A model for ultrasonic shot peening: optimization of chamber design in an industrial context

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Abstract.

The paper presents a CAD-based model, developed specifically for Ultrasonic Shot Peening (USP). It allows simulating the shot dynamics (trajectories in the chamber and impacts on the peened sample) in industrial configurations. The model supports complex 3D geometries, rotating parts and employs efficient collision detection algorithms to achieve short computation times. The aim is to improve peening chamber designs and the choice of process parameters. Quantitative and visual feedbacks are given for the shot dynamics and the process control criteria (surface coverage, treatment homogeneity and intensity). A case study on a spur gear has been selected to test the model in an industrial configuration. The results show a high correlation between model predictions and experimental data.

Keywords: Ultrasonic shot peening, shot dynamics, CAD-based model, simulation, complex geometries

Introduction

Ultrasonic shot peening (USP) is a mechanical surface treatment process, developed by SONATS (Stressonic® technology), that enhances the mechanical strength, the fatigue life span and the resistance to stress corrosion cracking of the high-added value metallic components, often with very complex geometries, such as bladed disks, compressor impellers, gears and nuclear power plants pressure vessels. This is achieved by projecting spherical shot onto the surface of a component (part), at high velocities (up to 20 m/s), with the help of a sonotrode. The latter is part of an acoustic system that vibrates at ultrasonic frequencies (generally 20 kHz). In an industrial context, customized peening chambers are usually designed for each type of components. It holds and locates the part in place and contains the bouncing shot, thus influencing its flow and dynamics. This results in complex and repetitive interactions between the spheres and the rest of the peening setup, *i.e.* sonotrode, chamber and part. The measurement of impact velocities is difficult, although it is necessary that it should be well distributed to ensure homogeneous treatment (coverage, intensity, residual stress fields). The peening chambers are thus designed with trial and error processes to verify the impact density with, for example a coverage analysis. As a result, the design of USP chambers and the choice of process parameters remain empirical, making it time consuming and partially optimized especially for complex parts.

It is important to specify that the induced residual stresses highly depend on the shot diameter [1] and total mass, the amplitude of the sonotrode [2], the peening time [3], as well as the shot impact velocities [1] and angles [4]. It is thus of interest to construct a predictive model of the shot dynamics for ultrasonic shot peening in any chamber geometry. Therefore, a dedicated model of USP, capable of simulating the process for complex parts in industrial conditions, is developed while keeping the computation times to a minimum. The objective of the model is to facilitate the design of shot peening chambers, as well as the choice of the process parameters. The developed USP model is detailed in Section 2. An experimental validation is presented in Section 3, showing good correlation between experimental and numerical data. In Section 4, the use of the model for optimizing peening chamber designs is discussed.

Ultrasonic shot peening model

The shot dynamics during an USP operation exhibits similar properties than vibrated granular gases. The USP model is therefore inspired by one of these models [5–7]. In this section, the input and output data are listed, followed by the model's main assumptions.

The main requirement of the model is to simulate an USP operation as realistically and accurately as possible, which implies:

- Using a *faithful 3D representation of the peening setup*. In our case, a triangular finite element (FE) mesh is constructed from CAD models.
- Using the *range of values for all adjustable process parameters* used in USP, *i.e.* the shot quantity, diameter and material, the amount of sonotrodes and their respective amplitude, frequency and direction of vibration.
- Using *material related parameters* to account for energy dissipation during collisions.
- Adding the possibility to *rotate the peened part* dynamically during the simulation.

Then from the simulations are extracted qualitative and quantitative data on the shot dynamics, *i.e.* the surface coverage and its rate, the spatial and statistical distributions of impact speeds, angles and dissipated energies. From this raw data, an equivalent Almen Intensity [8] can be determined at any point of the component geometry (Figure 1).

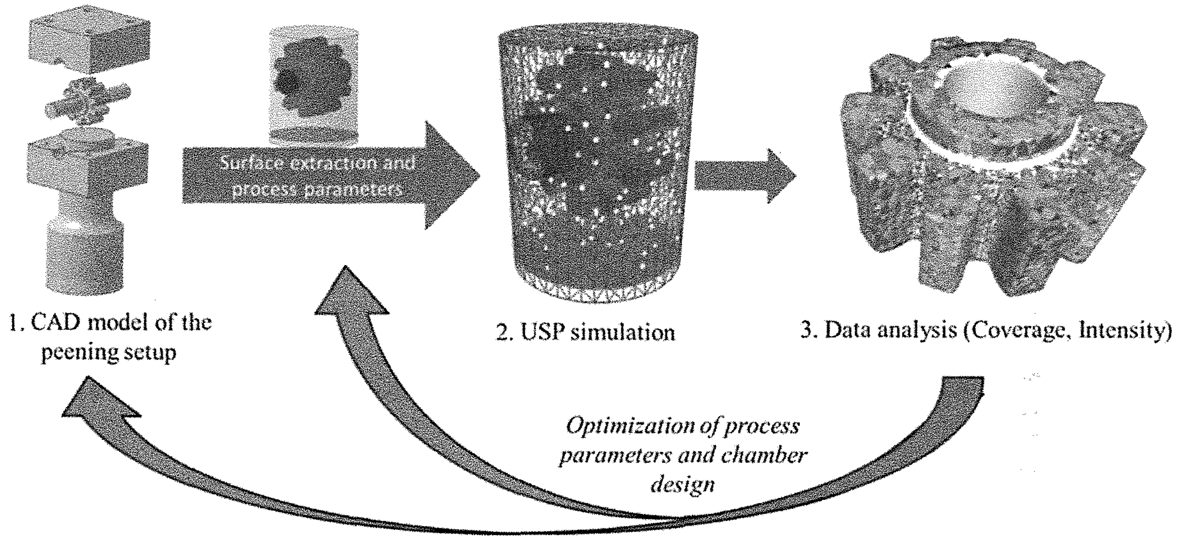

Figure 1: Global numerical approach.

The CAD-based model is developed using C++. It allows a continuous tracking of shot trajectories and collisions, regardless of their type: Sphere-Sphere and Sphere-Mesh collisions. Efficient collision detection algorithms [9] are also used to reduce computation times. This allows simulating hundreds of thousands of impacts in very reasonable computation times, *i.e.* few seconds to few hours to simulate 60 seconds of USP.

As mentioned previously, the physics implemented in the USP model are based on what can be found in vibrated granular gases models. In other words, the shot is composed of rigid spheres. Energy dissipation due to yielding and friction is taken into account through normal C (*Eq.* 1), and tangential μ restitution coefficients, and Coulomb friction coefficients f. The normal restitution coefficient is velocity dependent; faithfully modeling dissipated energies due to yielding at impact. These coefficients are applied to collision rules used for calculating the rebound velocity of colliding shot.

$$\begin{array}{lll} Visco-elastic & |\Delta V\,| < V_0 & C = C_0 \\ Plastic & |\Delta V\,| \geq V_0 & C = C_0\left(\frac{|\Delta V|}{V_0}\right)^{-0.25} \end{array} \qquad (1)$$

With $|\Delta V\,|$ the relative normal impact speed; V_0 the speed threshold after which collision are considered fully plastic; C_0 the normal restitution coefficient for viscoelastic collisions.

Experimental validation

Experimental setup & simulation

Ultrasonic shot peening of an aluminum spur gear (series 2000) is considered as a case study for testing and validating the model. The experimental setup is presented in Figure 2, along with the process parameters. For this validation, a gear is mounted onto a high-density polyethylene (HDPE) shaft and placed in a high strength steel cylindrical peening chamber, composed of two sections. The five lower teeth of the gear are painted in blue, for an increased visibility of the indents, and are placed facing the sonotrode. The sonotrode is cylindrical and is placed under the chamber, facing upwards. The total peening time, during which the gear remains static, is set to 5 seconds to limit the impact density: this allows a better visualization of the impacts. Simulating the 5 seconds of USP required 45 seconds of computation time on a laptop computer, using a single core of an Intel^{TM} i7 processor (1.74 GHz, 2GB of RAM).

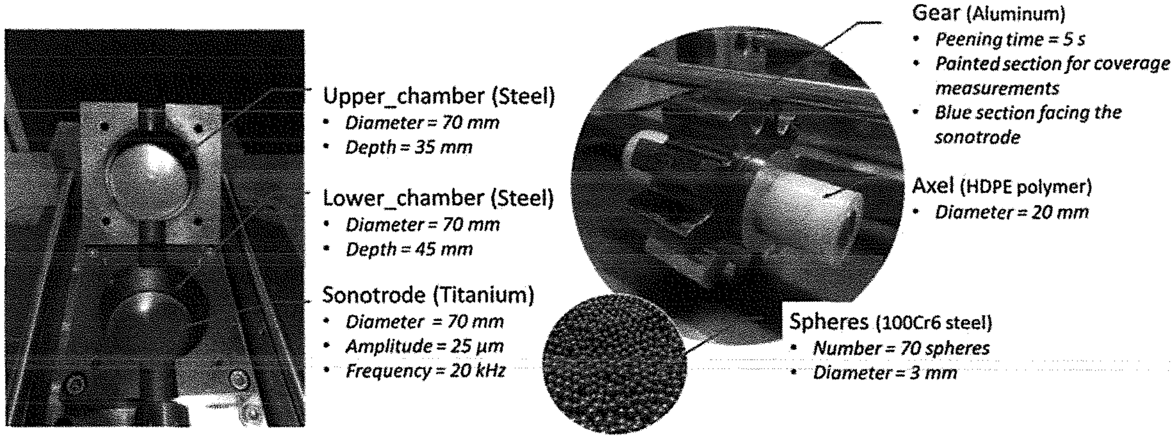

Figure 2: Experimental setup and parameters used for the model validation.

Results

Figure 3 presents the CAD model of the gear and its position with respect to the sonotrode (left side), as well as all the registered plastic impacts predicted by the model (right side). A color map has been attributed to the impact points, according to their normal impact speed, and then projected onto 3 orthogonal plans. The results show heterogeneous spatial distribution of impact speeds; which would be expected since the gear was kept static during the treatment. Impacts speeds up to 8 m/s (equivalent to 7.05 mJ) are reached at the surface of tooth T_3.

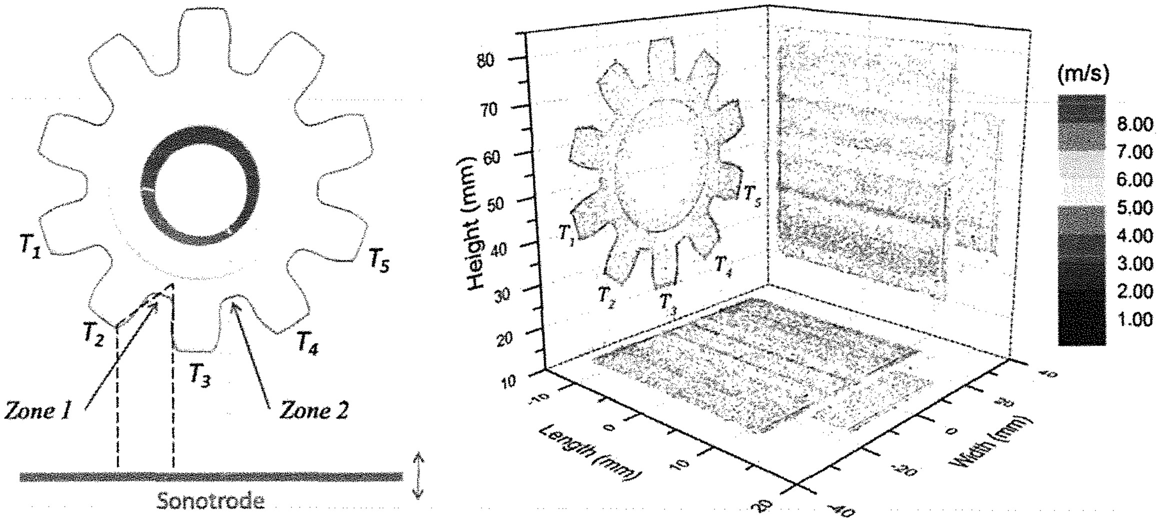

Figure 3: The studied zones used for the validation (left) and the projection of all registered inelastic impacts on the gear (right).

Figure 4 contains a reconstructed picture of the teeth 2 and 3, denoted as *zone 1*, showing the experimental indents (left side), and the numerical impacts predicted by the model for the same area (right side). Experimentally, impacts on the surface of tooth 2 have in average lower diameters than on tooth 3, indicating lower normal speeds. Numerically, the same conclusions can be drawn. For a quantitative validation, Table 1 compares the number of indents found on the teeth 1, 2 and 3 of the gear to the number of indents predicted by the model. Although the model predictions underestimate the experimental data, the committed error is lower than 5 %. Clearly the model offers valuable results in terms of impact density and velocity of impacts.

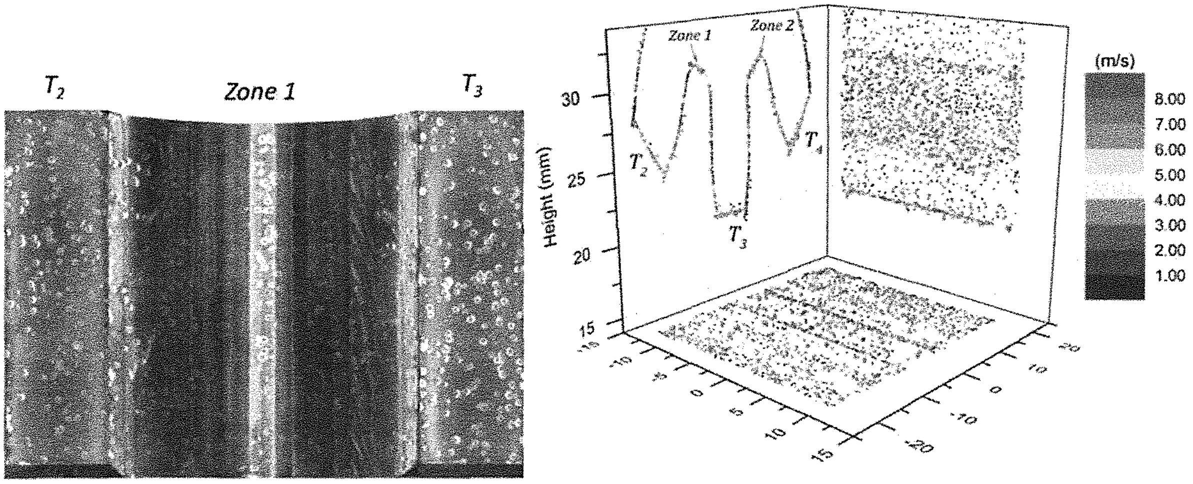

Figure 4: Qualitative comparison between the experimental (left) and the numerical (right) spatial impact distributions on the lower section of the gear.

Table1: Quantitative comparison between the experimental and numerical number of indents found on teeth 1, 2 and 3.

Tooth	Number of indents		Error (%)
	Experimental	Numerical	
T_1	153	146	-4.5
T_2	207	199	-3.9
T_3	214	207	-3.3

Integration in the design process

With a predictive model, it becomes possible to evaluate the influence of peening chamber designs on the outcomes of USP (coverage and intensities). The case of an output shaft (Figure 5) from the automotive industry will be considered for this section. Such components, existing in different variants, are ultrasonically shot peened. So far, the qualification of the process is conducted for each variant, using specific chamber designs. However, for cost issues, a generic peening chamber had to be made to treat all variants. In this particular case, the model enabled to identify the differences in treatment (coverage rate, impact speeds and intensities...) between the specific chambers and the generic chamber. The overall results showed that impact speeds are similar between the generic and specific chamber designs. However, the generic design exhibited lower coverage rates (-12%), in certain cases. This was due to an increase in the chamber volume. Such data was then used to optimize the peening parameters in order to fully satisfy the client's requirements.

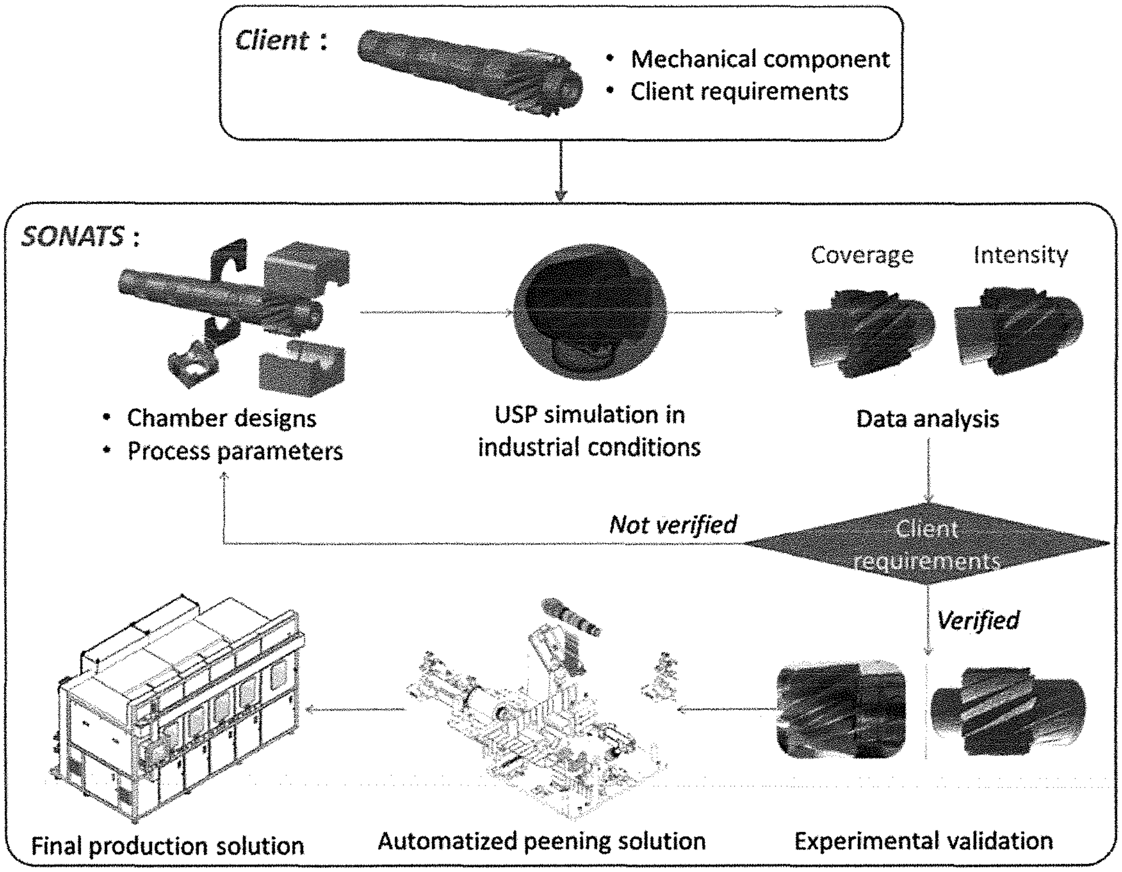

Figure 5: Integration of the CAD-based model in the design process of peening chamber and production solutions.

Conclusions

The model presented in this article allows a predictive study of the shot dynamics within an ultrasonic shot peening chamber. This is achieved with highly reasonable computation times while including visual animations of the motion of the shot. One can then evaluate the influence of the process parameters and of the peening chamber design on the outcome of an ultrasonic shot peening treatment. The model was also tested on industrial applications and allowed successfully to optimize peening chamber designs and/or process parameters, depending on the application.

The results for the model could also be used as input data to the residual stresses prediction models. From this research project, ongoing work is being conducted to successfully link the process parameters to the induced residual stress fields within a complex geometry [10,11].

Acknowledgment

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