Discrete elements method simulation of the movement of media and the velocity between the media and treated parts during the vibratory peening process

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Abstract

Vibratory peening combines the shot peening and vibratory finishing processes into one process. It has the same effect as shot peening that increases fatigue life by inducing compressive residual stresses while polishing the treated part, which is usually done by vibratory finishing. In this work, the vibratory peening process was investigated to assess if a correlation can be made with the shot peening process using Almen strips. A vibratory peening machine was equipped with a data acquisition system that can measure the displacement of the whole machine in a three-dimension space. Then, Almen strips were treated using 3 mm steel bearing balls while the data acquisition system recorded the vibrations modes of the tub from 10 Hz to 30 Hz. The vibratory peening process was simulated using a model based on the discrete element method (DEM) and its main output was the impact velocity of the media on the Almen strip. Simulations were compared to the vibratory peening treatments on Almen strips and to the literature on conventional shot peening.

Keywords: Vibratory peening, DEM simulation, impact velocity

Introduction

Shot peening (SP) is a largely studied surface enhancement process on metallic parts. Indeed, it can increase fatigue life up to 20 times, when compared to the as-machined parts [1]. SP consists in blasting spherical media particles at high velocity on a metal part, which generates plastic deformation by inducing a layer of compressive residual stresses and cold working. The shot peening process increases fatigue life because its compressive residual surface stresses delay crack initiation. However, SP increases surface roughness that is unfavorable to fatigue life since it creates local stress concentrations. A post finishing process is usually applied onto the shot peened part to reduce surface roughness [2]. The vibratory finishing (VF) process is a mass finishing process developed for polishing, deburring and cleaning small workpieces. This process consists in vibrating a tub filled with polishing media. The workpieces are inserted inside the polishing media, and the vibrations induce a relative motion between the workpiece and the media particles that polishes the workpieces [3].

The vibratory peening (VP) process is a manufacturing finishing process that aims to combine both SP and VF by fixing the workpiece in the tub filled with media. The kinetic energy transmitted to the treated surface by the impacts is higher, when compared to the vibratory finishing process, because the fixed workpiece is submitted to that of higher velocity impacts. VP induces similar effects to those of SP on the workpiece, such as compressive residual stresses, while decreasing the surface roughness simultaneously. Therefore, it couples the same effects of both SP and VF.

The purpose of this study was to assess the motion of the media inside a vibratory peening machine, which is essential to understand the behavior of both the vibratory peening machine and the impacts between the media and the treated part. It is a preliminary study that aims to further guide the modelling of the vibratory peening process.

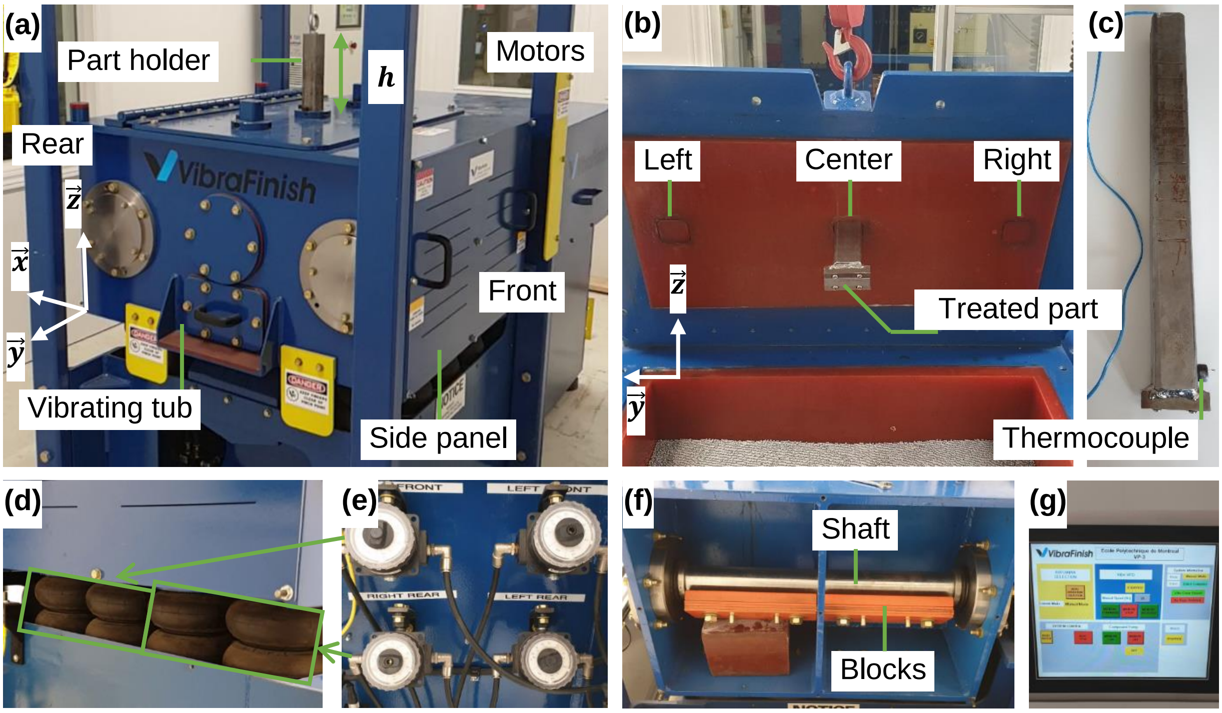

Figure 1 Images of the vibratory peening machine illustrating its operating parameters. (a) The vibrating tub is filled with media and the depth of the part inside the media is controlled by **h,** which is the height of part holder above the tub. (b) The part holder is tightened at the center of the tub lid and two other positions (left and right) are available. (c) The part holder is equipped with a thermocouple probe to measure the temperature during the operation. (d) Two-pair airbags are located on each side of the tub. (e) The pressure in each pair is adjusted by a manometer. (f) The rotating shafts behind the side panels. The number of blocks installed on the shafts determines the eccentricity. (g) The motor drive panel controls the motor speed.

Experimental Methods

The vibratory peening machine was equipped with a setup of six laser sensors that provided the 3D displacement of the vibratory peening machine. The VP machine was filled with 3 mm diameter steel particles. The workpieces in the VP machine were Almen A strips having dimensions of $19 \times 76 \times 1.27$ mm^3 . The main modes of vibrations determined experimentally were used as input of the discrete element model.

The operation consists first in fixing an Almen strip on an aluminum holder that is inserted into media inside the tub and fixed on the cover as shown in Figure 1 (a)-(b). The tub lays on airbags for which the inflating pressure can be changed (Figure 1 (d)-(e)). The vibrating motion is induced by eccentric masses on rotating shafts (Figure 1 (f)) controlled by the motor drive panel (Figure 1 (g)). A thermocouple was installed to measure the temperature near the Almen strip during operation.

A DEM model was developed to simulate the media movement inside the vibratory peening tub to obtain the impact velocities of particles against the Almen strip, and to study the correlation between Almen intensity and the corresponding impact velocity against the strip. The simulations were based on the vibratory peening tests with shaft frequencies of 17.5, 20, 22.5, 25, 27.5 and 30 Hz, a media mass of 544 kg, an eccentricity on shafts of 24 kg/shaft, an airbag pressure of 2.8 bar, a height of media above the workpiece of = 150 mm, the workpiece in the middle of the tub and a lubrication rate of 20 rpm.

Figure 2 illustrates the locations of the six sensors on the three surfaces of the tub. Two sensors were installed on the top of the tub, one sensor in the front surface and three sensors on the right surface, as shown in Figure 2 (a). The vibration amplitudes of the tub were computed with the measurements recorded from these six sensors. Figure 2 (b)-(e) shows the location and installation of each sensor on the actual vibratory peening machine.

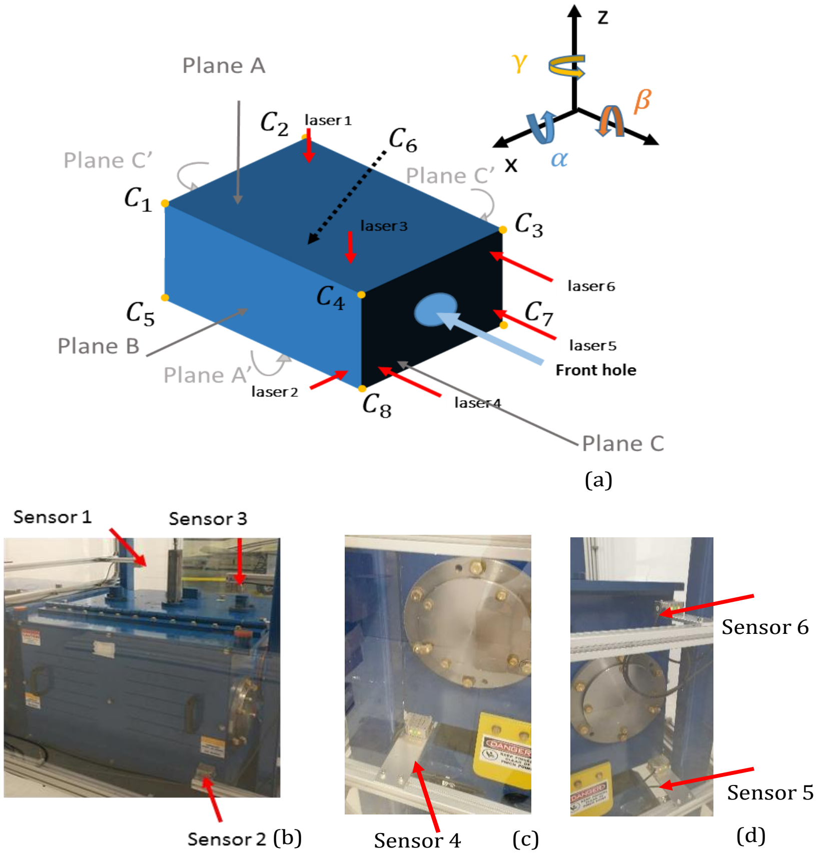

Figure 2 Installation of the six laser sensors at the three surfaces of the vibratory tub. (a) Location of the six sensors around the tub, (b) Installation of lasers 1, 2 and 3, (c) Installation of laser 4, (d) Installation of lasers 5 and 6.

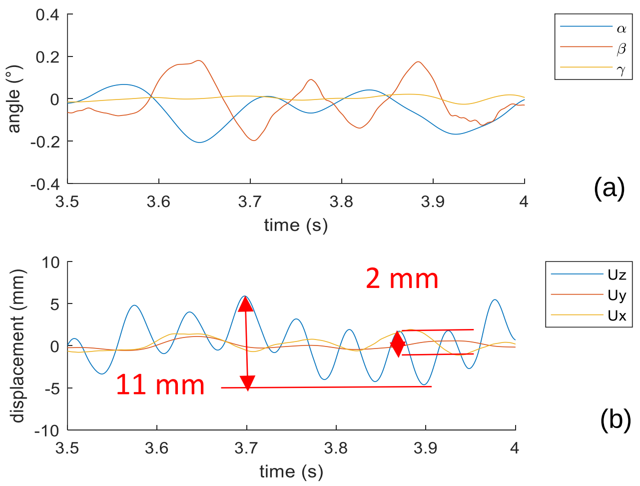

Figure 3 Computed rotations (a) and displacement (b) of the vibratory peening machine.

Experimental Results

Figure 3 presents the computed rotation and displacement of the center of the tub as a function of time for a media mass of 544 kg, an eccentricity on shafts of 24 kg/shaft, an airbag pressure of 2.8 bar, a height of media above the workpiece of 150 mm, the workpiece in the middle of the tub and a lubrication rate of 20 rpm. The figure shows that the maximum amplitude of Uz (the displacement in the z direction) is 11 mm, which is larger when compared to the maximum amplitudes in the x and y directions, which are of the order of 2 mm. The three rotation angles $(\boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\gamma})$ lie in the range of [−0.3°, 0.2°], which suggests that the tub remains relatively at the same orientation during operation. Therefore, only Uz is considered as the vertical amplitude of the movement of the tub for further simulations of the vibratory peening process.

Figure 4 shows the (y, z) cross-section of the DEM model with an Almen holder in the middle of the tub with same steel properties as those of the media. The dimensions of the holder are of $20 \times 100 \times 20$ mm^3 and the Almen strip dimensions are of $20 \times 80 \times 1$ mm^3. The depth between the bottom of the tub and the Almen strip is 250 mm. The thickness of the DEM model in the x direction in Figure 4 is 20 mm. The restitution coefficient between two spherical steel impacting media is defined as 0.95, according to Lecornu [4]. The restitution coefficients between the media and the Almen holder and between the media and the Almen strip were also assumed at 0.95. The restitution coefficient between particles and the tub was estimated manually by dropping one media onto the same rubber surface as the line of tub. The position of the initial drop and the position after one rebound were measured and used to compute the restitution coefficient. The restitution coefficient between the media and rubber material is defined as:

$$\boldsymbol{C_r} = \sqrt{\frac{\boldsymbol{H_{re}}}{\boldsymbol{H_{ini}}}} \tag{1}$$

where $\boldsymbol{H_{ini}}$ is the height measured at the initial position and $\boldsymbol{H_{re}}$ is the measured height after the first rebound. The drop tests were carried out 10 times and an average of restitution coefficient $\boldsymbol{C_r}$ = 0.71 was obtained. The maximum value was max($\boldsymbol{C_r}$) = 0.72 and the minimum value obtained was min($\boldsymbol{C_r}$) = 0.70 from Equation 1.

Figure 5 (a) presents the simulated average normal impact velocities to the Almen strip for six shaft frequencies of 17.5, 20, 22.5, 25, 27.5 and 30 Hz, with a media mass of 544 kg and vibrating for two seconds. Figure 5 (b) shows the Almen intensity experimentally measured after VP. In the post treatment of the simulation, every collision is tracked between all particles and the Almen strip. Every collision is associated to a normal impact velocity so all the impact velocities are saved. The normal impact velocity presented in Figure 5 (a) is the average velocity of all the impacts against the Almen strip. There is a linear correlation between velocity and shaft frequency.

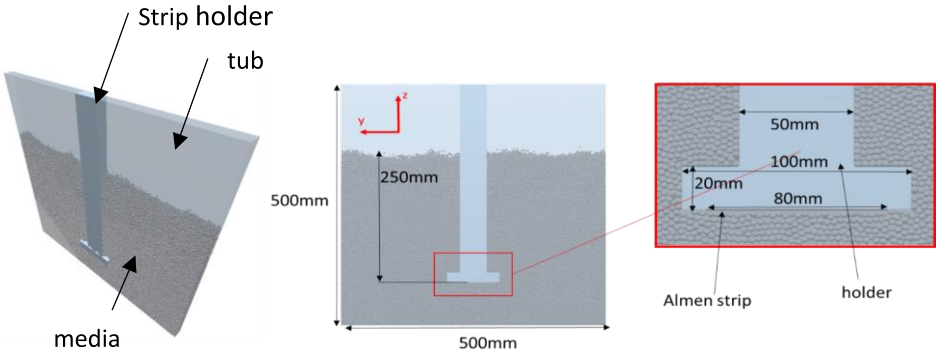

Figure 4: DEM model with 110,000 steel particles with diameter of 3 mm.

Figure 6 reports the experimentally measured Almen intensity as a function of the predicted impact velocity of the media. Figure 6 also plots the analytically predicted Almen intensity by Miao et al. [5]. The figure shows that the range of Almen intensities reached is almost the same for the six measurements (0.1 mmA to 0.2 mmA) and conventional shot peening (0.095 mmA to 0.200 mmA), which means that the vibratory peening process can achieve the same Almen intensity range as conventional shot peening. From both simulations and experimentations, an empirical linear correlation can be obtained between impact velocities and Almen intensity:

$$\boldsymbol{I} = \mathbf{0.2564} \times \boldsymbol{V} - \mathbf{0.0724} \tag{2}$$

where $\boldsymbol{I}$ is the Almen intensity (mmA) and V the normal impact velocity of the particles (m/s).

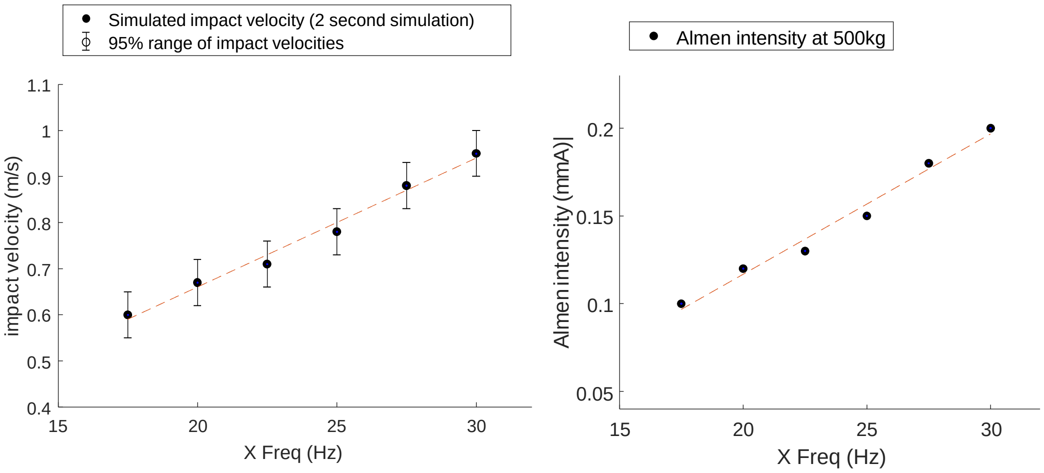

Figure 5: Impact velocity and Almen intensity according to shaft frequency of the VP machine. (a) Simulated impact velocity (b) experimentally measured Almen intensity after VP treatment.

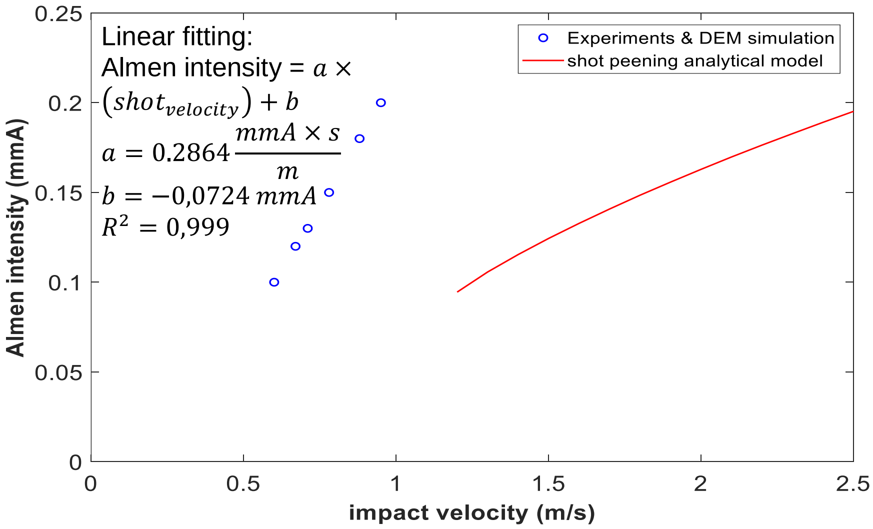

Figure 6: Experimental Almen intensity vs simulated impact velocity from DEM simulations.

A coefficient of determination $R^2 = 0.999$ was obtained for the experiments and DEM simulation points. In the case of the impact of a round steel particle on a steel surface, the relation between Almen intensity and impact velocity is also linear, as shown in Figure 6. It can be seen that larger impact velocities (1.2 m/s to 2.5 m/s) are needed to reach the same Almen intensities as those obtained for lower velocities (0.6 m/s to 0.95 m/s) during vibratory peening. This could partly result from the several layers of particles that increase the inertia of the shot impacting the strip, and therefore the energy transmitted to the Almen strips. This could explain the lower range of impact velocities for the vibratory peening process to reach the same Almen intensity range than the shot peening process. Further investigation is required for a deeper understanding of the difference of the two processes.

Discussion and Conclusions

A vibratory peening machine was equipped with a data acquisition system to measure its overall displacement. A discrete element method (DEM) model was developed to simulate the media movement inside the tub. The experimental results show that the vibratory peening machine has a dominant vibration mode in the vertical direction while the lateral and angular modes can be neglected. The range of achievable Almen intensities is the same as that of shot peening. However, the impact velocity range with the vibratory peening process is lower than the shot peening process, which means that energy is not only transferred by the first range of media impacting the part, but also by the other layers of particles under the first layer that transmit their inertia. Moreover, those simulations have permitted to create an empirical relation between shaft frequencies and Almen intensity. This allows to master the intensity that needs to be reached just by choosing the frequency of the vibratory peening machine. The limitation of this work is that it has been done with specific machine parameters. Therefore, it cannot directly be extrapolated to other machine parameters. Nevertheless, it provides a window of operation in which the Almen intensity can be predicted.

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