a coated or not coated substrate are nearly the same. Both the coating and the substrate manage the contact as it is explained before (figure 1). So the stress field in the substrate is modified due to the presence of the film.

Other intermediate calculations of impact have been made. They lead to the following conclusions. For particles of low diameter ( $50\ \mu\text{m}$ ) the influence of the coating is sizeable for any impact velocity considered (decreasing of 70% on  $|\sigma_{zz}|$  in the substrate). For particles of  $250\ \mu\text{m}$  diameter the coating is still efficient when the impact velocity is less than  $200\ \text{m/s}$  (reduction of 30% on  $|\sigma_{zz}|$  in the substrate). In all the other cases the coating is not efficient.

Previous calculations assumed that the behaviours of materials are perfectly elastic. But, the stresses in the coating and in the particle locally reach the strength limits of the coating and particle.

Moreover, fragmentation of the particle may occurred at the first beginning of the impact loading, as it is suggested by Hutchings<sup>13</sup>. This failure would modified the impact loading of the coating and the substrate. The elastic simulations show that stresses increase faster in the particle than in the layer and in the substrate. So, the particle may fragment before the coating fails.

In order to improve the modelling, we have to introduce a more precise mechanical behaviour for all the materials, such as plasticity, evolution with the strain rate, strength of failure and we have also to take into account the state of initial stresses in the structure substrate layer (due to the deposition process of the coating). Erosion experiments<sup>14</sup> let understand that initial compressive stresses in the layer improve the coating performance under multi impact loading.

## 5 Influence of an initial stress field

Many papers, in the literature, deal with the initial stress field in thin films obtained by PVD deposition. This stress field is assumed plane, isotropic and compressive in the depth of the coating. Moreover, its amplitude can reach very high values according to the works of Thornton and Hoffman<sup>15</sup>, Juliet and al<sup>16</sup>, Gachon<sup>14</sup>, and Paturaud<sup>17</sup>.

The repartition and the amplitude of the initial stress field in all the structure are unknown. However, it is possible to simulate a stress field. We generate isotropic local plane compressive stresses in the coating, in accordance with a thermo-mechanical simulation. We assume that the compressive area is large enough compared with the volume affected by the impact. Then, we analyze the effect of local isotropic compressive stresses on the stress field and on the direction of the maximum principal stress reached under the impact.

In the case of an impact of low kinetic energy (sphere of diameter 50,  $\mu\text{m}$ , initial velocity of 50 m/s) and with a local initial compressive stress in the coating of 1.6 GPa, the results are:

- the volume affected by the impact is reduced in the radial direction and the maximum value of tension of the principal stress  $\sigma_3$  is reduced from 0.9 GPa to 0.2 GPa in the coating. Moreover, the local tension stresses reached at the surface and at the interface disappear thanks to the local initial stress. (Figure 4 case a3)
- the direction of the maximum principal stress, which is a tensile stress, changes, in the coating under the presence of the initial stresses (figure 5). Without prestress this direction is oriented at  $45^\circ$  in accordance with the Hertz's cone crack for a brittle material. Moreover, close to the axis of symmetry, for interface points this direction is parallel to the interface. In presence of initial stresses, the direction of stresses is always perpendicular to the interface under the contact zone and there is no more tension at the interface near the axis of symmetry.
- the initial stresses have no influence on the stress field (intensity, repartition and direction of maximum principal stress) reached in the sphere.

We notice that in the case of an impact of low kinetic energy the presence of the prestress influence the stress field reached under the contact as soon as its value reaches 0.5 GPa.

For a high kinetic energy impact the influence of initial stresses is not so convincing as the precedent case. The results presented on the figure 4 in the case b3 show that a local initial compressive stress of 1.6 GPa in the coating induces:

- a small decrease of the tension area in the surface near the contact area and of the level of tension stresses reached at the interface (when we observe the contact area at a high magnification)
- no change on the direction of the maximum principal stress reached in the coating.
- no change in the repartition and the level of the stress field reached in the particle.

In fact, the influence of the initial stresses depends strongly on the impact loading. In low energy case, they allow to improve the level of stress reached in the structure substrate-layer by reducing the affected volume by the impact loading. The initial stresses induce a concentration of the impact effects under the contact area. So the interactions between two very close impacts that may occurred at the same time, should be minimised. In the high-energy cases, the level of initial stresses is not high enough to localise the effects of impact loading.

To specify the range of impact velocity and radii of sphere for which initial stresses would reduce the impact loading effects, complementary numerical studies must be performed.

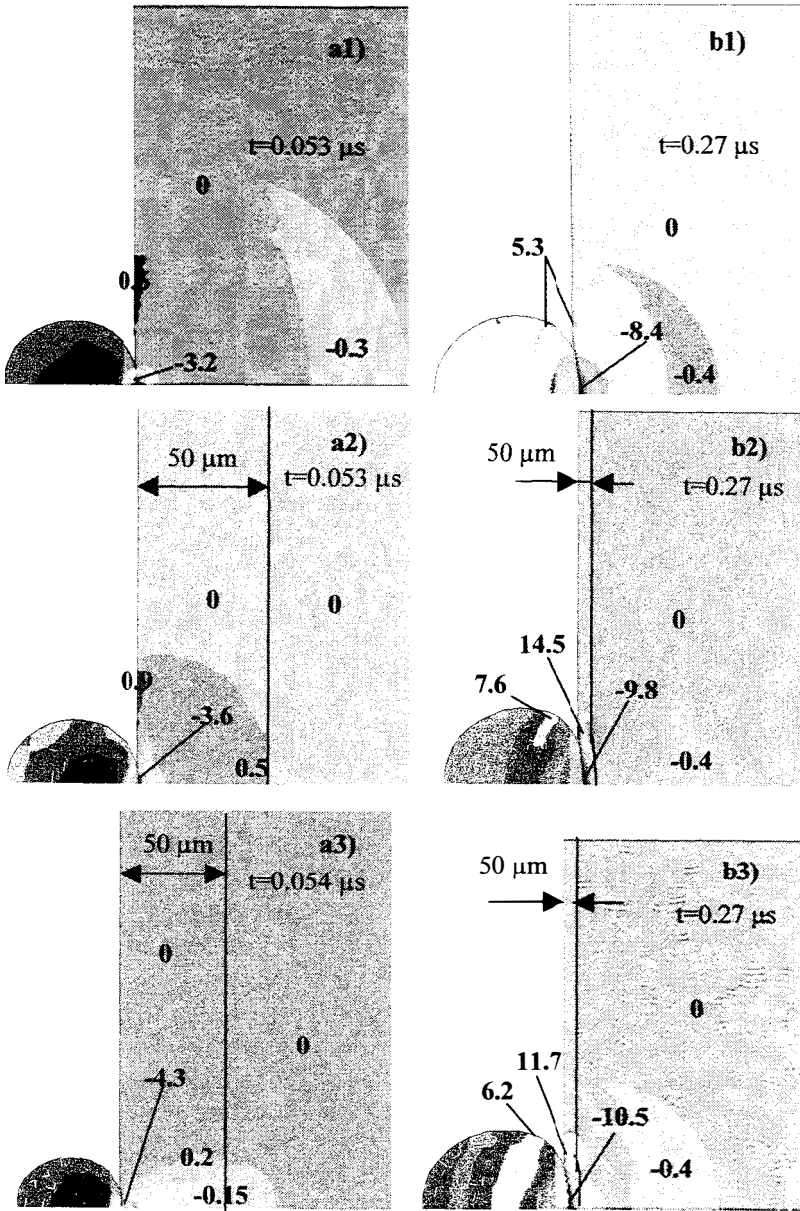


Figure 4: Representation of  $\sigma_3$  (GPa) during impact loading: a) sphere of diameter 50  $\mu\text{m}$  and initial velocity of 50 m/s, b) sphere of diameter 600  $\mu\text{m}$  and initial impact velocity of 300 m/s. 1- substrate, 2- substrate and layer, 3- substrate and layer with initial compressive stresses of 1.6 GPa.



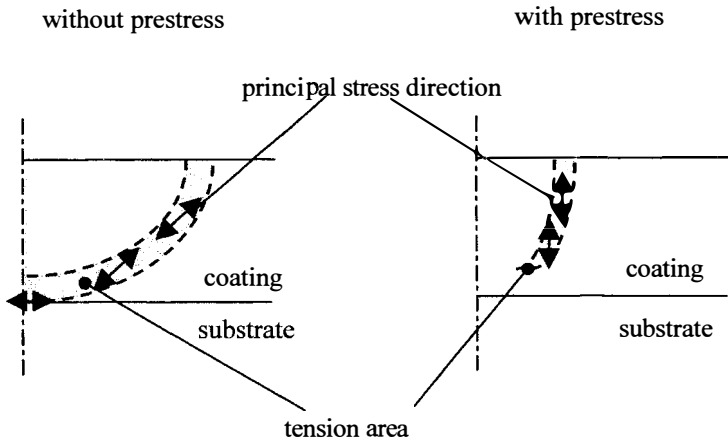


Figure 5: Prestress effects on the maximal principal stress direction, in the case of an impact at low incident kinetic energy.

## 6 Conclusions

For hard particle impacts, the determination of contact geometry and stresses are not evident when the loading condition depends on three elements such as: the particle, the coating and the substrate. Thanks to a finite element modelling, we get a lot of information about the stress levels reached over the structure.

Moreover, the service conditions impose a range of loading that can not always be considered as quasi-static. The quasi-static impact theory of Hertz can only be used for impact velocities lower than 100 m/s.

The study of loading as a function of impact time shows that reached stresses can be critical for the strength of the coating and the particle. Possibility of the particle fragmentation should change the story of loading and modify the impact effects on the coating and on the substrate.

Moreover, the influence of initial stresses on the amplitude, on the distribution and on the direction of the maximum principal stress is not the same if the impact kinetic energy is low or high.

These no doubt that at low impact energy, the presence of coating and of coating initial stresses seems to be useful to decrease the damages due to the impact. But, in the case of the most severe impact, simulation results show that the presence of coating and initial stresses have different effects. The presence of the coating always increases the stress level reached in the sphere, so its fragmentation should appear at the first beginning of impact time. If a fragmentation occurs, the stress level reached in the structure should be reduced and consequently, the initial stresses should improve the performance of the structure against the impact loading.

So, if the structure is to be prevented from impact loading, we have to consider the level of the associated kinetic energy. Hence, the mechanisms of stress reduction will be different. On the one hand, it is due to the presence of the coating; on the other hand it is the non-linear local behaviour that governs the capacity of resistance (damage, plasticity..). In other words, at low kinetic energy impact the loading effects are localized into the coating and the substrate is protected. At high kinetic energy impact, the coating is quasi transparent to the impact loading. And the substrate is protected if the particle fragmentation occurs.

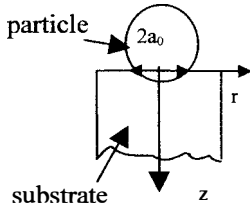
In order to improve the modelling, we have to take into account more elaborated behaviour laws for all the components. We want to show what is the role of plasticity when the coating is a ductile material.

We want also to model the influence of the fragmentation of the particle on the impact history and on the stresses reached in the structure.

Experiments should allow to determine the damage mode of the structure according to the initial conditions. They would lead to find a criterion of failure or fragmentation of the particle by using an inverse method.

## APPENDIX A

### Main definitions of Hertz's theory



#### Radius of contact zone:

$$a_0 = (3/4 P_{\max} R/E^*)^{1/3}$$

#### Maximal contact load:

$$P_{\max} = K [5m/(4K) V^2]^{3/5}$$

$$K = 4/3 R^{1/2} E^*$$

$$E^* = \{ (1-\nu_p^2)/E_p + (1-\nu_m^2)/E_m \}^{-1}$$

#### Maximal contact pressure:

$$P_0 = 3 P_{\max} / (2\pi a_0^2)$$

#### Axial stress:

$$\sigma_{zz}(z,r=0) = P_0 \{ 1 + z^2/a_0^2 \}^{-1}$$

#### Radial stress:

$$\sigma_{rr}(z,r=0) = P_0 \{ (1+\nu_m) \{ 1 - (z/a_0) \tan^{-1}(a_0/z) \} + 0.5(1+z^2/a_0^2)^{-1} \}$$

$R$ ,  $V$ ,  $\nu_p$ ,  $E_p$ ,  $m$  denote respectively the radius, the velocity, the Poisson's coefficient, the Young's modulus and the mass of the particle and  $\nu_m$  and  $E_m$  are respectively the Poisson's coefficient and the Young's modulus of the massive.

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