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DYNAMIC SIMULATION OF A PEEN FORMING JET BLAST

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Abstract. *Peen forming is a plastic cold work process of shaping a metallic sheet or panel through the impact of a regulated blast of small round steel shots on its surface, in order to produce a previously desired curvature. The application of the shot peening as a forming process has been a well known technique in the industry for the last decades, but even in the recent years a good amount of research has been done in order to improve it. Peen forming process planning requires the measurement and control of several variables concerning the dynamics of the shot jet and its interaction with the piece to be shaped, As previously shown by several authors, impact velocity is one of the variables that most contribute to the development of the residual stress field that causes the material to bend. In this article we present a simplified dynamical model describing the motion of a large number of small spheres (shot) impelled by a steady air flow and suffering multiple collisions with each other and with the piece to be shaped. Computer simulations of this model permitted to identify correlations between the shot field velocity and the parameters of the process, a first step to furtherly design controlled systems for peen forming machines.*

Keywords*: shot peening, two-phase flows, peen forming, process planning*

1. INTRODUCTION

Peen forming is a plastic cold work process of shaping a metallic sheet or panel through the impact of a regulated blast of small round steel shots on its surface. This impingent flow of shots gives rise to a thin compressive residual stress which, in turn, produces a permanent elastic deformation in the worked surface (Stotsko and Stefanovych, 2010). If properly controled, local previously desired curvatures can be produced over the whole surface.

In order to design suitable peen forming processes, it is necessary to measure and control several variables encompassing the shot characteristics (diameter and material properties), the nozzle operation (massic shot flow, jet speed and angle), the part characteristics (dimensions, material properties, and boundary conditions) and the interaction between shots and part (impact velocity and exposure time) (Fleury et al., 2011). As previously shown by several authors (Al-Hassahi, 1981; Iida, 1984; Guagliano et al., 1999), impact velocity is one of the variables that most contribute to the induced residual stress field. Therefore, methods for either measuring or estimating the impact velocity distribution over the shaped part surface are of paramount importance for peen forming processes planning.

Lecoffre et al. (1992) developed an optical device able to continuously measure the velocity of individual shots on a small control volume of approximately 4 mm^3. The modulated signal of light due to the passage of a particle through the illuminated volume is captured by a calibrated photosensor and, after being properly conditioned, it is postprocessed and transformed in the shot temporal velocity signal. Linneman et al. (1996) used two photoelectric barriers separated by a defined distance to estimate the mean shot velocity, a process that requires identifying the paired signal peaks showing the passage of a particle through those barriers and calculating the respective interval time. The device proposed by Clausen and Stagenberg (2002) uses two rotating parallel linked disks – one with a small hole at certain distance of its center, the other (known as 'registration disk') provided with an angular scale for registration; using such a device, shot mean velocity can be expressed as a function of the arc linking the centroid of the shotted zone and the trace of the central line of the hole on the registration disk. Barker et al. (2005) reports a series of experiments to measure the shot velocity at the exit of a shot peening nozzle, for different input air pressures and nozzle geometries, using an instrument that determines the phase-shift of the signals arising from two electro-optical sensors that probe the shot flow.

A large number of articles concerning the simulation of granular flows and fluidized beds have been published in the literature (Valle, 2012; Berres et al., 2004), but only a few of them focuses shot peening processes. Sriram and Kosel (1987) implemented a mathematical computer model able to predict both the path through the deformable target material as well as the rebound velocities of spherical shots during the complete event of a collision with the target. The recently published article by Nguyen et al. (2014) addresses the implementation of a three dimensional mathematical model for the shot blast dynamics. These authors used a CFD commercial tool to describe the air flow while computed the individual trajectory of shots accordingly to a Lagrangian point of view. The results produced by the implemented computational model encompasses the distribution of shot velocities around the part and the correspondingly coverage (% of area impacted by the shots).

In the present article we propose a simplified two-dimensional mathematical model for describing the downstream velocity field of the solid particulate ejected by a Venturi nozzle during the application of shot peening processes to shape flat plates. Both the referred model as well as the results given by the computer simulations are presented and discussed in the next sections.

2. PHYSICAL MODELING

In a typical pneumatic shot peening machine, every shot describes a relatively complex path starting at the shot warehouse, passing through a pressurized chamber, a feeder valve and a long pipeline, to ultimately being expelled through a Venturi nozzle towards the surface of the part to be shaped. Clearly, the region comprising the exit section of the nozzle and the surface of the plate (Fig.1) is where the dynamic events that most contribute to induce a residual stress field take place. Therefore, only such a region will be focused in the present article.

To simplify even more the model, it is assumed that both the air flow and the shot motion are two-dimensional; in other words, that the shot flow is radially symmetrical. Moreover, it is admitted that the shot motion does not affect the air flow and that this have been achieved the steady state, following the typical pattern of a Gaussian impinging jet over a flat surface. The effect of friction impulsive forces during the collisions are neglected since, otherwise, a very thorough analysis would be required (Brossard, 1994), increasing significantly the complexity of the model. It is also assumed that collisions between shots are perfectly elastic, while those between shots and the plate are dependent on an empirical coefficient of restitution. The local deformations and global deflection of the plate were also neglected, as a way to simplify the model.

As the flow upstream the nozzle exit section is not taken into account in this model, the following assumptions regarding the shot flow at the exit section were made: 1^{st}) shots are randomly distributed along the diameter; 2^{nd}) the velocity magnitude of a shot coincides with that of the air flow at the same location; 3^{rd}) velocity magnitude of the shots (and also of the air) is normally distributed, its maximum being at the centre of the exit section; 4^{th}) the orientation angle of the shot's velocity follows a Gaussian distribution with mean 0 at the center of the exit section (i.e., it is assumed that shots on the center of the nozzle are more likely to go straightly forward when leaving the nozzle than shots near the borders of the nozzle).

The reference data encompassing the relevant geometrical and operational parameters of the shot jet (Fig.1) are presented in Tab. 1.

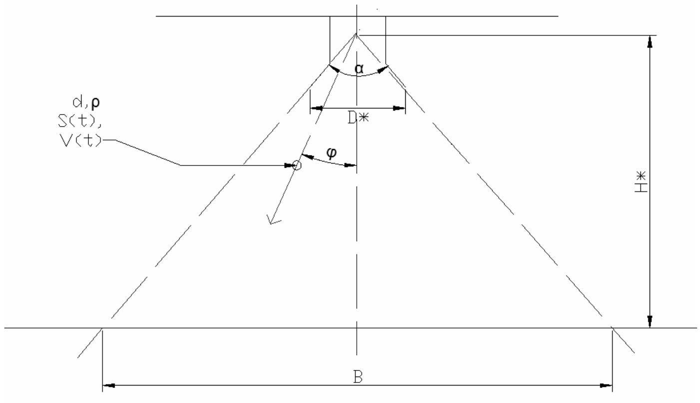

Figure 1. Reference geometry adopted in the simulations.

Parameter	Reference Value
Shot diameter (*d*)	1.18 mm
Nozzle diameter (*D*)	9.5 mm
Distance between plate and exit nozzle section (*h*)	120mm
Coefficient of restitution for collisions between plate and shot (*Cr*)	0.5
Mean particle velocity at the nozzle exit (*V*)	28 m/s
Nozzle opening angle (*α*)	45^{o}

Table 1. Reference parameters

3. MATHEMATICAL MODELING

In order to describe the motion of the shot through the air jet, the Basset-Boussinesq-Oseen equation for incompressible fluids (Hryb *et al*., 2009) was adopted:

$$\rho^p\left(\frac{dv^p}{dt}\right)=\left(\rho^p-\rho^f\right)g+\frac{3}{4}\frac{\rho^f}{D^p}C_d\,(v^f-v^p)\,|\,v^f-v^p\,|-\frac{\rho^f}{2}\frac{dv^p}{dt} \tag{1}$$

where

ρ^p and ρ^f represent the particle and the fluid densities respectively,

v^p and v^f are the instantaneous velocities of the particle and the fluid, respectively,

g is the gravitational acceleration,

D^p is the shot's diameter,

C_d is the drag coefficient .

Equation 1 takes into account all the relevant forces acting on the shots. Considering only the right side terms, the first represents the net gravitational force (weight minus buoyancy), the second corresponds to the drag force and the last corresponds to the added mass force.

The drag coefficient is supposed to depend only on the particle's Reynolds number (*Re^p^*). According to Perry and Green (1973), the following empirical equations can be used to determine C_d :

$$C_d=24\cdot\left(1/\mathrm{Re}^p\right) \qquad \mathrm{Re}^p<0{,}1$$
$$C_d=24\cdot\left(1/\mathrm{Re}^p\right)\cdot\left(1+0{,}14\,\mathrm{Re}^{0{,}7\,p}\right) \qquad 0{,}1<\mathrm{Re}^p<1000$$
$$C_d=0{,}445 \qquad 1000<\mathrm{Re}^p<35000$$

By making explicit the particle acceleration term on Eq. (1), one gets:

$$\frac{dv^p}{dt}=\frac{2}{2+\rho^*}\left[(1-\rho^*)g+\frac{3}{4}\frac{\rho^*}{D^p}D_d\,(v^f-v^p)\,|\,v^f-v^p\,|\right] \tag{2}$$

It can be noticed that if the air flow were known *a priori*, the numerical integration of the above equation for each shot would generate the temporal description of its velocity and position.

In this work, the analytical model of a Gaussian impinging jet, presented by Xu et al. (2012) is adopted. According to those authors, the stream function and the radial and axial components of the velocity are given, respectively, by:

$$\psi=-\frac{k}{2}\left(1-e^{-r^2/k}\right)+r^2e^{-r^2/k}\sum_{n=1}^{\infty}c_nL_n^1\left(\frac{2r^2}{k}\right)e^{-\left(\sqrt{8n/k}\right)z} \tag{3}$$

$$u(r,z)=re^{-r^2/k}\sum_{n=1}^{\infty}c_nL_n^1\left(\frac{2r^2}{k}\right)\left(\sqrt{8n/k}\right)e^{-\left(\sqrt{8n/k}\right)z} \tag{4}$$

$$w(r,z)=re^{-r^2/k}+2\left(1-\frac{r^2}{k}\right)e^{-r^2/k}\sum_{n=1}^{\infty}c_nL_n^1\left(\frac{2r^2}{k}\right)e^{-\left(\sqrt{8n/k}\right)z}+re^{-r^2/k}\sum_{n=2}^{\infty}c_ne^{-\left(\sqrt{8n/k}\right)z}\,\frac{\partial L_n^1\left(2r^2/k\right)}{\partial r} \tag{5}$$

where

$$r = r^* / R^* \qquad z = z^* / H^* \tag{6}$$

$$k = 2.2\left(0.07\frac{H^*}{R^*} + 0.294\right) \tag{7}$$

In the above equations r and z are the dimensionless coordinates of the flow, r^* and z^* their respectively actual values, R^* is the nozzle radius and H^* is the distance between the nozzle exit section and the plate . L_n^1 and $\partial L_n^1 / \partial r$ are, respectively, Laguerre polynomials and their radial partial derivatives, both of which can be approximated by recursive formulas presented in the same article (Xu et al., 2012).

For the reference parameters of Table 1, equations 3 to 5 give rise to the air velocity streamlines sketched at Fig.2.

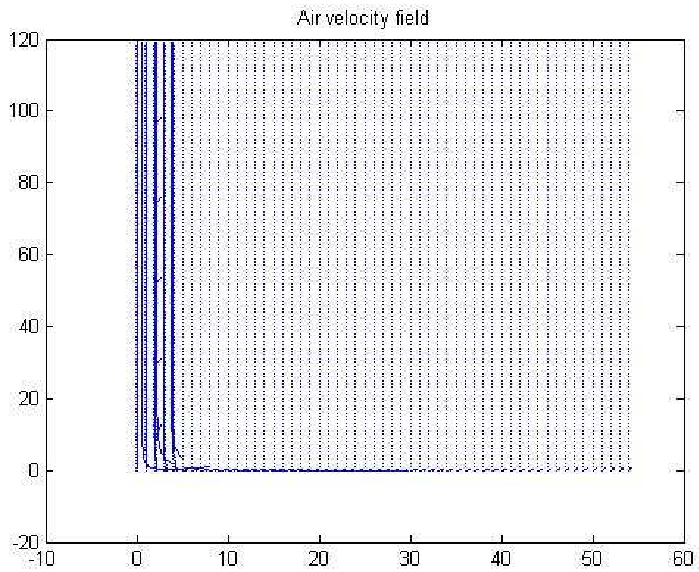

Figure 2. Air velocity field.

As mentioned above, since v^f be known, the iterative numerical integration of equation (2) provides at time t the estimations for $\vec{v}^p(t+dt)$ and $(x^p(t+dt), y^p(t+dt))$. However, it is necessary to verify, at each step, the ocurrence of an eventual between the considered shot and either the plate or another shot. This can be done by simply testing if another shot belongs to a small neighborhood of the focused one or if this is very close to the plate surface. In the case where collision between shots occurs, the velocities of the shots immediately after the collision are given by

$$\vec{v}_{i2} = \left(\frac{m_i - m_j}{m_j + m_i}\right)\vec{v}_{j1} + \left(\frac{2m_j}{m_i + m_j}\right)\vec{v}_{j1}$$
$$\vec{v}_{j2} = \left(\frac{m_j - m_i}{m_j + m_i}\right)\vec{v}_{j1} + \left(\frac{2m_i}{m_i + m_j}\right)\vec{v}_{i1} \tag{8}$$

where the indices i and j are the labels of the colliding shots and the indices 1 and 2 account to the states immediately before and after the occurrence of a collision between particles i and j .

On the other hand, since the collisions with the plate are assumed as inelastic and frictionless, the shot velocity immediately after the collision with the plate is given by:

$$v_y^p = -v_y^p * C_r \qquad 0 < C_r < 1 \tag{9}$$

4. RESULTS AND ANALYSIS

Using Matlab™, the mathematical model presented before was firstly simulated for the reference state. Then, a design of experiments was implemented based on Table 2, where typical values are assigned for the following parameters: coefficient of restitution (C_R), shot diameter (d), exit nozzle diameter (D), distance between nozzle and plate (H^*) and mean velocity at the nozzle exit section ($\overline{v}_n$). Combining these values according to a fractional factorial design, suitable data (histograms for shots position, velocity, number of impacts and kinetic energy) for sensibility analysis has been generated.

Parameter	Values					Unit
d	0.5	0.85	1.18	2	3.35	[mm]
D	6.4	7.9	9.5	12.7	15.9	[mm]
H^*	60	90	120	150	180	[mm]
C_R	0.1	0.3	0.5	0.7	0.9	
v_n	7.78	17.78	27.78	37.78	47.78	[m/s]

Table 2. Parameters used to analyze sensibility.

As shown in Fig. 3, a simulation based on the reference parameters allowed to identify the trajectories of the first 100 shots expelled by the nozzle.

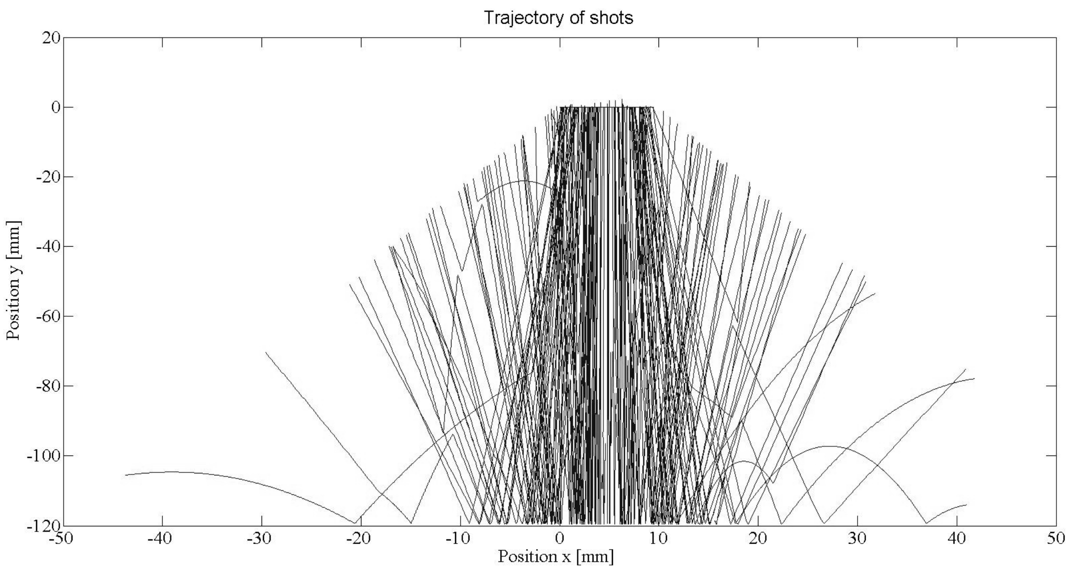

Figure 3. Trajectories of the shots.

Using also the reference values and considering the motion of 250 shots, the spatial distribution of collisions between shots, several other distributions could be identified.

Figure 4a. shows that collisions between two shots occur mostly on the regions far from the nozzle, where most of the shots that rebound after hitting the plate collide with the incoming ones. This region is also where shots with minor velocities continue to shock with others, since these do not have enough speed to leave this region by themselves, and are dependent on the fluid to get dragged out horizontally. In order to reach and collide in positions near the nozzle, the shots must overcome the barrier of incoming ones, which makes this path harder to get through. As a result, the number of collisions decreases on regions closest to the nozzle.

Figure 4b. shows a binormal distribution of velocity with a bigger peak in the interval comprising the negative velocities. This behavior occurs because almost every incident shot will shock with a rebounding, low speed one, so it is reasonable that the number of incoming shots that collide will not be greater than the number of rebounding shots. The left peaks gets bigger as these slower shots collide with each other. The two peaks seen in this graphic represent the mean velocity of the impingent shots and the velocity of shots just after hitting the plate.

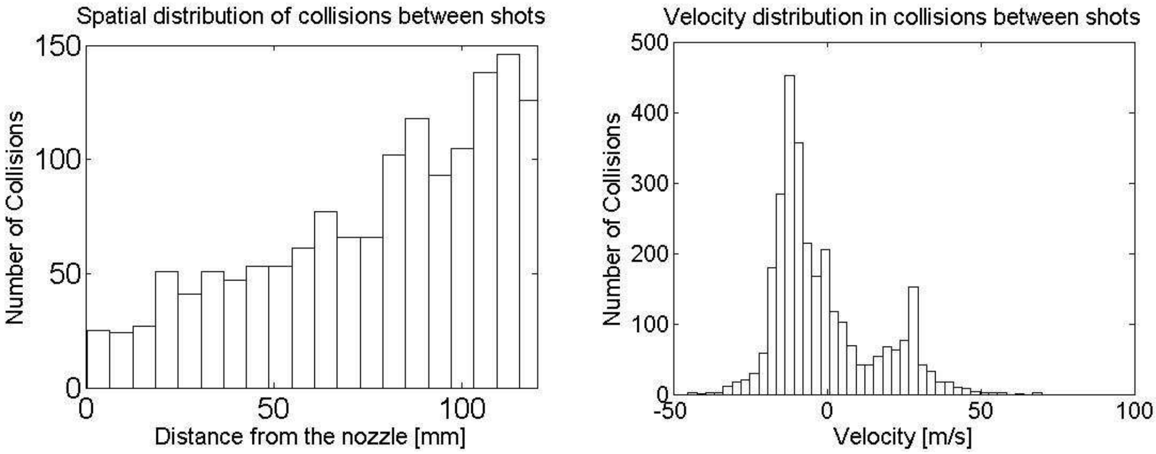

Figure 4. Collisions between shots. (a) Spatial distribution; (b) Velocity distribution.

Fig. 5a suggests that the distribution describing the collisions with the plate is Gaussian. Similar pattern can be observed in the histogram of Fig. 5b, concerning the spatial distribution of the kinetic energy transferred to the plate.

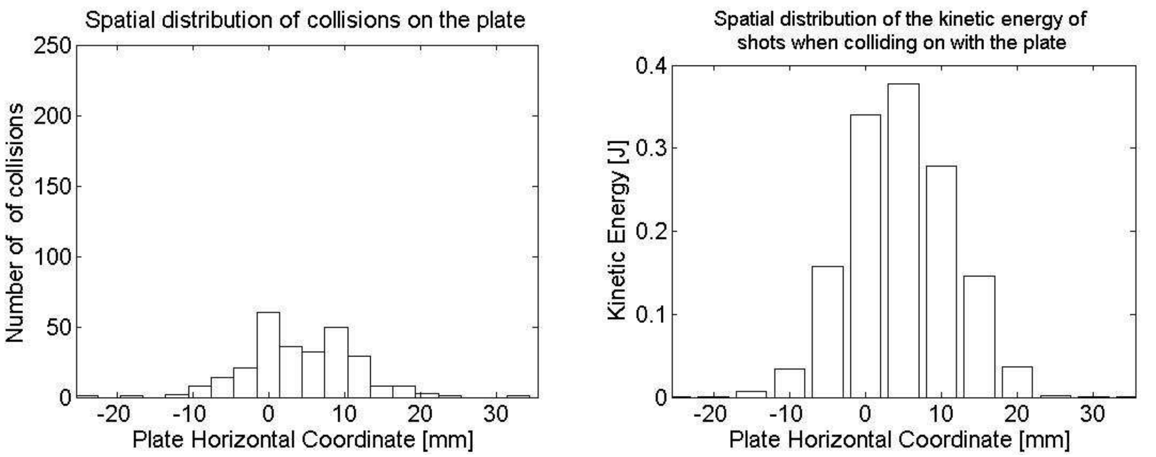

Figure 5. Collisions with the plate: (a) Spatial distribution (b) Transferred kinetic energy distribution.

Simulations of the model for several combinations of the parameters values from Table 2 gave rise to important results.

In Figs. 6a-b it can be observed that the use of shots with different diameters leads to significant changes in the number of collisions between shots and in the quantity of kinetic energy transferred to the plate. As the shot diameter increases, the average free space between shots diminishes; so, the number of collisions increases. However, as shown in Fig.7, increase in the number of collisions does not change the binormal characteristic of the distribution of velocities.

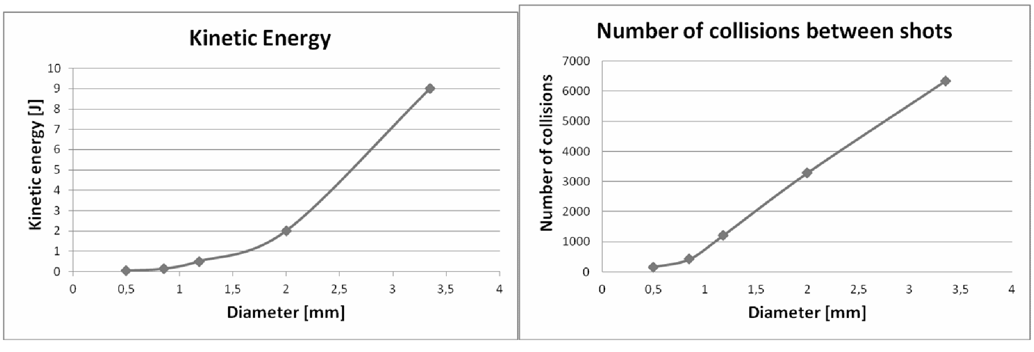

Figure 6. Effects of shot diameter: (a) kinetic energy transferred to the plate; (b) collisions between two shots.

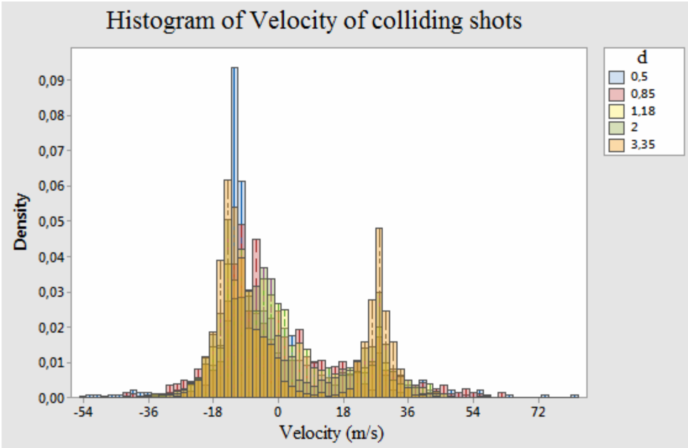

Figure 7. Velocity of shots during collisions.

Concerning the coefficient of restitution, as it decreases the same occurs with the velocity of rebounding shots, forcing them to stay near the plate and increasing the number of collisions between shots and between shots and plate (see Figs. 8a-b). However, no relevant changes in the distribution of the transferred kinetic energy can be observed, since these new collisions with the plate are all due to slow shots. On the other hand, both the spatial and the velocity distributions are altered. The first one gets stretched to the left, meaning that most collisions happen near the plate (Fig.9a) while the latter has the left side of the peak increased and moved to values near zero (Fig.9b).

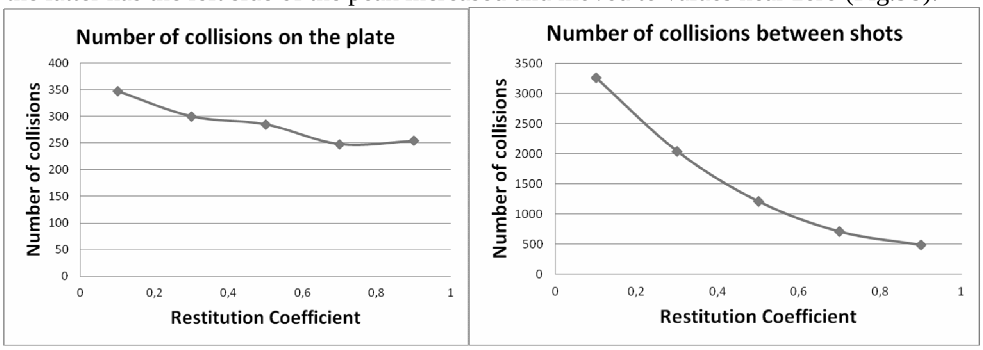

Figure 8. Coefficient of restitution effects. (a) collisions with the plate (b) collisions between two shots.

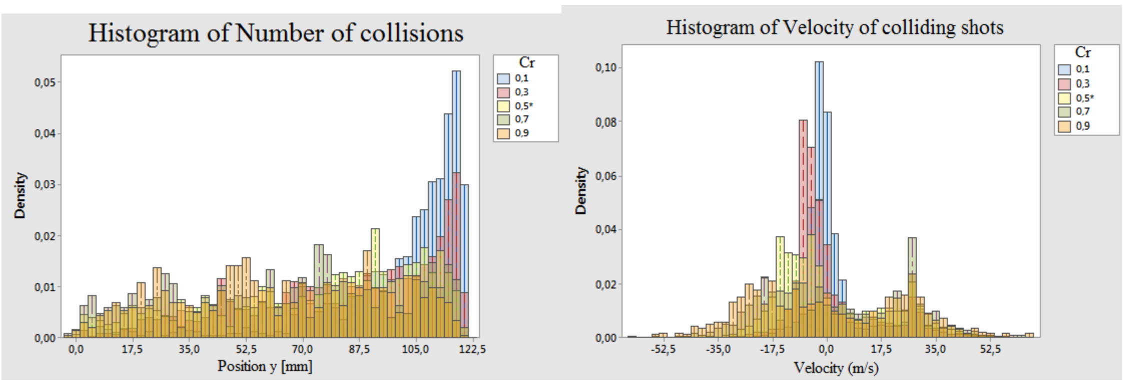

Figure 9. Coefficient of restitution effects on collisions: (a) spatial distribution (b) velocity distribution.

The variation in the air velocity at the nozzle exit section has a smaller impact on the kinetic energy transferred to the plate when compared to the shot diameter's influence (Fig 10a). Although the kinetic energy varies quadratically with the velocity, the mass increases with the cube of the shot diameter. As it can be seen at Fig. 10b, when the air velocity at the nozzle exit section is reduced, there is an increase in the number of collisions between shots. It is also noted that as the mean velocity decreases, the distance between peaks in Fig.9.b decreases, but the characteristics of the velocity distribution of collisions continue the same.

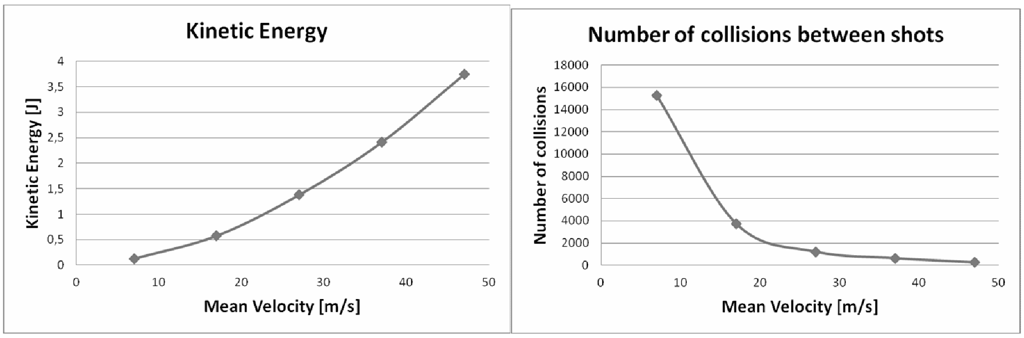

Figure 10. (a) total kinetic energy applied to the plate (b) number of collisions between two shots

The influence of the nozzle diameter and the distance between nozzle and plate are not much noticeable. The only facts that can be observed are that the area covered by the jet increases slightly and the kinetic energy of the shots gets more dispersed in both cases. The number of collisions with the plate and between shots is not significantly altered, and nor is the number of shots that never reaches the plate.

5. CONCLUSIONS

Despite the simplifying assumptions adopted to construct the mathematical model of a shot peening jet impinging on a flat plate, the first results provided by numerical simulations of this model, encompassing variations on the values of four design parameters of the process (shot diameter, exit nozzle diameter, air velocity at the exit section of the nozzle, distance between the exit nozzle and the plate) and an operational one (coefficient of restitution, dependent on the materials of the shots and the plate), indicate that it is possible to identify a proper combination of process parameter values that generate a shot blast able to transfer to the plate the necessary kinetic energy to produce previously known local deformations.

The essential outcome variable to be calculated, which is the plate's residual stress field, has not yet been introduced in the analysis, but will be investigated in further studies. By calculating this variable, it will be possible to estimate local deformations on the plate. This will be an important result to design controlled systems for peen forming machines.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Al-Hassani, S.T.S., Mechanical aspects of residual stress development in shot peening. Proceedings of the 1sr Conference on Shot Peening, 1981, p.583-602.

Barker, B., Young, K., Pouliot, L., Particle velocity sensor for improving shot peening process control. *Proceedings of the 9th International Conference on Shot Peening*, 2005, p. 385-391.

Berres, S., Bürger, R., Tory, E.M., On mathematical models and numerical simulation of the fluidization of polydisperse suspensions. *Applied Mathematical Modelling*, 29, 2005, p.159-193.

Brossard, J.P., *Mécanique Générale*. INSA de Lyon, 1994.

Clausen, R., Stangenberg, J., Device for the determination of impact velocities in shot peening. *Proceedings of the 8th International Conference on Shot Peening*, 2002, pp. 89-95.

Fleury, A.T., Martins, F.P.R., Almeida, R.Z., Szilagyi, G., Delijaicov, S., Pavanello, R., Button, S.T., Bravo, C.M.A.A., Gonçalves, M., Ponge-Ferreira, W.A., Braga, A.P.V., Modelagem, simulação e validação experimental de processos de peen forming em placas de ligas de alumínio. *Anais do 6º Congresso Brasileiro de Engenharia de Fabricação*, 2011, 10p.

Guagliano, M., Vergani, L., Bandini, M., Gili, F., An approach to relate the shot peening parameters to the induced residual stresses. Proceedings of the 7th International Conference on Shot Peening, 1999, p.274-282.

Hryb, D., Cardozo, M., Ferro, S., Goldshmit, M., Particle transport in turbulent flow using both lagrangian and an eulerian formulation. *International Communications in Heat and Mass Transfer*, Vol.36, n.5, 2009, p.451-457.

Iida, K., Dent and affected layer produced by shot peening. *Proceedings of the 2nd International Conference on Shot Peening*, p.283-292.

Lecoffre, Y., Bonazzi, X., Jouet, F., Huet, D., A real-time particle velocity measurement system for use in shot peening. *The shot peener*, Vol. 7, no. 2, 1992, p. 22-24.

Linnemann, W., Kopp, R., Kittel, S., Wüstfeld, F., Shot velocity measurement. Proceedings of the 6th International Conference on Shot Peening, 1996, p. 118-129.

Nguyen, V.B., Poh, H.J., Zhang, Y.H., Predicting shot peening coverage using multiphase computational fluid dynamics simulation. *Powder Technology*, Vol.256, 2014, p.100-112.

Perry, R.H., Green, D.W., *Perry's Chemical Engineers' Handbook*, McGraw Hill. 1973.

Rodriguez, O.M.H., Mudde, R.F. Oliemans, R.V.A., 2006. Stability analysis of slightly-inclined stratified oil-water flow and intermediate wave theory. In *Proceedings of the 11th Brazilian Congress of Thermal Sciences and Engineering - ENCIT2006*. Curitiba, Brazil.

Sriram, T.S., Kosel, T.H., Computer modeling of the rebound characteristics of spherical erodent particles. *Proceedings of the 7th International Conference on Erosion by Liquid and Solid Impact*, 1987, 8p.

Stotsko, Z.A., Stefanovych, T.O., Ensuring uniformity of strengthening for machine parts surfaces by shot-peening. *Journal of Achievements in Materials and Manufacturing Engineering*, Vol. 43, Nov. 2010, p. 440-447.

Valle, Romero. Numerical Modeling of Granular Flows in Rotary Kilns. *Literature Survey Report*. Delft University of Technology. 2012.

Xu, Z., Hangan, H., Yu, P., Analytical solutions for a family of Gaussian impinging jets. *Journal of Applied Mechanics*, V.75, 2008, 12p.

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