HETEROGENEOUS ULTRASONIC SHOT PEENING : EXPERIMENT AND SIMULATION

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Abstract
We study the behaviour of an ultrasonic shot peening process from two viewpoints: a) an experimental setup made of a chamber with a sonotrode (frequency 20kHz, amplitude $25\mu m$) and shot of diameter *3mm* and b) a Molecular Dynamics simulation of a model of inelastic hard spheres that are fluidized by a vibrating bottom wall. The simulation cell has the same characteristics and parameters as the experimental setup. It is found that the impact profile on the sample depends strongly on the value of the particle side wall restitution coefficient c_w and a heterogeneous distribution of impacts on both the sample and the sonotrode is obtained with decreasing c_w. We compute within this model impact parameters such as impact angle, impact velocity, etc. and compare them with our experimental findings.

Key words : ultrasonic shot peening, treatment parameters, restitution coefficient, shot velocity, hard sphere model

1. Introduction

Shot peening is a mechanical surface treatment widely used in industry to enhance fatigue life and corrosion resistance of mechanical parts [1-4]. This improvement is achieved by inducing compressive residual stresses and work hardening effects in the layers close to the surface. As nearly all fatigue and stress corrosion failures originate at the surface of a part, the superficial compressive residual stresses can prevent crack initiation and propagation as well as close pre-existing cracks. They thus can provide considerable increases in structural component lifetime.
Since 1980, a new type of shot peening process has been working its way, i.e., ultrasonic shot peening [5]. Like conventional shot peening (CS), the ultrasonic shot peening process (US) consists in impacting the surface of the part to be treated with shot. Instead of using machines based on pneumatically assisted shot jets as it is the case in CS, the US process uses high-power ultrasounds.

This process is governed by different parameters directly dependent on the experimental setup such as the diameter and the quantity of shot, the shot material, the geometry of the chamber, the amplitude and frequency of vibration. Nevertheless, it is also controlled by physical parameters which can be related to the previous ones but are more difficult to characterize. Among those, we mention the dissipated energy of the system induced by the plastification of the chamber wall and the impact angle or the impact velocity.

In this study, we aim to better characterize the parameters which control the ultrasonic peening process like the shot velocity or the energy dissipated in the system during the impacts. Experimental tests are thus coupled to simulation results to evaluate the contribution of these parameters to the process. A particular attention is devoted to the effect of inelastic collisions on the profile of the impacts at the surface of the treated part.

2. Experimental method

Experimental tests have been carried out using a 20kHz ultrasonic generator which makes a cylindrical sonotrode (70mm diameter) to vibrate with an amplitude of 25 μm (see Figure 1). The 100C6 steel shot (200 of them - 3mm diameter) is in contact with the vibrating sonotrode so that it is bombarded and moves randomly around the inside of the cylindrical chamber, like gas particles.

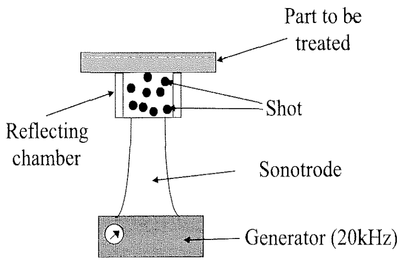

Figure 1 : Principle of the process.

The part to be treated is an aluminium plate which is placed at the top of the reflecting chamber (40mm height). It is peened with a very high number of impacts in a very short time. In order to study the influence of the interaction between the shot and the chamber wall, and to create different types of inelastic shock, two kinds of chamber have been used : an aluminium chamber (Al - high restitution coefficient c_w) and one covered with a polymer adhesive strip (AlS - low restitution coefficient c_w).

2.1. Heterogeneity of the process

As shown in Figure 2-a, the surface of an aluminium part that has undergone a long peening treatment (with polymer covered chamber - AlS) appears to display heterogeneity of the impacts. The average roughness R_a of this sample indeed varies from 4 μm at the center to 7,4 μm near the border. The origin of this phenomenon can be attributed to the inelastic collisions that occur in this case between the shot and the chamber wall (low c_w) as we will see below. This heterogeneity can be also measured from the surface impact frequency N as a function of the radius of the peened sample (see Figure 2-b). A counting of N based on circular sampling shows that the higher the radius is, the higher N becomes: N increases from a value of 0,65 at the center of the sample to a value of 0,95 on the border. The same tendency (Figure 2-b, horizontal lines) can be noticed using a different way of counting (rectangular sampling). In this case, the N values at the centre and in the periphery of the sample are 0,73 ± 0,16 and 1,03 ± 0,25 respectively (solid horizontal lines in Fig.

2b). If an aluminium chamber is used, the counting results give 1,25 ± 0,12 and 1,66 ± 0,39 respectively.

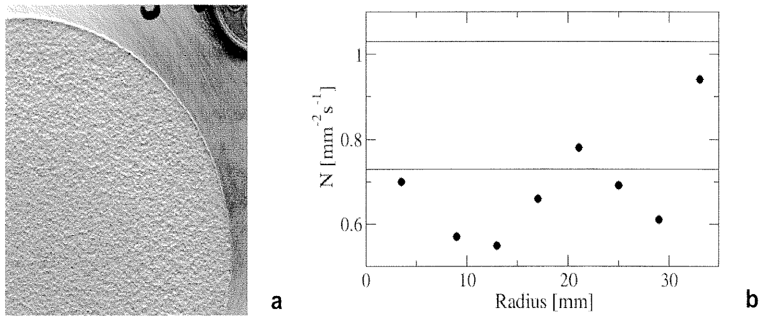

Figure 2 : **a)** Macrography of a quarter (R=35mm) of the peened surface of an aluminium sample treated for 4 minutes. **b)** Surface impact frequency on an aluminium sample (treated for 1s) as a function of the radius of the AlS chamber.

From a general point of view, the surface impact frequency N is lower with the (AlS) chamber compared to the (Al) one. This fact can be attributed to a lower value of c_w for the (AlS) chamber as we will see it in the next paragraph. We note also that the sampling is allowed for small peening times only, whereas roughness measurements can be only realised for long time peened samples. But both clearly display heterogeneity.

2.2. Estimation of the restitution coefficient

The evolution of the normal restitution coefficient c_w has been studied as a function of the shot velocity for the two (Al) and (AlS) chambers. To this end, the rebound height of a 3mm shot on aluminium and polymer striped aluminium plates has been measured using a video camera.

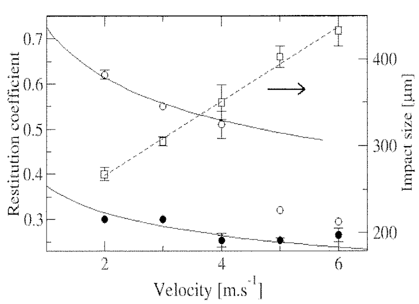

Figure 3 : Measured restitution coefficient with respect to velocity for a normal impact on aluminium (open circles) and adhesive striped aluminium (filled circles). The solid lines correspond to a fit with Thornton's model [6]. Variation of the impact size (right scale) with velocity.

The shot velocity varies from 2m.s^{-1} to 6 m.s^{-1}. The results are displayed in Figure 3. They show that, whatever the chamber type, c_w decreases gradually with an increasing velocity to reach a more or less stable value at high velocity. Moreover, the c_w coefficient is lower in the case of the (AlS) chamber and tends towards a value of 0,3. This fact can explain the lower values of the impact frequency N with the (AIS) chamber presented in §2.1 and is consistent with the following simulation.

2.2. Estimation of the shot velocity

An aluminium plate has been impacted with one 3mm diameter shot whose velocity was fixed between 2 and 6 $m.s^{-1}$. The evolution of the impact size has been determined as a function of the shot velocity (Figure 3- left) and has a linear variation in the velocity range of interest. Thanks to this linear calibration curve, the measurements of the impact sizes on different aluminium treated samples revealed that the actual shot velocity roughly ranges from 2 to 10 $m.s^{-1}$. These values are closely connected to those previously reported in the ultrasonic shot peening process [7,8]. Further measurements are in progress to determine a statistical evolution of the impact velocity as a function of the radius of the sample.

3. Numerical simulation

The treatment process can be also studied with a molecular dynamics simulation of inelastic hard spheres that are fluidized by a vibrating bottom wall representing the sonotrode. The collisions are followed in a system that presents the same parameters (shot, size of the reflecting chamber) as the experimental setup. Rules for the inelastic collisions between the spheres or between spheres and the walls (top, bottom, side) involve the sphere velocities before and after the collisions and different velocity restitution coefficients [9]. The algorithm is made of the computation of selective collision times between the shot and the sample (with velocity restitution coefficient c_t), the shot and the side walls (c_W), the shot and the sonotrode (c_S=1 arising from a rescaling of the amplitude of the sonotrode) and between pairs of spheres (c=0.91 for steel spheres [10]). The collision corresponding to the lowest collision time is selected and all trajectories are actualised in a dynamic subject to gravity. The next collision time is then searched for and the simulation followed for a given number of collisions.

In order to make comparisons with the experimental shot peening, we have taken for the sample (top) restitution coefficient c_t=0.60 which is the value for aluminium in the range of the mean impact velocity (see Fig. 3). This then leaves the side wall restitution coefficient c_W as an adjustable parameter which was taken either as 0.60 or 0.30 to ensure the correspondence with the (AI) and (AIS) chamber.

Figure 4 shows a map of the impacts on the sample after a peening time of one second for an aluminium-like sample in an (Al) and (AIS) chamber and for the sonotrode in an (Al) chamber. From the first two panels, the results show clearly that when c_W is lowered, the distribution of impacts becomes heterogeneous. The heterogeneity is however moderate as compared to the one displayed on the sonotrode (third panel) thus suggesting that effects of c_i (i=t,S) also contribute to the shape of the distribution. With an increasing difference between c_i and c_W, the energy dissipation on the walls becomes very different and leads to increased granular temperature and density gradients that promote non-homogeneous peening [9].

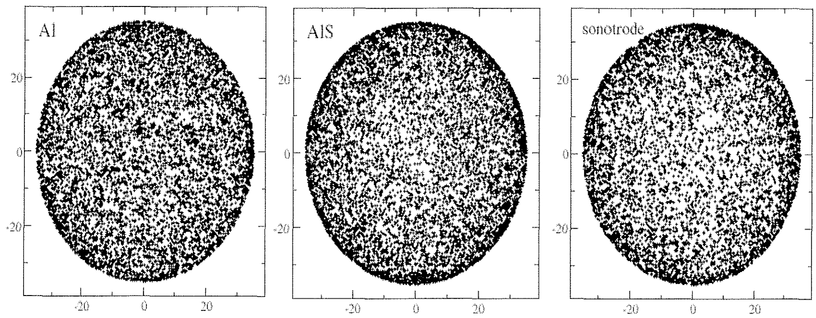

Figure 4 : Simulated impact profiles on an aluminium-like sample (peening simulation time 1s) in the case of aluminium (Al, cw=0.60) and adhesive striped aluminium (AlS, cw=0.30) side walls, and the sonotrode (cw=0.60) during a peening time of 1 second.

This general behaviour from Figure 4 can be made more quantitative by computing the surface impact frequency N with respect to the radius of the chamber (Figure 5, left panel). As one can see, for the aluminium sample, N remains almost constant at a value about 0.3 $mm^{-2}s^{-1}$ up to a radius of 30 mm and an increase up to 0.9 $mm^{-2}s^{-1}$, whereas for the sonotrode the starting surface impact frequency is lower and there is a continuous growth up to the border of the sample.

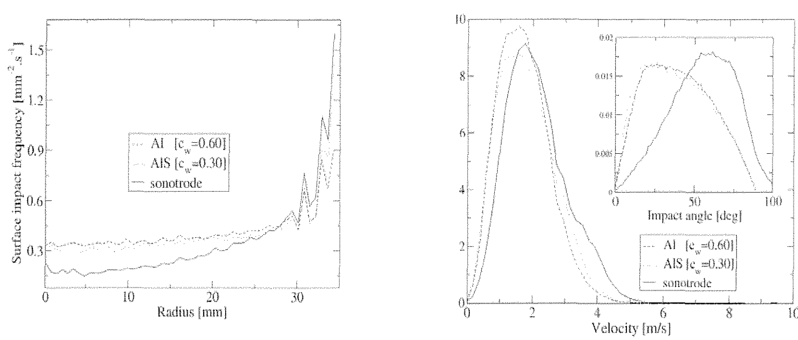

Figure 5 : Left panel: Simulated surface impact frequency N on the aluminium-like sample for the Al and AlS side walls, and the sonotrode for Al side walls. Right panel: Normal impact velocity distribution for Al and AlS side walls. The insert shows the corresponding impact angle.

Finally, we monitor the normal impact velocity and the impact angle distribution of the shot (Figure 5, right panel) for both chambers. We obtain a sample velocity distribution that remains almost the same even if a small broadening is obtained for the (AlS) with respect to the (Al) chamber. The mean normal impact velocity (about 1.8m/s) remains the same and is close to the one found previously (see also [7,8]). The broadening is more pronounced for the sonotrode. Concerning impact angle distributions, the simulation leads to an unexpected result: most of the shot impact the treated sample with an angle ranging from 20° to 50°. Moreover, impact angle distributions are radically different between the aluminium sample and the sonotrode with a higher number of oblique impacts (>50°) for the latter. Note that the angular distribution of the sonotrode contains values that are larger than 90° because spheres can collide twice with the sonotrode (the second time, $v_z>0$) in a small time interval.

4. Conclusion

We have shown from experiment and by simulation the existence of a heterogeneous distribution of impacts in an ultrasonic shot peening process. This behaviour seems to be mostly driven by the inelastic collisions on the side walls. The nature of the sample and the way the shot collides on it (through the restitution coefficient c_t) also affect the overall distribution of impacts and manifests in the present study by a different peening regime between the aluminium-like sample and the sonotrode.

The range of shot velocity has been determined by experience and confirmed from the simulation. It is however much lower than in the case of conventional shot peening (CS) which is generally of the order of 20 et 110 $m.s^{-1}$ [11, 12]. Further experimental measurements are in progress in order to establish a statistical distribution of impact sizes and impact velocities as a function of the sample radius and these results will be further analysed by comparison with the simulation.

5. References

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