

Dynamic interactions of polystyrene particles with microstructured surface manufactured by cold spray

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Abstract. Dynamic interactions of particles with component surfaces often occur during production, processing and transport of granular materials. The morphology of component surfaces has a significant effect on the impact behaviour of particles. The micro processes during an impact (e.g. rebound, rolling, sliding and sticking) can be changed by microstructuring of the surface. This paper deals with the estimation of the energy dissipation processes of polystyrene particles (400 – 700 μm) impacting on a stainless steel surface. The surface was structured with stainless steel particles (mean particle size 3.5 μm) via a cold spray process. Impact experiments were performed and restitution coefficient was measured. The proportion of the energy dissipation by impact on structured surface was 3.87–10.92 times higher than the dissipation on a polished surface. The additional energy absorption can be explained by multiple particle contacts with the steel asperities and additional friction due to the indentation of these asperities in the polystyrene particles. The particle size did not show any influence on the average energy absorption by collision on the microstructured surface. Only the coefficient of variation got higher, because of the inhomogeneous particle distribution.

1 Introduction

During production, processing and transport particles often collide with the component surfaces. Due to contact stresses and adhesion, the particle sticking, breakage or attrition or surface erosion can take place. Therefore the particle impact was investigated widely. Many experiments with different impact scenarios were performed. Brach et al. describe the particle impact with flat surfaces and consider the rotational dissipation [1,2]. Antonyuk et al. investigated the breakage of granules at high impact velocities [3]. The influence of wet surfaces on the energy dissipation was investigated by Crueger et al. [4].

Besides the materials properties the morphology of surfaces has also a significant effect on the micro processes of the particle impact. Therefore a detailed investigation on the surface morphology is needed. This paper deals with the influence of an inhomogeneous microstructure on the energy dissipation of fine, elastic and soft particles during impact. A stainless steel surface was structured with stainless steel particles (mean diameter of 3.5 μm) via a cold spray process. Polystyrene particles were chosen as contact partner for impact tests. The diameter of these particles is larger than the asperities height of the surface by a factor of 100, so multiple contacts between particle and surface were possible.

2 Materials and methods

Single particle tests were carried out by a free fall setup (figure 1). Spherical polystyrene particles from MICROPARTICLES GMBH in a size range of 400 – 700 μm were used. The experiments were performed with a microstructured and polished surface of the same material. The manufacturing of the microstructured surface is explained in section 2.2. Each experiment was performed 50 times to obtain the influence of particle and surface roughness. The coefficient of restitution (CoR) e was used for the evaluation of the energy absorption during the particle impact. The energy absorption is equal to the energy dissipation by the particle. This coefficient depends on the ratio between kinetic energies of the translational movement after ($E_{kin,rebound}$) and before ($E_{kin,impact}$) particle impact at the point of contact and is defined as:

$$e = \sqrt{\frac{E_{kin,rebound}}{E_{kin,impact}}} = \sqrt{1 - \frac{E_{abs}}{E_{kin,impact}}} = \frac{v_{rebound}}{v_{impact}} \quad (1)$$

where E_{abs} describes the energy absorption. v_{impact} and $v_{rebound}$ are the total velocities of the particle before, respectively after impact. Furthermore is the CoR an important parameter for contact models in discrete element method (DEM) simulations.

2.1 Experimental setup for impact tests with microparticles

The particles were fixed by a vacuum nozzle and drop under gravity onto the surface. The impact velocity was adjusted by the height of fall of the particle. The vacuum

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nozzle consists of a dosage needle and a vacuum pump. The smallest inner diameter of the needle is $60\ \mu\text{m}$. Thus particles $> 60\ \mu\text{m}$ can be investigated. The particles were released by switching off the pump or opening a valve to execute a shock pressure to overcome van der Waals forces. The experiments took place in ambient air. The impact was recorded with three high speed cameras. Two cameras were arranged at an angle of 90° to gain a three-dimensional measurement method for the particle trajectory and velocity. The velocity and trajectory can be obtained for particle diameter down to $50\ \mu\text{m}$. The frame rate of the recording of the first two cameras depends on the particle size. The minimum frame rate is 4,200 fps with a resolution of $1920 \times 1280\ \text{px}^2$. With smaller particles the frame rate can increase up to 20,000 fps and higher. In figure 2 the recorded velocity profile of a polystyrene particle is shown. With this profile the impact velocity can be determined directly. The micro processes of the impact were recorded by a third high speed camera with a microscope objective. This camera has a minimum frame rate of 9,300 fps with a resolution of $1600 \times 1200\ \text{px}^2$ and can record particles with a diameter down to $10\ \mu\text{m}$.

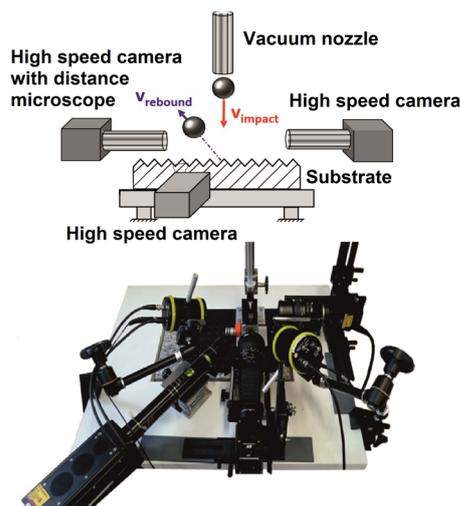


Figure 1. Sketch and image of the experimental setup for particle impact testing

2.2 Cold spray process

The surface was structured by a cold spray method [5]. Single stainless steel particles were dispersed in a nitrogen gas stream, heated up to 500°C and accelerated through a Laval nozzle up to supersonic velocities. Particles impacted on the surface and are fixed on the surface since the kinetic energy is transferred into heat in the contact zone. Nevertheless some particles with a small kinetic energy rebound from the surface and leave craters (figure 3) in the contact zone. Due to a small particle concentration in the sprayed aerosol and fast movement of the substrate vertical to the spray direction a statistically structure of the surface was created. In figure 3 the structured surface is shown. To compare the structured and original polished

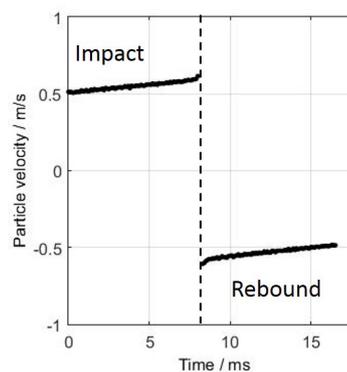


Figure 2. Velocity profile of $665\ \mu\text{m}$ polystyrene particle before and after impact

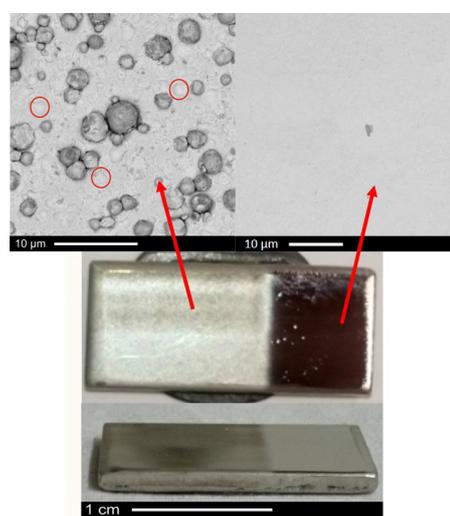


Figure 3. Top: SEM images of cold sprayed and polished surface. Examples of craters are within the red circles. Bottom: Image of the steel substrate for experiments

surfaces only a part of the steel substrate was cold sprayed by steel particles.

2.3 Characterisation of the surface morphology

The topography of the surfaces was measured via scanning probe microscopy (SPM). With a triboindenter from HYSITRON the surfaces were scanned with a Berkovich tip, which is used for nanoindentation. This measurement was performed within an area of $90\ \mu\text{m}^2$ for cold sprayed surface and an area of $40\ \mu\text{m}^2$ for polished surface (figure 4). With the data of the SPM the maximum height, average height and the roughness were determined (table 1). The maximum height of the microstructured surface corresponds roughly to the mean radius of the steel particles. However the average height is $646\ \text{nm}$, because of the plastic crater-shaped pits remained due to rebound of some particles and inhomogeneous particle distribution on the surface. The surface is not completely covered with particles (figure 3). Therefore there are many areas on the surface without particles which decrease the average height.

Compared to the microstructured surface the polished surface is very smooth. The SPM measurements revealed an average height of 15 nm and a root mean squared roughness of 5 nm. The asperity peak (figure 4) of 107 nm can be explained by impurities on the surface.

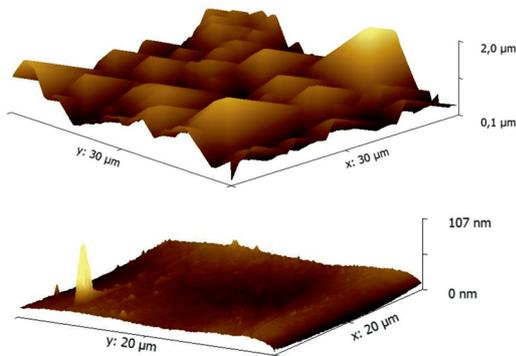


Figure 4. Topography of the surfaces: (top) cold sprayed surface; (bottom) polished surface

Table 1. Topography of polished and microstructured surfaces

	polished	structured
maximum height	107 nm	2 μm
average height	15 nm	646 nm
root mean squared roughness	5 nm	311 nm

3 Results and Discussion

The experiments were performed with two different particle sizes (400 and 665 μm) and velocities (0.3 and 0.6 m/s). The CoR was obtained for a polished and microstructured surface to determine the influence of the microstructure on the energy dissipation. The ratio $f_i = \frac{E_{abs,i}}{E_{kin,impact,i}}$ were used to determine the energy absorption. The comparison between the different scenarios were executed by the ratio $\frac{f_a}{f_b}$ where a and b stand for the different impact scenarios.

3.1 Influence of microstructuring on energy dissipation

In figure 5 the CoR is shown for 655 μm polystyrene particles by different impact velocities. The proportion of the energy absorption due to the microstructuring was by a factor of 3.86 higher than the polished surface at 0.3 m/s. The ratio of the energy absorption due to the microstructuring increased with increasing impact velocity. At 0.6 m/s the ratio between structured and polished surfaces was 10.92.

A comparison of the influence of the impact velocity, for the same surface, shows that a reduction of the velocity led to an extra energy dissipation. The proportion of the particle energy loss was 3.37 times higher at the polished and 1.19 times at the structured surface.

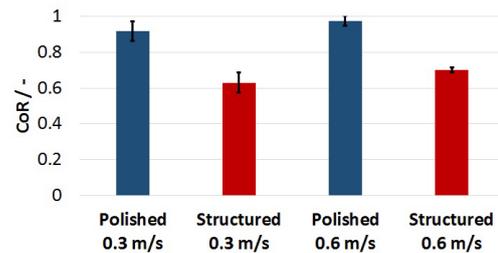


Figure 5. Comparison of the coefficient of restitution (CoR) for polished and microstructured surfaces. The polystyrene particle had a diameter of 655 μm

The additional energy dissipation due to produced microstructure can be explained with the sketch in figure 6. During the particle impact on the microstructured surface several local contact points with stainless steel asperities are formed. Due to the multiple contacts no continuous contact area, as in the case of smooth contact surfaces, is created. The contact force is distributed in the contact points of asperities with the particle. It is evident that these local forces are acting not normal to the impact direction that can lead to the additional energy dissipation due to local stressing in the tangential direction and to an oblique rebound of the particle. Furthermore the steel asperities can indent into the polystyrene particle, because the polymer is much softer than steel. The indentation causes friction during impact and rebound of the particle. This process results in an additional dissipation of the energy. A plastic deformation of the steel asperities can be excluded, because the high stiffness of asperities and high softness of the polymer particles. Also the kinetic energy of the particle before impact was not high enough to cause plastic deformation. The polystyrene particles can deform plastically due to the local forces and stressing.

The additional energy absorption by microstructuring with increasing impact velocity can be explained with the contact area of the particle and surface. These area increased with the velocity. Therefore more asperities of the microstructuring surface can indent into the particle.

The higher energy dissipation at lower impact velocities can be explained with the electrostatic adhesion and van der Waals forces. They contribution to the energy loss is increased with decreasing the particle velocity because of the decrease of kinetic energy of the particle. Compared to the polished surface the contact area and thereby van der Waals forces of the microstructured surface were smaller. Therefore the proportion of the energy dissipation increased slightly.

3.2 Influence of particle size on energy dissipation on microstructured surface

The influence of the particle size on the energy dissipation processes was determined on the microstructured surface with an impact velocity of 0.3 m/s. In figure 7 the results of the experiments are shown. The particle size did not have an influence on the average energy dissipation. The CoR

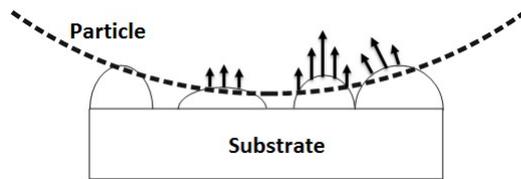


Figure 6. Sketch of asperities indentation into particle

was obtained by around 0.6 for both particle sizes. The ratio between the 400 μm and 665 μm was 1.05. Nevertheless the coefficient of variation of the CoR for the smaller particles is higher (12% to 6%) compared to the 665 μm particles. This can be explained with the inhomogeneous stainless steel particle distribution on the microstructured surface. The SEM image (figure 3) of the surface shows places of original surface and small craters between the cold sprayed steel particles. Smaller polystyrene particles had a higher probability to collide with this particle free, flat part of the surface which led to less energy dissipation. Also the probability to collide only with steel particles could be higher which led to more energy dissipation. Montaine et al. and Gunkelmann et al. investigated that small asperities can cause transfer of linear momentum into rotations which lead also to an energy dissipation. The scatter of the coefficient of variation was also caused by the asperities density [6,7]. Therefore the coefficient of variation of the impact tests of the CoR was at 400 μm particles twice as big as the deviation of 665 μm particles.

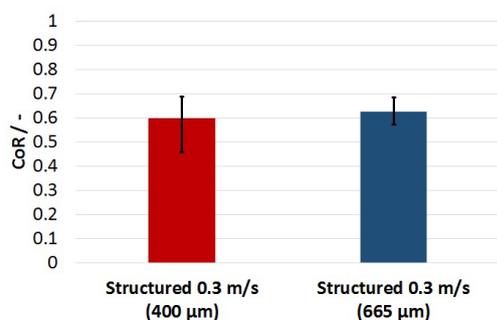


Figure 7. Comparison of the coefficient of restitution (CoR) for 400 μm and 665 μm particles. The particle impacts were performed with the structured surface at an impact velocity of 0.3 m/s

4 Conclusion

In this paper the influence of a statistically microstructured stainless steel surface on the energy dissipation during

particle collision was investigated. Experiments were performed with polystyrene particles in the size range of 400 – 700 μm at different impact velocities (0.3 – 0.6 m/s). The experiments have shown that the energy dissipation depends on the microstructure and impact velocity. The microstructured surface absorbed relative to the kinetic energy at impact around 3.87 – 10.92 times more energy compared to a polished surface due to an inhomogeneous stress distribution at the particle contact with asperities. Furthermore, an additional dissipation is caused by friction during the indentation of the steel particles into the polystyrene particles. A variation of the particle size did not show any effects on the average energy dissipation for the structured surfaces at an impact velocity of 0.3 m/s. However the coefficient of variation of the 400 μm was higher compared to the 665 μm particles. This is caused by the inhomogeneous particle distribution of the cold sprayed particles on the microstructured surface. Because of the smaller diameter, there is a higher chance for the 400 μm particles to collide with a polished area, so that no additional friction processes occurs.

Acknowledgements

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