INTERNATIONAL DESIGN CONFERENCE - DESIGN 2012
Dubrovnik - Croatia, May 21 - 24, 2012.

CAD BASED SIMULATION OF ULTRASONIC SHOT PEENING PROCESS

J. Badreddine, S. Remy, M. Micoulaut, E. Rouhaud, V. Desfontaine,
F. Chateau, G. Doubre-Baboeuf and P. Renaud

Keywords: ultrasonic shot peening, CAD, design tool, simulation, mesh

1. Introduction

Ultrasonic shot peening is a mechanical surface treatment process that consists in shooting spherical shot onto a metallic surface. The shot is contained in a peening chamber, designed especially for the part to be treated. A generator delivers a signal, with a pre-set frequency (usually 20 kHz), to a piezoelectric crystal that transforms it into a vibration. The latter is amplified by a booster and transmitted to the sonotrode, thus propelling the shot upwards, with velocities that can reach 20 $m.s^{-1}$.
During a peening operation, shot bounce around in the chamber, and back and forth between the sample and the sonotrode. The multiple impacts on the sample induce compressive residual stresses that enhance the mechanical properties of the sample material, i.e. higher yield strength and rupture limit, as well as its life span. These residual stresses highly depend on process parameters such as shot velocities, the impact angles and the surface coverage [Xing and Lu 2004], [Mordyuk and Prokopenko 2007] and [Boyce et al. 2001]. This process is used in the aeronautic, energy and automotive industries.
On a numerical point of view, numerical models of all kind can be found in the scientific literature dealing with the effects of shot peening on the treated material. These models, whether they are semi-analytical or analytical models or based on the Finite Elements Method (FEM), take for input on one hand process parameters that are known and easy to access, like the diameter and amount of shot, the sonotrode amplitude and frequency of vibration, or the chamber geometry. On the other hand, physical parameters, that are unknown or very difficult to measure, are also expected to achieve the calculation, such as the shot velocities, the impact distribution and velocities or the angles of impact. The compressive residual stresses induced in the peened material are governed by these physical parameters, themselves dependent on the various process parameters. Therefore, it is very important to understand exactly what happens in the peening chamber, in term of shot dynamics, and associate it to the process parameters, in order to obtain realistic and precise predictions on the residual stresses generated in the sample. So far, all the existing models try to reproduce the effects of the process on the peened component, but with very little knowledge on the process itself, i.e. what is happening in the ultrasonic peening chamber, considered as a black box. After identifying a crucial need in the field of ultrasonic shot peening, a model of the shot dynamics has been created, based on granular gases theory, and allows tracking the trajectories of the spheres. In doing so, we are able to simulate thousands of impacts on the treated surface, from which statistical studies can be made to obtain direct information on the physical parameters. These results can afterwards be used by the existing models to predict the effects of the process on the impacted component. It is important to precise that a specifically designed ultrasonic shot peening chamber must be made for each mechanical part that needs to be shot peened. However, no dedicated tool for the design and/or optimization of the

ultrasonic peening chamber, using feedback based on the shot dynamics, is available at this time. Everything is done empirically or based on the designer's experience and knowledge making the design process costly and time consuming for complex parts, hence the importance of our approach.
In this paper, the general hypothesis and structure of the analytical model will be presented in the first section. In the second section, the integration of a CAD environment into the model will be presented and explained in more detail. A comparative study will then be made between the analytical and CAD based model to make sure we obtain the same results, for a given peening setup and parameters.

2. Analytical model of the shot dynamics

The fact that the shot (spherical balls) used in ultrasonic shot peening is submitted to high frequency vibrations, produced by the sonotrode, makes it act like the particles of a granular gas. This allowed us to develop a model based on the theory of confined vibrated granular gases [Badreddine et al. 2011a]. In its current version, we can simulate the ultrasonic peening process for simple chamber geometries, i.e. a cylinder, a box and a prism, that gives an insight on the behaviour of the spheres, excited by the vibrating sonotrode, in a confined environment (Figure 1). All surfaces are defined by their Cartesian equations. This allows performing analytical calculations making the model precise and very fast to compute.

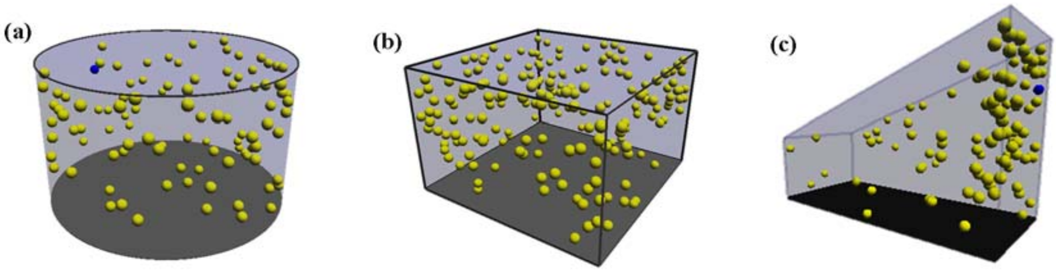

Figure 1. Screenshots of peening chamber geometries supported by the analytical model. a) cylinder, b) box and c) prism. (color online)

The model uses an Event-Driven algorithm that allows tracking all of the spheres by calculating the shortest next time of impact T_{BEST} between all possible collisions, i.e. Sphere-Sphere and Sphere-Wall collisions. Between two collisions, a sphere P, defined by its initial position $\overrightarrow{OP} = (x_0, y_0, z_0)$ and velocity $\vec{V} = (V_x, V_y, V_z)$, follows a parabolic trajectory arising from gravity g, as shown below:

$$\begin{aligned} x(t) &= V_x.t + x_0 \\ y(t) &= V_y.t + y_0 \\ z(t) &= -\tfrac{1}{2}g.t^2 + V_z.t + z_0 \end{aligned} \tag{1}$$

$(x(t), y(t), z(t))$ are the coordinates of the particle P at an instant t. In case of a Sphere-Wall collision, these coordinates correspond to the boundary conditions defining the Wall, i.e. its analytical equation embedded in the model. The energy dissipation due to air friction and rotational energy is neglected. The shot is modeled as solid hard spheres. The impacts are considered inelastic where contact is instantaneous. Sphere-Sphere and Sphere-Wall collisions are detected and take into account the energy dissipation at impact through normal (C_i, i = [SHOT, WALL, BOT, TOP]) and tangential restitution coefficients. The latter is considered constant with a value of 1 and related to friction and surface topography. However, the normal coefficients follow the power law given bellow; according to phenomenological models [McNamara and Falcon 2005] and experiments [Micoulaut et al. 2007]:

$$C_i(v) = \begin{cases} C_0^i & if\ v < v_0^i \quad (elastic\ deformation) \\ C_0^i \left(\frac{v}{v_0^i}\right)^{-0.25} & if\ v \geq v_0^i \quad (plastic\ deformation) \end{cases} \tag{2}$$

In equation (2), v corresponds to the normal impact velocity of a sphere, v_0^i is the normal velocity threshold signalling the start of important local plastic deformation at the point of impact. The normal coefficient threshold C_0^i, corresponding to v_0^i, dictates the amount of kinetic energy restored to the sphere after rebound for an elastic impact. Figure 2.a shows the impact distribution obtained experimentally when peening a 10 mm thick aluminum plate, placed on top of a cylindrical chamber and 15 mm from the sonotrode, for 50 seconds. Figure 2.b also shows the impact distribution obtained with the analytical model, using the same experimental process parameters, for impacts with normal velocities higher than v_0^i, as only these impacts will leave a crater at the surface of the material. The crater size in Figure 2.b, has been chosen proportionally to the normal impact velocities.

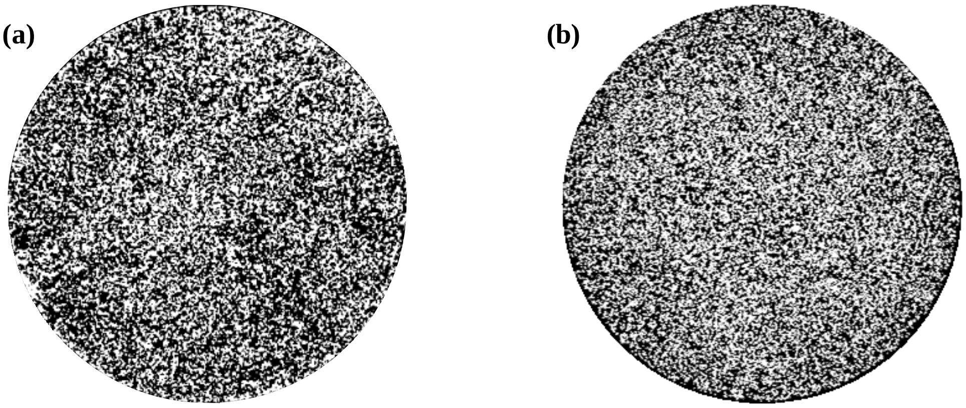

Figure 2. Surface coverage C_{ov} obtained a) experimentally (C_{ov} = 39%) and b) numerically (C_{ov} = 41 %) on the upper surface of the cylinder, using the same process parameters. Black areas correspond to non-impacted zones

Although, some differences can be observed between the experimental and numerical impact distributions due to surface roughness and irregularities of the used materials, it can be observed that the surface coverage C_{ov}, the percentage of impacted area by the total area to be ultrasonically shot peened, are very close in both cases. A surface coverage of 39% and 41% are obtained respectively from the experimental and numerical data. A more detailed study of the influence of process parameters on the impact velocities and angles, using the analytical model, can be found in [Badreddine et al. 2011b].

3. Integration of a CAD based model

The model, as described above, allowed gaining valuable information about the physics taking place in the chamber. However, its limitations are reached when wanting to simulate the process on realistic mechanical parts, i.e. complex geometries that cannot be simply described by analytical equations. Even if possible, modifications must be made in the source code itself, reducing the flexibility of the model. To better grasp the difficulties of describing complex geometries using only analytical equations, let us consider a gear**.** Gears have geometries that are not trivial to model and are a good example of mechanical parts commonly shot peened as they are subject to high loading and fatigue.

One way to go beyond this limitation is to integrate a CAD based model of the entire peening setup in the simulation. The best way to simulate manufacturing processes, as shown by [Derigent et al. 2007], is to use a finite element meshed geometry, made of a TRI3 triangular mesh, to describe the different surfaces of the setup (sonotrode, chamber and part to be peened) that define the space in which the shot can move. In our case CATIA V5 was used as a CAD environment, in which the different elements were created, assembled then meshed, before being exported into a ".data" file format. It is important to precise that the model is compatible with all CAD software, and not only CATIA V5, as long as it can generate a mesh. By doing so, the CAD based model will allow optimizing the design of peening chambers for components with complex geometries. For each mechanical component to be ultrasonically shot peened, designing a customized peening chamber is required. However, accessing physical data during the peening process is very difficult and tedious, which results in limited feedback for the designer. Therefore, having the right tool will allow obtaining the optimum peening chamber geometry more easily and in a shorter time. In addition, this will also allow a better choice of the process parameters to achieve optimal results on the peened part, for a chosen chamber design.

3.1 Analytical resolution using a TRI3 triangular mesh

The main advantage in using a mesh with triangular elements is the possibility to describe each triangle analytically with its Cartesian equation (3). By doing so, it is still possible to conduct an analytical resolution using a discretized geometry. To achieve this, the analytical calculation of the shortest time of impact T_{BEST}, for Sphere-Wall collisions, must be generalized as follow:

1. *Pre-calculate the Cartesian equation of each triangle:*
   Let us consider a point M, defined by $\overrightarrow{OM} = (x, y, z)$ in the global reference (XYZ), and a triangle ABC from the generated mesh, defined by its three vertices A, B and C, its barycenter G and its normal vector $\vec{n} = (n_x, n_y, n_z)$. If M belongs to the plan defined by ABC, then the dot product between $\overrightarrow{MG}$ and $\vec{n}$ must be equal to zero, i.e. the two vectors must be orthogonal.

$$\left(\overrightarrow{OM} - \overrightarrow{OG}\right).\vec{n} = 0 \equiv n_x.x + n_y.y + n_z.z - \overrightarrow{OG}.\vec{n} = 0 \tag{3}$$

2. *Obtain a general quadratic polynomial equation:*
   Intersect the trajectory of a particle P (1) with the analytical equation of a triangle (3) to obtain the polynomial equation (4) necessary to calculate T_{NEXT}: the time needed for the considered sphere to impact the triangle being tested, here ABC.

$$\left(-\frac{1}{2}g.n_z\right).t^2 + (\vec{V}.\vec{n}).t + \left(\overrightarrow{OP}\vec{n} - \overrightarrow{OG}\vec{n}\right) = 0 \tag{4}$$

3. *Solve equation (4):*
   The first thing to calculate is the discriminant Δ of equation (4) then tests its sign which give direct information on whether an impact will occur with the plan of the considered triangle. If and only if $\Delta > 0$, i.e. an impact might occur, calculate the roots of (4) and save the smallest positive root as T_{NEXT}.
4. *Test if collision in the triangle:*
   If a T_{NEXT} could be calculated, then test if the corresponding impact point belongs to the considered triangle. If so, test whether $T_{NEXT} < T_{BEST}$ then set T_{BEST} to T_{NEXT} if the inequality is verified.

Another advantage comes from the simplicity and efficiency in handling and visualizing a triangular mesh. Such mesh can also be a support for post-treatment of the simulation results, allowing direct visualization on the meshed geometry. Once the results are linked to the mesh, they can be exported to another solver in order to conduct more detailed calculations. However, minor changes in the code need to be done in order to support mesh related data and avoid problems due to discretizing the geometry, such as the ones listed below:

1. A significant increase of the computing time, if each triangle needs to be checked for calculating the next time of impact T_{BEST}.
2. Taking into account rolling spheres across various triangles, instead of a single plane.
3. Managing spheres with zero velocity, typically ones that get stuck on the mesh due to complex geometry, in order not to slow the calculations or generate an infinite loop.

3.2 Main structure of the algorithm

The structure of the CAD-based model in its current version is described in Figure 3.

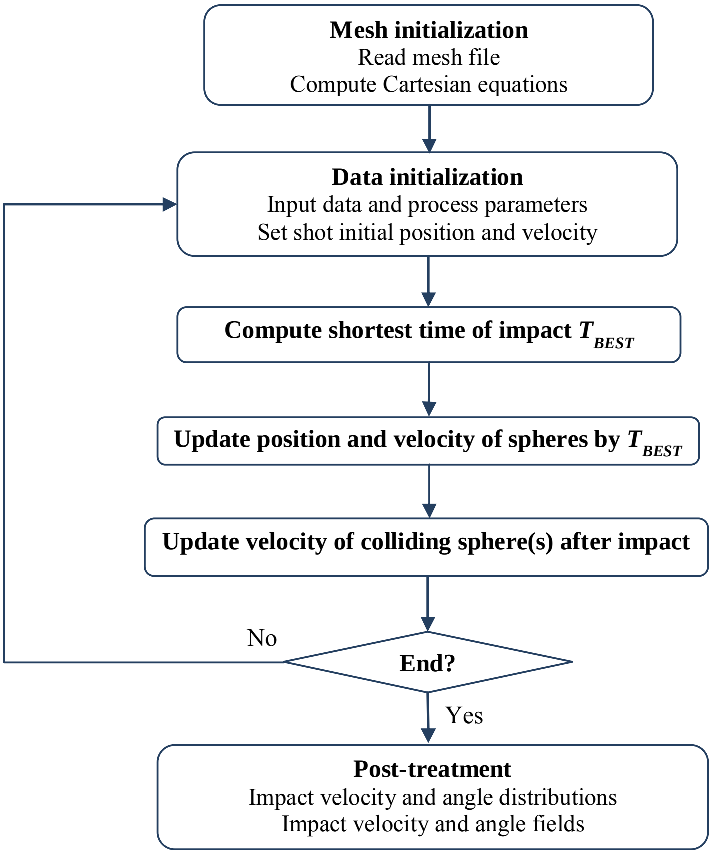

Figure 3. Algorithm of the CAD based model

4. Analytical model vs CAD-based model

Before applying the CAD-based model on complex geometries, such as a gear, it is important to make sure that it generates the same results as the analytical model when considering identical geometries and process parameters. Therefore, a comparison of the results obtained with the analytical and meshed geometries will be made using a cylindrical chamber and a flat peened surface (Figure 4).

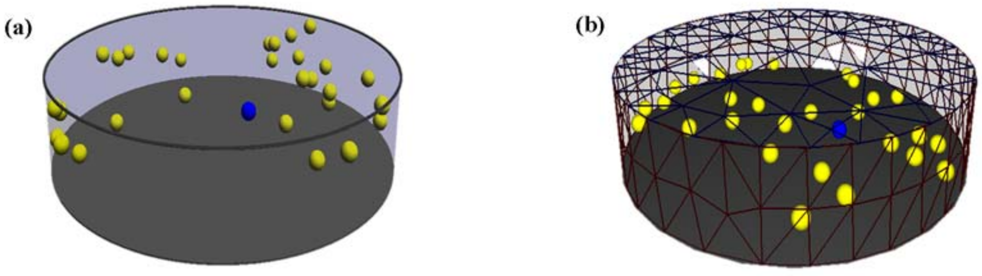

Figure 4. Screenshot of the a) analytical model and the b) CAD based model, used for simulating an ultrasonic shot peening operation in a cylindrical chamber, containing 30 spheres of 3mm diameter (color online)

The Figure 5 Compares the impact distribution on the peened surface, referred to as TOP, obtained experimentally with the distributions generated by the analytical and CAD-based models.

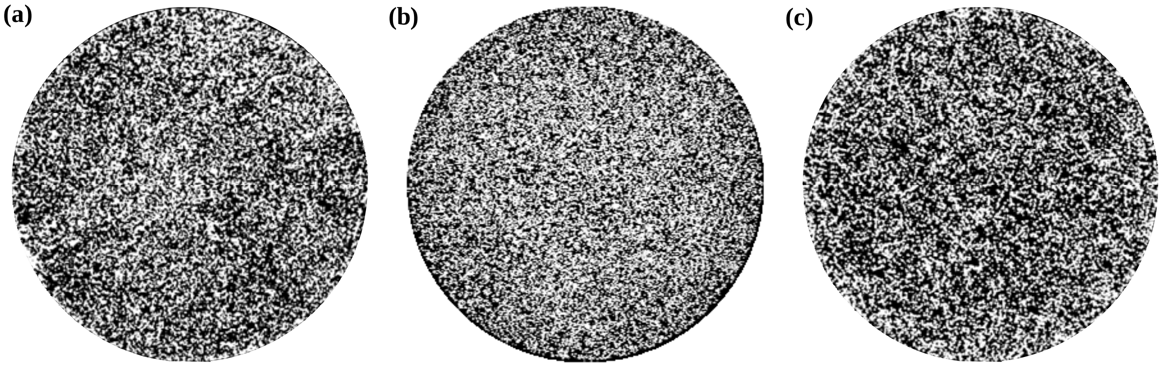

Figure 5. Impact distribution on the upper surface obtained a) experimentally (C_{ov} = 39%), b) with the analytical model (C_{ov} = 41%) and c) with the CAD-based model (C_{ov} = 40%). Black areas correspond to non-impacted zones

5. Perspectives

Having shown the utility of the analytical model and that the CAD-based model generates the same results than the analytical one, the next steps of development will be as follow:

1. Reducing the time of calculation by optimizing the search of the next impact time. Having a way to access directly the triangles that only lay in the path of a considered sphere, will prevent testing all the triangles of the mesh, allowing to accelerate the simulation. Accessibility and visibility algorithms, as well as collision detection structures and algorithms – axis aligned bounding boxes (AABB) [Held et al. 1995] and oriented bounding boxes (OBB) [Coming et al. 2006] – will be studied and applied. These algorithms are already used in video games but also in the mechanical industry to test manufacturability, for example [Derigent et al. 2007].
2. Adding an algorithm that manages, on one hand, rolling spheres on meshed surfaces, as well as “lift-off” when detecting an important change of slope between two neighboring triangles, and on the other hand, spheres with zero velocity that would get stuck for example in narrow places. Here again, algorithm used in manufacturing simulation will be studied as the behavior of a rolling ball and the behavior of a spherical mill are quiet the same.
3. Adding the possibility to animate certain regions of the mesh, for example the ones corresponding to the peened mechanical part. This step is less vital than the previous ones, but is interesting as it allows taking into account mechanical parts rotating around their revolution axis during the peening operation. The most forward approach, but not the best to adopt, would consist of updating the mobile part of the mesh by recalculating the equations of its triangles after each step of the calculation. The trouble is the computing time, which will increase dramatically.

Once the developments 1) and 2) are integrated into the current CAD based model, a complex mechanical part, like the one of a gear presented in Figure 6, can be submitted to an ultrasonic shot peening operation and simulated with the model. A comparison between both numerical and experimental results could then be made to evaluate the performances of the CAD based model. The experimental analysis will be made using a method specially developed to access surface coverage and shot trajectories during an ultrasonic shot peening operation, described in [Badreddine et al. 2011a].

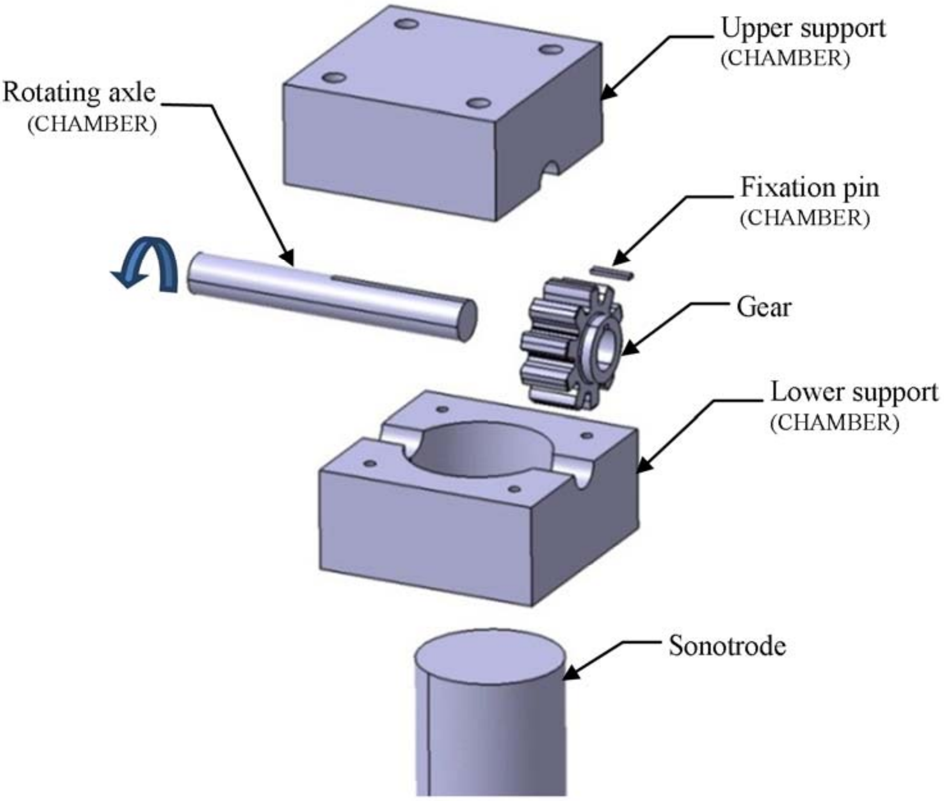

Figure 6. Exploded view of the peening setup showing its different components (color online)

6. Conclusion

To conclude, it was shown that for simple geometries, the analytical model produces very close results to those measured experimentally (Figure 2). Ongoing experimental studies on simple geometries show that the measured data is in good qualitative and quantitative correlation with the results obtained with the model. The details of this study will be the subject of a future publication.

For complex geometries that cannot or can hardly be defined with analytical equations, using a meshed model is considered to be the most suited solution to describe the geometry, as each triangle of the mesh can be described by an analytical equation. When comparing the data obtained by the analytical and CAD based models, for a cylindrical ultrasonic peening chamber (Figure 4), the results are usually within a ± 5 % error from the experimental data, as shown in Figure 5. Future studies will be conducted using the CAD based model for complex geometries, such as the one presented in Figure 6. The main difficulty that will need to be overcome is the important increase of computing time. Solutions will have to be found in order to run simulations in a relatively short period of time.

It was also shown, in this paper, the necessity behind the development of the analytical model and its potential on an industrial level. The latter being a refined understanding and control of the ultrasonic shot peening process. In addition, the CAD based model will provide a robust tool for achieving an optimal design of the ultrasonic peening chambers and choice of the process parameters. Furthermore, it will also establish an important link between the peening parameters and the prediction of the effects of USSP in the peened material, i.e. the residual stresses profile.

Acknowledgement

It is a pleasure to acknowledge ongoing discussions and support from D. Le Saunier and M. Prioul. Snecma (Groupe SAFRAN) and Sonats (Europe Technologies Group) are gratefully acknowledged for their financial support.

References

Badreddine J., Rouhaud E., Micoulaut M. et al., "Simulation and experimental approach for shot velocity evaluation in ultrasonic shot peening", Mécanique & Industries, Vol.12, No.3, 2011, pp. 223-229.

Badreddine J., Micoulaut M., Rouhaud E., et al., "Impact velocity and distribution in ultrasonic shot peening", In : Proceeding of the eleventh international conference onshot peening, 2011, pp. 99-104.

Boyce B.L., Chen X., Hutchinson J.W., Ritchie R.O., "The residual stress state due to a spherical hard-body impact", Mechanics of Materials, Vol.33, No.8, 2011, pp. 441-454.

Coming D.S., Staadt O.G., "Kinetic sweep and prune for multi-body continuous motion", Computers & Graphics, Vol.30, 2006, pp. 439-449.

Derigent W., Chapotot E., Ris G. et al., "3D Digitizing Strategy Planning Approach Based on a CAD Model", Journal of Computing and Information Science in Engineering, Vol.7, No.1, 2007, pp. 11-19.

Held M., Klosowski J.T., Mitchell J.S.B. "Evaluation of collision detection methods for virtual reality fly-throughs", In: Proceedings of the seventh Canadian conference on computational geometry, 1995. p. 205–10.

McNamara S., Falcon E., "Simulations of vibrated granular medium with impact-velocity-dependent restitution coefficient", Physical Review E, Vol.71, No.3, 2005, pp. 1-6.

Micoulaut M., Mechkov S., Retraint D. et al., "Granular gases in mechanical engineering: on the origin of heterogeneous ultrasonic shot peening", Granular Matter, Vol.9, 2007, pp. 25-33.

Mordyuk B.N., Prokopenko G.I., "Ultrasonic impact peening for the surface properties' management", Journal of Sound and Vibration, Vol.308, 2007, pp. 855-866.

Xing Y.M., Lu J., "An experimental study of residual stress induced by ultrasonic shot peening", Journal of Materials Processing Technology, Vol.152, No.1, 2004, pp. 56-61.

Dr. Sebastien Remy
Assistant professor
Université de Technologie de Troyes
12 rue Marie Curie, 10000 Troyes, France
Telephone: +33 (0)32 571 8556
Telefax: +33 (0)32 571 5675
Email: sebastien.remy@utt.fr
URL: http://www-lasmis.utt.fr/fr/membres/remy.html#top