Relating Shot Peening Process Parameters to Residual Stresses –
A computational/ Stochastic Marriage

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Introduction

Shot peening is a surface engineering treatment used to push the fatigue resistance of metals beyond their natural ability. This is achieved through the induction of near surface compressive residual stresses and (or) cold work. The first creates a virtual environment of lower macro-strains compared to those from the far-field source, while the second will either locally increase the dislocation density creating a difficult obstacle for further dislocation movement or, if severe, will deformed the grains minimising the distance between the grain boundaries. Of course there are additional benefits due to interactions between residual stress and cold work, i.e. when the crack propagates inside the cold work area; the plane favouring dislocation motion can change. Another interaction product comes from the increase in the plasticity induce closure for long cracks. Of course it is important to mention that there are also detrimental effects, in terms of fatigue performance; namely, surface roughness creating an amplified stress field and excessive cold work leading to loss of ductility and incorrect distribution of residual stresses leading to premature relaxation. The enhanced stress field, due to surface roughness, can overshadow part of the residual stress field and deliver reduced fatigue performance, especially when the application targets the region of high cycle fatigue. In addition, it can increase the natural scatter of the material in terms of fatigue life. The latter depends on the triangle grain size distribution, surface condition and type of loading. As a result, shot peening can cause an irregular performance which is beyond the design principles for which the material was first chosen. The reader here should keep in mind that there is limited knowledge relating material selection to shot peening and hence unless critically assessed, shot peening might not deliver the maxima. A second problem relating to surface roughness is the average grain size of the material. Herein, fine grains are more sensitive to roughness and usually deliver a less favourable result. Similarly, cold work, both in terms of profile as well as in terms of value, should be specifically designed in order to meet specific requirements. It is of outmost importance to understand that: a) material with natural tendency to cyclic hardening can react badly to increases in the dislocation density; b) the irregularity caused in the development of local plastic strain can significantly affect residual stresses relaxation, etc. The third and equally important factor is related to the geometry of the component and the expected type of fatigue crack. Herein, improvement from shot peening can be found simply by changing the geometry of the generated crack. In other words, we can select the shot peening parameters in order to enforce specific crack geometry with slower a propagation rate. Of course the above is decisively related to the specific industry and engineering component. For example, in the automotive industry where most components operate under conditions of fail safe, increases in the fatigue limit are mostly required. In this case, the engineer should be in a position to select the shot peening parameters so as to provide a crack shape which is most likely to be arrested (fatigue limit). On the other hand, the aerospace industry, with well established inspections, will benefit from crack geometries allowing them to minimise the cost of maintenance.

For many years, all the above have been examined through Almen strips, saturation curves, and coverage. Yet, the above parameters are not necessarily related to either the residual stresses or cold work. There are numerous examples where the selected parameters have not performed as expected. It is therefore important to realize that in order to move away from the time and money consuming process of trial and error, a more scientific procedure should be developed. Computational mechanics is a rather straightforward tool to replicate the mechanical phenomena involved. However, its simplicity can lead to unprecedented and erroneous results if all the phenomena characterising the process are not considered. Herein, the reader can find numerous cases and written scientific reports with unsuccessful results. Perhaps the problem is related to the large number of shot pellets constituting the shot stream. A typical Almen A strip can theoretically receive up to 200,000 shot impacts in one pass. Yet, its true coverage will never achieve 100% since shot interaction, deflections, and turbulence will minimise their impact energy, initial impact angle, contact time, etc. The number of shot pellets is so big as to prevent any deterministic approach and hence the use of stochastic theories is necessary.

In this work the authors try to examine a stochastic methodology able to provide the necessary information to feed a computational model for the prediction of residual stresses. The work represents an on going collaboration for the development of an in-house code for Superior Shot Peening, Inc to be able to predict the optimum SP parameters as a function of material and operational stress/environment envelop.

Stochastic Analysis of Shot Stream

The parameters controlling the shot stream are namely, the diameter of the nozzle (ND); the working distance (WD); the incidence angle (IA); the number of passes from the same spot (NP); the shot flow (SF); the nozzle line speed (LS), the shot velocity (SV) and finally the shot size (SS). Control of the stream should be defined in terms of the dent distribution that can be achieved when impacting an area able to accommodate it. A schematic of the flow stream can be seen in Figure 1.

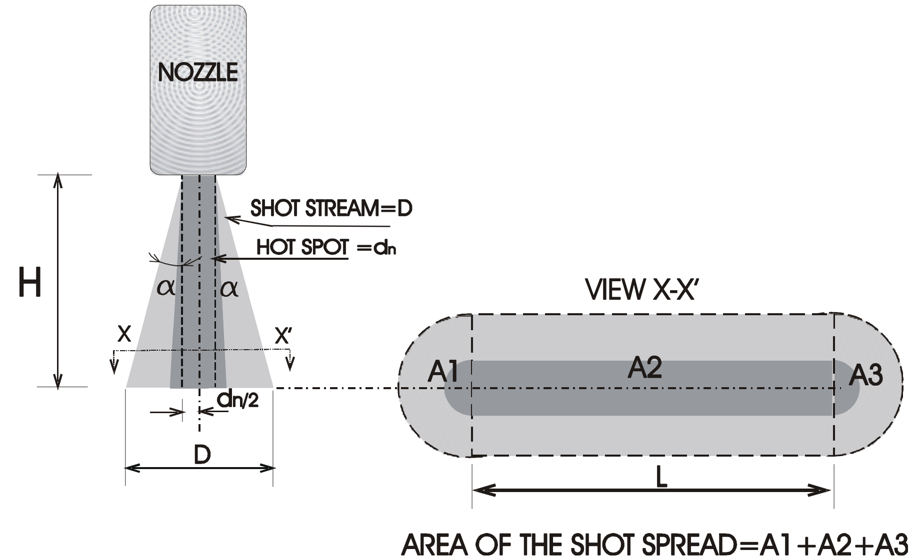


Figure.1: Simplified schematic representation of shot stream and impact geometry.

There are two critical factors controlling the effectiveness of the stream and hence the production of residual stresses and cold work. The first is related to the fact that impacts follow a normal distribution perpendicular to distance L in order to address flow characteristics. The second reflects the fact that even within the hot spot, only a fraction of the shots will impact the surface according to the original process parameters. The phenomenon is characterised by: shot micro deflections due to size and shape variations within the stream prior to impact, rolling contact friction due to turbulent flow (shot pellets are in contact and constrained by their neighbours), and most importantly that the stream characteristics at some distance from the target differ due to interactions with the deflected stream. As a result, theoretical prediction based on ideal process parameters can vary significantly to experimental. The above can been seen in Figure 2.

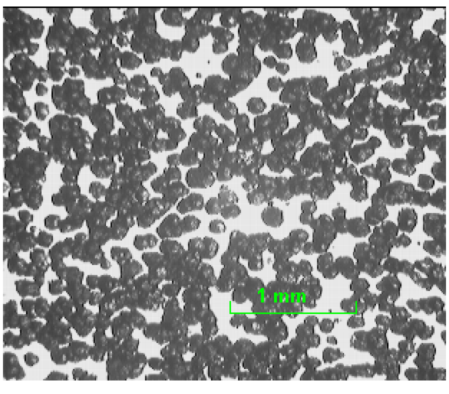


Figure.2: Image taken from an Almen A strip under theoretical conditions of 266% coverage (area of dent multiplied to the number of shots). The true coverage has been optically measured using Systat-SigmaScan

to be 85.2-89.6%. The coverage variation reflects the size of the selected area. The above results come from inspection areas of 1x1mm and 2x2mm respectively. The estimated number of shot impacts within the strip from a single pass is 91,530.

Due to the number of parameters involved and their unknown interactions, a stochastic analysis is implemented. A germ-grain model may provide a good description of irregular patterns observed in image analysis. Probably the best known model is the Boolean model formalizing a configuration of independent, randomly placed particles. The model is configured by placing random balls centred at the points of a Poisson process. Those points are called the germs and the associated balls the grains. To account for the fact that during shot peening not all the shots will impinge the surface identically (same kinetic energy), it is important to assign an intensity range on the formation of the balls. The range should be realistic enough as to discriminate against shots which are not likely to affect the residual stress field. For that reason, an initial FE model has been performed in order to identify such boundary. Using ANSYS Version 11, it has been realized that for speeds up to 80m/sec when two shot pellets are touching each other, the plastic deformation during impact is unlikely to change the generated residual stresses. The second and most crucial task is to identify the relation between intensity and the scaled boundary radius considering that the expected distribution of the stream will not be affected. The above, includes complex mathematics which are beyond the nature of this article. A Matlab program has been written in order to provide the information related. A typical output is depicted in Figure 3.

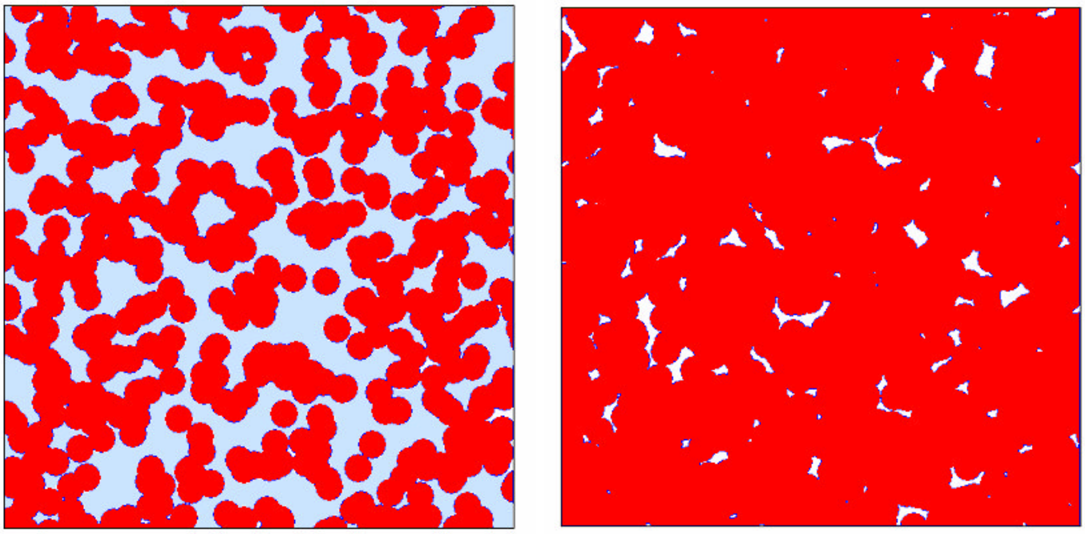
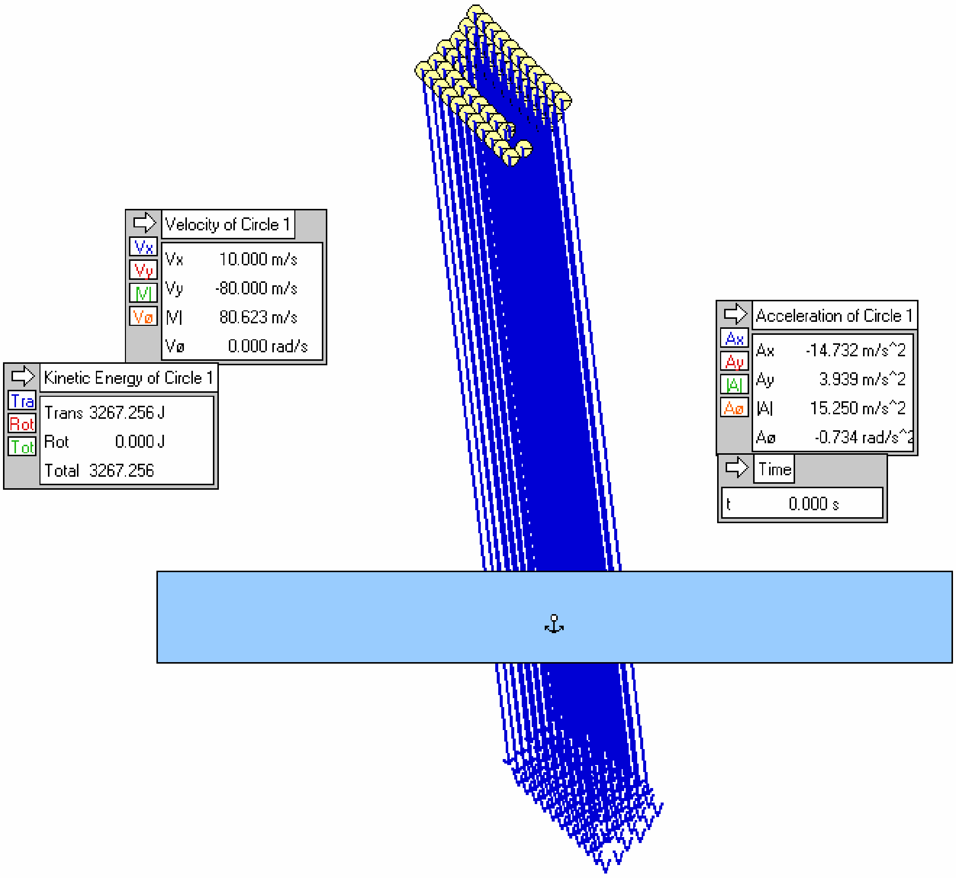
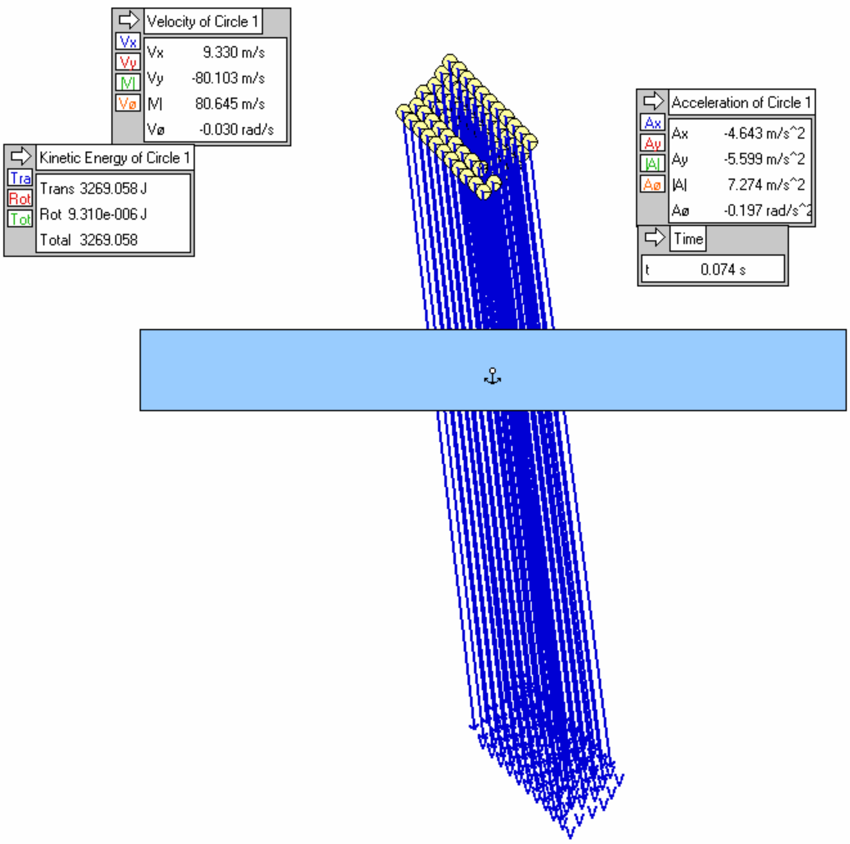
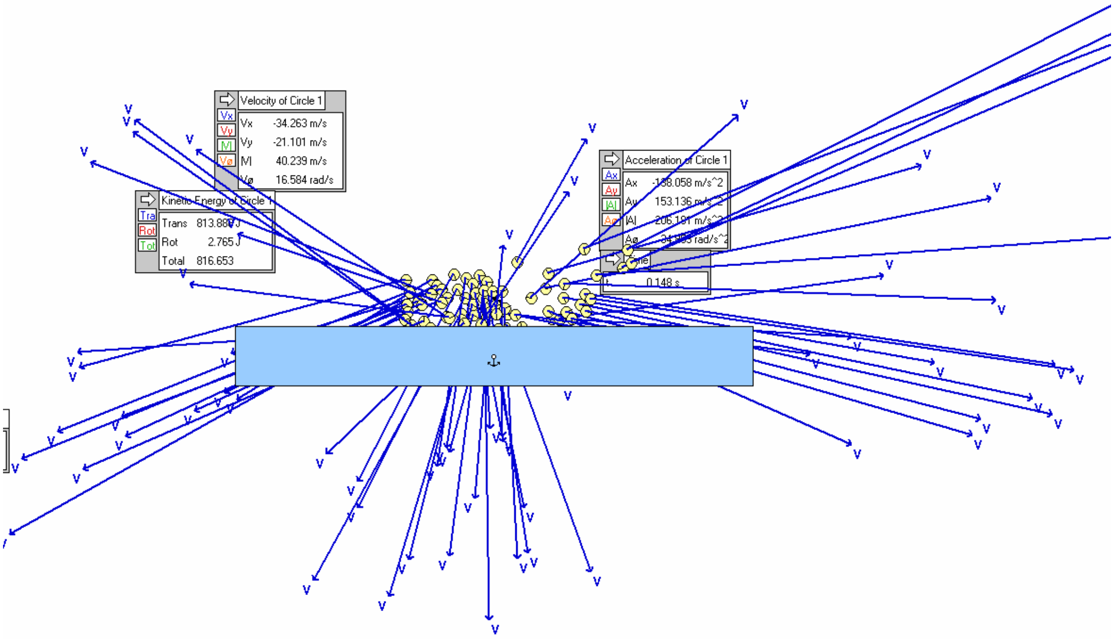


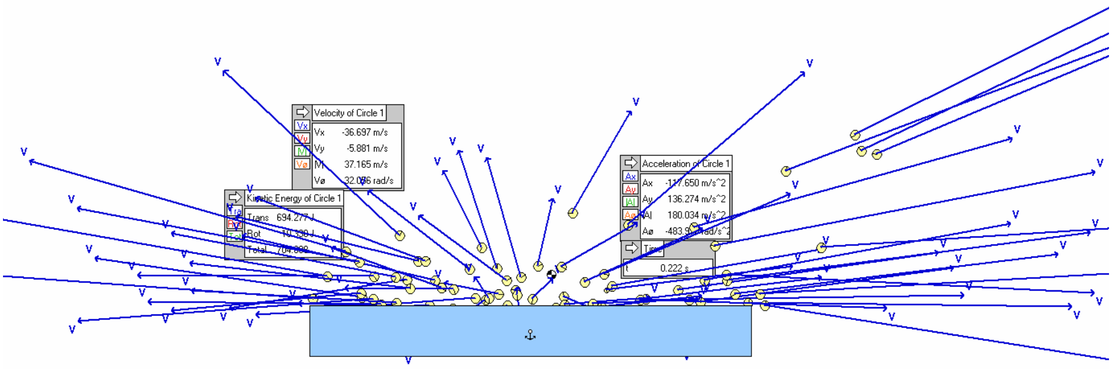
Figure.3: Germ-Grain representation of 75 and 98% coverage. The corresponding mean value of the normally distributed coverage is 0.76 and 0.99.

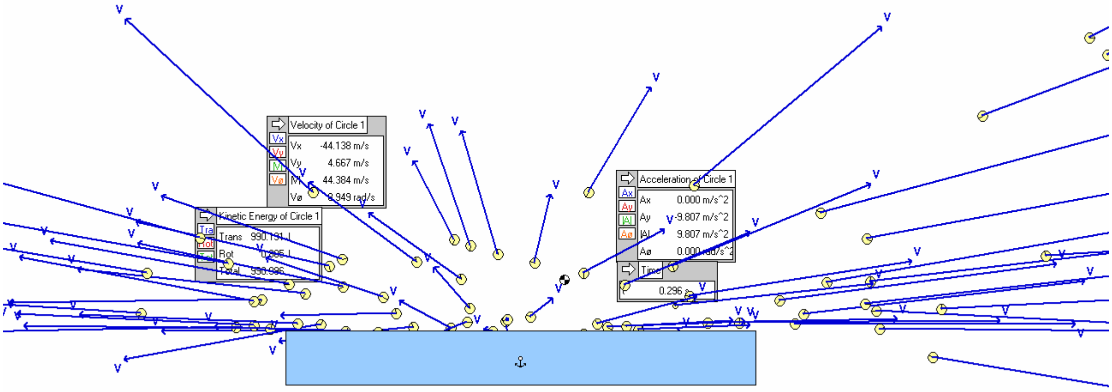
To account for the fact that not all the shot pellets will hit the target, a thinning process is engaged. This is done considering a selected survival probability. Its value can be obtained by either teaching a neural network using experimental data or by simulating the most crucial phenomenon, that of the interaction between the incoming and deflected stream. The first is rather straightforward, but requires a significantly large amount of data. The second can only represent a scaled model due to computational limitations. The latter however, can be more precise in implementing some basic impact parameters, i.e. speed, shot size, hardness of shot and target, etc. In this work, survival probability has been determined using MSC-Interactive Physics 6.0.0.1. Snapshots from the actual simulation are shown in Figure 4. The velocity vectors are kept to demonstrate the interactions. Of course in all the simulations, we have maintained a constant flow and hence problems associated with sieving, air pressure consistency, wear of the nozzle, etc have not been accounted for.


Velocity of Circle 1
Vx 10.000 m/s
Vy -80.000 m/s
|V| 80.623 m/s
Vø 0.000 rad/s
Kinetic Energy of Circle 1
Trans 3267.256 J
Rot 0.000 J
Total 3267.256
Acceleration of Circle 1
Ax -14.732 m/s^2
Ay 3.939 m/s^2
|A| 15.250 m/s^2
Aø -0.734 rad/s^2
Time
t 0.000 s


Velocity of Circle 1
Vx 9.330 m/s
Vy -80.103 m/s
|V| 80.645 m/s
Vø -0.030 rad/s
Kinetic Energy of Circle 1
Trans 3269.058 J
Rot 9.310e-006 J
Total 3269.058
Acceleration of Circle 1
Ax -4.643 m/s^2
Ay -5.599 m/s^2
|A| 7.274 m/s^2
Aø -0.197 rad/s^2
Time
t 0.074 s


Velocity of Circle 1
Vx -34.263 m/s
Vy -21.101 m/s
|V| 40.239 m/s
Vø 16.584 rad/s
Kinetic Energy of Circle 1
Rot 2.765 J
Total 816.653
Acceleration of Circle 1
0.148 s


Velocity of Circle 1
Vx -36.697 m/s
Vy -5.881 m/s
|V| 37.165 m/s
Trans 694.277 J
Acceleration of Circle 1
Ay 136.274 m/s^2
|A| 180.034
0.222 s


Velocity of Circle 1
Vx -44.138 m/s
Vy 4.667 m/s
|V| 44.384 m/s
Kinetic Energy of Circle 1
Trans 990.131 J
Acceleration of Circle 1
Ax 0.000 m/s^2
Ay -9.807 m/s^2
|A| 9.807 m/s^2
0.296 s

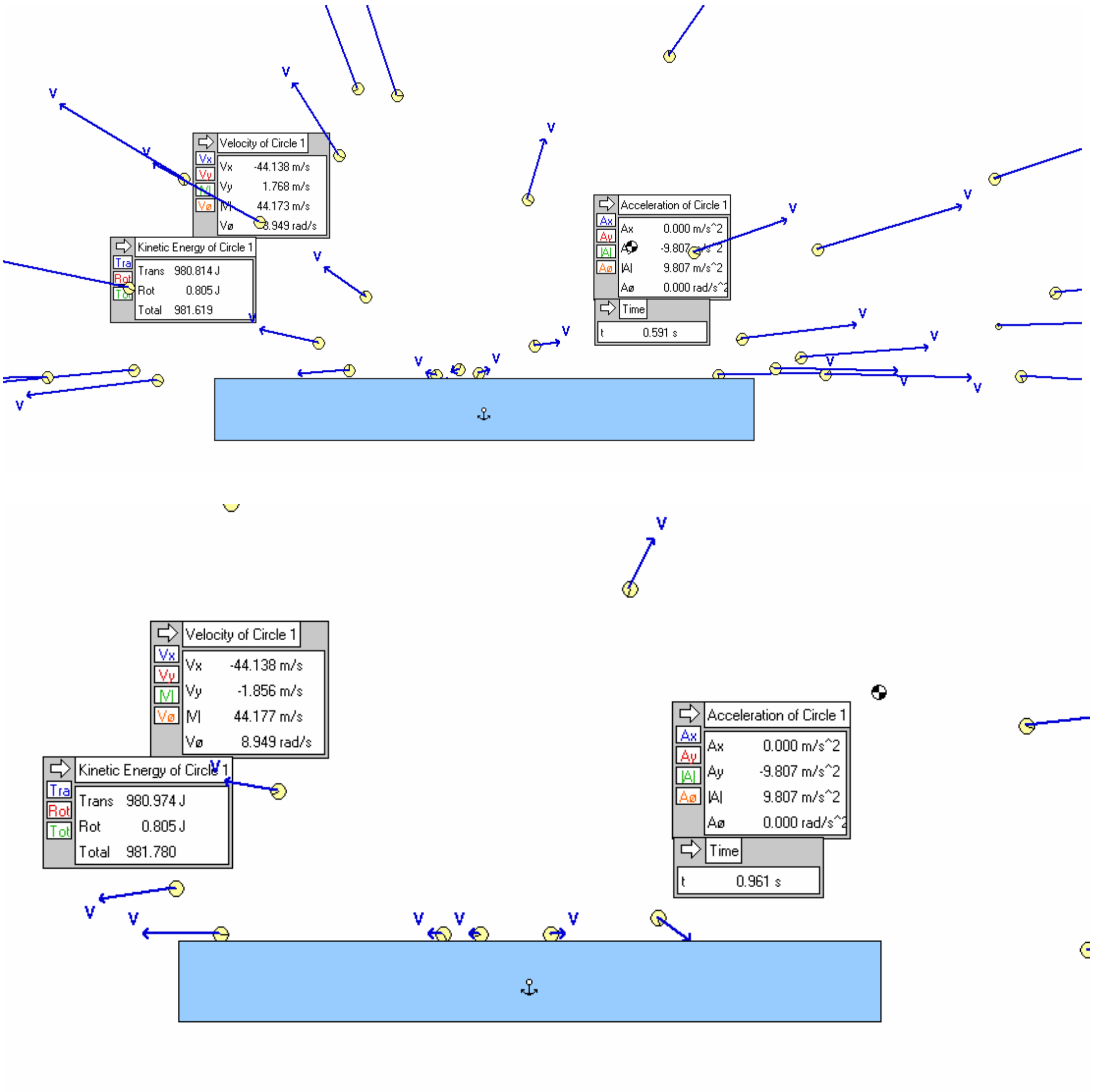


Figure.4: Snap shots from impact simulation. Some of the parameters are: shot S110, the target material is steel, the incidence angle is 78 degrees, the shot speed is 80m/sec and the air friction is 0.3. The shot pellets are allowed to rolling contact. The impact is considered plastic with penetration depth up to 2/5 of shot diameter. Shots that did not loose more than 1/3 of their kinetic energy were considered not to be affecting residual stresses. From the deflected angles, the variation in dent shape can also be determined.

From the simulation, the parameters mostly affecting the survival probability are in order of severity: the incidence angle; the working distance and finally the deformability of the target material. A typical example of the effect of the angle is shown in Figure 5. The effect of the shot material is shown in Figure 6.

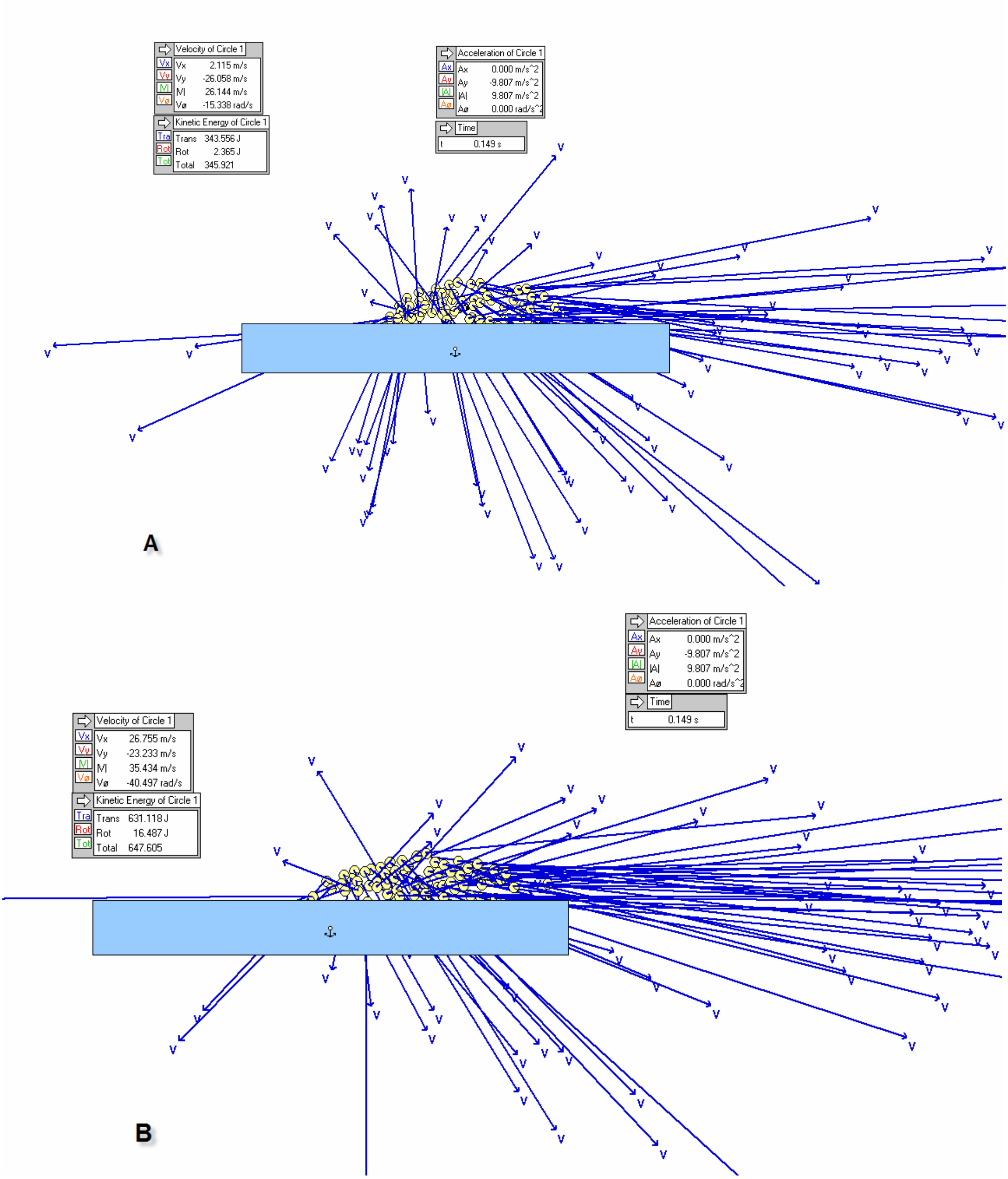
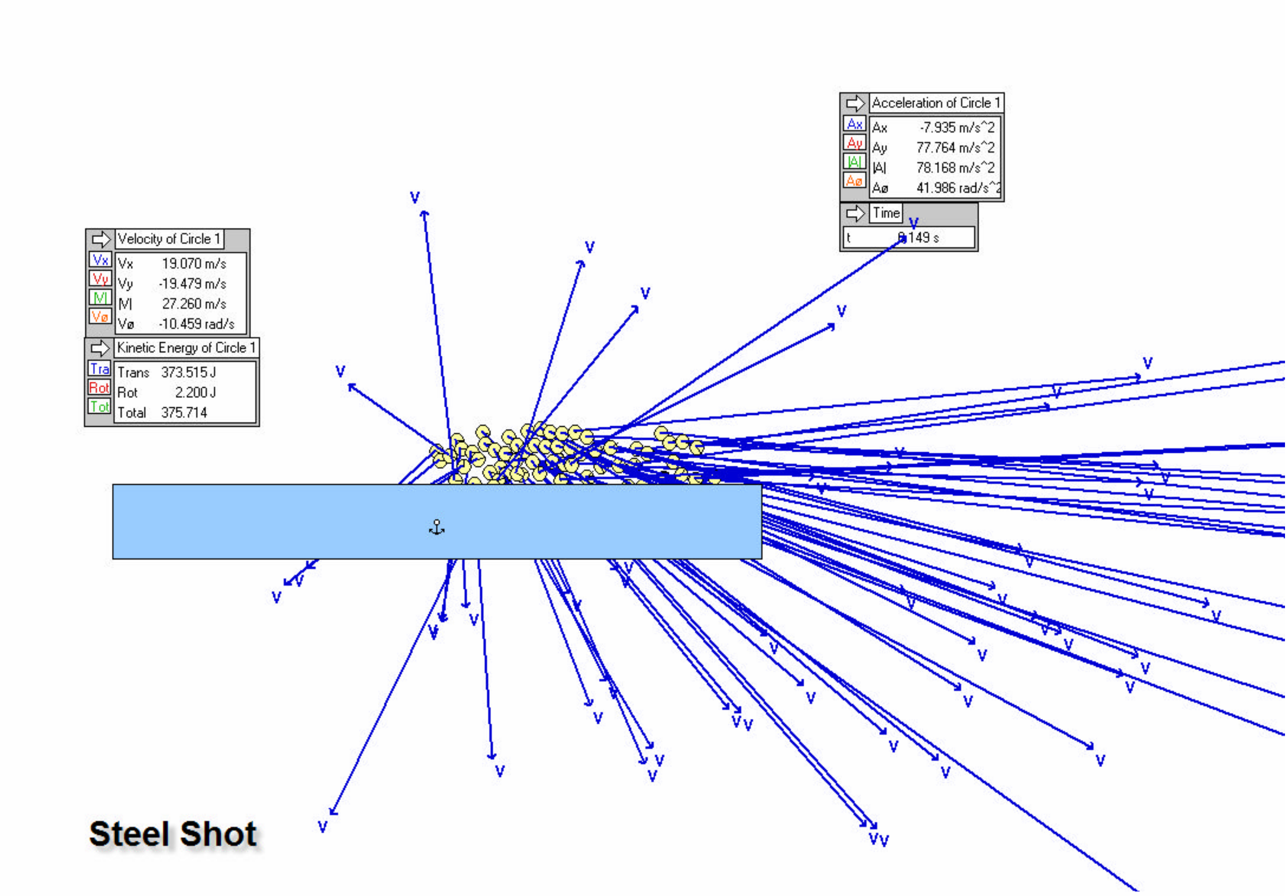
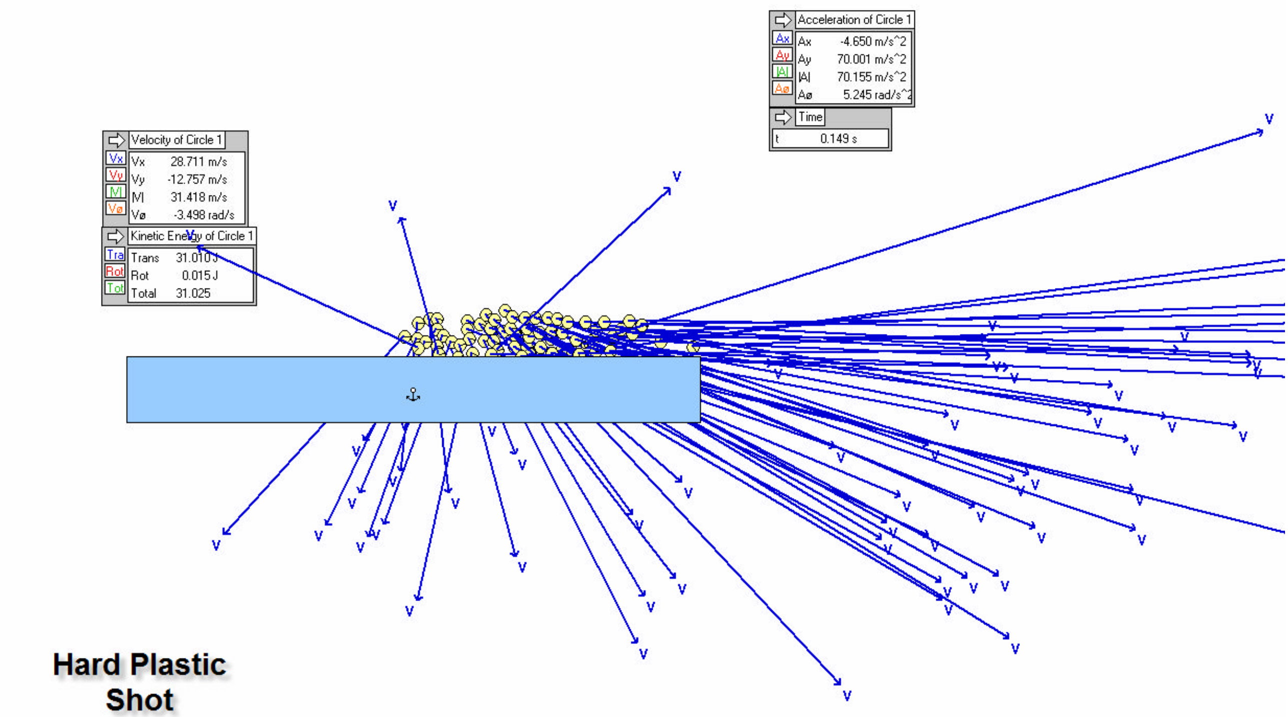


Figure 5: The effect of incidence angle: a) 75 degrees and b) 35 degrees at first impact. Using the velocity vectors, the reader can easily identify the change in the symmetry of the distribution with smaller angles. In addition, the actual number of shot pellets of a velocity able to induce a nominal value of residual stresses (kinetic energy) is found to be inversely proportional to angle.



Acceleration of Circle 1
Ax -7.935 m/s^2
Ay 77.764 m/s^2
|A| 78.168 m/s^2
Aø 41.986 rad/s^2
Time
t 0.149 s
Velocity of Circle 1
Vx 19.070 m/s
Vy -19.479 m/s
|V| 27.260 m/s
Vø -10.459 rad/s
Kinetic Energy of Circle 1
Trans 373.515 J
Rot 2.200 J
Total 375.714
Steel Shot



Acceleration of Circle 1
Ax -4.650 m/s^2
Ay 70.001 m/s^2
|A| 70.155 m/s^2
Aø 5.245 rad/s^2
Time
t 0.149 s
Velocity of Circle 1
Vx 28.711 m/s
Vy -12.757 m/s
|V| 31.418 m/s
Vø -3.498 rad/s
Kinetic Energy of Circle 1
Trans 31.010 J
Rot 0.015 J
Total 31.025
Hard Plastic Shot

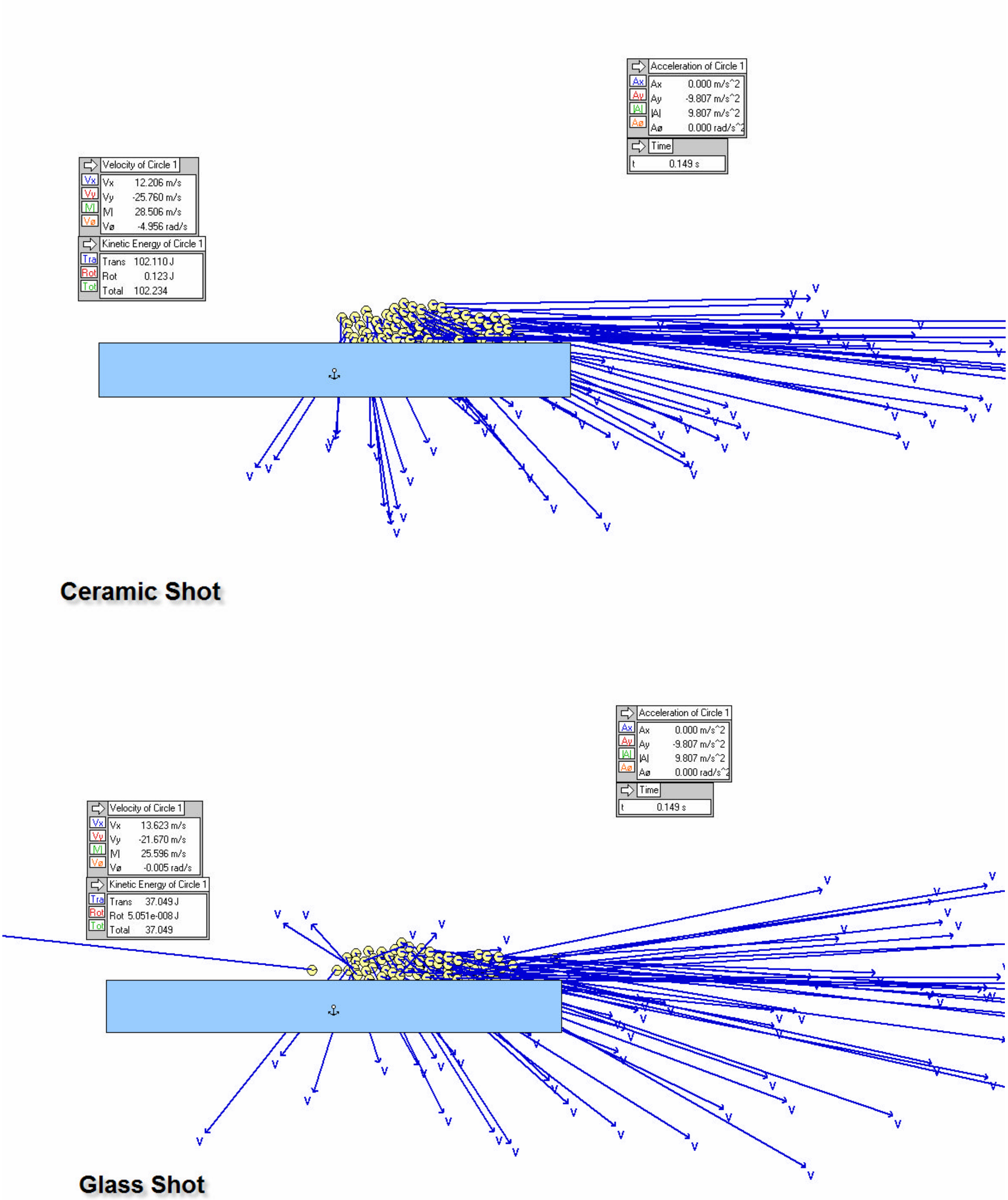


Figure.6: Effect of shot material on a steel target at a 35 degree incidence angle. Due to differences in rolling contact, air friction and impact timing it can be seen that the ceramic and glass shot delivers a more dense impact. Of course the kinetic energy of the steel shot is higher but it exhibits severe flow interference. Such finding could explain their enhanced performance of ceramic and glass shot in terms of residual stresses.

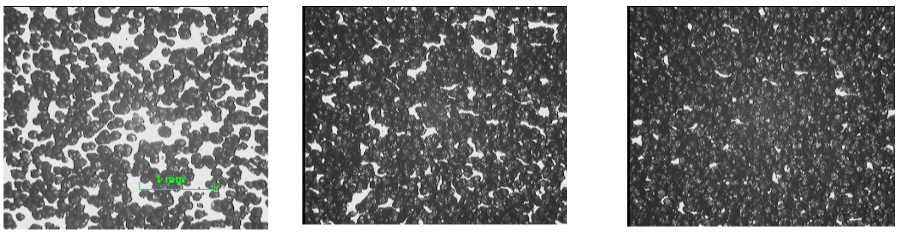
From a large number of simulations the authors conducted a sensitivity analysis based on the following criteria: standard deviation, length D (see Figure 1), kinetic energy difference, time to impact, effectiveness of individual shot pellets, and the effect of rolling contact. The above provide a classification framework for the shot size in relation to the nozzle diameter, distance to target, angle, flow rate, etc.

Comparison between Experimental and Computational/Stochastic Prediction

Any simulation needs to be validated for its accuracy with proper experimental data. The authors used a large database that has been created in the past of behalf of Airbus UK, QinetiQ and several others for the optimization of shot peening and forming. A typical validation procedure is demonstrated below. As shown in Table 1, the database provides all the necessary information in an identical manner to those used in the simulation. Whether parameter weights can be used in order to minimize the effort and potentially the cost, is a matter associated with individual requirements and quality. In this respect, Superior Shot Peening, Inc. demanded the best possible precision of results independently of actual running costs associated with the continuous and rigorous monitoring of the process. In this, it is necessary to mention that the instance that someone diverts from the simplified use of Almen strips and intensity plots and approaches the problem from a more scientific and genuine angle, the financial gains decrease. Of course, mending is expected from the potential increase in competitiveness. A typical increase of experimentally determined coverage with number of passes is shown in Figure 6. The range in coverage values from the images in Figure 7 has been created considering that the experimental facilities for measuring residual stresses are having a fixed scanning area. For hole drilling this is about 2.01 mm^2 and for neutrons up to $16mm^2$. Herein the coverage range represents selection of an area of 2.01 mm^2 exhibiting maximum and minimum coverage. The experimental results are compared to those predicted in Figure 8.

Table1. Experimental Process Parameters

Parameter	Value
Diameter of the nozzle (ND)	6.4 mm
Working distance (WD)	152.4 mm
Incidence angle (IA)	30 degrees
Number of passes (NP)	1
Shot flow (SF)	0.27 Kg/sec
Nozzle line speed (LS)	125mm/sec
Shot velocity (SV)	80m/sec
Shot size (SS)	S110 (0.279mm)
Target Material	AA 7150



1st pass; 83.2-89.6% 2nd pass; 86.2-94.0% 3rd pass; 89.1- 98.9%

Figure.7: Experimental built up of coverage.

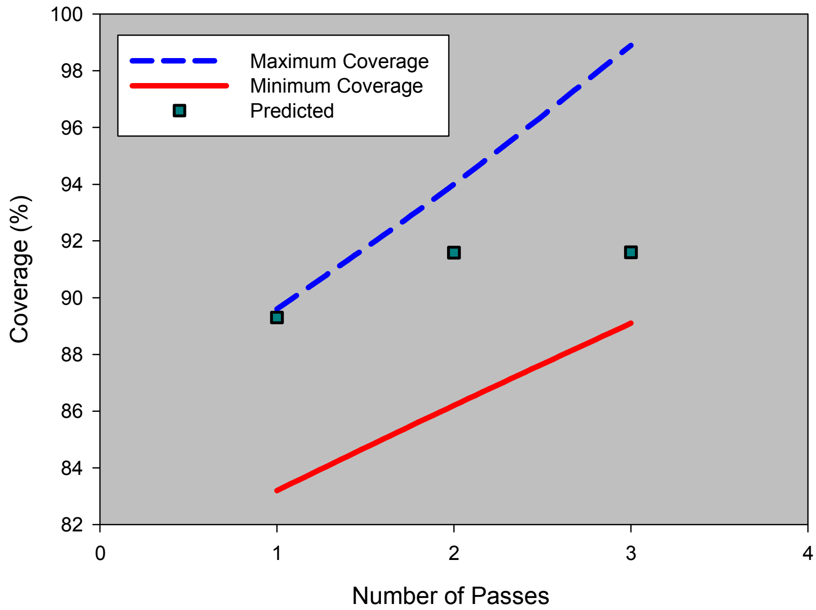
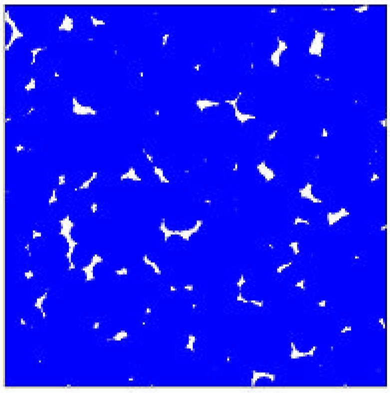


Figure.8: Comparison between experimental (from Figure 6) and predicted coverage.

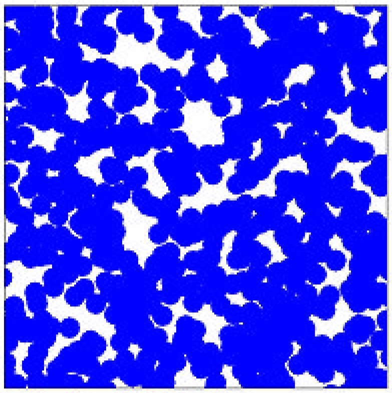
More than 280 comparisons have been performed using different shot peening parameters and 9 different target materials. In all case the predicted values have been found to be within 89% of the experimental range.

Modelling of the Residual Stress

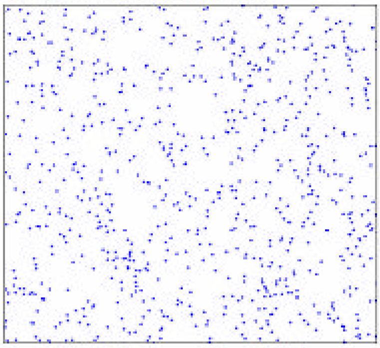
Having established the thinning parameters, the germ-grain model is revisited. Thinning, with values from 0.4 to 0.9, to cover incidence angle range from 89 to 20 degrees is used. The process in steps is shown in Figure 9. In brief, after selection of the process parameters, the germ-grain modelled is initially established. Stream interactions as previously discussed are engaged in order to provide the corresponding thinning value. The formed thinned model is used to identify minimum coverage. This is done by running a discrimination function in order to obtain the specific inter-distance from centers within the selected area. Herein, the reader should understand that impact at an area previously deformed will only increase the residual stress field if the achieved strain rate is higher. In any other case the residual stresses will exhibit relaxation. In physical terms the next impact should be centred at a point where the contact area is smaller than the initial dent, i.e. peak. In this work we have considered a maximum inter-distance from centers equal to that of 1/3 of the dent diameter. From the above formulation, representative coordinates can then be extracted. Therefore, the process allows the identification of the representative number of shots; these need to be modelled by Finite Element, in order to approach reality. A typical example is shown in Figure 10. Herein, the FE model representing the case of 81% coverage and the corresponding nodal solution of the displacements at the moment of impact is shown in Figure 11. The model considers that the material exhibits kinematic hardening. The predicted residual stresses are taken as the average value from an area similar to that used for their experimental determination (see Figure 12). The analysis can also provide vital information related to the displacements from the impact and provide an indication of roughening (Figure 13).



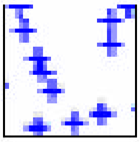
Initial Germ – Grain model



Thinned model with 0.5.



Position of Centres after Thinning



Selection of Centres for Finite Element Simulation

D	E
x	y
0.2352941	0.0705882
0.2705882	0.2352941
0.3764706	0.4588235
0.3764706	0.5764706
0.4705882	0.7176471
0.9176471	0.1764706
1.0588235	0.0705882
0.9176471	0.3529412
0.8470588	0.8941176
0.6352941	0.9647059
0.3764706	0.99
0.3058824	0.99

Coordinates for Finite Element Simulation

Figure 9: The methodology followed to deliver the impact centres for Finite Element simulation.

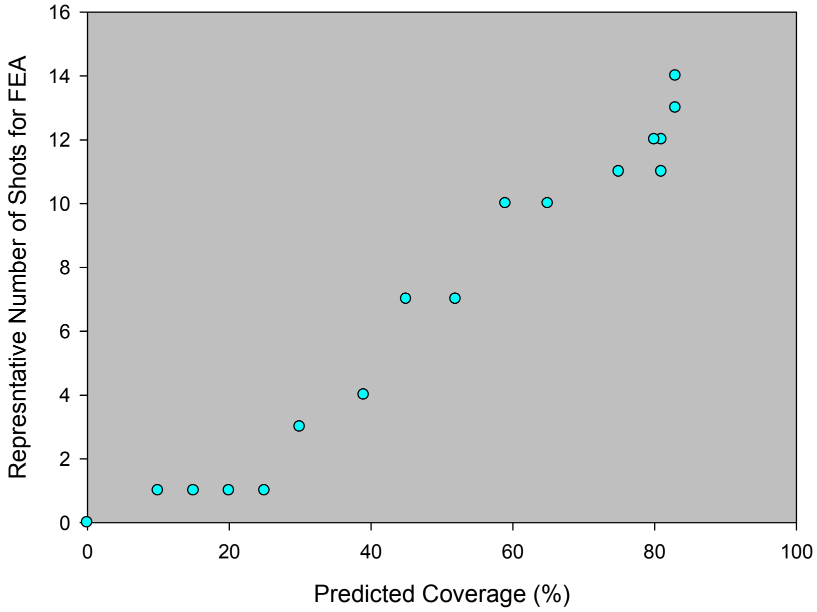


Figure.10: Predicted number of representative shots for FE analysis for 1x1mm representation.

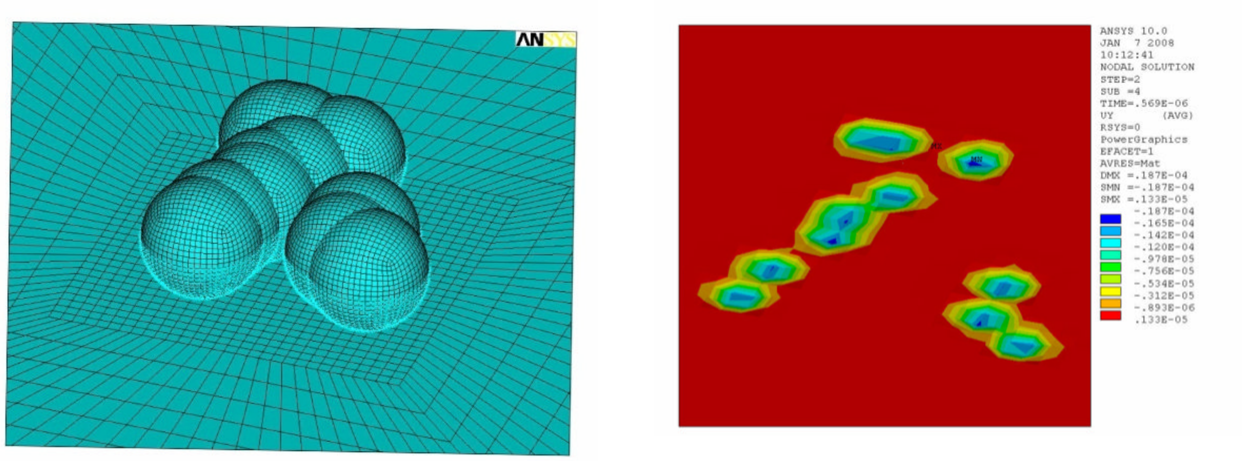


Figure 11: FE model demonstrating the case of the simultaneous impact of 11 shots at coordinates from Figure 9.

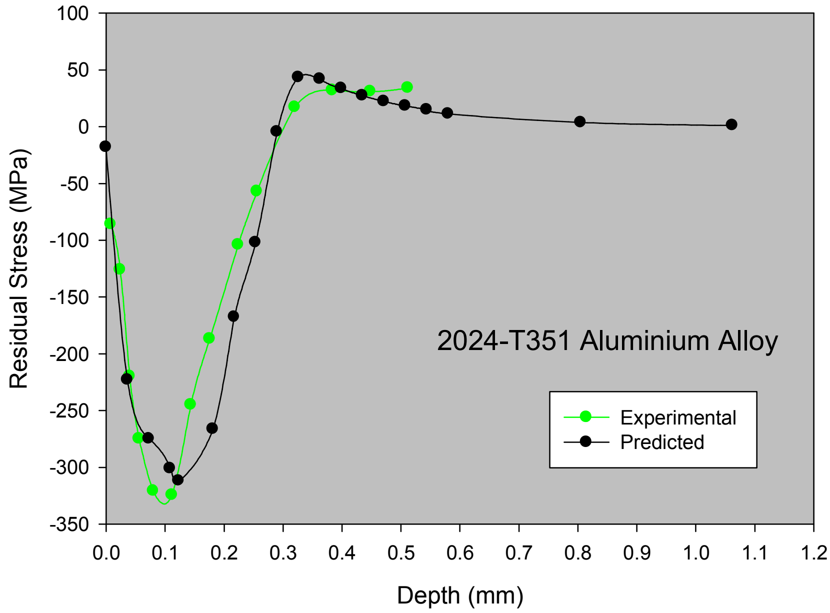


Figure.12: Comparison in residual stress profile between experimental and numerical results.

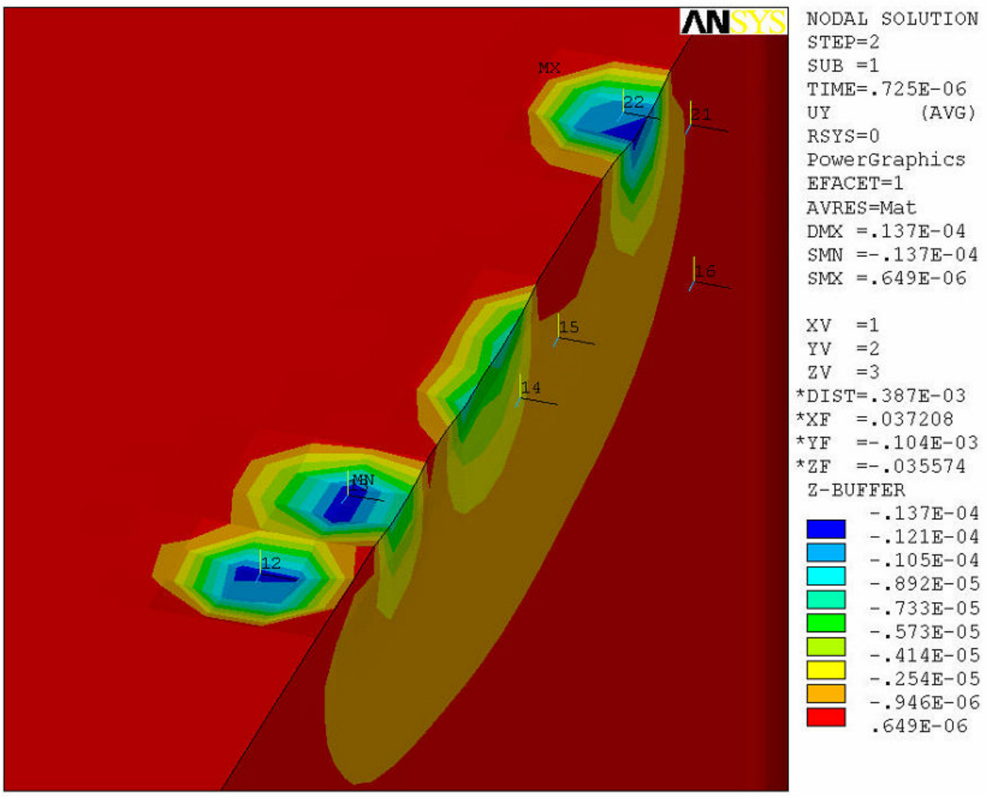


Figure 13: Cross section of displacements in the direction of depth.

Conclusions

In this work the authors tried to shed light into the difficulties associated with the modelling of shot peening and especially the prediction of residual stresses. Shot stream interactions depend on a number of pre and post impact parameters and hence they need to be discriminated in terms of importance. This can be achieved via simulation of the process. The result should provide solutions to the survival probability required to realistically replicate coverage. Having this information we can then create a finite element model. Herein, the mechanical properties of the target material, the displacement constraints, the shot and the coordinates of the impact system should be tuned as to provide realistic results when compared to experimental data. To some extend the approach can be used to provide useful parameter control when the residual stress profile is critical to a particular application. The model can also predict the amount of cold work as well as surface roughness. With such information in hand, process parameters can be scrutinised in terms of delivering optimum values. The above along with a micromechanical fatigue life prediction model can used to estimate the potential improvement from shot peening.

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