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3D FINITE ELEMENT ANALYSIS OF SHOT ANGLE IN SHOT PEENING OF METALLIC SHEETS

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Abstract. *Manufacturing of large structures in the aeronautical industry is highly dependent on processes such as shot peening and peen forming. To know these processes and the involved technology in both production and simulation is a continuous learning process. The study of the effect of balls impact with different incidence angles and process conditions, such as friction coefficient, is important to evaluate the distribution of residual stresses and strains on the formed component. Using a simulation tool ensures adequate conditions to obtain results which define the angles of impact which better reproduce the real phenomenon. To solve such complex modeling process the finite element (FE)MSC.Dytran code was adopted for 3D simulation of elastic-plastic strains during shot dynamic impact on aluminum alloy sheets used in aircraft panels. In the finite element (FE) model shots were considered as a spherical cap with rigid shell elements. The simulation demonstrated that the effect of oblique impacts results in different permanent deformations, residual stress and strain, and that friction coefficient affects only the profile of residual stress and deformation but not the depth of the plastic layer.*

Keywords: *shot peening ; shot angle; residual stress; finite elements; impact*

1. INTRODUCTION

Shot peening (SP) is a cold forming process used to modify the surface of many metallic components. It consists in shooting very small balls against the workpiece surface to produce compressive stresses which increase the components service life and fatigue resistance. Due to these advantageous characteristics shot peening has been extensively applied in the automotive and aerospace industries for many decades.

The residual stresses induced by SP directly influence the material resistance to fatigue, fracture, wear and corrosion. Therefore it is very important to determine the residual stresses profile as function of many SP parameters, and that has recently become possible by the numerical simulation with the Finite Element Analysis (FEA) (Silva and Button, 2011).

There are many useful models available to determine the residual stresses with FEA, from the simple 2D models and single impact to the complex 3D models with multiple impacts. The recent work of Kim *et al.* (2013), presents the simulation of 3D residual stresses during the SP with oblique impacts, and analyses the influence of the dynamic friction and strain rate sensitivity on the Rayleigh damping observed in the peened material The authors used the Finite Element (FE) commercial code Dytran (MSC.Dytran, 2005) to simulate the oblique impact and the friction influence on the residual strains.

2. SHOT PEENING

The technology associated to SP is very complex. To understand the main concepts involved it is necessary to divide its analysis in some topics like historical aspects of the process, fundamentals, medias, residual stress distribution, coverage and saturation, equipment and recent developments (Kirk, 1999).

2.1 Shot peening history

Shot peeening is not an innovative process. Since ancient times it is known that a pre-stressed or cold formed metal could generate harder and durable materials. From the ancient city of Ur, Mesopotamy, ca. 2700 BC there are records of handmade shot peened gold artifacts. During the Crusades, AD 1100 to 1440, the swords of Damasco and Toledo were cold worked to increase the flexibility and strength of the steel.

Peen, meaning hammering with a small ball hammer, was used before the Bronze Age to forge and to increase the strength of armors, swords and metallic appliances. In the American Civil War barrels of shotguns were peened to increase the steel hardness. The fillet radii of connecting rods used in the first European race cars were also hand-

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peened with customized hammers. Nowadays automated machines are used to peen surfaces by the impact of very small balls made of steel, ceramics or glass.

Although peening presented a considerable development in the 20th and 21th centuries, the overall concept is the same: shot the material surface with thousands of small spheres at high speeds, as it was done in the ancient times by hand-hammering. The modern automated blast stream presents 30,000 impacts by second on the region of the part covered by the blast stream.

According Deburring (2013) the first work on SP was published in Germany by 1929, and patented in 1934. The first research report in the automotive industry was published by Zimerly in 1940. John Almen extended his researches to use SP in the aircraft industry during the War World II. In 1950 Peen Forming (PF) was first presented as an engineering process and was used to shape the wings of the Super Constellation.

2.2 Shot peening fundamentals

The atoms at the surface of a metallic part generally present a residual tensile stress generated by rolling, welding, heat treatment and other manufacturing processes.

By shot peening the surface, atoms are forced to the surface (Figure 1) to rearrange the original atomic structure. Deeper atoms are pulled towards the surface interacting with the atoms of the compressed region, generating tensile stresses, balancing the compressive stresses at regions near the surface, and finally preventing cracks propagation.

Special SP techniques were developed to create sub-surface stresses high enough to avoid premature cracks where the nucleation of cracks is less likely than at the surface under tension and to prevent that the excessive number of impacts may cause the surface failure by breaking the metallic bonds. Therefore due to the hydrostatic pressure developed in the process, it is possible to cause high plastic deformations by peening, without cracking.

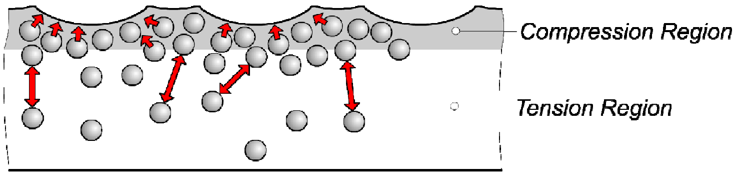

Figure 1. Shot peening at atomic level.

SP is a cold work process in which a metallic part is blasted by very small particles (shots), usually small steel balls, or small wire pieces, glass or ceramics balls, with diameters in the range 0.1 to 0.5 mm, at high speeds (100 m/s). Although SP is confused with abrasive blasting, these two processes present very different effects. Abrasive blasting is used to clean metallic surfaces by removing corrosion and oxidation sub-products, while SP is used to improve the material resistance to fatigue, fatigue under corrosion and wear.

Despite being simple in fundamentals, only recently SP became technically understood because it is very difficult and complex to evaluate how the properties of the peened material are affected by the several impact modes caused by shots with many characteristics (material, diameter, hardness and shape), and by other process variables like impact angle, stream intensity, nozzle diameter, exposure time and blast coverage.

2.3 Residual stresses

SP forms a thin layer which is plastically deformed and presents compressive residual stresses generated by a large number of impacts (Figure 2). Figure 2a shows the impression caused by the impact of shots normal to the surface under plastic deformation which generates the stress distribution in the plastic layer with thickness h_p shown in Figure 2b. The compressive stress at the surface is approximately half of the ultimate tensile strength or two thirds of the yield strength of the material in the strain hardened layer.

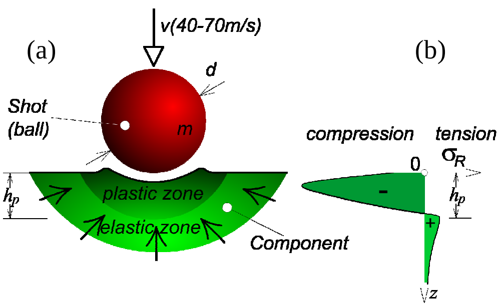

Figure 2. Shot peening: (a) impact of one shot; (b) distribution of residual stresses.

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2.4 Impact speed

The speed (v) shots blast the surface is perhaps the most important variable among the many which represent the shots (size, shape, mass, density, hardness), because speed takes part in the equation of the kinetic energy of a moving particle with mass (m).

To accelerate one particle it is necessary to generate work by pressurizing air (Figure 3a) at one side of the particle. The pressure gradient around the particle creates the acceleration force. In SP with pressurized air, speed is a function of the pressure at the exit of the nozzle and of the nozzle diameter. The shot impact also can be created by the centrifugal force generated by a centrifugal wheel as shown in Figure 3b where the particle speed is a function of the rotation and of the wheel diameter. The distribution of residual stresses and the material hardness are very different after each of these two procedures (Osk, 2005).

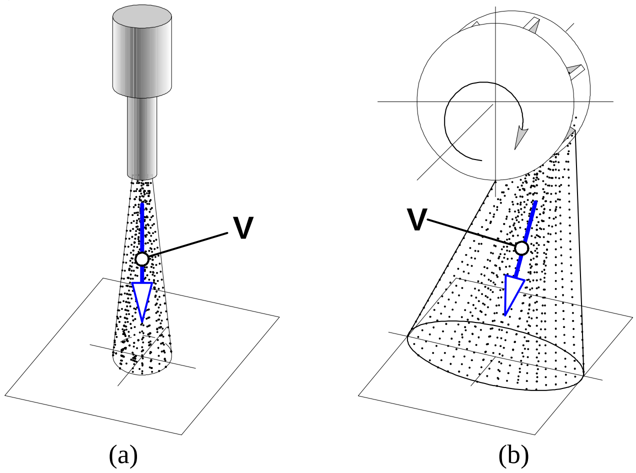

Figure 3. Some variations of SP principle: (a) air pressure; (b) centrifugal wheel.

2.5 One shot impact

One particle at high speeds when colliding to a metallic surface generates an indentation (Figure 2-a) because its high kinetic energy. At the moment of the contact, stresses tends to infinite because being punctual, generate plastic deformation which increases the contact area and rapidly reduces the surface stresses to values below the yield strength when deformation is finished and the particle is stopped. With the impact the particle loses part of its kinetic energy and springback makes the particle to rebound and change its moving direction. The kinetic energy is transformed in impact work and can be measured by the impact force times the penetration distance. The material moves laterally by the plastic deformation generated by the tensile stress, and ultimately creates the compressive surface stress (Figure 2-b).

2.6 SP medias

SP blasting medias (with different shapes and materials of the shots) must have a smooth profile commonly idealized by a spherical shaped particle. The necessary condition to the process is the availability of lots of perfectly spheroidal particles, with very high hardness and high resistances to wear, corrosion and fracture. In practice, the choice is restricted to four materials: cast iron, steel (cast or cut-off from drawn wires), glass and ceramics. The steel balls manufactured by atomization and wires cut-off and wheelblasted are more common in industry because they present high wear resistance if compared to cast iron, and higher impact resistance if compared to glass and ceramics particles. When defining the particles it is essential that less than 10% of a standardized sample are out the specifications of particles shape and size. If the media is to be reutilized, the particles off specifications must be removed and substituted by new ones.

2.7 Residual stress distribution

There are two methods to shot peen a rectangular component. In the first method both sides of the component are peened and two layers with compressive stresses are generated which forces are balanced by the internal forces which act on a larger area and consequently present a smaller tensile stress.

In the second method, only one of the sides is peened (Figure 4a). In this case the balance is achieved by the deflection generated by the induced moments (Figure 4b). With the deflection the residual stress distribution is modified till the balance is reached. Almen´s strips are examples of this second peening method in which after the removal of the fixtures, the strips deflect and the Almen gauge is measured to estimate the residual stresses $\sigma_{res}(z)$

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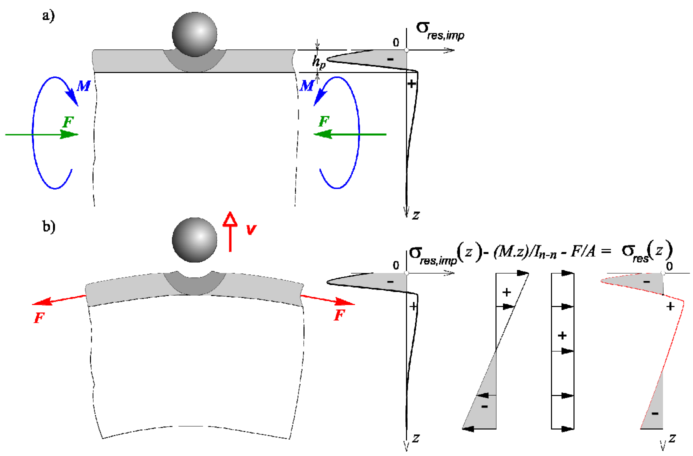

Figure 4. Determination of residual stress $\sigma_{res}(z)$ for an Almen strip before (a) and after the removal of fixtures (b): (a) strip is kept straight due the reaction forces (compressive force *F* and bending moment *M*); (b) after the removal of fixtures and restrictive boundary conditions.

2.8 Coverage and saturation

The surface coverage is increased due to the cumulative effect of repeated random impacts which generate many indentations on the surface (Figure 5).

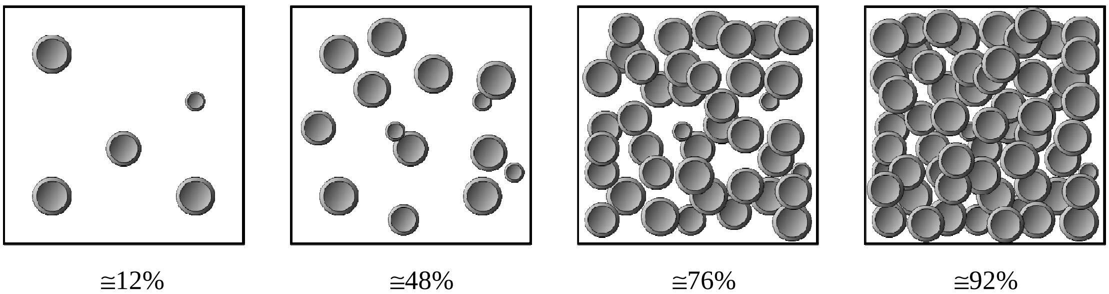

Figure 5. Number of indentations as a function of peening time.

Each impact causes a localized strain hardening and by superimposing more and more impacts, more plastic strain is generated and must be controlled to avoid the formation of surface cracks. The coverage is considered complete when 100% of the surface is peened. Figure 6 shows that most of the surface is peened by one impact (without superimposition) and that coverage reaches 86% after 10 seconds. After 20 seconds the coverage is increased to 98% which can be assumed to be the total coverage. Finally, it is observed that most of the peened surface was shot by four impacts.

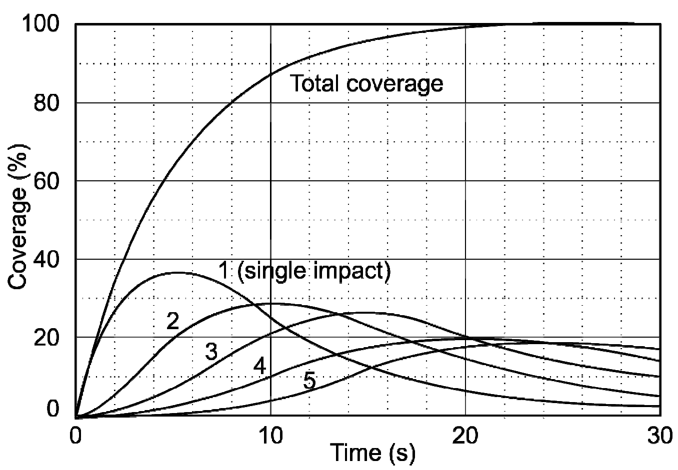

Figure 6. Contribution of different number of impacts to the total coverage, Kirk (1999).

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After defining the correct blasting intensity, it is necessary that the coverage be the most uniform as possible, what is determined by saturation curves which are obtained by evaluating Almen strips and gauges (Figure 7).

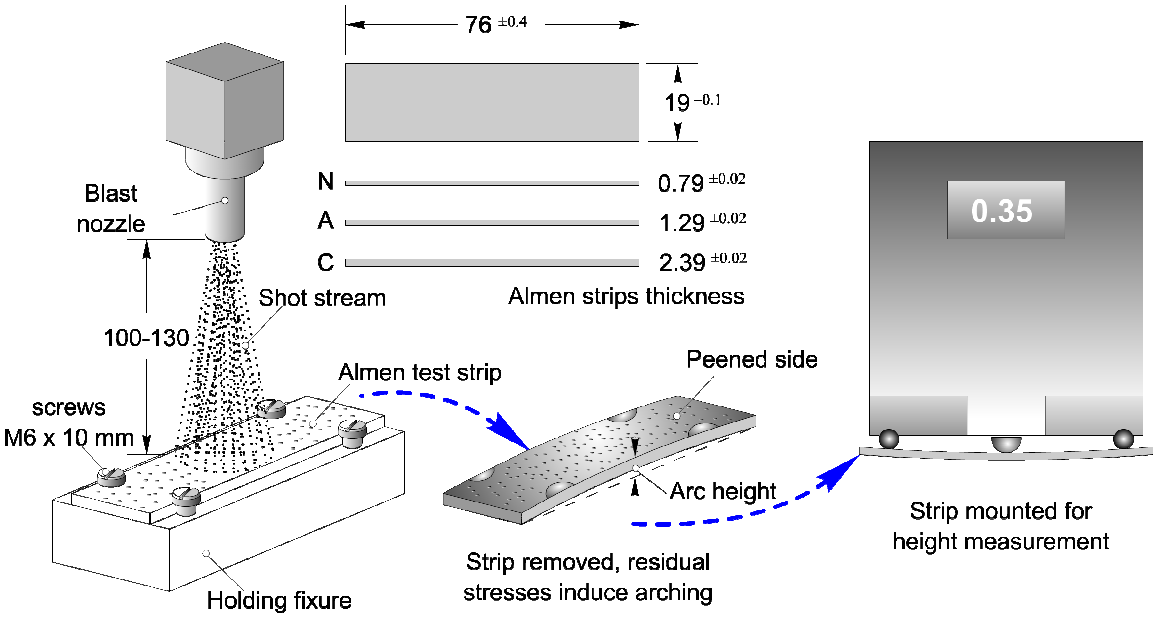

Figure 7. Almen strips deflected after shoot peening and measured with na Almen gauge.

A series of identical strips are exposed to spheres blasting with the same intensity but with different blasting times to obtain the saturation curve which is defined by the Almen deflection (Figure 8).

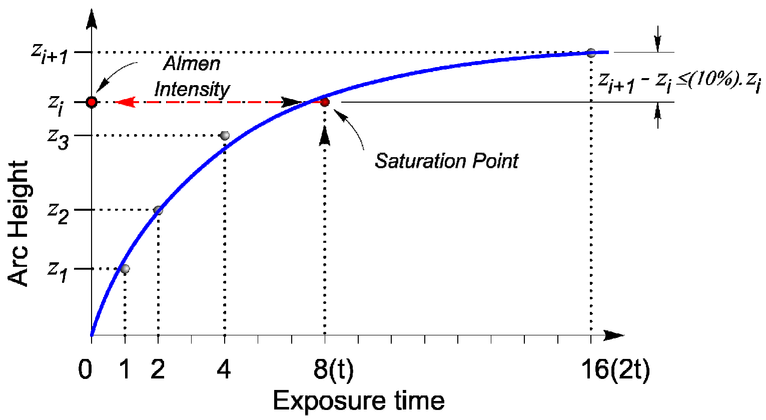

Figure 8. Saturation curve based on Almen tests.

The saturation is defined at the point of the curve in which doubling the blasting time will not increase the Almen deflection more than 10%. This minimum time t defines what is known as the “Almen intensity”.

3. MODELLING ONE SINGLE IMPACT

The dynamic modeling of one single impact was initially proposed by Johnson (1982) who developed a pseudo-dynamic approximation. In this work the elasto-plastic analysis of one and two impacts was modeled by using an explicit dynamic finite element model.

3.1 Finite element method

All the simulations were carried out with the commercial software MSC.Dytran 2005r3; the pre and post-processing were made with the software MSC.Patran 2005r3. The spheres with radius R which collide with the workpiece surface at a normal angle as shown in Figure 9a were modeled as shells and only in one half-quarter to reduce the computational time. The workpiece was modeled as a block 8 x 8 x 4 mm^3 to evaluate the same process conditions studied by Han *et. al*, (2002).

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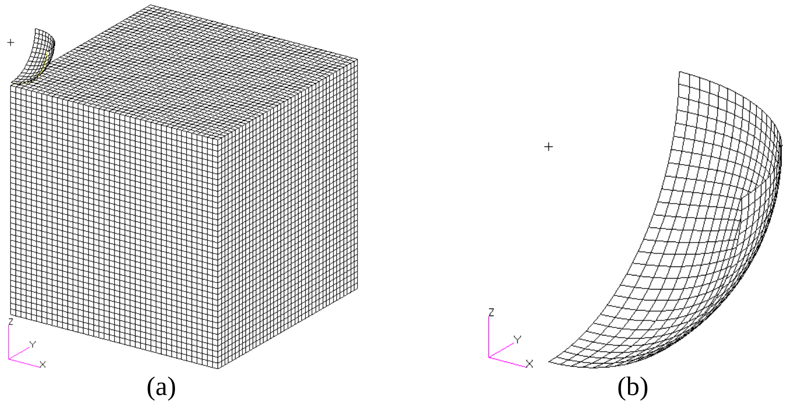

Figure 9. Finite element models: (a) workpiece modeled in one quarter;
(b) spherical shell 0.1 mm thick, modeled in one half-quarter with rigid shell elements.

The steel sphere (ρ = 7850 kg/m^3) is modeled as a rigid body, for having a higher hardness than the workpiece to be peened, and for being more appropriate for the most impact simulations, as verified by Meguid *et al.* (2002). The mas of the bulk sphere is an important input datum and was assumed to be m = 4.11x10-6 kg with a radius R = 1.0 mm. The materials of the workpiece ElasPlas(DYMAT24) and sphere Rigid(MATRIG) were chosen from the software library (Silva and Button, 2011). Table 1 shows the workpiece and shot properties used in the simulations.

Table 2. Material properties of the workpiece and shot.

Workpiece Properties	**Steel**	**Al Alloy 7050 T7651**
Density (ρ)	7.8x10^{-6} kg/mm^3	2.83x10^{-6} kg/mm^3
Elastic Modulus (E)	200.0x10^3 MPa	72.0x10^3 MPa
Poisson Ratio (ν)	0.3	0.33
Yield Stress (σ_y)	600.0 MPa	450.0 MPa
Tangent Modulus (E_t)	800.0 MPa	120.0 MPa
Sphere Properties	**Steel**	**Steel**
Density (ρ)	7.85x10^{-6} kg/mm^3	7.85x10^{-6} kg/mm^3
Diameter (D)	1.0	1.4
Mass (m)	4.11x10^{-6}kg	1.12x10^{-5}kg

3.2 Modeling of oblique impact

In real conditions the vector of the shot is rarely normal to the workpiece surface, because the surface geometry is seldom very complex and uneven. Furthermore, peening is very random, and shots can be transported either by pressurized air or by a centrifugal wheel as shown in Figure 3.

Shots streams have different shapes moving the spheres in several directions, therefore the spheres collide inside the stream and after they rebound at the workpiece surface.

To evaluate the effect of one single oblique shot the workpiece was modeled with half-symmetry and many different incidence angles were tested in the range 30 to 90º. The effect of the friction coefficient (μ) was evaluated with the incidence angle of 30º and tested in the range 0.0 to 0.5.

Al-Hassani *et al.* (1999) discretized a model to simulate SP with single oblique shot and used the software ABAQUS with the isotropic Coulomb friction equal to 0.1. The authors presented the results of axial stress versus peening time. Similar results are presented in this work and compared to Al-Hassani´s.

4. RESULTS E DISCUSSION

4.1 Single oblique shot

The kinetic energy of the shot is mostly transformed in plastic work. Since most of the impacts are not normal to the workpiece surface that energy is reduced by the velocity resolution, and is affected by the normal velocity component, and by the indentation depth (Figure 10b). As a result, the surface geometry is modified by the tangential component (Figure 10a).

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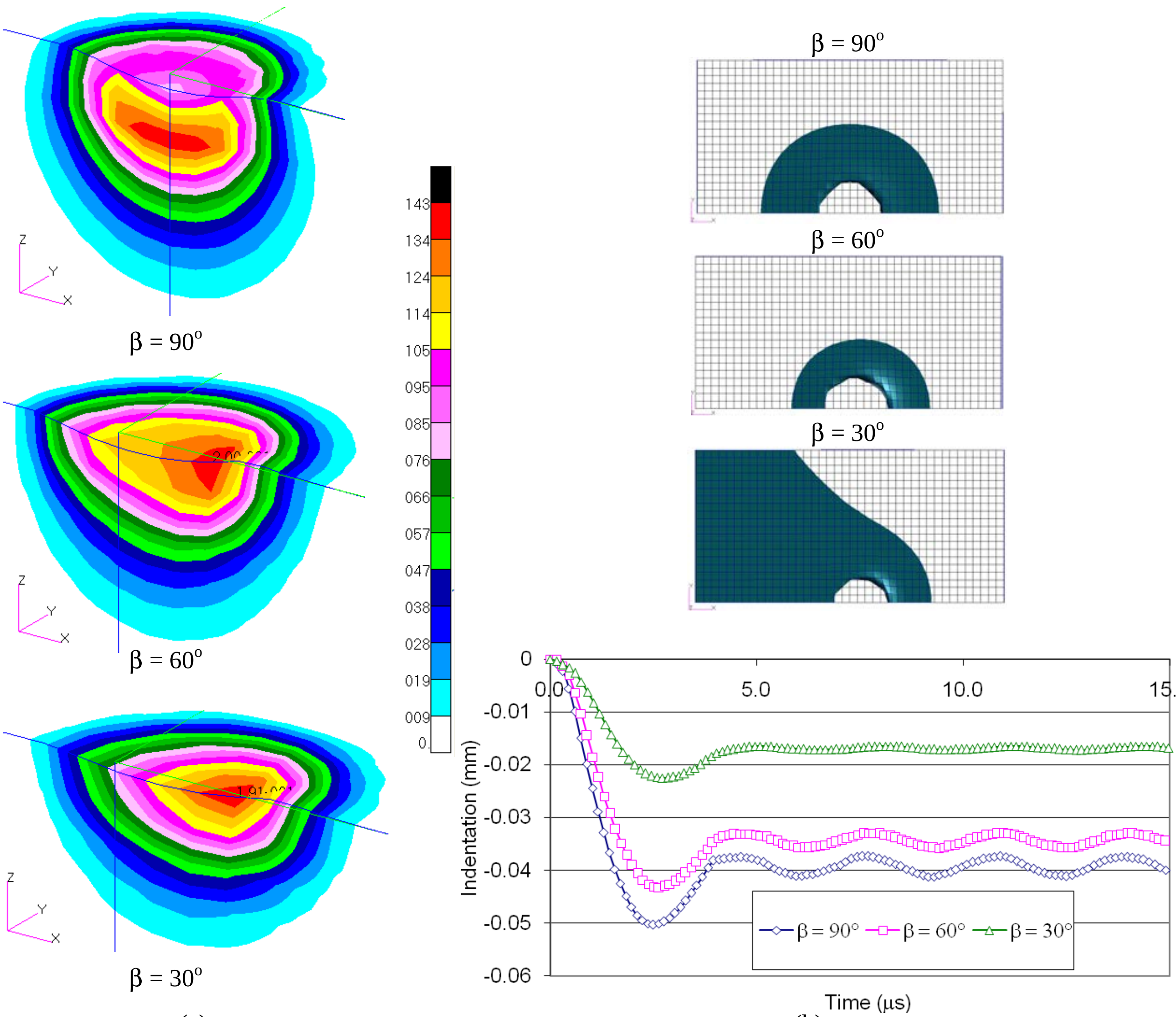
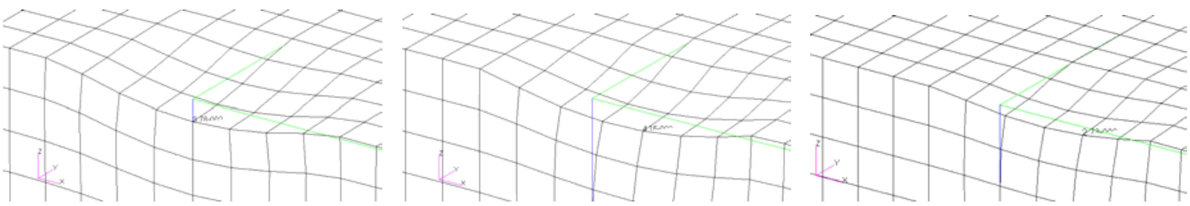
Figures 11 and 12 show the effect of the impact angle (β) on the depth of the compressed layer and on the distribution of residual stress for an impact 36 m/s fast in the direction of axis *x*, and impact angles 30, 60 and 90º with the workpiece surface, with Et = 120 MPa, μ = 0.2, and without damping.



(a) (b)

Figure 10. Effect of one single shot on: (a) equivalente plastic strain; (b) Z-displacement (indentation depth) (v = 36 m/s; R = 0.7 mm; μ = 0.2).



β = 90° β = 60° β = 30°

Figure 11. Effect of many oblique impacts of one sphere on the geometry deformation (v = 36 m/s; R = 0.7 mm; μ = 0.2).

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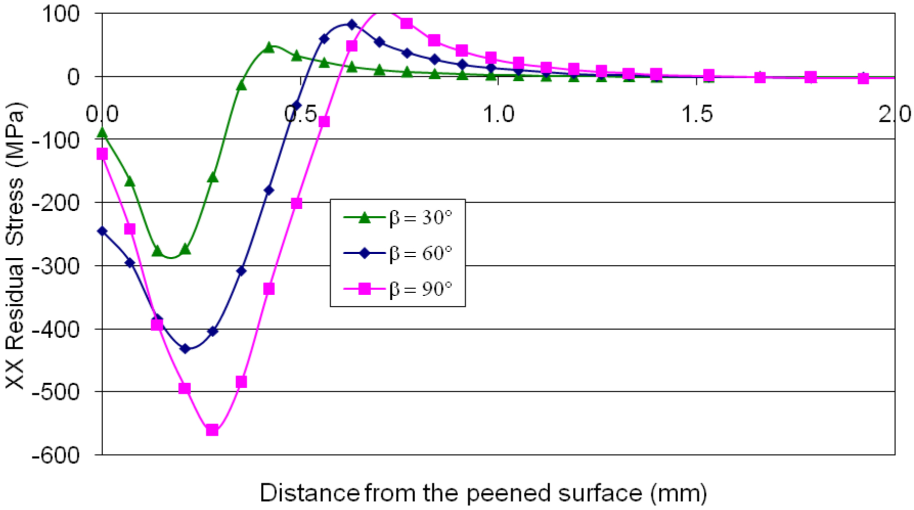
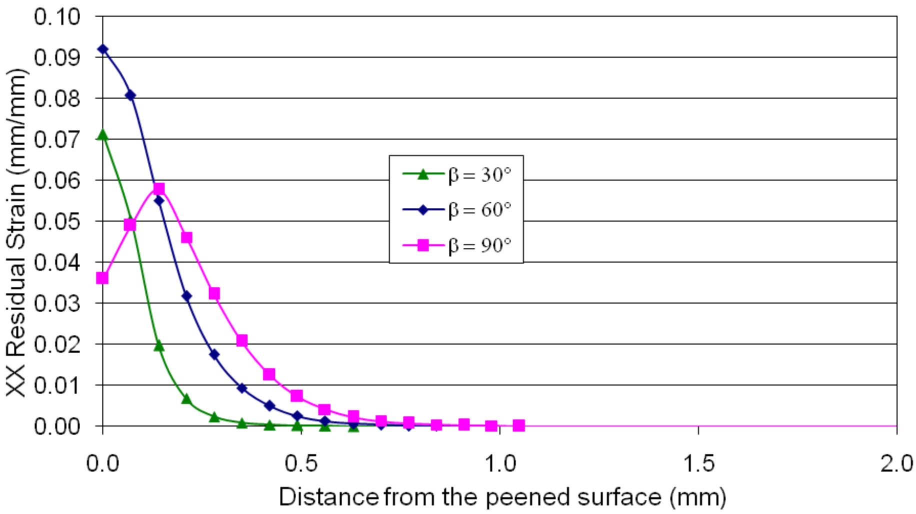


(a)



(b)

Figure 12. Effect of many oblique impacts of one sphere on: (a) XX residual stress in the indentation depth, (b) XX strain in the indentation depth (v = 36 m/s; R = 07 mm; μ = 0.2).

The indentation depth, the depth of the plastic region and the maximum compressive stress are increased with the incidence angle (β). An asymmetric region is formed from the impact normal to the surface (Figure 11).

4.2 Influence of the oblique impact and friction

Figure 13a shows that the depth of the plastic layer is not significantly affected by the friction coefficient for an incidence angle of 30º. Otherwise, the distributions of residual stresses and axial strains are substantially modified when the friction is increased as shown in Figure 13b. The dynamic damping coefficient (α) assumed to be 0.0012.

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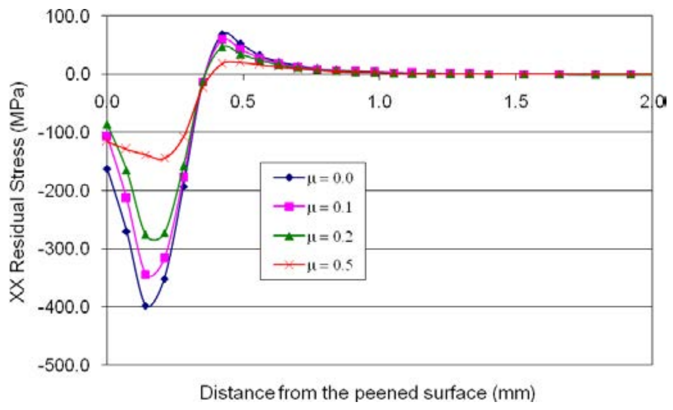
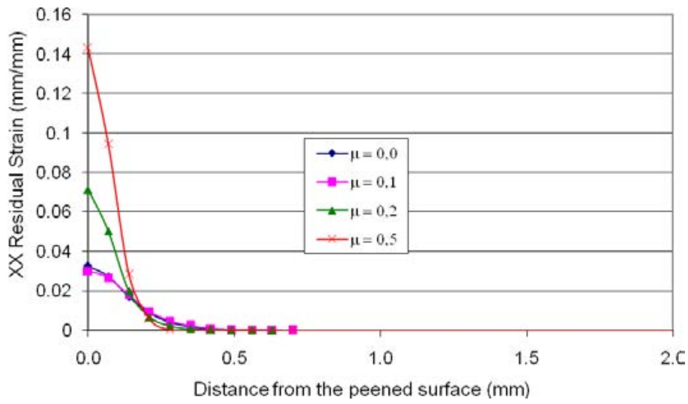


(a)



(b)

Figure 13. Effect of friction coefficient in the oblique impact ($\beta = 30^o$) on: (a) XX residual stress along the indentation depth, (b) XX plastic strain along the indentation depth. (v = 36 m/s; R = 0.7 mm; α = 0.0012).

Figure 14 shows that plastic strain at the impact point increases with the friction coefficient for an oblique impact ($\beta = 30^o$). The compressive stress is concentrated below the surface as the friction increases (Figure 15).

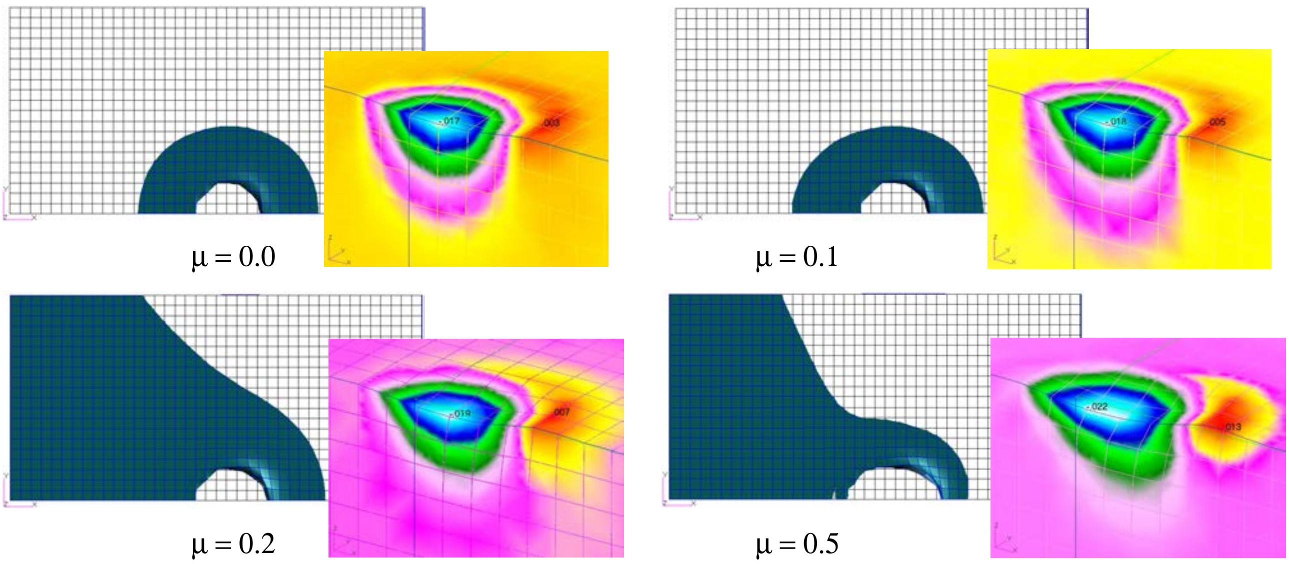
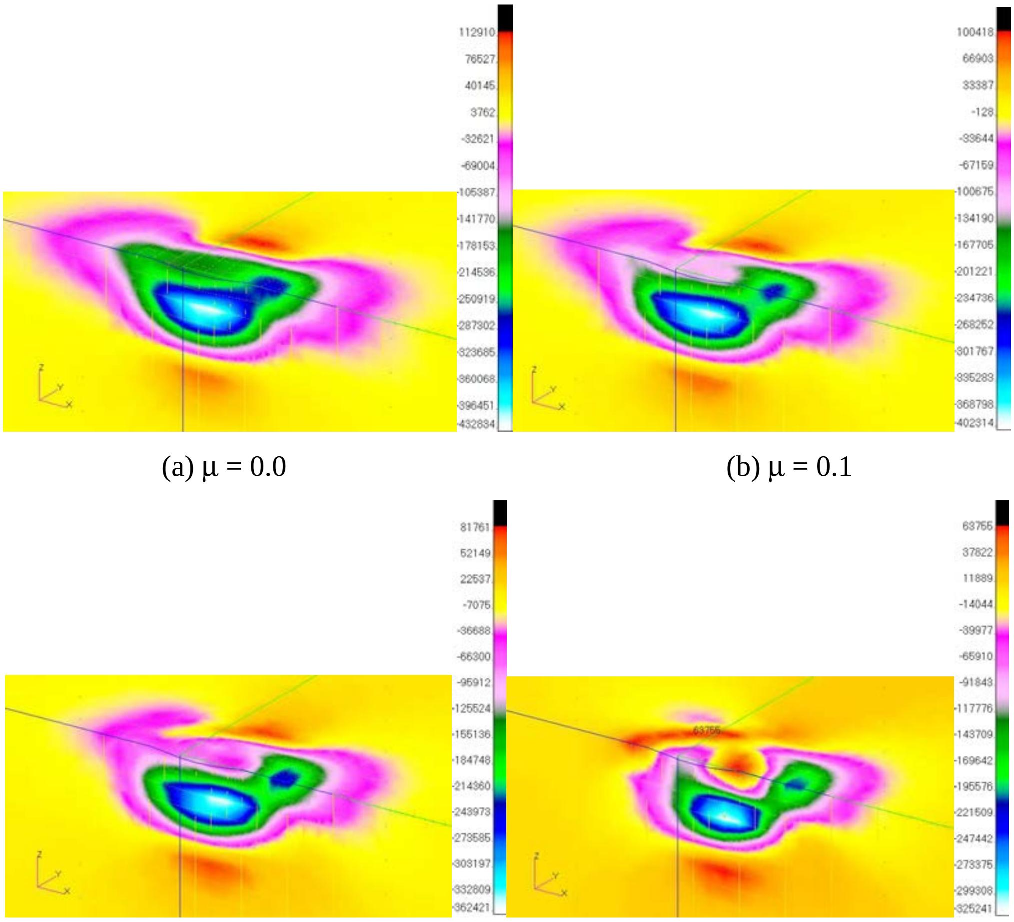


Figure 14. Influence of the friction coefficient for one oblique impact ($\beta=30^o$) on the geometry deformation at the impact surface (v = 36 m/s; R = 0.7 mm; μ = 0.2; α = 0.0012)



(a) $\mu = 0.0$ (b) $\mu = 0.1$

(c) $\mu = 0.2$ (d) $\mu = 0.5$

Figure 15. Influence of the friction coefficient for one oblique impact ($\beta=30^o$) on the XX residual stress (v = 36 m/s; R = 0.7 mm; μ = 0.2; α = 0.0012)

5. CONCLUSION

The residual stresses generated by peen forming give information of great industrial interest. Silva (2008) confirmed the results of Guagliano *et al.* (1999) that the main contribution to the residual stresses is due to the first impact, it was defined in this work that the analysis of one single oblique shot would be useful to evaluate the residual stresses.

The commercial software MSC.Dytran was used to simulate with the finite element method a tridimensional non-linear dynamics model. This model was used to evaluate the distribution of residual stress as result of shot peening with one single oblique impact.

Some process parameters which influence the stress distribution were evaluated for one single impact of one sphere assumed as rigid. The dynamic damping coefficient (α) assumed to be 0.0012 showed to be appropriate to dissipate the kinetic energy immediately after the impact.

As the incidence angle (β) decreases from 90 to 30º the surface deformation is significantly reduced, but a salience is formed at the right of the impact. The compressive residual stresses and the depth of the plastic layer are increased with the increase of the incidence angle.

With a constant incidence angle (30^o) the increase of friction reduces the compressive residual stresses and increases the plastic strain elongating the indentation, but do not affect the plastic layer depth.

All these results show the different influence of the friction coefficient when the incidence angle is changed: with an angle of 90º the results converge for μ=0.2 while they are not changed if the angle is equal to 30º.

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