Numerical analysis of Al coating using different particle shape in LPCS

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Abstract. Cold spray (CS) is a unique spraying process where the spray materials are not melted in a spray gun. Instead, the particles are kinetically deposited on the substrate at low temperature using compressed gas. This study investigates the deposition behaviour of different particle shape of Al coating using low pressure cold sprayed (LPCS) through smoothed particle hydrodynamics (SPH) simulations, which are achieved by modelling the multiple particle impacts on Al substrate. The impact of Al particle on the Al substrate is analysed by evaluating the shape of deformation, porosity between particle, and effect of stress on the substrate. The results show that the irregular particle shapes (horizontal and vertical ellipse) tend to detach the bonded particle from the substrate and thus increase the potential risk of high tensile stress. That is really harmful to the coating quality, which never happens for spherical particle. Deposition using irregular particle exhibits tensile stress at the depth coating, whereas spherical particle exhibits compressive stress. Compressive stress is generally ensure a longer component life due to their positive effect on the fatigue life and wear resistance application.

1. Introduction
Cold spray is the process that produces coating with a very low oxygen and porosity content [1]. Powder particles are accelerated to a velocity ranging from 200 m/s to 1200 m/s through a de Laval type nozzle by a supersonic compressed gas jet at a temperature below the melting point of the powder material [2]. The velocity is approximately 200 – 1200 m/s depending on the particle size and shape, type of process gas and conditions such as pressure and temperature [2]. Bonding in cold spray occurs when the powder particles impact on to the substrate above the critical velocity.

Al is widely known as a non-ferrous metal with high corrosion resistance [3-4]. Lightweight metal combined with the high strength is the reason Al is the major material for aircraft construction for the past sixty years [5]. The metal is ductile and strong which led to the widespread use in transportation and as an effort to reduce fuel consumption which in turn reduces emission and consequent global impact [6].

According to Lee et al, [7] Al coating deposited using LPCS has higher hardness because of the peening effect. Previous study by Yusof et al., [8] proved that LPCS is suitable for the deposition of light materials such as Al. However, it is noticed that the existing works regarding the deposition
behaviour of Al particle using the optimum velocity of LPCS mainly focused on the spherical powders, very few studies concerned about the irregular powders. Irregular particle, including horizontal and vertical ellipse are more easily accelerated, obtaining higher impact velocity. But then, they are easier to be produced with shorter time and lower cost in comparison with spherical powder. Therefore, it is of great importance to pay more attention on the different particle shape. Investigating the particle and substrate deformation via experiment is difficult because of the short duration of the deposition process [1]. Based on these results, numerical simulation can best elucidate the LPCS deposition mechanisms [3].

In this study, the deposition mechanism of Al particle using different particle shape were investigated by SPH simulations of multiple particle impact of Al particle on Al substrate. An analysis was conducted by evaluating deformation behaviour, porosity between particle, and residual stress on the substrate to understand the deposition mechanism of LPCS process.

2. Numerical Method
The impact of LPCS particle was modelled by SPH, a mesh free adaptive Lagrangian particle method. This numerical technique uses smoothed particles, instead of a mesh, as interpolation points to represent materials at discrete locations [1, 9]. Al was selected as the particle and substrate material for irregular multiple particle impacts. For the different particle shape simulations, LPCS simulation was performed in this study with initial particle velocity LPCS was at 400 m/s. Ogawa et al. [3] reported that the critical velocity of Al under LPCS is approximately 300 m/s. Based on this finding, any value above this velocity is capable of depositing on the substrate. The particle size was set to 25 μm and the initial temperature for the particle and substrate was assumed to be at room temperature (300 K). The parameters of the Johnson Cook model and the state of equation for Al were obtained from literature [3, 10].

3. Result and discussion
The effect of different particle shape on the impact behaviour was simulated for Al/Al for spherical and irregular particle shape (horizontal and vertical ellipse) using LPCS at 400 m/s. The shape deformation behaviour and temperature contour of different particle shape is given in Figure 1 to Figure 3. The spherical particle shape at the bottom (label 1) in Figure 1 changed to lens shape and deeply penetrated substrate after the impacting process. It is clear that the metal jets are formed at the edge of each particle. The powder particle at the top (label 2) are slight deformed. The powder particle at the bottom (label 1) using horizontal ellipse which is shown in Figure 2 was deformed with a slight deformation and no deformation occurred on the substrate. The results from magnified view show that the deformation of particles after deposition. Besides, it can be seen that the top particle (label 2) of horizontal ellipse almost has no change, the shape still remain which may increase the risk of detachment of bonded particle from the substrate and thus may resulted in large pores forming between these particles. These results are due to the low plastic deformation dissipated in the particles during deposited process. For the vertical ellipse is given in Figure 3 shows that the particle at the bottom (label 1) experience deformation, thus the particle at the bottom completely flatten but there was very slight deformation occurring on the substrate. Unfortunately, there is almost no change occurred for the top particles (label 2) of vertical ellipse. There are no changes for the top particle (label 2) due to the low plastic deformation dissipated in the particles which may increases the pores formation and resulting to the worse bonding between particle and particle. Based on this reason, the optimum velocity of irregular particle need to be higher than that of spherical particle in order to promote better bonding. A study performed by Yin et al. [11] also reported that the optimum velocity of irregular particle shape need to be higher than spherical particle shape.

Figure 4 shows the flattening ratio of the particle deformation for different particles shape. It is obviously seen that the flattening ratio of the vertical ellipse has the highest value, achieving 2.4,
followed by horizontal ellipse, achieving to 1.52, then followed by spherical particles, amounting to 1.14. The gap of the flattening ratio between particles at the bottom (label 1) and at the top (label 2) show larger differences for vertical and horizontal. The larger differences of the flattening ratio between label 1 and label 2 will results in higher pores form between particles. This is mainly attributed to the different size of radius particle. Spherical particles shape has a same radius in axis – x and y. But, for the horizontal ellipse, axis – x has a major radius and a minor radius in axis – y. Otherwise, vertical ellipse has a major radius in axis – y and minus radius in axis – x.

Figure 1. Deformation pattern for spherical particle shape. Figure 2. Deformation pattern for horizontal particle shape. Figure 3. Deformation pattern for vertical particle shape.

However, it is significant that the temperature in the region of the most severely deformed particle near the substrate is the highest mainly due to the subsequent impact from top particles (label 2). Time history of the maximum temperature of different particle shape is given in Figure 5. Clearly, the simulation results demonstrate that for horizontal case, particles at the bottom (label 1) flatten due to the subsequent impact from another particles nearly absorb all the kinetic energy which contribute for the particles flattened on the substrate. For the vertical case, the particles at the bottom (label 1) has the highest value of flattening ratio, but the particles did not experience intensive deformation on the substrate due to the all total energy dissipated in the particles rather than in the substrate. There is a good agreement between the results obtained by this simulation analysis with Yin et al., [11]. A study performed by Yin et al., [11] using irregular particle reported that coating deposited with irregular particle shape shows higher coating porosity and worse bonding than coating deposited with spherical particle shape. A by Ghelichi et al., [12] also claimed a similar result by using different aluminium powders. Both studies provide strong evidence to the numerical simulation in this study.

Figure 4. Flattening ratio of different particle shape. Figure 5. Time history of the maximum temperature of different particle shape.

The through-thickness residual stress profile for the spherical and different particles shape, irregular (horizontal and vertical particles shape) are shown in Figure 6. At the depth of 10 µm, the stress for horizontal which is shown in triangle shape starts compressive above – 400 MPa. Whereas, for vertical
ellipse starts with the compressive stress, 325 MPa and begin to reach the tensile stress at the depth of 60 µm, 100 MPa. The dissimilarity of the results is mainly attributed to the different value of the total energy and temperature. These result compare fairly well with Shayegan et al., [13]. A study performed by Shayegan et al., [13] shows that when particles shape (irregular) pass the spherical particles shape, compressive residual stress on the surface increases and tensile stress spreads to the depth and become tensile.

Figure 6. The comparison of the through-thickness residual stress measured in the different particles shape.

4. Conclusion
In this study, numerical analysis was used to investigate the Al coating using different particles shape in LPCS. The optimum velocity of irregular particle need to be higher than that of Al spherical particle in order to promote better bonding. These results are due to the low plastic deformation dissipated in the particles during deposited process. Deposition using irregular particle exhibits tensile stress at the depth coating, whereas spherical particle exhibits compressive stress. Compressive stress is generally ensure a longer component life due to their positive effect on the fatigue life and wear resistance application.

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