Validation of open source computational fluid dynamics software for shot peening applications

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Abstract

Shot peening is a well-established surface treatment that is widely used in industry for improvement of fatigue performance of metal components. Numerical methods have shown great potential to achieve significant cost and time reductions during shot peening process development. In this study, Open source Field Operation and Manipulation (OpenFOAM®) has been applied to the shot peening application. The initial stage of the work involved building a model that can predict in-flight media particle velocity and impact locations on the workpiece. Experimental results were used to validate the solvers. Preliminary results suggest good agreement for media particle velocity and impact coverage between the results from the OpenFOAM® solver and experimental work. In addition, the OpenFOAM® flow field was also compared to ANSYS-FLUENT results and showed only minor differences. Current results suggest that the model can be used to further improve the nozzle design.

Keywords: shot peening, coverage, OpenFOAM®, nozzle, simulation, optimisation

Introduction

Shot peening is a mechanical surface treatment to enhance the fatigue performance of metallic components. The process involves impacting a workpiece surface with shot peening media with sufficient energy. These impacts introduce compressive residual stresses into the material which improves the fatigue life [1]. Two key indicators for shot peening performance are peening intensity and peening coverage.

Process development through the traditional experimental approach requires a high investment of time and human resources. Recently, simulation has become an alternative means for users to predict peening performance and at the same time to optimise the shot peening process.

Various methods had been adopted to model the shot peening process through simulation. Murugaratnam et al. [2] used a combined Discrete Element Method (DEM) with the Finite Element Method (FEM) approach in commercial software to optimize peening parameters and residual stresses on a workpiece surface. Wang et al. [3] adopted a similar method by coupling the Smoothed Particle Hydrodynamics (SPH) and FEM method in LS-Dyna to model the shot peening process. However, their models do not account for the pressurized gas flow and its effect on the peen particles. Zhang et al. [4] studied the impact pressure in cavitation peening using ANSYS-FLUENT although the process is slightly different from shot peening.

The majority of shot peening modelling work had been conducted using commercial software. This limits the accessibility and flexibility of the codes required for different applications and most importantly add significant costs due to licensing. In this study, the two objectives are firstly to develop an Open source Field Operation and Manipulation (OpenFOAM®) software for shot peening applications and secondly to optimize a typical nozzle design for shot impact velocity and coverage enhancement using the developed OpenFOAM® model.

The first stage of this work involves the development of an OpenFOAM® model that is capable of predicting the in-flight particle velocity and the impact locations on the workpiece. At the same time a similar computational model is also developed using the commercial software ANSYS-FLUENT, to verify the confidence level of the developed OpenFOAM® model. Experimental results are then used to validate the solvers.

Methodology

Experiment

A 14 mm diameter straight nozzle was adopted and the target workpiece was A36 mild steel flat plate with surface finish (R_a) between 0.1 to 0.4 µm. Table1 summarises the peening parameters used in both simulation and experimental work. Figure 1 shows the experimental setup using a computer controlled robotic shot peening machine.

Before flat plate peening, the particle velocity was measured using a ShotMeter G3 system as shown in Figure 2. The device captures particle illumination with two electro-optical sensors and hence the phase shift is used to calculate velocity [5]. Figure 2 (a) shows the experimental setup for particle velocity measurement. To analyse the coverage area, the centre point of the peening stream was marked as an origin in Figure 2(b). The coverage area was determined by visual inspection with a 10x magnification magnifying glass. Three experienced inspectors evaluated the coverage. A grid with 10×10 mm cells was used to determine the distance from the origin to the limit of the full coverage (minimum 100%) region.

To determine the full coverage region, three points P1, P2, and P3 in Figure 2(b) were determined from the original point (0,0) along x and y directions. Given the three points, the radius of the full coverage region was calculated with equation of a circle given three points on the circumference.

$$r^2 = (x - h)^2 + (y - k)^2 \qquad \text{Eq (1)}$$

where r is the radius and the point (h, k) is the centre of the circle. That is, h is the x-coordinate of the centre and k is the y-coordinate of the centre.

Simulation

A similar methodology was adopted for both the OpenFOAM® and ANSYS-FLUENT simulation platforms to permit reliable comparison between both models. The continuous phase of air was modelled as compressible flow in an Eulerian frame of reference. The Peng-Robinson equation of state was employed to compute the thermodynamic properties of air while Sutherland's law was used to model temperature-dependent gas. The Reynolds Averaged Navier- Stokes (RANS) equation was solved together with the Re-Normalisation Group (RNG) k-ε two-equation turbulence model.

Table 1 Shot peening parameters

Operating pressure	1.75 bar
Media flow rate	3 kg/min
Offset distance	150 mm
Angle of impingement	80 degree
Dwell time	3 seconds
Media type	ASR110

Figure 1: Shot peening experimental setup

(a) (b)

Figure 2: (a) Shot velocity measurement set-up (b) Set-up for coverage assessment and coverage assessment on plate

In ANSYS-FLUENT, a Discrete Phase Model (DPM) was used to model the discrete phase of shot peen media under the assumption that the particle loading was less than volume fraction of 10-12%. This assumption was further confirmed based on the calculated peen loading flow rate and computed gas flow rate which yielded a volume fraction of 0.0265%. In OpenFOAM®, a discrete particle model which is the same as the DPM model in ANSYS-FLUENT was employed. Stochastic dispersion of the shot peen media due to turbulence was also considered.

The 3D computational domain shown in Figure 3 includes the pipe and hose downstream of the pressure gauge, the nozzle and the air domain surrounding the nozzle and the workpiece. The workpiece surface, nozzle, pipes and hose wall were treated as a non-slip wall. The gas and peen injector inlets were defined as pressure inlet while the air domain boundaries were treated as pressure outlets. A pressure difference was applied across the inlets and outlets which drove the flow and accelerated the shot peen media. A separate validation case was also created without the presence of a workpiece for comparison with the experimental peening velocity.

The computational domain was then divided into structured quadrilateral grids and the governing equations were solved on these grids. Figure 4 (a) shows that grids inside the nozzle and along the gas pathway to the workpiece are finer than the surrounding domain to have a higher flow resolution. Figures 4 (b) and (c) represent an enlarged image of the quadrilateral mesh at the nozzle entrance and the zoomed-in nozzle throat region respectively.

Results and analysis
Experimental measurements
Three repeated measurements of particle velocity were made and mean values within one minute interval were calculated as 64.50, 64.30 and 64.50 m/s respectively. Based on the coverage assessment, the fully peened region laid between 18.0 to 21.0 mm in radius from the centre of the peened circle. Dimples were found around 200 mm away from the centre point. However, these sparse dimples could be due to multiple rebound of particles. To assist on simulation validation, different coverage percentages were classified.

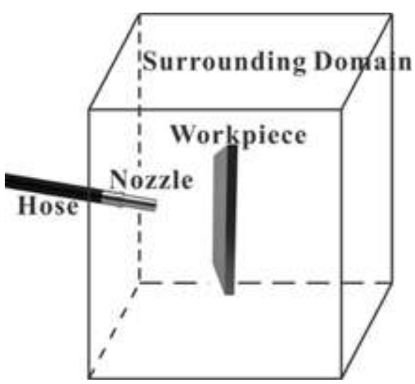


Figure 3: Computational domain (partial) and its boundaries

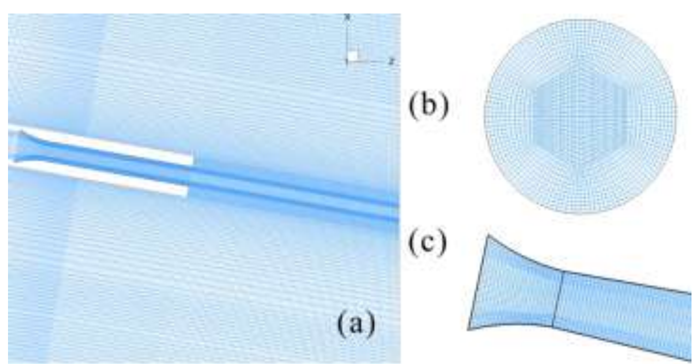


Figure 4: Mesh at the mid-range cutting plane in the span-wise direction. (a) nozzle and zone around the nozzle until the workpiece (b) entrance of the nozzle (c) enlarged part of the nozzle

Table 2Table 2 shows magnified images captured at different locations (A to D) from the centre point with the corresponding coverage level and radius from the centre point (0,0) respectively. 100% coverage (location A and B) was observed until 18 mm. A region with coverage level of 5 to 10 % was identified and assumed to be equivalent to last peened boundary which is a baseline used to validate the simulation work. From the experiment, the last peened region fell between 34 to 38 mm radius.

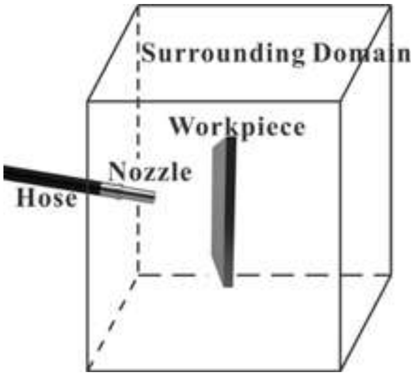


Figure 3: Computational domain (partial) and its boundaries

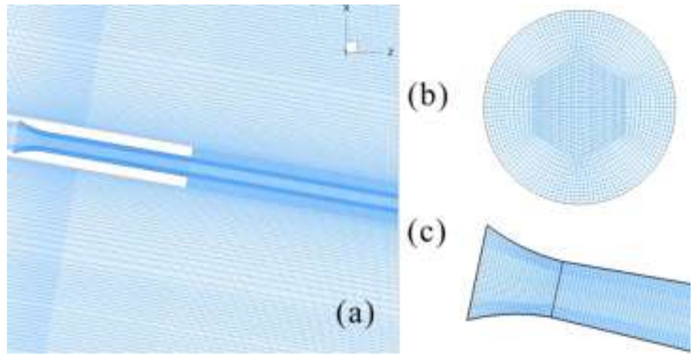
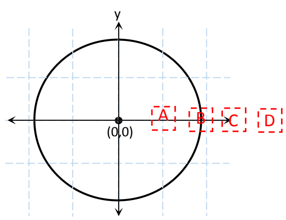
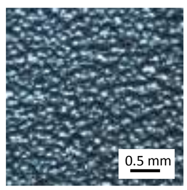
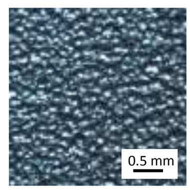
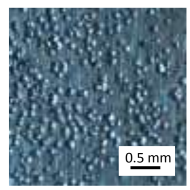
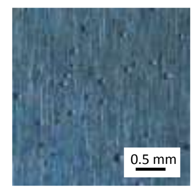


Figure 4: Mesh at the mid-range cutting plane in the span-wise direction. (a) nozzle and zone around the nozzle until the workpiece (b) entrance of the nozzle (c) enlarged part of the nozzle

Table 2: Coverage assessment for three plates and based on three operators

	 **A**	 **B**	 **C**	 **D**
Coverage level (%)	100	100	35 – 50	5 – 10
Radius (mm)	4 – 8	14 – 18	24 – 28	34 – 38

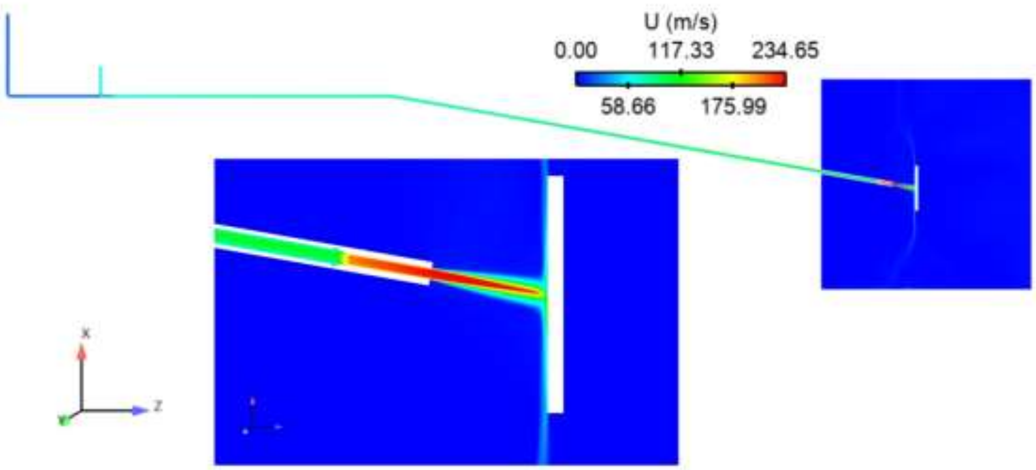


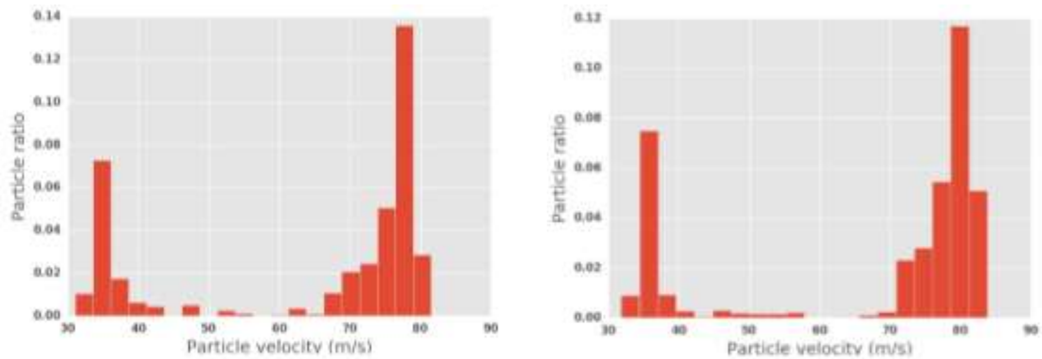
Figure 5 Gas flow velocity contour at the middle range cutting plane

Comparison between solvers and validation with experimental measurements

Results obtained from OpenFOAM® were compared with those obtained from ANSYS-FLUENT to validate the accuracy of the OpenFOAM® solver. Figure 5 shows the velocity contour of the gas flow at the middle range cutting plane of the peening system. Mixing of gas from media inlet and gas inlet can be observed and the zoomed-in insert shows more clearly the gas acceleration due to nozzle geometry. The flow experiences fast divergence due to obstruction by the workpiece and most likely will carry the particles radially outwards. However, this effect may be not significant because the diverging gas layer is very thin. The maximum flow velocity deduced from the OpenFOAM® and ANSYS-FLUENT models is 230 m/s and 235 m/s respectively.

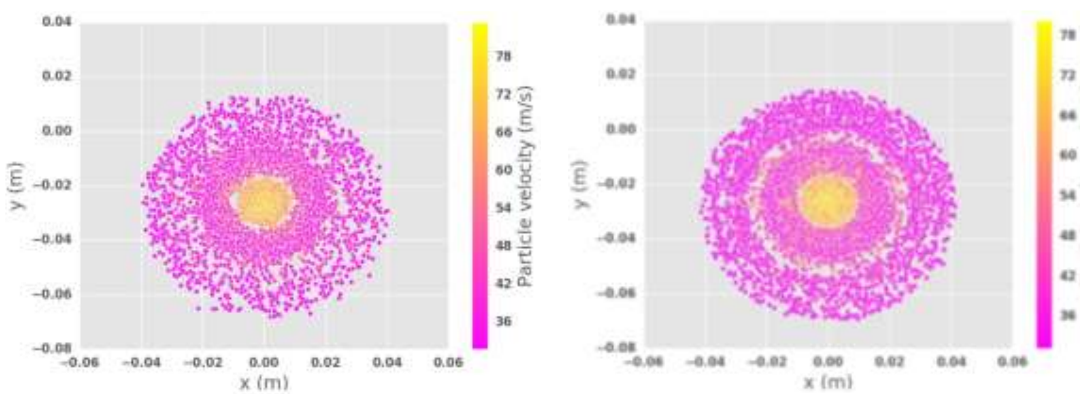
The shot peen media velocity was calculated at the same location as measured in the experiment using the ShotMeter G3 (150 mm from the exit of nozzle). Figure 6 shows a histogram of shot velocity from (a) OpenFOAM® and (b) ANSYS-FLUENT. It can be seen that the distribution of peen velocity from both simulations are similar. The mean particle velocity was calculated as 67.04 m/s and 63.93 m/s for OpenFOAM® and ANSYS-FLUENT respectively. The value closely corresponds with the experimental average value of 64.43 m/s within +/-5% tolerance.

Figure 7 shows the coverage area coloured by the shot media impact velocity. In this numerical simulation, a stochastic turbulence model was adopted to include the effect of flow instabilities on the particle trajectories and its locations on the substrate. The peened area was reflected by probability where the denser area indicates higher probability as compared to the scattered area



(a) (b)

Figure 6 Peen velocity histogram at measurement plane from (a) OpenFOAM and (b) ANSYS-FLUENT



(a) (b)

Figure 7 Distribution of peens on the substrate surface: (a) OpenFOAM® and (b) ANSYS-FLUENT

as lower probability. In this simulation the gap observed between the peened areas in Figure 7(b) indicates a low probability of particle as long as the region at both sides of the gaps is dense.

From the distribution of peened velocity, it can be seen that velocities higher than 60 m/s are concentrated in the centre of the peened area for both OpenFOAM® and ANSYS-FLUENT solvers. This also corresponds to the concentric velocity distribution of the gas flume. 100% coverage was observed until a radius of 18 mm to 20 mm for both OpenFOAM® and ANSYS-FLUENT. These agree with the experimental work, where 100% coverage fell at 18 mm radius. Finally, the last peened region was observed at a radius of 43 mm for both simulation solvers. Results for the last peened region were subject to a larger difference from the experiment results, this could be due to the difficulty in differentiating between the last peened area and multiple particle rebounds due to the visual inspection method adopted.

Conclusions

Computational models of a shot peening process were developed in both OpenFOAM® and ANSYS-FLUENT. Results for shot velocity and 100% coverage area from the simulations agree well with the experimental results. In addition, the OpenFOAM® model provided the same level of confidence in terms of both gas flow and particle physics computation as compared to the ANSYS-FLUENT model. This means that companies could perform CFD simulation without the need for licenses on commercial software. Furthermore, the current results suggest that the OpenFOAM® model can be used to further improve nozzle design for peening coverage and shot velocity optimization. This could potentially lead to a reduction in process times and running costs during production through use of optimized nozzle designs. An ongoing study is being conducted to explore the optimization of different nozzle designs to this effect.

References

[1] J. Champaigne (2001) "Shot Peening Overview" in *Shot Peener*

[2] K. Murugaratnam, S. Utili, N. Petrinic (2015) "A combined DEM-FEM method for shot peening optimisation"*. Advances in Engineering Software*, Vol 79, pp. 13-26.

[3] J. Wang, F. Liu, F. Yu and G. Zhang (2011) "Shot peening simulation based on SPH method". *International Journal of Advanced Manufacturing Technology*, Vol 56, pp. 571-578

[4] H. Zhang, B. Han, X. G. Yu and D. Y. Ju (2013) "Numerical and experimenal studies Cavitation behaviour in water-jet cavitation peening processing". *Shock and Vibration*, Vol 20, pp. 895-905

[5] J. Whalen (2012) "A New Standard for Peening Process Control and Operator Interface". in *Shot Peener*