Predicting of shot velocity in shot peening process

Guechichi H. and Benkhattab M.
Laboratoire d'Elaboration et Caractérisation Physico Mécanique et Métallurgique des Matériaux, Department of Mechanics, Faculty of Science and Technology, Mostaganem University, Algeria,
hguechichi@hotmail.com

Keywords: shot velocity, Almen intensity, Almen strips, residual stress.

Introduction

Shot peening is a cold working process in which small spherical parts called shots or peening media are blasted on a surface of a metal work-piece with velocities. Shot peening has wide spread application particularly in the field of the automotive and aerospace industries. The main process parameters which influence the characteristics of the surfaces and surface layers are : machine type, nozzle geometry (spread, diameter), mass flow, shot type (material, form), peening angle, peening time, shot velocity, mechanical properties and the geometrical shape of work material. The velocity of the shots is a significant parameter of shot peening process but it is not used as a controlled parameter by the shot peening industry. Shot velocity is one of the most important parameter of the shot peening process because it governs the kinetic energy of the impacting shot and hence the peening intensity. The velocity can be changed by regulating the air pressure or, in the case of a wheel, by adjusting its speed until the required Almen intensity and coverage are attained. In the industry the Almen gauge, made from SAE 1070 spring steel, is widely used as a standard measurement device for monitoring the arc height of a strip of material after its exposure to a blast of shot. Almen intensity is employed to ensure the repeatability of the peening process of identical parts. Champaigne [1] presented, in more detail, the calibration of Almen gage; the Almen intensity is determined from the interpretation of an Almen saturation curve. The shot peening intensity curve, which produces the specified intensity, will determine the correct set up of the shot peening machine being used.

Shot peening process needs to find the optimal parameters. In practice, the higher Almen Intensity is not necessary to be the adequate parameter for the shot peening process. Though Almen strips are widely used in the industry, very few researches have been conducted on the subject of the shot peening velocity. However, the majority of publications have been experimental in nature. In order to reduce the costly use of Almen strips, it is interesting to correlate Almen intensity to shot velocity. The main aim of this study is to propose a method for prediction of the shot velocity using analytical method. The present paper establishes a framework for predictive modeling of shot velocity.

Objectives

Shot peening process is able to increase fatigue life of the part by introducing, near-surface, hardening strain and compressive residual stresses which restrain the opening of microcracks in the surface layer and thus would reduce or even arrest the growth of these cracks. To estimate the residual stress profile induced by shot peening, in a general metal part, it is necessary to identify the shot velocity which is unknown throughout the shot peening process. It is, therefore, important to predict the shot velocity from the known Almen intensity values, and to know how residual stresses vary by changing the shot peening parameters. The problem requires understanding of the relationship between the compressive induced stresses caused by the impact of the shot and the arc height of an Almen strip. The knowledge of the residual stress field, as a function of depth from the surface, is essential in determining the arc height of an Almen strip. To predict residual stress distribution after shot peening, different simulations and modelling of the process have been conducted. Proposed shot peening models are numerous in the literature; they are of three kinds: analytical, semi-analytical and numerical. The main objective of the present paper is to establish, through an analytical model for practical and extensive use, a relationship between the shot velocity and the Almen intensity data. A computer program was developed in order to enable users to find the shot velocity for a given Almen intensity. In order validate the consistency of the model, the predicted shot velocity are compared with the available experimental results. This work furnishes an important tool for developing and evaluating the shot peening process.

Methodology

The shot velocity stands in a complex relationship to the material properties, Almen intensity, shot size, angle of impact and also Almen strip dimensions. Experimental observations made by Hahn et al. [3] showed that the Almen strips material, i.e. SAE 1070 spring steel, has an elastic-plastic behavior with linear-kinematic-hardening. Its mechanical properties are the following: cyclic yield stress $\sigma_s = 803$ MPa, hardening modulus $C = 2773$ MPa, Young's modulus $E_m = 200$ GPa and Poisson's ratio ν_s =0.3. Both steel and ceramic shots are used in this investigation. For each shot material, three commercially available shot sizes were studied, i.e. S110, S170 and S330 for steel shot and Z300, Z425 and Z850 for ceramic shot. Kirk [4] shows that each type of shot is defined by its nominal and average shot diameters. In this study, the nominal shot diameter was used for calculation.

For this purpose, we have developed a model to evaluate the shot speed from Almen intensity data. The method simulates the impact of shots on the surface as a cyclic loading. The Hertzian elastic contact theory is adopted taking into account the dynamic effect of impacts. A schematic contact between the rigid shot and the elastic semi-infinite body is shown in Fig. 1. The incidence angle α is close to the normal direction ($80° \le \alpha \le 90°$). The contact is considered frictionless. The model neglects also the tangential velocity component. Consequently, the "Hertz effect" can be supposed more important than the "hammering effect".

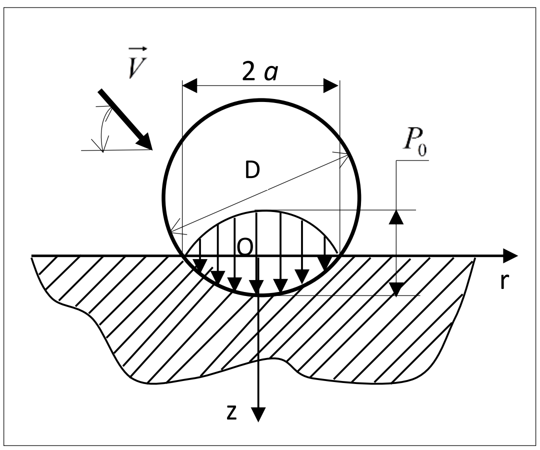


Figure 1. Contact region between the shot and surface of semi-infinite body.

The problem requires knowledge of the relationship between the compressive residual stresses generated by the impact of shots and the deflection of an Almen strip which is considered of thickness h in the z direction which contains uniformly distributed induced stresses generated by the shot peening. The determination of the profiles of induced stresses $\sigma^{ind}(z)$ follows the procedure as given in our previous work [2] which uses a simplified analysis method which is based on an elastic-plastic material behavior with linear kinematic hardening. The arc height Arc at the center of the shot peened area is given by:

$$Arc = \frac{3M\,L_x^2}{2E_m\,h^3} \tag{1}$$

where: E_m is the Young's modulus of the Almen strip material, L_x is an Almen strip dimension. The bending moment M of the unit (per unit of length) is computed with the following expression:

$$M = \int_0^h \sigma^{ind}(z)\left(\frac{h}{2} - z\right)dz \quad (2)$$

The arc height Arc is compared with Almen intensity Al. For a given Almen intensity Al, the corresponding shot velocity V is the one for which the following relationship fulfils :

$$Arc = Al \quad (3)$$

The details of the proposed methodology and the flowchart of the computer program for prediction of shot velocity is described in the previous paper [5].

Results and analysis

Validation of the model

Experimental measurements of the shot velocity are very rare. In order to validate the model, the predicted shot velocities were compared with experimental data found in Barker et al. [6]. The experiments were conducted on the Almen strip A using a steel shot S 110. The measured shot velocities are obtained for six different values of Almen intensities A : 0.14, 0.16, 0.2, 0.22, 0.26 and 0.28 mm. In Fig. 2, the analytically obtained shot velocity (as a function of Almen Intensity) is compared with one that was experimentally measured. We can observe that the predicted and experimental values are very close. As can be seen, it is revealed that the relationship between the Almen intensity and shot velocity can be described by a nonlinear function. All the trends of the shot velocity obtained by the proposed simulation will be discussed in the present paper.

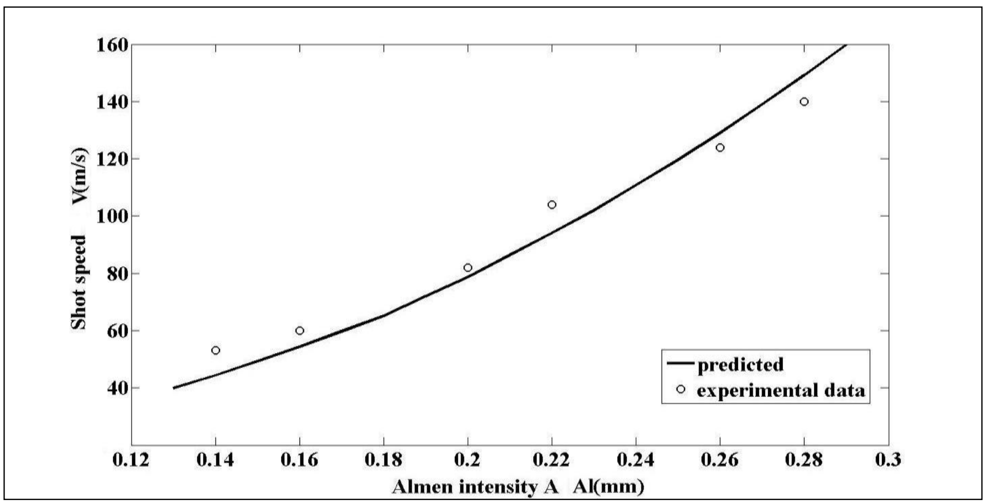


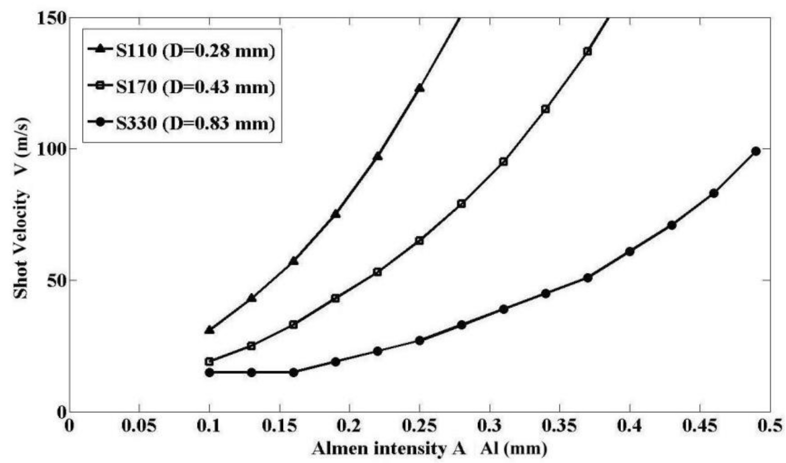
Figure 2. Comparison between predicted shot velocity and existing experimental data found in Barker et al. (2005).

Influence of Almen intensity and shot material on velocity

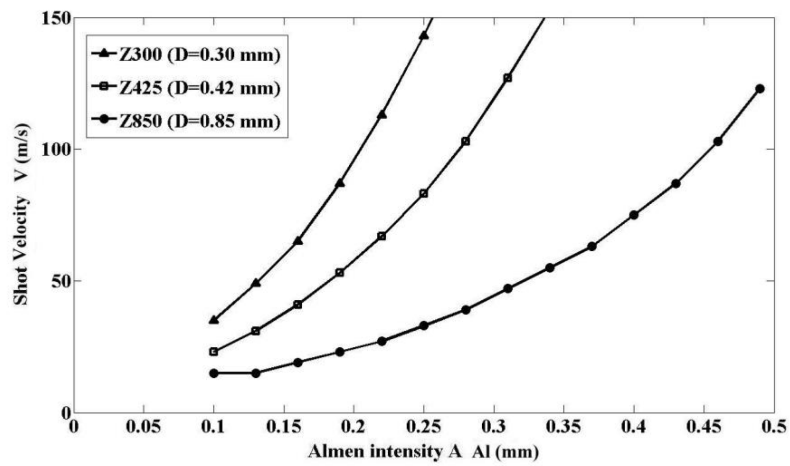
In order to evaluate the effect of Almen intensity on velocity, a series of calculations were conducted. The plots in Fig. 3 illustrate the predicted shot velocity versus Almen intensity for various shot sizes. These curves are obtained for two shot materials, i.e. steel (Fig. 3a) and ceramic (Fig. 3b). For each shot material, three different types of shot size were considered, i.e. S110, S170 and S330 for steel shot and Z300, Z425 and Z850 for ceramic shot. From these curves, it is important to note that the same Almen intensity can be obtained by different shot sizes and/or material shots. It should also be mentioned, for both steel and ceramic shots, that the shot velocity V can be expressed by a third order polynomial function of Almen intensity Al as :

$$V = \xi_1 Al^3 + \xi_2 Al^2 + \xi_3 Al + \xi_4 \quad (3)$$

where the coefficients ξ_1, ξ_2, ξ_3 and ξ_4, are identified from the plotted curves (Fig. 3). These coefficients depend on the material and size shots and also on all shot peening parameters.



(a)



(b)

Figure 3. Predicted shot velocity versus Almen intensity for various shot sizes and for two shot materials: steel (a), ceramic (b).

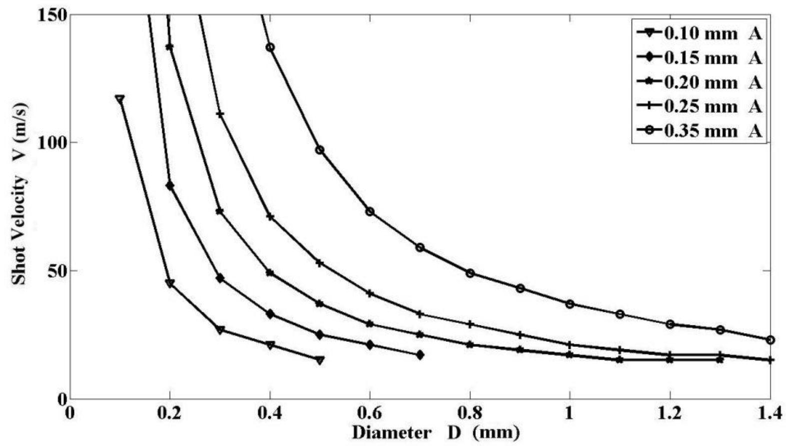
Table 1. Values of the coefficients ξ_1, ξ_2, ξ_3 and ξ_4 given by equation (3) which determine the trends of the shot velocities corresponding to the shot peening parameters used in the investigation.

Coefficients	Shot material					
	Steel S110	Steel S170	Steel S330	Ceramic Z300	Ceramic Z425	Ceramic Z850
ξ_1	5.5 10^3	3.1 10^3	6 10^2	6.6 10^3	3.7 10^3	1.1 10^3
ξ_2	-1.7 10^3	-1.2 10^3	30	-2.1 10^3	-1.1 10^3	-3.1 10^2
ξ_3	6.9 10^2	4.2 10^2	19	8.3 10^2	4.6 10^2	1.3 10^2
ξ_4	-29	-16	11	-37	-17	2.7

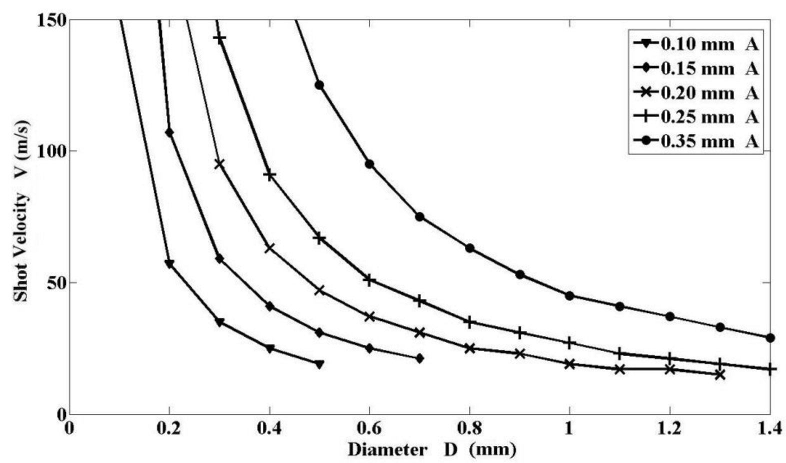
As an example for this calculation, the numerical values of the coefficients are given in Table 1. The shot velocity V and the intensity Almen Al are expressed respectively in m/s and mm A. These coefficient values are only valid for the range of Almen intensity A (for each curve), represented in Fig. 3, and should be used with the same shot peening parameters as those used in this study. One must be cautious when trying to apply the model to conditions outside the validated set of conditions. It is interesting to notice that the plotted curves can be employed as a tool to determine possible combinations of shot peening parameters to achieve a desired shot velocity. It must be noted that the model leaves users free to choose desirable shot peening parameters in order to obtain the resulting trends of shot velocities.

Influence of the shot diameter on velocity

Similarly a series of calculations were conducted in order to evaluate the effect of the shot diameter on velocity while keeping a constant Almen intensity. Fig. 4 shows the shot velocity variation with the shot size for three different values of Almen intensity and for two types of material shots: steel (Fig. 4 a) and ceramic (Fig. 4 b).



(a)



(b)

Figure 4. Shot velocity variation versus shot size for various Almen intensities and for two shot materials: steel (a) and ceramic (b).

With regard to a previous work [2], the profiles of residual stresses are particularly defined by the magnitude of maximal compressive residual stress and the peened layer. The magnitude of the compressive residual stress depends mainly on the cyclic yield stress of shot peened materials. Whereas the peened layer depends on the behavior of the shot peened material and shot peening parameters. Eqs (1), (2) and (3) demonstrate that the Almen intensity is dependent on the area under the residual stress-depth curve of the Almen strip, i.e the bending moment M represents this area. Thus, if the Almen strip is made of another material, one cannot achieve the same curve of the residual stress profiles as in SAE 1070 steel because the behavior of both materials is different. This remark is very important for users to find the satisfactory shot peening parameters while keeping the Almen intensity constant.

Conclusions

The Almen system combines the effects of all the shot peening process parameters into one measurement, allowing for measurement and repeatability of the process. Liu et al. [7] investigated the influence of shot peening Almen intensities on the high cycle fatigue; with regard to the fatigue performance the results exhibit the optimum Almen intensities. Indeed, it is essential to find the relationship between Almen intensity and shot velocity. In this study, the complexity of shot peening process is simplified in order to make progress in modeling and calculation, i.e., to make useful predictions and to elucidate process fundamentals.

The current work suggested a simple analytical model to predict the shot velocity with regard to Almen intensity. The predicted shot velocities were in good agreement with published experimental results. The simulations given by the present methodology showed that the same Almen intensity can be produced by different kinds of shot sizes and/or material shots. The present results clearly show that once the shot material and its size are known the shot velocity depends directly on Almen intensity. We have found a relationship between Almen intensity and the shot velocity. The main criticism to this proposed shot velocity prediction methodology is its practical use. The trends of the shot velocity obtained by the model can be explored in order to determine the optimum shot peened parameters. As an application, the trends of the shot velocity done by the proposed model provided an excellent tool for help the designer to predict the component fatigue life with more confidence. In fact, once the optimum Almen intensity is identified experimentally such as in the work found in Liu et al. [7], the methodology described here can be used to establish whether the velocity is adequate to ensure fatigue performance for various metallic materials.

References

[1] Champaigne J. (2002). Almen gage calibration. In: *Proceedings of the 8th International Conference on shot peening*, Garmisch - Partenkirchen, Germany: 108-113.

[2] Guechichi H., Castex L., Frelat , J., Inglebert G. (1986). Predicting residual stress due to shot peening. In: Meguid, S. A., Ed. *Impact Surface Treatment*. London: Elsevier, pp. 11–22.

[3] Hahn G.T., Bhargava V., Chen Q. (1990). The cyclic stress-strain properties Hysteresis loop shape and kinematic hardening of two high-strength bearing steels. *Metallurgical translations A* Vol. 21A: 653-665.

[4] Kirk D., (2009). Size and variability of cast steel of shot particles. *The shot peener* Vol. 23(1): 24-32.

[5] Guechichi H., Castex L. , Benkhattab M. (2013). An analytical model to relate shot peening Almen intensity to shot speed. *Mechanics based design of structures and machines* Vol. 41-1: 79-99 .

[6] Barker B., Young K., Pouliot L. (2005). Particle velocity sensor for improving shot peening process control. In: Schulze, V., Niku-Larin, A. Eds. *Proceedings of the 9th International Conference on Shot Peening*. Paris, France : IITT International, pp. 385-391.

[7] Liu W.C., Dong J., Zhang P., Korsunsky A.M., Song X., Ding W.J. (2011). Improvement of fatigue properties by shot peening for Mg-10Gd-3Y alloys under different conditions. *Mater. Sci. Eng.* A528: 5935-5944.