# Estimation of Residual Stress Distribution Induced by Shot Peening

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*This paper describes an estimation method for the residual stress distribution induced by shot peening. First, process modeling taking into account material nonlinearities under high strain and high strain rate along with derivation of the residual stress profile is introduced. Results obtained with the proposed method are validated against experimental curves. Finally, using fitting expressions, a prediction method for the residual stress profiles depending on the material properties and shot peening conditions is introduced.*

***Key Words**: residual stress distribution, shot peening, material characterization, elasto-plastic material, numerical analysis*

## 1. Introduction

To improve the durability of mechanical components, the control of the surface residual stress is of utmost importance. Invented around the end of the 1920s, the shot peening process has been extensively applied in the industry for this purpose. Besides the control of subsurface residual stresses, the shot peening process has also other usages, such as surface cleaning or parts deformation (shot forming).

As shown in **Fig. 1**, the shot peening process consists in colliding at high speed a large number of hard particles against the target surface to be treated resulting in the following effects1):

1. Generation of residual compression stress on the target material subsurface
2. Hardening of the target material surface
3. Modification of the target material surface roughness
4. Erosion or cleaning of the surface

However, while the target material surface structure may exhibit improved fatigue life through the process, subsurface induced stresses and deformation may have a negative effect on the whole part geometrical accuracy, especially for slender components, which is highly undesirable. For this reason the proper control of the shot peening process is critical.

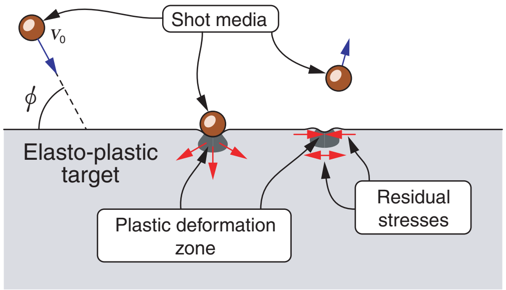


**Fig. 1** Impact of hard particle with elasto-plastic target

Shot peening conditions usually comprise the distance between the target material surface and the nozzle, the orientation between the surface normal and the particles flow, the size, shape, velocity, mass, hardness and flow rate of shot media, the treatment time, as well as the mechanical characteristics of the target surface. The distribution of the subsurface residual stresses depends greatly on these parameters. So far, the conditions needed to obtain a satisfying residual stress distribution for the considered application are determined through trial-and-error process, which is both time and money consuming. Consequently, in order to improve the process efficiency and to reduce development costs, it has become increasingly important to develop a theoretical method able to estimate the residual stress distribution based on shot penning conditions and on mechanical characteristics of the part to be treated.

To date, there have been several papers discussing residual stress after shot peening simulations, see for instance2)-4), but the methods proposed either failed to describe the target material accurately (elastic perfect plastic model) or did not propose a convenient method for residual stress prediction which limits their usefulness.

The authors chose a material model that faithfully reflects the material non linear characteristics under high strain rate (viscous behavior). They tried to build a theory to evaluate the residual stress distribution by shot peening using the principal values of the stress tensor and validated the simulation results using experimental data. In addition, based on the procedure developed here, an approximation method that allows the estimation of the residual stress distribution curve by shot peening was developed.

## 2. Shot Peening Residual Stress Distribution Calculation

The calculation model is shown in **Fig. 2**: the elasto-plastic target is modeled as a cylinder clamped at its base. The model coordinate system ($x$, $y$, $z$) is also given in the figure. Shot media are modeled as steel spheres (purely elastic material) and their distribution on the $xy$ plane is assumed to follow a hexagonal lattice of parameter $d_0$. Furthermore, in order to avoid simultaneous collision of shot media against the target material surface[2)], the distance between the each particle and the target surface was set randomly. In the current study, the distribution of neither the shot media radii $R$ nor the initial velocity $v_0$ was considered. The frictional coefficient between shot media and the target surface was set to 0.4.

According to the model layout shown in **Fig. 2**, the stress distribution is assumed to be axisymmetric along $z$, with two principal components of the stress tensor $\sigma_{//}(z)$ of equal value parallel to the target surface and one component $\sigma_{\perp}(z)$ perpendicular to it. The stresses mean values are calculated as follow:

$$\left.\begin{aligned}\sigma_{//}(z) &= \frac{1}{N_{el}}\sum_{i=1}^{N_{el}}\frac{\sigma^i_{xx}+\sigma^i_{yy}}{2}\\ \sigma_{\perp}(z) &= \frac{1}{N_{el}}\sum_{i=1}^{N_{el}}\sigma^i_{zz}\end{aligned}\right\} \qquad (1)$$

In equation (1), $z$ denotes the distance from the shot target material surface to the $j^{\text{th}}$ layer, and $N_{el}$ is the number of elements in the $j^{\text{th}}$ layer. In addition, $\sigma^i_{xx}$, $\sigma^i_{yy}$, and $\sigma^i_{zz}$ are the stress tensor component for each element in the considered coordinate system.

The stress components $\sigma^i_{xx}$, $\sigma^i_{yy}$, and $\sigma^i_{zz}$ in each element i were computed using dynamic FEM software (Abaqus/Explicit solver, from SIMULIA Co.,Ltd.) and the equation (1) was used to calculate the residual stress value for each element layer. However, in the shot peening dynamic simulation, eigenmodes of the target are excited. For this reason, the target equilibrium configuration after the shot peening simulation was solved using the Abaqus/Standard static solver before extracting the stress results.

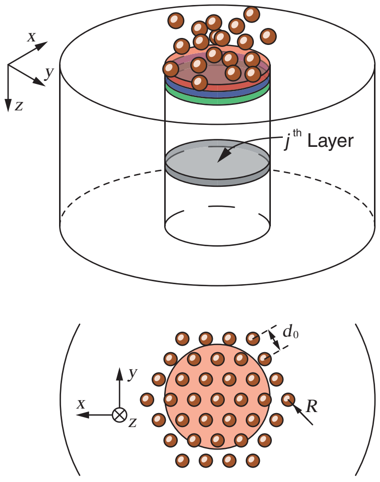


**Fig. 2** Simulation model configuration and coordinate systems definition

## 3. Results Validation

In order to verify the accuracy of the equation and the method discussed in **Section 2**, results comparison between simulations and experimental data for two conditions was performed. The conditions are the specifications conforming to Wonder Process Craft (WPC, from Fuji manufacturing Co., Ltd.), with small particles traveling at high velocity, and a standard specifications extensively used at JTEKT, with larger shot and slower velocity. Both condition use steel balls for shot. The size distribution of the shot media used in the experiment was determined by optical or scanning electron microscope for the standard and the WPC conditions respectively.

The test piece was a plate measuring 2.5 mm×3.5 mm with a thickness of 2.5 mm. The material characteristics were obtained from tensile tests, using a servo-hydraulic testing machine (INSTRON 8872). Strain rates ranged from $1.39 \times 10^{-4}$ to 4.8.

Since the strain rate during shot peening is far higher than the maximum strain rate attainable by the testing machine, the Johnson-Cook model[6)] (see equation (2)) was used to extrapolate the results to higher strain rates and used directly in the FEM solver.

$$\sigma = (A + B(\varepsilon_{pl})^n)\left[1 + C\ln\left(\frac{\dot{\varepsilon}_{pl}}{\dot{\varepsilon}_0}\right)\right] \qquad (2)$$

In the equation (2), $A$, $B$, $n$, $C$ and $\dot{\varepsilon}_0$ are coefficients that describe mechanical characteristics and must be determined for each material. On the other hand, $\varepsilon_{pl}$ and $\dot{\varepsilon}_{pl}$ are the plastic strain and plastic strain rate, respectively.

Since the temperature generated in the shot peening process remains far lower than the melting point of steel, for the current work, the temperature dependence of the Johnson-Cook model was not taken into account. **Table 1** shows the conditions for the WPC and standard shot peening conditions.

Finally, the initial velocity of the media was chosen in accordance with the machine specifications, and the shot media were assumed to impact perpendicularly against the target material surface.

**Figure 3** shows the comparison between numerical and experimental results. The horizontal axis gives the depth $z$ from the target surface and the vertical axis the residual stress $\sigma_{//}$ parallel to the target surface. As can be seen from **Fig. 3**, residual stresses for the WPC conditions are shallower than those for the standard conditions. Furthermore, good agreement within the numerical dispersion is observed between numerical and experimental results.

Looking deeper at the results from **Fig. 3**, we may observe that the difference between calculated and measured results is slightly larger closer from the surface (WPC specifications < 0.01 mm; standard specifications < 0.06 mm). This phenomenon may be explained recalling the shot media were considered impacting the surface at a normal angle. However, as explained in **Fig. 4**, because of the swinging movement of the nozzle, the complex airflow characteristics and the difficulty to maintain the target fixed during the process, the condition of perpendicular impact during the surface treatment is unlikely to be satisfied.

**Table 1** Simulation parameters for validation experiments

| | Standard specifications | WPC specifications |
|---|---|---|
| $A$ | 1 265 | |
| $B$ | 870 | |
| $n$ | 0.245 | |
| $C$ | 0.0017 | |
| $\dot{\varepsilon}_0$ | 1.05 | |
| $v_0$ | 80 m/s | 200 m/s |
| $R$ | 350 μm | 15 μm |

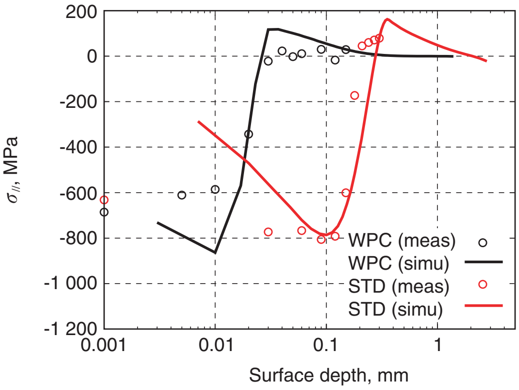


**Fig. 3** Comparison between measured and simulated residual stress profiles for two shot peening conditions

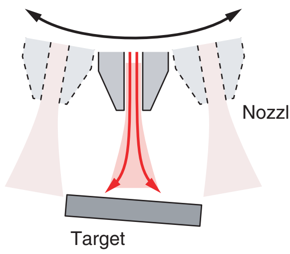


**Fig. 4** Nozzle swing of shot peening machine and flow orientation with target surface

Based on this assumption, the influence of the impacting angle $\phi$ on the residual stress profile was investigated. Three simulations were run with impacting angle of 90° (normal impact), 60°, and 45°, and the results are shown in **Fig. 5**. From **Fig. 5**, one can see that as the impacting angle $\phi$ decreases, the compression stresses in the shallow subsurface region tend to increase, while the deeper zone remains unaffected. Indeed, oblique impacts will induce more shear deformation of the surface, leading to stronger residual stresses.

As can be seen from **Fig. 5**, for carefully chosen impacting angle, the simulation results tend to fit accurately the measured data.

## 4. Method for Shot Peening Residual Stress Prediction

From **Chapter 3**, it was shown that the shot peening residual stress distribution may be estimated accurately through numerical simulations using equation (1). In the present section, a method to predict the residual stress profile depending on the shot peening conditions, namely the shot media radius $R$ (mm) and the initial speed $v_0$ (m/s) and the target material characteristics will be discussed.

As shown in equation (2), the target material is modeled using the temperature independent Johnson-Cook model, which allows to fully describe the mechanical behavior using numerical parameters only, greatly simplifying the results treatment.

Using a relation proposed by Tufft$^{7)}$, the distribution of the shot peening residual stress parallel to the target surface $\sigma_{//}$ can be approximated using a combination of exponential and trigonometric functions.

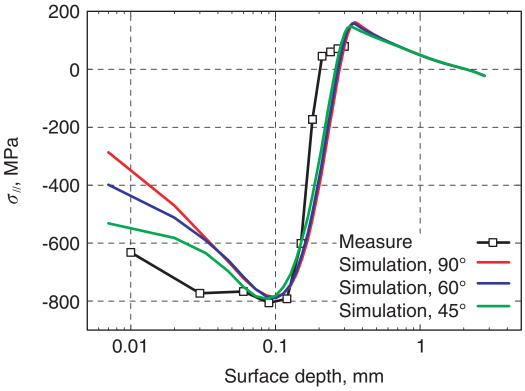


**Fig. 5** Influence of impact angle $\phi$ on residual stress distribution

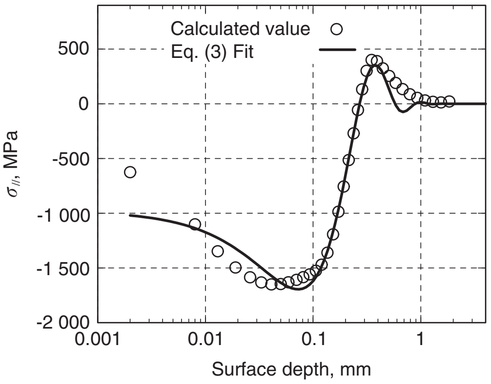
$$\sigma_{//}(z) = \alpha \exp\left[\frac{-z}{\beta}\right]\sin(\vartheta z + \lambda) \tag{3}$$

Furthermore, considering the results of equation (1), the authors proposed a relation based on the Log-Normal distribution to fit the distribution of the perpendicular components $\sigma_\perp$ :

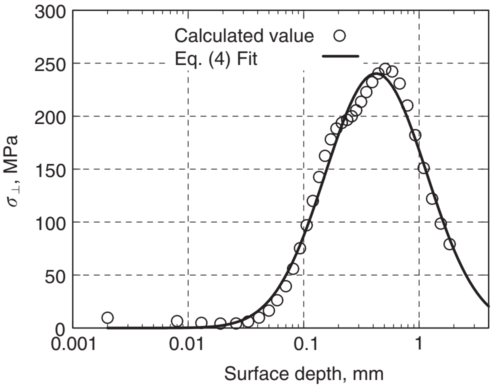
$$\sigma_\perp(z) = \kappa \exp\left[-\frac{(\log z - \mu)^2}{\xi}\right] \tag{4}$$

The parameters $\alpha$, $\beta$, $\vartheta$, $\lambda$, $\kappa$, $\mu$ and $\xi$ from equations (3) and (4) may be then expressed using shot peening conditions and material characteristics as follows.

$$\left.\begin{array}{l}
\alpha = f_1(A,\ B,\ n,\ C,\ \dot{\varepsilon}_0,\ v_0,\ R) \\
\beta = f_2(A,\ B,\ n,\ C,\ \dot{\varepsilon}_0,\ v_0,\ R) \\
\vartheta = f_3(A,\ B,\ n,\ C,\ \dot{\varepsilon}_0,\ v_0,\ R) \\
\lambda = f_4(A,\ B,\ n,\ C,\ \dot{\varepsilon}_0,\ v_0,\ R) \\
\kappa = f_5(A,\ B,\ n,\ C,\ \dot{\varepsilon}_0,\ v_0,\ R) \\
\mu = f_6(A,\ B,\ n,\ C,\ \dot{\varepsilon}_0,\ v_0,\ R) \\
\xi = f_7(A,\ B,\ n,\ C,\ \dot{\varepsilon}_0,\ v_0,\ R)
\end{array}\right\} \tag{5}$$



(a) Residual stress parallel component



(b) Residual stress perpendicular component

**Fig. 6** Prediction results of shot peening residual stress distribution

Where the function $f_i$ $(A, B, n, C, \dot{\varepsilon}_0, v_0, R)$ are linear models which parameters are calculated using a DOE (design of experiment) approach.

Having determined the coefficients of the linear models using ANOVA (analysis of variance) tables, the residual stresses profiles may be estimated depending on the shot peening conditions and on the material properties combining the equation (5) with the equations (3) and (4).

**Figure 6** shows the comparison between results of the residual stress distribution from the FEM simulation computed by equation (1) and the residual stress distribution predicted by the developed model using equations (3) and (4). Very good agreement is observed between both methods. That is, knowing the target material characteristic and the shot peening conditions, the residual stress distribution may be predicted with high accuracy using the equation (3) and (4) introduced in this paper.

## 5. Conclusion

The residual stress profile on the shot target subsurface was investigated and a model to estimate the stress distribution was built. The results obtained are the following.

1. A formula for estimating stress distribution generated by shot peening was derived taking in account the nonlinear mechanical behavior of the target material and the friction between shot media and the target surface.
   Results from the simulation were validated against measured data with good agreement.
2. The effect of the impact angle was investigated, and hints to improve the residual stress profile simulation accuracy were presented.
3. Fitting relations to express the residual stress profile by shot peening were presented, along with a model to predict residual stress distribution from the the target material characteristics and the shot peening conditions.

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