A comprehensive stream analysis and a numerical simulation of shot peening for the prediction of representative impact patterns

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Abstract
The present paper is an attempt for set the basis for a realistic shot peening (SP) process simulation that will be capable to predict the corresponding products. The work is divided in three parts. The first part refers to the calculation of the realistic number of shots that impact to a representative area and the calculation of shot velocity and angle distribution as a function of shot peening process parameters via a kinematic simulation model. The second part includes the development of a numerical simulation model which is applied to investigate the shot interactions. The third part refers to the shot patterns generation by developing a Boolean model.

Keywords Shot peening, stochastic modeling, finite element modeling, residual stress

1. Introduction

In the recent years some researchers have realized the significance of simulating multiple shot impacts. Such numerical models are presented by Majzoobi in [1] who modeled multiple shot impacts on a high strain rate sensitive AISI 4340 steel material. Miao [2] has developed a numerical model that consists of an aluminum target plate impacted by rigid shots that are generated randomly within a reference area of 1mm^2 and Klemenz [3] has simulated 121 rigid shots impacting with the same velocity to a steel target material. In 2002, Wang and Platts [4] presented a dynamic algorithm and a static algorithm for spring-back simulation developed in ABAQUS FE code; they simulated 1000 impacts and predicted the final curved shape of a small sized aluminum 2024-T351 specimen after shot peening. In order to realistically simulate shot peening process, a deep understanding of the shot flow behavior within the stream and the interactions between the shots is required. In 2008, Hong [5] published a discrete element analysis which is used to study the multiple particles dynamics within the shot flow. The discrete model is an improved version of his previous work [6] published in 2005; the analysis includes the impact of 10000 shots with specific process characteristics.

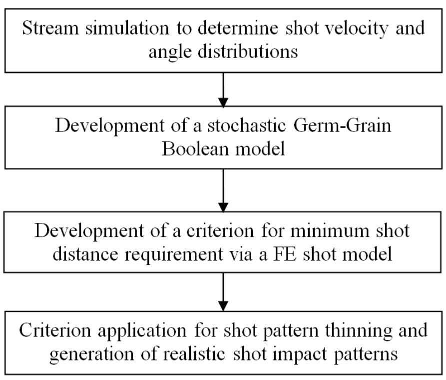


Figure 1 Steps followed to develop shot patterns

In this work the importance of the stochastic SP nature is taken into account by examine the shot flow inside the nozzle, the shot interactions within the shot stream, and the shot velocity and angle just before impact via a kinematic simulation model. A criterion is developed via a 3D numerical model. The numerical model is applied to examine the shot interactions. In order to develop shot impact patterns a Germ-Grain Boolean model is utilized and the criterion previously developed is applied to the stochastic model to conclude with the final shot patterns. The steps followed are shown in Figure 1. The patterns are then introduced to a 3D numerical model of the full plate geometry in order to calculate the RS, surface roughness, geometrical stress concentration factor and cold work (CW) percentage [7].

2. Stochastic modeling

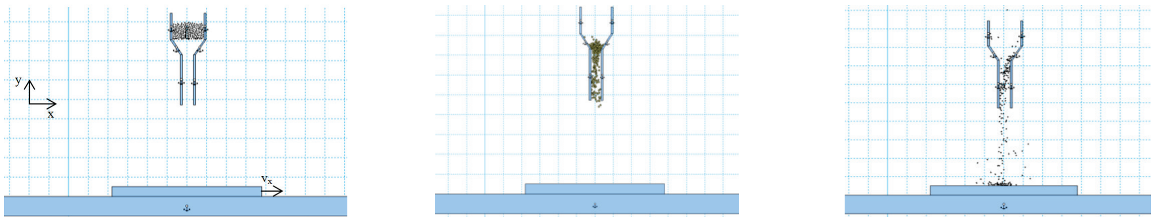
It is well known that a very large number of shots are involved in a SP treatment. A realistic analysis with simple calculations is performed. Starting with an Almen strip which has an area of 1450 mm^2 and by taking into account the min. and max. nozzle cross-sectional area which is 28 and 254 mm^2 respectively, the number of passes required, can be approximated by assuming some overlap. Depending on the nozzle linear velocity (from 50 to 300 mm/s), the total peening time can thus be approximated and the total number of shots coming out of the nozzle can be calculated by knowing the shot mass flow rate. To realise the large number of shots involved in SP process, the number of shots that are coming out of a 6 mm diameter nozzle for 1 s is presented in Table 1. The data corresponds to $\dot{m}$ equal to 0.183 kg/s and to four shot types considered. It is also well known that the most of the RS measurement methods are considering a relatively small area of averaging the measured data, which is typically from 0.5 to 2 mm^2. Thus the reference area can be defined as an average area of 1 mm^2 [3]. With such speeds, the shots impacting the treated material surface for time 0,14 and 0,023 s are summarised in columns 4 and 5 of Table 1. For the needs of the present analysis, shots of steel material are considered as typical in SP process. The shot shape is considered to be perfectly spherical with average shot diameters referring to types S110, S230, S330 and S550.

Shot type	Average shot diameter S_s (mm)	Total shots /s	Number of shots impacting on the treated material surface for time 0,14 and 0,023 s		Reduced number of shots impacting on the treated material surface for time 0,14 and 0,023 s	
			Nozzle velocity 50 mm/s	Nozzle velocity 300 mm/s	Nozzle velocity 50 mm/s	Nozzle velocity 300 mm/s
S110	0.30	1621845	227058	37302	34059	5595
S230	0.60	202731	28382	4663	4257	699
S330	0.85	71304	9983	1640	1497	246
S550	1.40	15958	2234	367	335	55

Table 1 Shot impacts for $\dot{m}$ equal to 0.183 Kg/s

The dent's shape from impacted surfaces shows different geometrical characteristics even within the hot spot. This observation triggers the idea that only a fraction of the shots will impact the surface according to the original process parameters values (angle and velocity). SP is characterised by: shot size and shape variations, shot interactions inside the nozzle, shot interactions within the stream prior to impact and oncoming flow interactions with the rebounding shots (after impact). In order to validate the above statements, a kinematic 2D simulation model of the shot stream is developed in Interactive Physics code [8] to predict the shot interactions within the stream and to calculate the distributions of the real shot velocities and shot impact angles at the time of impact onto the target surface. The innovation of the current model is that for a first time the target plate, the shot parameters (shot shape, shot dimensions, initial shot velocity), the nozzle parameters (shape, dimensions, linear speed, inclination with respect to the target surface), as well as process parameters such as working distance and mass flow rate are taking into account. Typical nozzle shapes include a straight and a Venturi bore with various lengths and diameters. Nozzles are filled with shots randomly in order to simulate and take into account the shot interactions into the bore. This approach is controversy to the method described in [5, 6]. As target plate, a typical Almen strip geometry is introduced in the simulation. In Figure 2a the complete model set-up is shown. A second plate it is also considered underneath the treated plate, which acts as a support.

The developed kinematic model is solved for several combinations of process and nozzle parameters. The combinations include: long and short straight and Venturi nozzles, three nozzle diameters (6, 12 and 19 mm), two peening angles (90^o and 65^o), two working distances (30 and 50 mm), four types of shots (S110, S230, S330, S550) and several different initial velocities in the range of range 20 to 120 m/s. The total number of simulations performed is about 200. As an example, the shots flow inside the nozzle and their motion as they move towards the target plate, are presented in Figure 2, for the case of shot type S230, straight long nozzle type with internal diameter 6 mm, working distance (W_d) 30 mm, impinging angle 90^o and initial velocity 100 m/s.



(a) t_0 = 0 s (b) t_1 = 0.2 ms (d) t_2 = 0.8 ms

Figure 2 Shot flow simulation inside the nozzle and towards the target media

The outcome of the Interactive Physics shot flow simulation model is the calculation of shot impact velocity (v_{imp}) and shot angle (a_{imp}) at the time of impact onto the target surface. The recorded shot velocities just before impact (v_{imp}) are divided by the initial shot velocity (v_{in}) and a velocity ratio is calculated for each condition simulated. It can be observed from Figure 3a, that about 70% of the shots will impact the surface with a velocity between 0 and 10 m/s. Velocity zero implies also shots that never impact the material surface due to shot interactions. The results calculated are similar to Hong [5]; Hong reports that for similar process parameters, the shot percentage which is impacting the surface with a velocity between 0 to 20 m/s is about 86%. A significant difference is that shots never reach the surface are not taken into account in [5, 6] as the effect of the shot interactions inside the nozzle and into the stream is neglected due to the randomly generated shots at the tip of the nozzle cross section. Figure 3b shows the scatter from the initial angle and how many shots retain their initial angle (a_{in}). In this case, scatter is not very large; about 55% of the shots will retain their original angle and the rest of the shots will impact with an angle smaller than the initial.

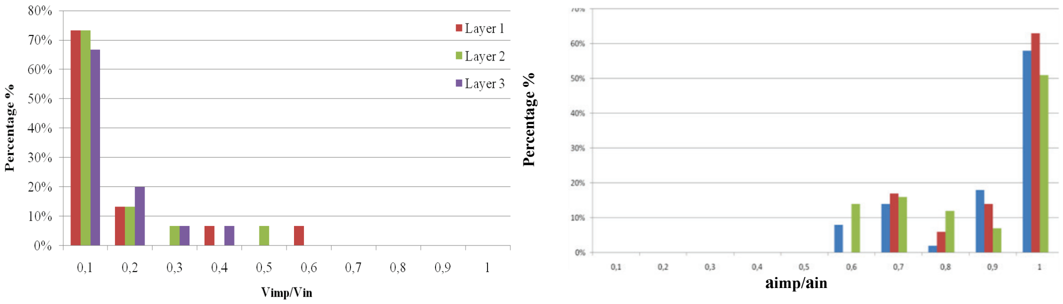


Figure 3 Shots percentage impacting to surface with a) velocity V_{imp}/V_{in} and b) angle a_{imp}/a_{in}

Shots impacting with a lower velocity are excluded from the analysis so Table 1 can be updated showing the reduced number of shots in columns 6 and 7. These numbers are further reduced when the reference area of 1 mm^2 is considered; the data are presented in Table 2. Data from Table 2 applied to develop the stochastic model (intensity λ).

Shot type	Total shots / s	Number of shots impacting on the treated material surface for time 0,14 and 0,023 s	
		Nozzle velocity 50 mm/s	Nozzle velocity 300 mm/s
S110	1621845	1216	200
S230	202731	152	25
S330	71304	53	9
S550	15958	12	2

Table 2 No. of shot impacts on the reference area of 1 mm^2 for $\dot{m}$ 0.183 Kg/s after stream simulation

3. Numerical model

The 3D numerical model developed using the explicit Pam-Crash 4.5 FE code. The entire target plate is modelled, in order to introduce the exact plate boundary conditions (Figure 4a). The plate geometry is parametrically introduced. The target plate material is the high strength AA7449-T7651, modelled as an elastic-plastic material with kinematic hardening. The elastic modulus is 70 GPa, the yield stress 519 MPa, ultimate tensile strength 600 MPa, Poisson ratio 0.33 and mass density 2700 kg/m^3. High strain rate material properties are also applied as derived in a previous author's work [9]. The shot is considered as rigid.

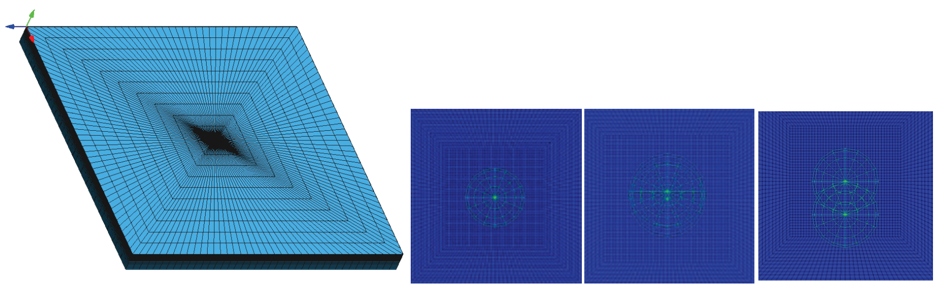


Figure 4 (a) Target plate geometry developed in Pam-Crash FE code and zoom at fine mesh area showing (b) single shot impact, and two shot impacts at distance (c) 0.2Ss and (d) Ss

Different shot locations for a single shot and for 4 neighbour distances examined (0.2Ss, 0.35Ss, 0.5Ss, Ss and 2Ss); an example is shown in Figure 4b, c and d. The RS built-up through the plate thickness at the centre of the first impact is initially examined. The RS developed at the same location is also examined for the 4 neighbour distances, as well as for the subsequent impact. For a shot velocity of 40 m/s, the effect of the neighbour shot impact with distance above Ss and the overlapping shot impact at the initial RS computed at the centre of impact profile is negligible as it can be seen in Figure 5a. Figure 5b shows the average RS over the reference area of 1 mm^2 plotter versus the through plate thickness.

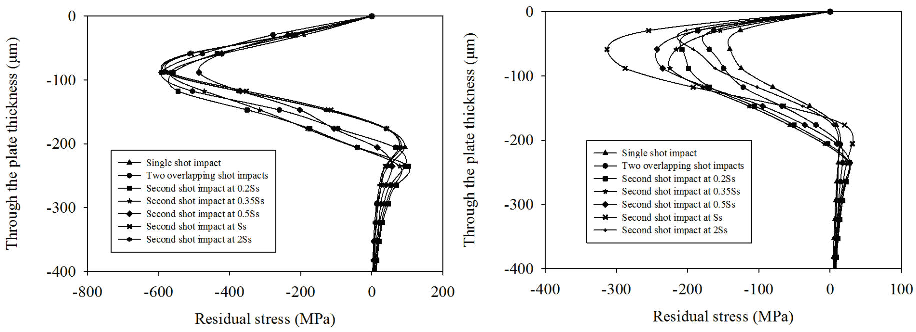


Figure 5 RS versus plate thickness computed at the centre of impact

From the above numerical results the following conclusion can arise; the RS built-up at the centre of single shot impact is not significant affected by neighbour and overlapping impacts. The same applies to RS built-up over a reference area of 1 mm^2 for the case of overlapping impact. A significant change of the RS field over a reference area of 1 mm^2 is performed by the neighbour impacts. The above statements lead to the following criterion: 'any shot impacting at a distance smaller than 0.35Ss from an initial impact can be neglected'.

4. Stochastic model

A suitable model in formalizing a set of independent, randomly placed particles is the Boolean model [10]. A Boolean model can be realised to achieve overlapping circular particles which are called "Grains" to a plane surface. Having calculated the intensity "λ" (Table 2) a Germ-grain Boolean model is developed. A total number of 89 grains for shot type S230 are schematically presented in Figure 6a (for nozzle velocity 175 mm/s according to Table 2). Stochastic geometry is applied to extract the germs from the computed grains as it is shown in Figure 6b. In order to exclude the germs that are not able to affect further the RS field, the criterion previously developed is applied.

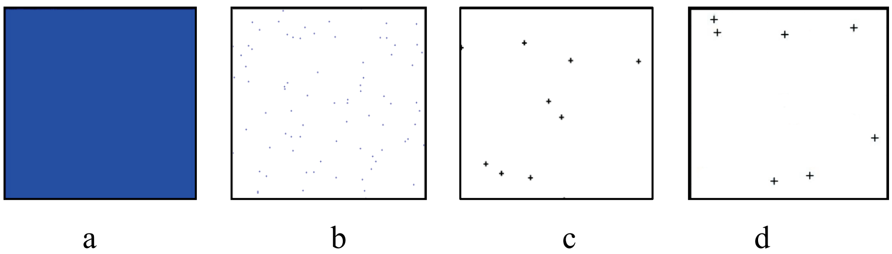


Figure 6 Germ-grain model showing (a) the grains and (b) the corresponding germs. Final pattern for shot type S230 representing (c) 100% and (d) 45% coverage

The distance between the centres of grains (Figure 6a) are plotted in Figure 6b (germs). The nearest neighbour distance distribution is plotted for the germs in Figure 7a, as it is computed by the software. As it can be seen in Figure 7a the 100% of the shots are within a distance of about 0.15Ss. The method of thinning is applied in several steps in order to reduce the number of shots. When the criterion which ensures that the min. distance between impacts is higher than 0.35Ss is satisfied, the thinning operation stops (Figure 7b). The outcome is the pattern shown in Figure 6c; the coverage produced by 10 impacts is less than 100% optical coverage; but in [4] the relationship of plastic coverage and optical coverage are defined.

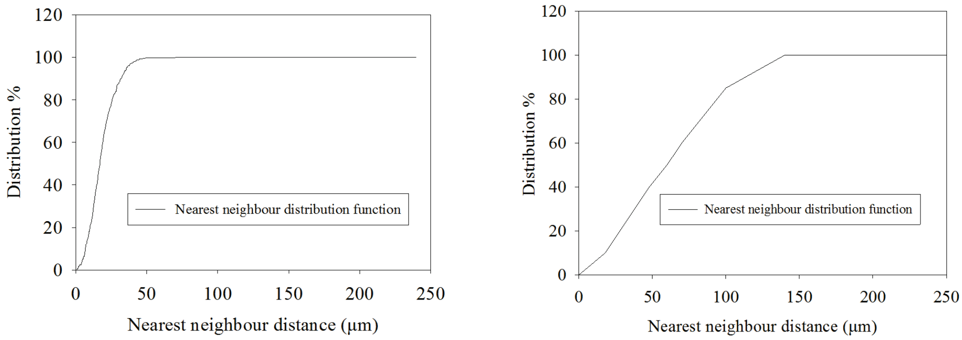


Figure 7 Nearest neighbour distances distribution for (a) 89 and (b) 10 germs

As it is presented 100% plastic coverage corresponds to only 50% optical coverage. This is in accordance to the findings of the present work. By using results of reference [4] it is possible to compute the number of shots required in order to simulate coverage less than 100%. This can be done by developing a stochastic model for a new geometry, apply the thinning criterion and reduce the number of shots impacting until the desirable plastic coverage is obtained. In this spirit, the shot pattern for simulating plastic coverage 45% for shot type S230 is computed and presented in Figure 6d. Patterns can be computed for several shot types.

5. References

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