# MODELLING OF SHOT PEENING RESIDUAL STRESSES AND PLASTIC DEFORMATION INDUCED IN METALLIC PARTS

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**ABSTRACT**

A model has been developed by Guechichi (1) and improved by Khabou (2) to predict residual stresses and plastic deformations induced by shot peening in metallic parts. The major controlling factor were taken into account. This paper presents an extension of this model by taking into account the effect of friction, the angle of impingement and the hardness ratio. The material is characterised by using the model of Khabou (2) extended by Hamdane (3) in the case of triaxial loading. Application on a plate made of Udimet 720 shows a good agreement with the residual stresses obtained by X-ray diffraction analysis. Also calculations have been made by using different coefficients of friction and angles of impingement show a good correlation with the experimental data available in the literature.

**KEYWORDS**

Shot peening, Residual stresses, Hertizian contact, work-hardening, fatigue strength, surface treatement.

## INTRODUCTION

Shot-peening is a surface treatment used to improve the fatigue performance of metallic parts. This improvement is due principally to the favourable compressive residual stresses and to the material's hardening characteristics in the near-surface layers.

Predicting the resulting state of a shot-peened part is of great interest to both industrial and academic researchers as an essential step in evaluating the fatigue life of shot-peened components in service in order to optimize the peening parameters.

Extensive efforts have been made in a joint work between MécaSurf Laboratory and Metal Improvement Company aimed at investigating the various theoretical problems arising from the analysis of the peening process and understanding the influence of the various peening parameters on the material behaviour (1) (2) (4), the plastic deformations and the residual stresses induced in shot peened parts.

Most of the results of this research work have been included in a software, referred to as SHOTPEEN (5), intended as a design tool. This software enables the prediction of the plastic strains and the residual stresses induced by a specified set of peening conditions.

## SHOT PEENING PARAMETERS

This surface treatment consists of projecting shot made of steel, ceramic or glass, at relatively high velocities (20 m/s to 100 m/s) onto the surface of various metallic components. It produces both surface hardening and "favourable residual stresses" so as to ensure a better resistance against fatigue and corrosion.

The shot's impact generates a stress field in the near surface region. When the treated surface is totally covered (100% coverage) a residual stress distribution, varying in depth but uniform in surfaces parallel to the free surface, is created. The development of various methods to determine residual stresses both at the surface and in depth for different materials enables the induced residual stress profiles to be obtained.

The significant parameters of the process can be sorted in three different classes; each of them is associated to specific experimental effects as listed in the following:

first class : parameters describing the treated part (geometry, material properties , monotonic and cyclic elastic-plastic behaviour law).

second class: parameters of the stream energy produced by the process: properties of the shot (shape, size, material density and hardness, etc.), velocity, angle of impingement, distance between the nozzle and the treated part, duration of the treatment, etc.

third class: parameters describing the contact conditions: mainly coefficient of friction and coefficient of restitution which depends essentially on the ratio of the hardness of the treated material and the used shot.

## PHYSICAL PROCESS OF INTRODUCING RESIDUAL STRESSES

Wohlfahrt (6) explains the mechanisms of introducing residual stresses by two different processes of localised plastic deformation and consequently residual stress generation. The first process is the direct plastic elongation of layers very close to the surface as a consequence of tangential forces due to numerous indentations. The second residual stress generating process can be Hertzian pressure which arises as a consequence of the vertical force $F$ connected with the impact of each shot ball.

Not taken into account the tangential effect is the major drawback of the model developed by Guechichi and Khabou. In this model, the theory of elasticity is used to localise the external loading during the impact of the shot. The loading due to the normal force with a shear proportional to the load pressure is given by (7). The elastic-plastic calculation are made by using a simplified method of Zarka (8). A first step of calculation is made assuming a semi-infinite body, then a calculation of redistribution of the residual stresses and the plastic deformations is necessary to obtain the solution on the actual part.

## THE SHOT PEENING MODEL

### Hypothesis

The theoretical approach is based on the assumption that the deformation of a peened material qualifies as inelastic, pseudo-high velocity and cyclic as long as metallic parts are concerned. In addition, the following hypotheses have been employed in the implementation of the model (1) and (2):

1. the shots are spheres of uniform radius,
2. the area density of impacts is uniform and the residual stresses are supposed due to a uniform coverage.
3. the mechanical loading is pseudo-cyclic,
4. the mechanical state of the material is a stabilised one.

The principle of modelling is presented in the Figure1. The following assuptions are used to calculate residual stresses:

1. the shot velocity is supposed constant and it is determined by using (9),
2. the material behaviour law is modelled by using the theory of (2),
3. the solution of an elastic indentation by Hertzian contact is adopted as the external loading due to shot peening,
4. the elastic plastic calculations are made by using the simplified method of ZARKA (8),
5. the residual stresses and plastic deformations are determined by using the equilibrium equations and the compatibility conditions.

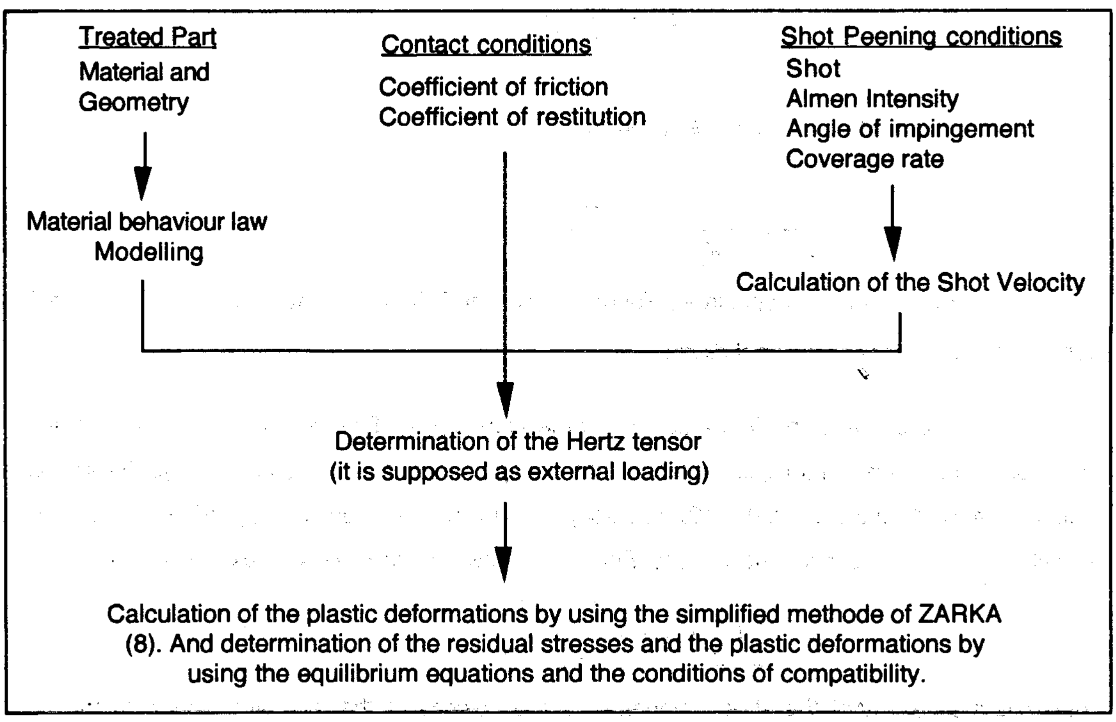


**Figure 1:** The flow chart of the model

**Impacts of shots and applied stress field due to shot peening**

***Hertzian pressure (Figure 2)***

According to Hertz's theory of elastic contact, the impact of a rigid shot on a semi-infinite body produces forces normal to the surface on a circular contact area of radius $a$, with a paraboloid distribution of pressure.

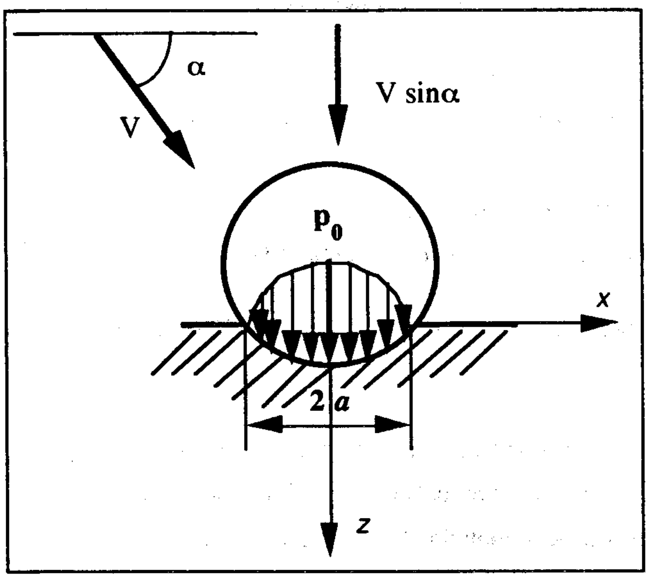


**Figure 2:** distribution of the Hertz pressure during the shot impact

The maximum pressure in the material is called Hertz pressure $p_0$ and given by Hertz (10):

$$p_0 = \frac{E_H}{\pi}\frac{2a}{D} \tag{1}$$

where $E_H$ is the equivalent modulus, given by:

$$\frac{1}{E_H} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \tag{2}$$

where $E_1$, $\nu_1$, $E_2$ and $\nu_2$ are respectively Young's moduli and Poisson's ratios of the shot material and of the processed material ; $D$ is the shot diameter.

To determine the expression of $a$ we use the same approach as Davies (11). The energy of deformation of the indentation is assumed equal to the kinetic energy restored by the shot. An hypothesis based on an experimental work made by Lida (12) was adopted. The normal pressure appears to depend only on the normal projection of the incoming velocity. Finally $a$ is given by the following expression:

$$a = \frac{D}{2}\left(\frac{5}{2}\pi\,\rho\,e^2\,\frac{V^2 \sin\alpha^2}{E_H}\right)^{\frac{1}{5}} \tag{3}$$

where $\rho$ is the density of the shot material, $V$ is the velocity of the incoming shot, $e$ is the coefficient of restitution depending on the ratio of the hardness of the treated material and the used shot, $\alpha$ is the angle of impingement.

## The global elastic loading due to the shot peening process

In this model, we use Hertz results for the elastic contact between a sphere and a semi-infinite body as an external loading due to shot peening. When the coverage is uniform, the non zero components of the depth distribution profile of the loading due the Hertz pressure (13) along the $z$- coordinate in the direction normal to the surface is given by:

$$\Sigma_{xx}(z) = \Sigma_{yy}(z) = P_0\left(1+\nu_2\right)\left(\frac{z}{a}\tan^{-1}\left(\frac{a}{z}\right) - 1\right) + P_0\left(\frac{a^2}{2\left(a^2+z^2\right)}\right) \tag{4a}$$

$$\Sigma_{zz}(z) = -P_0\left(\frac{a^2}{\left(a^2+z^2\right)}\right) \tag{4b}$$

If the motion of the nozzle is in the $x$ direction, the non zero components of the depth distribution profile of the loading due the tangential traction (7) along the $z$- coordinate in the direction normal to the surface is given by:

$$\Sigma_{xz}(z) = \mu P_0\left(\frac{z}{a}\tan^{-1}\left(\frac{a}{z}\right) - 1\right) + \mu P_0\left(\frac{a^2}{2\left(a^2+z^2\right)}\right) \tag{4c}$$

Where $\mu$ is the coefficient of friction between the treated material and the used shot.

**Plastic strain and residual stress determination**

## fundamental equations

When the semi infinite body is uniformly treated (uniform coverage), residual stresses and strains are only function of $z$. According to the local external loading and to the plastic flow rule (14) the plastic strain tensor can be written:

$$\underline{E}^p = \begin{bmatrix} E^p_{xx}(z) & 0 & E^p_{xz}(z) \\ 0 & E^p_{yy}(z) & 0 \\ E^p_{xz}(z) & 0 & E^p_{zz}(z) \end{bmatrix} \text{ with } E^p_{xx}(z) = E^p_{yy}(z) \tag{5}$$

and:

$$E^p_{xx}(z) + E^p_{yy}(z) + E^p_{zz}(z) = 0 \tag{6}$$

The equilibrium equations and the boundary conditions for the residual stresses lead to the following residual stress tensor expression:

$$\underline{R} = \begin{bmatrix} R_{xx}(z) & R_{xy}(z) & 0 \\ R_{xy}(z) & R_{yy}(z) & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{7}$$

A relationship between the plastic strains and the residual stresses in the semi-infinite body is given by the elastic plastic behaviour law:

$$E_{xx}^{p}(z) = -\frac{1}{E}\left(R_{xx}(z) - \nu R_{yy}(z)\right) \qquad (8)$$

$$E_{yy}^{p}(z) = -\frac{1}{E}\left(R_{yy}(z) - \nu R_{xx}(z)\right) \qquad (9)$$

- $$\frac{1+\nu}{E} R_{xy}(z) = 0 \qquad (10)$$

Finally the residual stress tensor is :

$$\underline{R} = \begin{bmatrix} R(z) & 0 & 0 \\ 0 & R(z) & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad (11)$$

with $\quad R(z) = \frac{E}{1-\nu} E_{xx}^{p}$

***The elastic plastic calculations***

A simple and straightforward method proposed by (8) and (14) is basically used to build up the residual stress prediction model. It applies to cyclic loading and relies upon a change of variable allowing an easier treatment of the plasticity criterion .

## APPLICATIONS

### Example of shot peening of a Ni-Base Superalloy Udimet 720 (16)

***Material and specimen***

A plate 20 mm thick made of a Ni-base superalloy Udimet 720 is taken as an illustrative example. Mechanical properties of the material are given in Table 1.

**Table1 :** Mechanical properties of the Ni-base superalloy Udimet 720 (16)

| E (MPa) | ν | YS 0.2 (MPa) | UTS (MPa) | ε % | BHN |
|---|---|---|---|---|---|
| 211 200 | 0.3 | 770 | 917 | 31 | 340 |

Shot peening was performed using S110 steel shots, the Almen intensity was 8A, the angle of impingement was 90° and 100% coverage. The residual stresses were determined by X-ray analysis.

***Modelling parameters***

Table 2 gives the parameters used to model the residual stresses introduced.

**Table 2:** Modelling parameters

| Process parameters | Contact parameters | Part parameters |
|---|---|---|
| Almen intensity : 8A | coefficient of friction: 0.4 | material: S0=400; P0=819 197; |
| angle of impingement: 90° | coefficient of restitution: 0.95 | S∞=1198; P∞=575. |
| shot: S110 | | Geometry: 20 mm plate |
| coverage: 100% | | thick (semi-infinite body) |

## Comparison of the calculated and measured residual stresses

The figure 3 shows calculated and evaluated residual stresses introduced by shot peening in the thick plate made of Udimet720. We observe a good agreement between the calculated residual stresses and those evaluated by X-ray diffraction analysis.

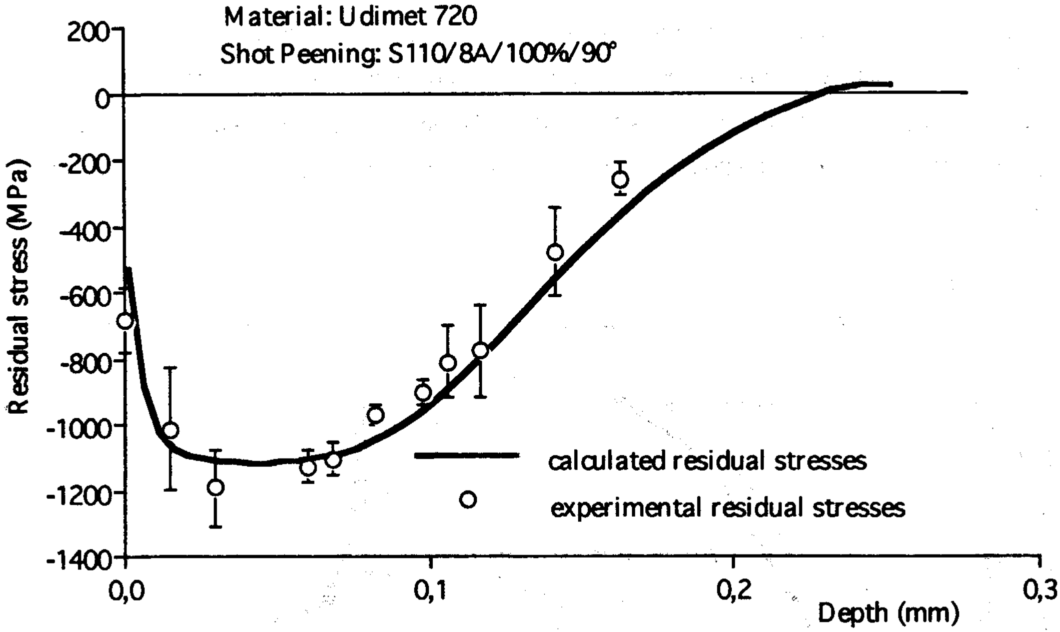


**Figure 3:** Comparison between the calculated and measured residual stresses

## Effect of the tangential friction

Figure 4 illustrates the residual stress and plastic deformation profiles calculated with two coefficients of friction 0.1 and 0.4. We observe that the effect of the tangential friction concern the first layers affected by the shot peening as it is described by (6). When the coefficient of friction increases, the value of the residual stress increases (the absolute value decreases) in the near surface region and the Von Mises equivalent plastic deformation increases.

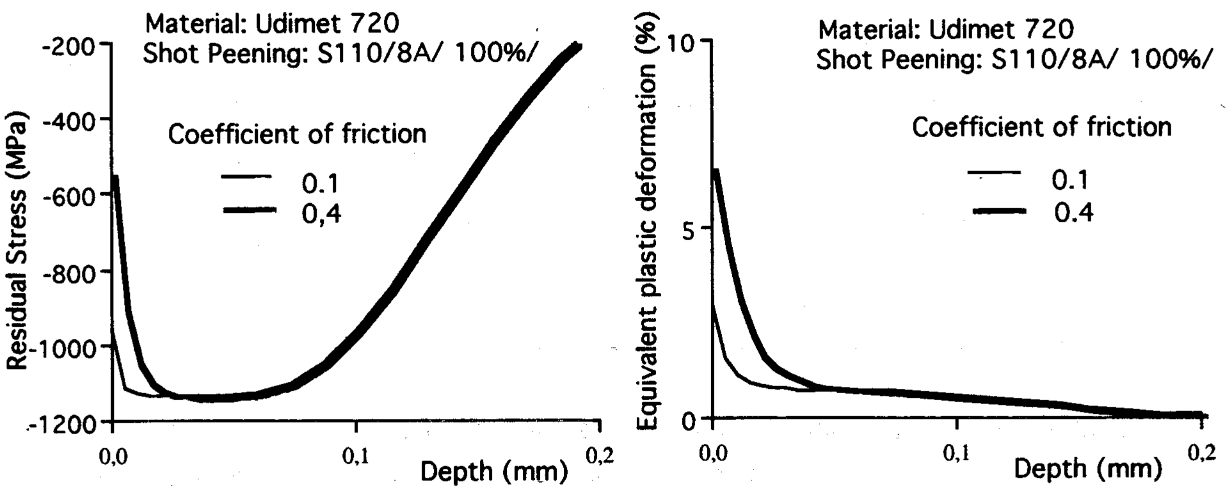


**Figure 4:** Residual stress and plastic deformation profiles calculated with two coefficients of friction.

***Effect of the angle of Impingement***

Figure 5 presents the residual stresses and equivalent plastic deformation calculated in the plate shot peened with three different angles of impingement (30°, 60° and 90°). We observe that the affected depth of the affected layer (15) and the results available in the literature (16) (17). the equivalent plastic deformation is slightly decreasing with the angle of impingement. More study of the shear distribution on the contact area are needed.

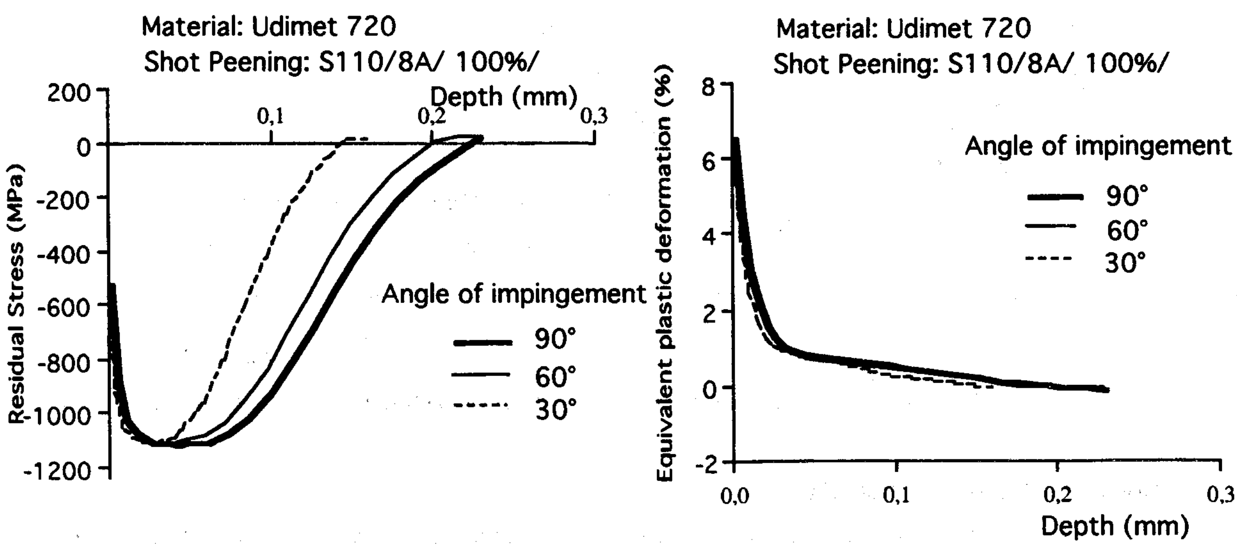


**Figure5:** Residual stress and plastic deformation profiles calculated with different angles of impingement

## CONCLUSIONS

(1) The main features of a predictive model developed by Guechichi and Khabou (1) (2) for evaluating the residual stresses induced by shot peening of metal components have been reviewed. The model

takes into account the major controlling factors including shot peening conditions, the properties and behaviour of the material. An extension of this model taking into account the angle of impingement and the contact conditions; coèfficient of friction and coefficient of restitution is presented.

(2) The dedicated SHOTPEEN software has been described. It enables the prediction of the plastic strains and the residual stresses induced in shot peened metallic parts as a function of the process parameters.

(3) Application to a thick plate made of Ni-base superalloy Udimet 720 shows that the residual stresses predicted by SHOTPEEN are in good agreement with those determined by X-ray diffraction.

(4) The induced residual stress profiles are calculated with different coefficients of friction and angles of impingement. We observe that the residual stress values and the equivalent plastic deformation increase in the near surface region with the coefficient of friction. And the affected depth decreases when the angle of impingement decreases. Those results are in agreement with the results in the literature(5) (17).

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**REFERENCES**

(1): Guechichi H., 1986, *Thèse de Doctorat*, ENSAM Paris,

(2): Khabou M.T. , Castex L. , Inglebert G., 1989, *The effect of material behaviour law on the theoritical shot peening results*, Eur. J. Mech., Vol A/Solid, 9, n°6, 537-549;1989.

(4): Fathallah R., 1994, Modélisation du procédé de grenaillage; angle d'incidence et taux de recouvrement, *Thèse de doctorat*, ENSAM Aix en Provence, 1994-15.

(5): Cao W., Fathallah R.,Barralis J. and Castex L., 1994, *Residual stress in shot peened metal components: An interactive prediction software*, 4th International Conference on Residual Stresses ICRS-4, Baltimore (USA), june 8-10, 1994.

(6): Wohlfahrt H., 1984,*The influence of peening conditions on the resulting distribution of the residual stress*, Proceedings of the Second International Conference on Shot Peening, Chicago, 5/1984, pp316-331.

(7): Sackfield A. and Hills D., 1983, *A note on the Hertz contact problem: a correlation of standard formulae*, Journal of strain analysis vol 18 No 3.

(8): Zarka J. and Casier J., 1979, *Elastic plastic response of a structure to cyclic loading*, Mechanics today, 6éd. Nemat-Nasser, Pergamon Press.

(9): Cao W., Fathallah R., Castex L., 1994, *A correlation of the Almen arc height with residual stresses in shot peening process*, (accepted to publication in Materials Science and Technology 21 November 1994).

(10): Hertz H., 1896, *On the contact of elastic solids*, Eds. Jones and Schott, London: Macmillan, 1896. [90,156].

(11): Davies R. M., 1949, *The determination of static and dynamic yield stresses using a steel ball*, Proc. R. Soc. A197, 416-432.

(12): Iida K. , 1984, *Dent and affected layer produced by shot peening*, I.C.S.P. 2, Chigago (USA), 14-17 May 1984.

(13): Sardain C., 1981, Contribution à l'étude du contact entre deux solides photoélastiques, *Doc. thesis*, Université de Poitiers France.

(14): Mandel J., 1978, *Propriétés mécaniques des matériaux: rhéologie plasticité*, Eyrolles.

(15): Inglebert G., Frelat J., 1989, *Quick analysis of inelastic structures using a simplified method*, Nuclear Engineering and Design, NED116,1989, 281-291.

(16): Fathallah R., Cao W., Castex L.& P. S. Webster. 1994, *Influence of differents shot peening parameters*, 4th International Conference on Residual Stresses ICRS-4, Baltimore (USA), june 8-10, 1994.

(17): Ebenau A., Vöhringer O.and Macherauch E., 1987, *Influence of the shot peening angle on the condition of the near surface layers in materials*, I.C.S.P. 3 in Garmisch-Partenkirchen (Germany).