MODELLING THE INFLUENCE OF THE SHOT SIZE DISPERSION ON THE EVOLUTION OF THE RESIDUAL STRESS PROFILES VS. TIME IN SHOT PEENING.

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ABSTRACT

The influence of peening time on residual stress profiles after shot-peening was studied as a consequence of the energy dispersion of shots.
An equivalent shot size $\phi_{equiv.}$ is defined to obtain the same coverage ratio as with the actual shot size distribution. A random approach of covering in shot-peening is proposed to define an evolution law for $\phi_{equiv.}$ vs. coverage ratio. Introduction of $\phi_{equiv.}$ in predictive residual stress models, calculated for different coverage ratios, gives a quantitative evaluation of the residual stress profiles evolution as a function of time, and shot size distribution.

A 45M5 steel (French standards) was used for experiments. Residual stress profiles were determined using X-ray diffraction on peened surfaces after different peening times. The evolution of the residual stress profiles vs. time, was compared between experiments and the proposed model.

KEYWORDS

coverage ratio, equivalent shot size, residual stress, shot size dispersion, X-ray diffraction, random model.

INTRODUCTION

Shot-peening is a widespread impact treatment used to improve fatigue and corrosion resistance, by inducing superficial compressive residual stresses in metallic parts [1-3].
During the peening process, the influence of time on surface characteristics (such as residual stress, roughness, hardness...) generally falls as soon as the surface is fully covered by impacts. Consequently, a full coverage is often specified for the process[4]. However recent studies demonstrate that this overall phenomenon, called saturation, depends on the cyclic behavior of the peened material[5,6].
Different sources of the "time effect" in shot-peening have been proposed by Fathallah[6]:

i) Evolution of the material behavior during cyclic loading: for example, cyclic hardening can increase the thickness of the affected layer.
ii) Evolution of the loading due to the superficial modifications of the peened material.
iii) Evolution of the average ball diameter to be considered, due to the superposition of impacts with dispersed shot size.

i) was implemented in a predictive model[7] of residual stress profiles after shot-peening, by modification of the material behavior vs. coverage ratio[6].
ii) has not yet been investigated quantitatively, to our knowledge.
iii) was assumed negligible by Fathallah, and was never quantified.

The aim of this study is the quantitative evaluation of the average effect of peening time, taking into account shot size dispersion, when shot-peening is considered as a random impact

THEORETICAL MODELLING

Coverage ratio and random approach to shot-peening:

The coverage ratio is defined as the ratio between the impacted areas and the total surface area on a partially peened surface. After full coverage, the definition changes and the coverage ratio becomes the ratio between the peening time and the time required to cover totally the surface by craters, also termed $T_{100\%}$.
Since a full coverage of the peened surface is required for process efficiency, this parameter is extensively used to determine the time of treatment and to monitor the process[1,4].

An analogy between covering in ultrasonic shot-peening, and a Boolean model, which is a classical random process used in Mathematical Morphology, was proposed by one of the authors elsewhere[8]. Consequently, the coverage ratio S% can be considered as a probability, defined by:

$$S\% = 1 - e^{-\theta A} \quad \text{with} \quad \theta = \text{impact density}, \; A = \text{mean crater area}. \qquad (1)$$

If the impact frequency f is independent of time during the process, Eq. (1) gives also:

$$S\% = 1 - e^{-f.t.A} \quad \text{with} \quad t = \text{processing time} \qquad (2)$$

This relation provides the coverage ratio on an infinite surface. Hence, full coverage is reached asymptotically only.
For an actual finite surface to be peened, $T_{100\%}$ is finite and can be reasonably defined introducing a trust interval for full coverage of the surface. Considering the actual surface as a finite window on a Boolean process, the Boolean model properties indicate that $T_{100\%}$ for a actual surface is equal to:

$$0{,}98 = 1 - e^{-f.T_{100\%}.A} \qquad (3)$$
with a 95% trust interval

Finally, eq.(3) gives a relation between the impact frequency, the mean crater area and $T_{100\%}$.

Shot size dispersion and Equivalent shot size

The size of the peening media is standardly dispersed, but this size dispersion is ignored in current predictive models of shot-peening: a mean diameter, or average in mass given by sieving, is introduced instead.

A definition of an equivalent shot size is proposed when the shot velocity V and the total impact frequency f can be considered as constant in space and time. A given size dispersion -noted $(p_i,\emptyset_i)_{i\in\{1,N\}}$ where p_i is the proportion in number of balls with a diameter ranging between $\emptyset_i-\Delta\emptyset$ and $\emptyset_i+\Delta\emptyset$- induces a dispersion of crater areas on the peened surface, noted $(p_i,A_i)_{i\in\{1,N\}}$ where A_i is the crater area after an impact of a ball with a $\emptyset_i$ diameter. A_i can be calculated using elastoplastic equations[9] (Fig. 1):

$$A_i = \frac{\pi}{4}\left(2.56\, V^{1/2}\left(\frac{\rho_b}{H}\right)^{1/4}\frac{\emptyset_i}{2}\right)^2 \qquad (4)$$
with ρ_b = volumic mass of shots
H = inital hardness of the peened material

The area of the peened surface impacted only by shots smaller than $\o_M$ is now introduced and noted $S_{\o\leq\o_M}$.
At any time, the ratio between $S_{\o\leq\o_M}$ and the total surface area is constant and given by (Fig.2):

$$P_{\o\leq\o_M} = \frac{S_{\o\leq\o_M}}{S_\o} = \frac{\sum_{\substack{k=1 \\ \o_k\leq\o_M}}^{N} p_k \cdot A_k}{\sum_{k=1}^{N} p_k \cdot A_k} \qquad (5)$$

By definition, the equivalent shot size $\o_{eq}$ corresponds to a $p_{\o\leq\o_i}$ ratio equal to 50%.

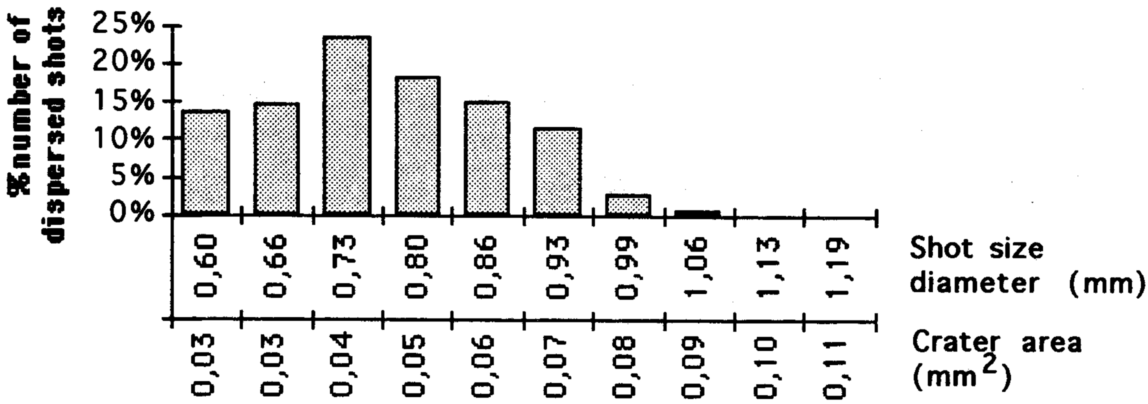

Figure 1: $(p_i,\o_i)$ and (p_i,A_i) for a S280 normalised shot size dispersion

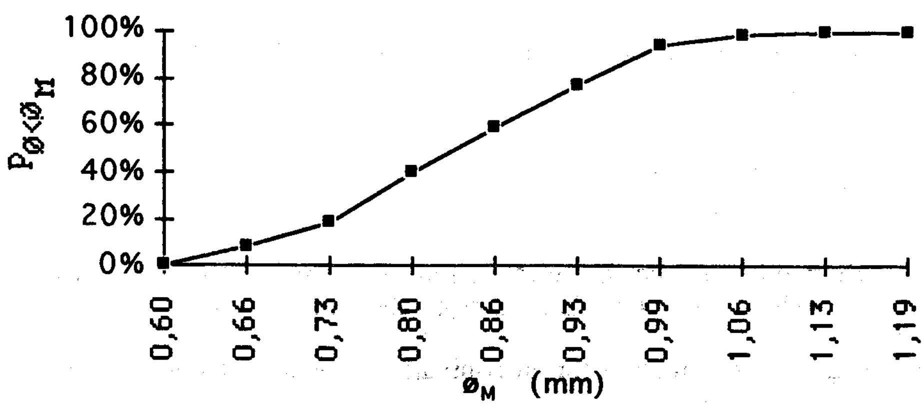

Figure 2: $p_{\o\leq\o_M}$ for a S280 normalised shot size dispersion

Evolution of the equivalent size with the peening time after full coverage

First of all, we have to define rules to take into accounts the superposition of impacts. The local effect of shot-peening is assumed to be influenced only by the maximum diameter of the shots received at the considered point of the surface.
Consequently, the smaller diameters are forgotten when a superposition of impacts occurs and $S_{\o\leq\o_M}$ or $p_{\o\leq\o_i}$ decrease down to zero with increasing peening time.

Let us introduce $\o_{thr}$ as the greater diameter with a nul $S_{\o\leq\o_M}$.
Due to the hypothesis on the superposition of impacts, the use of only shots greater than $\o_{thr}$ would have given the same effect on the peened surface.

An equivalent shot size, $\phi_{eq}^{\phi\geq\phi_{thr}}$, and $T_{100\%}^{\phi\geq\phi_{thr}}$, the time required to fully cover the surface by this restricted population, can be calculated by introducing the ratio between the area of the surface impacted by shots greater than ϕ_{thr} and smaller than ϕ_M and the area of the surface impacted by shots greater than ϕ_{thr} :

$$p_{\phi\leq\phi_M}^{\phi\geq\phi_{thr}} = \frac{S_{\phi\leq\phi_M}^{\phi\geq\phi_{thr}}}{S_{\phi}^{\phi\geq\phi_{thr}}} = \frac{\sum_{\substack{k=1 \\ \phi_{thr}\leq\phi_k\leq\phi_M}}^{N} p_k \cdot A_k}{\sum_{\substack{k=1 \\ \phi_{thr}\leq\phi_k}}^{N} p_k \cdot A_k} \tag{6}$$

The equivalent shot size $\phi_{eq}^{\phi\geq\phi_{thr}}$ for the restricted population (i.e. only the shots greater than ϕ_{thr}) corresponds to a $p_{\phi\leq\phi_M}^{\phi\geq\phi_{thr}}$ ratio equal to 50%.
The impact frequency for this population is defined by:

$$f^{\phi\geq\phi_{thr}} = f \cdot \frac{\sum_{\substack{k=1 \\ \phi_k\geq\phi_{thr}}}^{N} p_k}{\sum_{k=1}^{N} p_k} \tag{7}$$

Using the Eq. (3), $T_{100\%}^{\phi\geq\phi_{thr}}$ is calculated replacing f by $f^{\phi\geq\phi_{thr}}$ and A by $A_{eq}^{\phi\geq\phi_{thr}}$, where $A_{eq}^{\phi\geq\phi_{thr}} = \frac{\pi}{4}(\phi_{eq}^{\phi\geq\phi_{thr}})^2$.

$$0{,}98 = 1 - e^{-f^{\phi\geq\phi_{thr}} \cdot T_{100\%}^{\phi\geq\phi_{thr}} \cdot A_{eq}^{\phi\geq\phi_{thr}}} \tag{8}$$

To summarize, the superposition rules induce the introduction of a restricted population of shots characterized by a size threshold ϕ_{thr}, and which is equivalent to the real one when it reaches full a coverage ratio.
The random model properties give a formulation for an equivalent shot size of this particular population $\phi_{eq}^{\phi\geq\phi_{thr}}$ and define the time $T_{100\%}^{\phi\geq\phi_{thr}}$ when the equivalence between the two populations is valid.
Finally, the expected relation $\phi_{eq}(t)$ or $\phi_{eq}(S\%)$ is obtained using ϕ_{thr} as a parameter (Fig. 3).

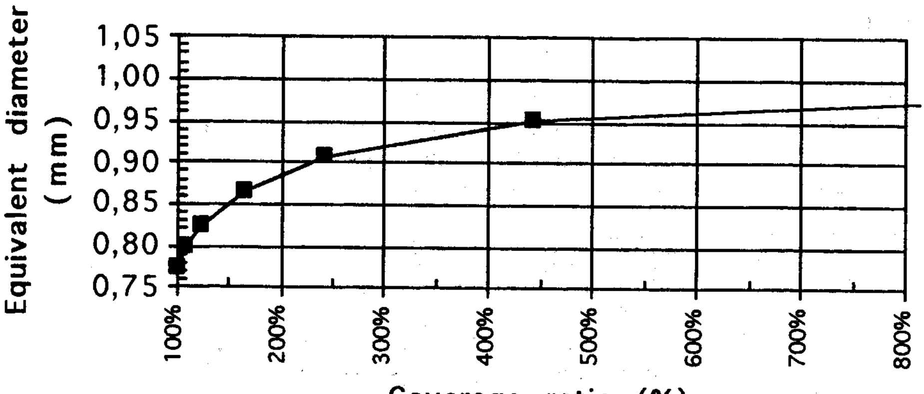

Figure 3: $\phi_{eq}(S\%)$ calculated for a S280 normalised shot size dispersion

EXPERIMENTAL CONDITIONS AND MODELLING PARAMETERS

Materials and specimen

45M5 specimens were used with the normalised goemetry of the Almen C strips (Table 1). The behavior of a 45M5 steel is described in Fig.4 after alternated loadings. A stabilization in the behavior is observed after 15 cycles.

Composition	C	Mn	Si
% Wt.	0.42-0.50	1.10-1.40	0.10-0.40

Table 1: Composition of a 45M5 steel

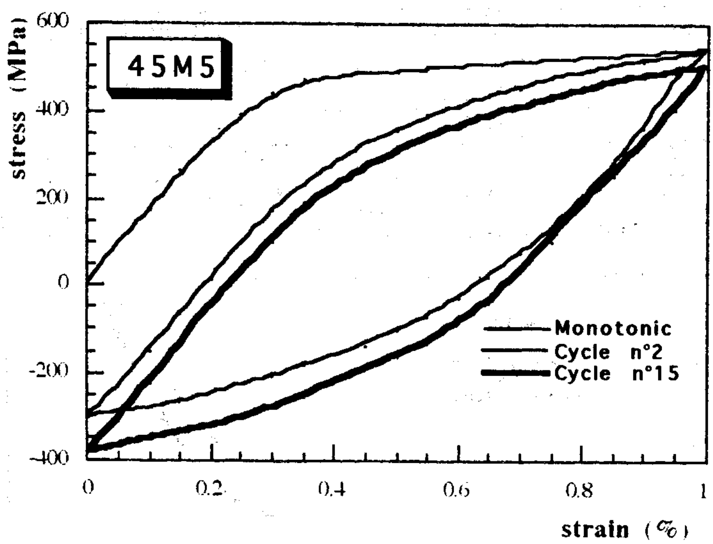

Figure 4: stress vs. strain for alternated cycles with 1% strain max.

Shot peening conditions

Shot	Almen intensity	coverage ratio
S280	F40A (1/100mm)	100%/200%/400%/800%

Table 2: Experimental shot peening conditions

Residual stress determination

The residual stress profiles were determined by X-ray diffraction, using the K_α Cr radiation ($\lambda_{K_\alpha} = 2{,}2896$Å) with the {211} planes in Fe_α. The "$\sin^2\Psi$ method" was employed[10].

Modelling parameters

The PEEN-STRESS™ software[11] was used to predict the residual stress profiles after different coverage ratios. Modelling parameters are summarized in Table 3. The ball diameter was determined on Fig. 3 for each coverage ratio. Then, the Almen intensity introduced in the sotfware was adapted to keep the impact velocity constant.

Material parameters	Nature of shots	Coverage ratio (%)	Almen intensity (mmA)	Ball diameter (microns)	Impact velocity (m/s)
$S_0 = 315$ MPa $P_0 = 210$ GPa $\Sigma_\infty = 450$ MPa $P_\infty = 15.5$ GPa	Steel balls	100	0.40	770	51
		200	0.45	900	
		400	0.48	950	

Table 3: Modelling parameters used in fonction of coverage ratio

RESULTS

Experimental and calculated residual stress profiles are shown in Figs 5 and 6 for different coverage ratios.
The PEEN-STRESS software predicts a plateau on residual stress profiles near the surface corresponding to the maximum compressive stresses. The plateau is difficult to identify on experimental profiles.
Experimental and calculated profiles are compared using the thickness of the compressive layer(Table 4).

Coverage ratio S%	$Ø_{eq}$ (µm)	Almen intensity (mmA)	thickness from experiments	thickness from simulations
100%	770	0.40	510µm	500µm
200%	900	0.45	585µm	550µm
400%	950	0.48	635µm	600µm

Table 4: Comparison between experimental and calculated thickness of the affected zone

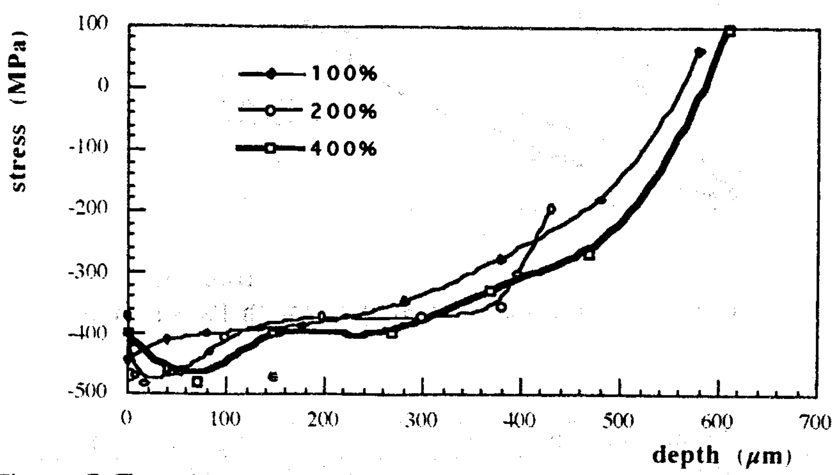

Figure 5: Experimental residual stress profiles vs. coverage ratios

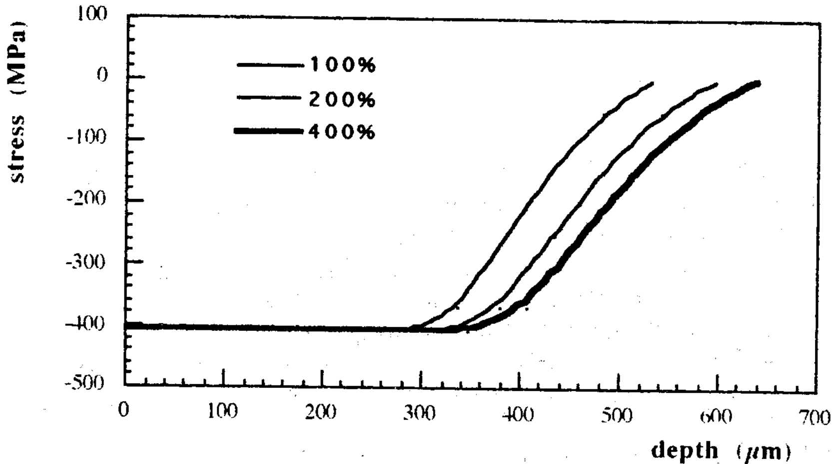

Figure 6: Calculated residual stress profiles vs. coverage ratios

DISCUSSION

First of all, the equivalent shot diameter proposed for a 100% coverage, which is equal to 770μm for normalised S280 shots, is smaller than the average diameter in mass classically used, which is equal to 850μm.

Experimentally, the most important effect of increasing time on residual stress profiles is an increase of the thickness of the affected layer (Fig. 5).
It can not be attributed to an evolution in mechanical behavior of the material because of the behavior stabilization after 15 cycles, which correspond to the mean number of impacts received at a point of the surface when the coverage ratio reaches 100%[9].
But, this effect can be obtained on calculated profiles by increasing the ball diameter and keeping the impact velocity constant (Fig. 6).

The proposed evolution of the equivalent shot diameter in function of coverage ratio, and introduced in the PEEN-STRESS software to predict the residual stress profiles vs. coverage ratio, induces a good agreement between the experimental and calculated thickness of the affected layer at each coverage ratio (Table 4).

CONCLUSION

An equivalent shot diameter for a given shot size dispersion, was proposed to be used in predictive models of shot peening.
Hypothesis on the superposition of impacts and a random approach of covering, developped elsewhere, give a method to calculate the evolution of the equivalent shot diameter, taking into account the shot size dispersion.

The evolution of the equivalent shot diameter proposed, coupled with the PEEN-STRESS software, predicted the evolution of the residual stress profiles vs. time on a peened 45M5 steel with a good agreement with experiments.

Further validation of the proposed evolution of øeq must be done using non normalised shot size dispersion.

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