USING DEM SIMULATION TO ELIMINATE DIAMOND DAMAGE IN A PARTICLE SORTING MACHINE

Surika J. Bezuidenhout[1] and Garry R. Morrison[2]

[1] De Beers Group Technology, South Africa
surika.bezuidenhout@debeersgroup.com

[2] De Beers Group Technology, South Africa
garry.morrison@debeersgroup.com

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Abstract Recently De Beers had an urgent requirement to adapt their particle sorting machine to be able to capture 3D models of a large number of individual diamonds. Handling diamonds comes with the additional constraint to minimise diamond damage (cracking) and prevent particle breakage.

Having identified the area in the particle sorting machine with the highest possibility of damaging diamonds, the movement of a range of diamond particles of different shapes was simulated. The diamond shapes were simplified versions of the high-fidelity models captured with the particle sorting machine.

From each trajectory, the maximum collision velocities were extracted and compared to an in-house model for diamond damage. This approach allowed modifications to be made to the material path through the machine. Simulations of the modified paths were run and showed that the collision velocities were reduced, resulting in reduced diamond damage.

1 INTRODUCTION

In many Discrete Element Method (DEM) applications it is the bulk behaviour of the particles that is of interest. In the case of diamond processing however value is associated with individual particles. Therefore in the design of diamond handling equipment it is important to ensure that individual diamonds are not damaged as this could lead to a reduction in their value.

There was a need to use the RhoVol single particle sorting machine to process batches of rough diamonds. Using DEM simulation, a design study was undertaken to ensure that the risk of damaging diamonds, while being processed by this machine, was minimised.

By simulating the movement of individual diamonds through the machine we analysed their trajectories in order to assess the likelihood that any diamond damage would occur. An area of high risk was identified and different design changes were explored to reduce the risk of diamond damage.

In the next section we will briefly explain the particle sorting machine and the area that we focused our attention on. We then discuss diamond damage considerations. Following on from that we discuss the important attributes of diamond particles. We will then discuss the set-up of our simulation and our results.

2 PARTICLE SORTING MACHINE

The RhoVol machine is a particle sorting machine developed by De Beers Group Technology. The main application of this machine has been for densimetric analysis of ore samples [1]. The RhoVol machine determines the density distribution of a sample of particles by measurement of the mass and the volume of individual particles.

However, because the machine generates a 3D model of each particle it can sort according to a variety of shape attributes in addition to being able to sort according to single particle mass or density. The material process path through the particle sorting machine is as follows:

- Presentation
- Weighing
- 3D model generation
- Particle attribute calculation (density, shape, …)
- Particle collection or particle sorting

The RhoVol machine is illustrated in Figure 1.

Figure 1: The RhoVol machine.

3 DIAMOND DAMAGE

De Beers Group Technology has developed their own in-house diamond damage model. The model is based on fracture mechanics principles and extensive single particle strength testing. Since diamond is a near-perfect elastic material, the Hertz theory of elastic contact is useful to assess the forces experienced by a diamond during impact with other objects.

Using the Hertz contact theory the maximum force, P, experienced between two objects, with the relevant material properties namely Young's modulus, E, and the Poisson's Ratios, υ, of masses m_1 and m_2, and radii of the spheres, R_i, colliding with an impact velocity of V_o is given by [2]:

$$P = \frac{4}{3}\left[E^{*2}\left(\frac{15}{16}\,m^{*2}V_o^2\right)^3 R^*\right]^{(1/5)} \quad (1)$$

Where:

$$E^* = \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right)^{-1}$$

$$m^* = \left(\frac{1}{m_1} + \frac{1}{m_2}\right)^{-1}$$

$$R^* = \left(\frac{1}{R_1} + \frac{1}{R_2}\right)^{-1}$$

From the equation for E^* above and the information in Table 1 it can be seen that E^* has its maximum value and hence the contact forces are highest for a diamond impacting on another diamond. Collisions with plastic materials making up the sorting tube and the collection bin do not result in significant impact loads. This is due to the fact that the Young's modulus of diamond is dominant relative to that of the other materials in the sorting machine. The properties of the material in the particle sorting machine are tabulated in Table 1.

Table 1: Material properties of different material in the particle sorting machine

Material	**Young's Modulus [GPa]**	**Poisson's Ratio**	**Density [kg/m^3]**
Diamond [3]	1050	0.10	3515
Nylon	4	0.35	1140
ABS Plastic	3	0.35	1070

Diamond is brittle, thus the extent of any damage will be related to the resolved tensile stress, which is related to the maximum normal contact force. From the equation for contact force (P) in equation (1) it can be seen that the contact force and hence the diamond damage risk increases with impact velocity and the effective mass of both stones.

The risk of diamond damage will vary as a function of the following factors [4]:

- Size
- Shape
- Diamond quality (cracks and flaws)
- Impact orientation

The biggest factors in diamond damage are the size and shape of the diamond. The in-house diamond damage model categorises the impact conditions into a hierarchy of levels based on the severity of observed damage. The severity levels are:

- < 1% breakage
- 1 % to 5% breakage
- 5% to 25% breakage
- > 50% breakage

4 DIAMOND PARTICLES

4.1 Size

The design requirement was for the machine to process diamonds in the range of 10 carats (2 gram) to 2 carats (0.4 gram). The diamonds are sized, by screening, before entering the particle sorting machine, thus it is assumed that there will only be collisions between particles of similar size.

4.2 Shape

Rough diamonds come in a wide range of shapes. The shapes of rough diamond are influenced by the crystallographic structure of diamond as well as the impact of various chemical and physical processes [5]. These processes alter the as-grown shapes during the transportation of diamonds from deep below the earth's surface to accessible deposits that are mined. Diamonds are classified into the following five broad shape classes:

- Dodecahedra
- Octahedra
- Maccles
- Cubes
- Irregular (typically broken)

4.3 3D Model generation

The RhoVol machine was used to generate accurate, high resolution 3D models of several diamond shapes. Figure 2 illustrates an image of some octahedral diamonds versus their 3D models that were generated by making use of the RhoVol machine. From Figure 2 it can be seen that the machine can generate high fidelity 3D models. The fidelity of the models are improved by passing the particles through the machine multiple times.

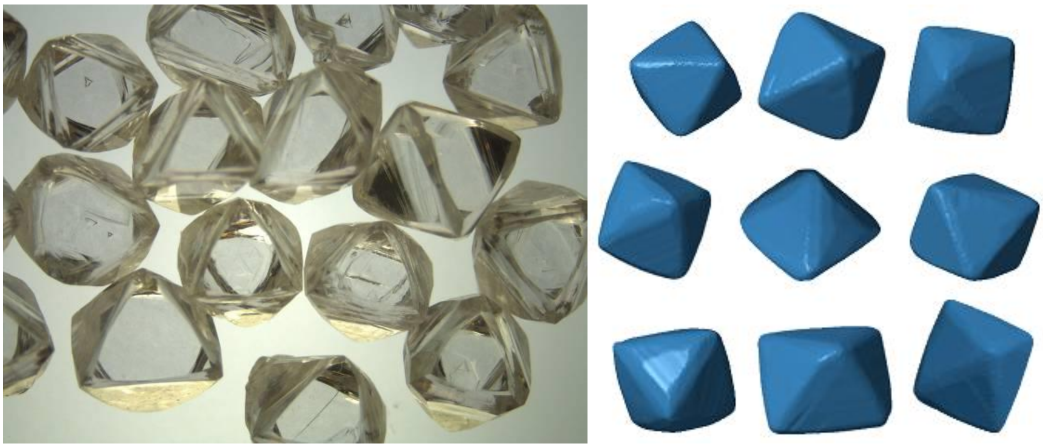


Figure 2: Examples of real octahedral diamonds vs high-fidelity images captured by the RhoVol machine.

5 SIMULATION SETUP

As diamond-on-diamond impacts were identified as the major cause of diamond damage, the machine was inspected for areas where diamond can contact each other. It was found that during most of the machine's internal processing, particles are processed in single file and would thus have a low risk of damage. However, ultimately all particles in a batch are collected together in a number of sorting bins and it was here where the diamonds contact other diamonds. The study thus focussed on these sorting bins.

We used Rocky to run the simulations and post processing was done with Matlab. It is only required to simulate a diamond as it is released into the sorting tube until it reaches a stationary position in the sorting bin. The simulation setup in Rocky can be observed in Figure 3. The inlet of the diamonds into the simulation is located (the red square) just above the sorting tube (blue).

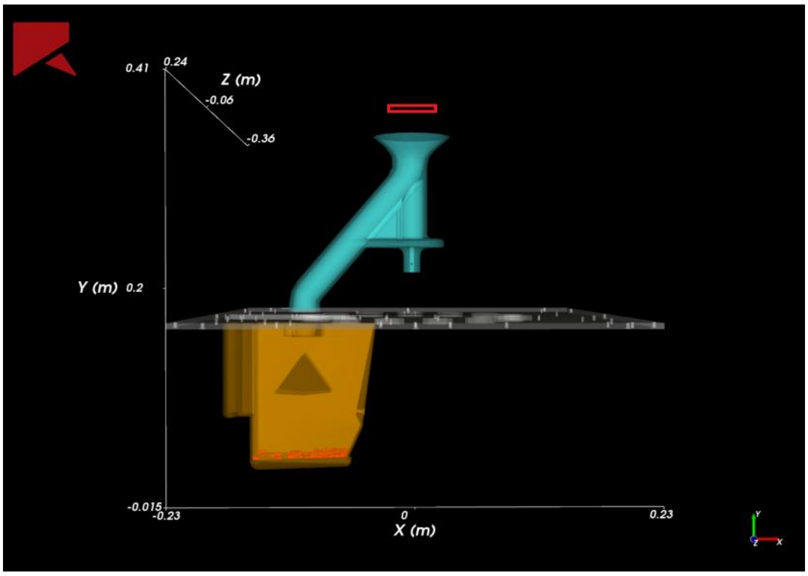


Figure 3: Simulation setup in Rocky. The particles are released (red square) into the sorting tube (blue) which directs them into the sorting bin (orange).

The sorting bin is made of ABS plastic. The sorting tube is made of nylon. In the simulation the properties of diamond were manipulated due to the fact that diamond has a very high stiffness compared to the rest of the materials in the simulation as tabulated in Table 1. We are only interested in the particle velocity as it moves through the machine. Our assessment of diamond damage occurs offline by extracting the maximum velocity at points where diamond on diamond collisions will occur. It was therefore not deemed necessary to simulate with the correct Young's Modulus of diamond. This would have made the timestep too small and the simulation too long.

The diamonds are screened before they enter the machine. The simulations are therefore only conducted on the upper and lower mass range of diamond as specified by the RhoVol machine. We assume that the trajectories, and hence maximum impact velocities, of intermediate sized diamonds will lie between the end members of our simulation.

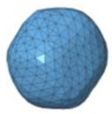
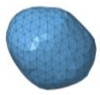
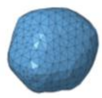
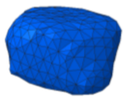
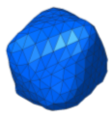
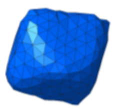
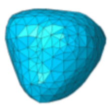
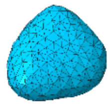
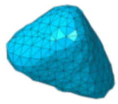
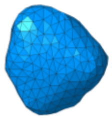
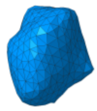
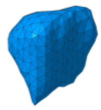
5.1 Shape representation in DEM

In single particle processes, particle shape plays an important role in the trajectories followed by the particles. In the particle sorting machine's application, it is therefore important to ensure that the simulation covers the full envelope of trajectories resulting from the different diamond shapes.

We simulated a number of different example particles for each classified shape class. We performed simulations of four different groups of diamond shapes namely dodecahedra, octahedra, maccles and irregular shapes. Cubes were not simulated due to time constraints, but for the purpose of this study it is assumed that their behaviour will lie somewhere between that of dodecahedra and irregular particles.

From previous work [6], sphere clumps are not an appropriate representation of particle shape in DEM simulation of sparsely populated systems. Thus we decided to use the polyhedron shape representation allowed by Rocky. Realistic diamond shapes are used for the simulations, which should result in more accurate results. However, the number of mesh elements used to represent each particle will affect the time to simulate each particle. Hence a reduced resolution mesh model of each particle is used. The representation of the diamond particles that are simulated can be observed in Table 2. On average a particle consists of 295 vertices.

Table 2: Mesh models of different diamond shapes that are used in the simulations.

Particle shapes		
Dodecahedra		
		
Octahedra		
		
Maccles		
		
Irregular		
		

5.2 Particle release variation

For each particle, multiple initial conditions were simulated. The different initial conditions covered a wide variation in position and initial particle orientation. This ensured that most of the possible trajectories were simulated.

5.3 Maximum velocities at impact

To retrieve the maximum possible diamond on diamond impact velocity it is assumed that there is a single layer of diamonds at the bottom the sorting bin. Thus for each diamond entering the sorting bin it is assumed that a diamond on diamond collision takes place.

It is also assumed that the maximum velocities that are retrieved from the simulations all relate to head-on collisions. This assumption will be the worst-case scenario for any diamond damage that results. Thus we expect that our diamond damage assessment based on these velocities will be an upper bound to what occurs in practice.

5.4 Design Parameters

To minimize diamond damage in the machine a number of sorting bin designs were simulated, and the impact velocities were extracted from the simulated particle trajectories. The trajectory of the particle influences the maximum velocity, which relates directly to the risk of diamond damage or breakage.

It was decided to investigate the trajectories of the diamonds without the presence of any impact body at the entrance of the bin. Figure 4 illustrates the sorting bin that was used in the first set of simulations. The sorting bin is symmetrical about the section plane.

Figure 4: Design A for the sorting bin.

6 RESULTS

6.1 Trajectories of diamonds

The trajectories obtained from the simulations for Design A of the sorting bin can be observed in Figure 5. It is noted that the sudden change in geometry at the end of the sorting tube, as illustrated in Figure 3, has an effect on the trajectory of the diamonds. The scope of this study did not permit us to simulate an improved sorting tube design to reduce this effect.

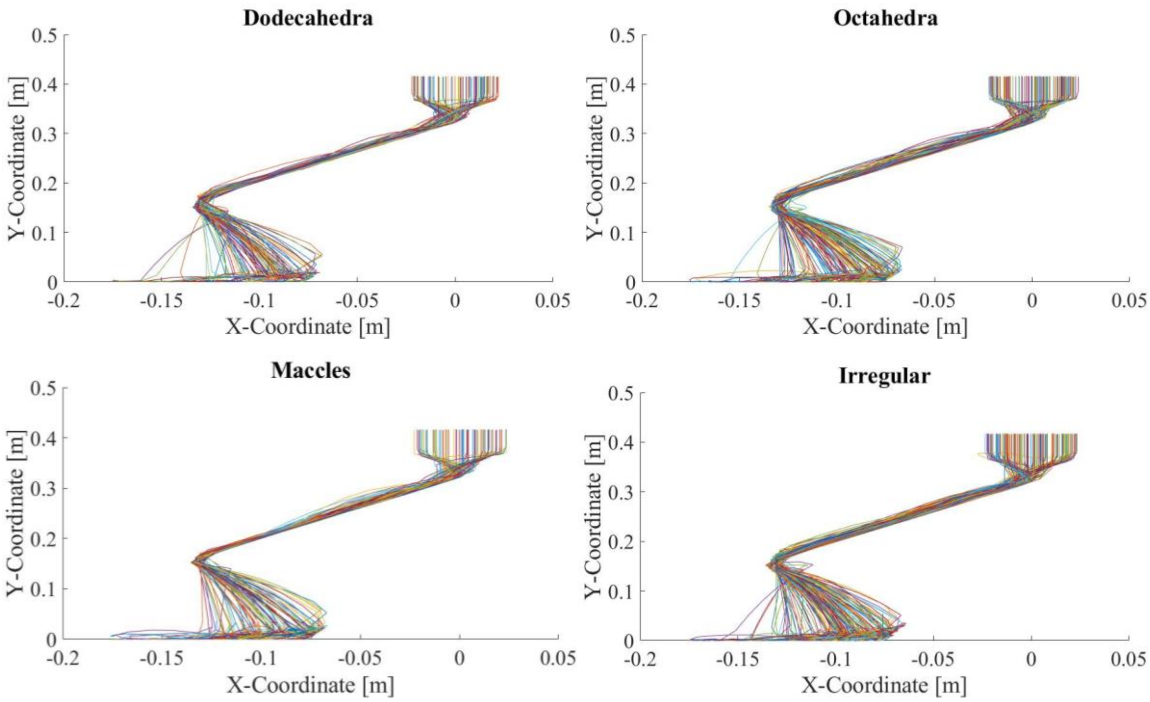


Figure 5: Trajectories for 10 carat diamonds grouped by particle shape for Design A.

The intuitive design for the sorting bin is to add a triangular impact body just below the point of entry. The triangle shape is intended to change the trajectory of the particles which will reduce the velocity at the point of possible diamond on diamond impact. Figure 6 is an illustration of a section view of Design B for the bin. The bin is symmetrical about the section plane.

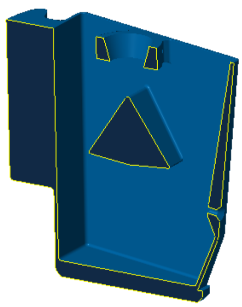


Figure 6: Design B for the sorting bin.

The trajectories obtained from the DEM simulation for Design B with the upper range mass (10 carats) diamonds are illustrated in Figure 7. From the particle trajectories it can be seen that the random initial position and particle orientation at the inlet doesn’t have a major influence on the trajectory of the particle in the bin. The sorting tube eliminates the effect of the initial position and particle orientation. The trajectories of the diamonds into the bin are asymmetrical, with 18% of all the simulated trajectories going one way and the other 82% going the other way.

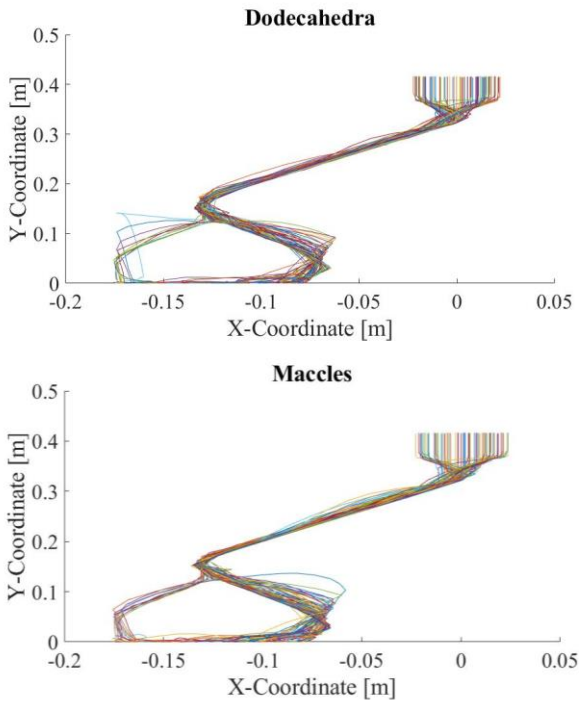


Figure 7: Trajectories for 10 carat diamonds grouped by particle shape for bin Design B.

The trajectories obtained from the DEM simulations for Design A and Design B were used to design a more effective sorting bin with the aim to further reduce the risk of diamond damage. The more impact points against the walls of the sorting bin, before reaching the other diamonds, will reduce the velocity, which will result in a lower risk of diamond damage. Our proposed improved sorting bin Design C is illustrated in Figure 8.

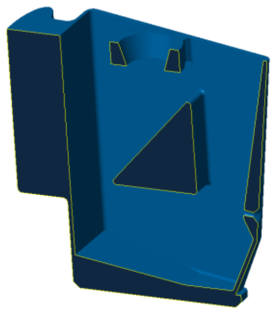


Figure 8: Design C for the sorting bin.

With this bin design, the path of the diamonds within the bin is more predictable as illustrated in Figure 9. As diamonds enter the sorting bin they will collide with the triangular impact body which will guide all the diamonds in one direction and force impact against the wall of the sorting bin. In addition, we introduced an incline on the bottom of the sorting bin to move the diamonds away from the high impact zone.

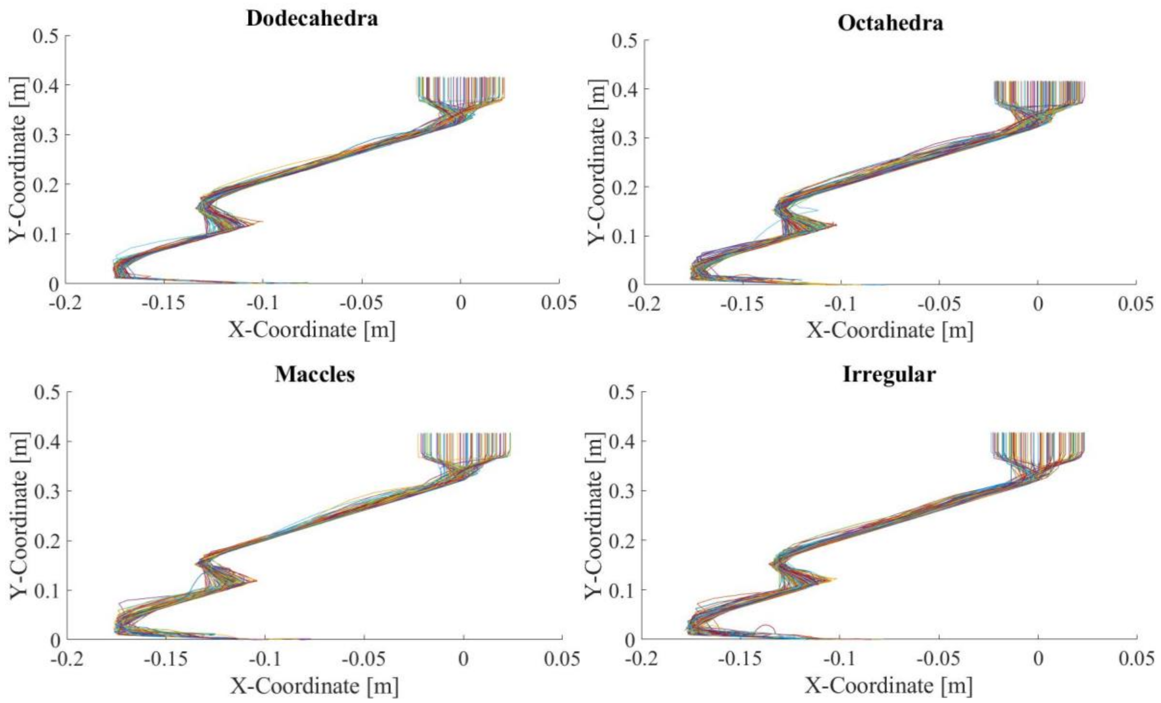
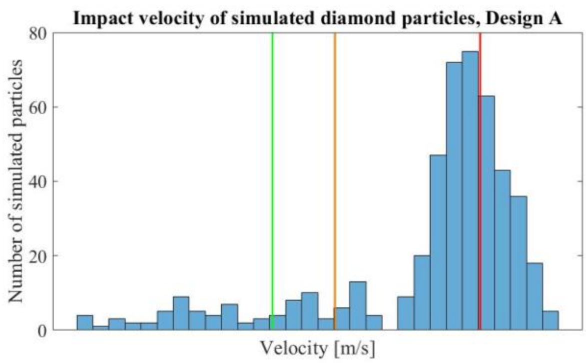


Figure 9: Trajectories for 10 carat diamonds grouped by particle shape for Design C.

6.2 Diamond damage analysis

As mentioned previously the diamond damage analysis happens offline. Figure 10 shows the distribution of the maximum impact velocities for the different bin designs. The impact velocities has a normal distribution. The diamond damage thresholds from our in-house diamond damage model are illustrated in Figure 10. The green, orange and red vertical lines relates to the 1%, 5% and 25% diamond damage thresholds respectively.



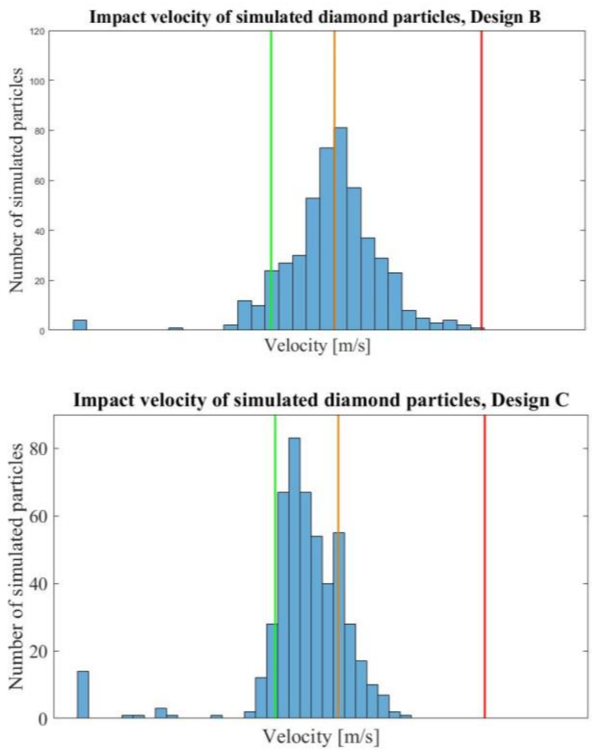
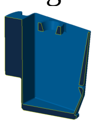
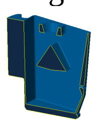
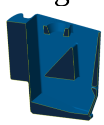
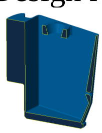
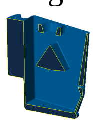
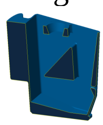


Figure 10: Maximum impact velocity distribution for 10 carat diamonds grouped by different bin designs.

The following results were obtained from the different diamond shapes and bin designs that were simulated. Table 3 summarises the percentage of simulated diamonds that will have more than 5% damage. The threshold is determined from the in-house diamond damage model. We emphasize that these results are not quantitative in nature, but only a measure of whether diamond damage is reduced.

Table 3: Percentage of simulated diamonds that will have more than 5% damage.

	10 Carats diamonds			2 Carats diamonds		
	Design A 	Design B 	Design C 	Design A 	Design B 	Design C 
Dodecahedra	86%	45%	13%	21%	15%	2%
Octahedra	85%	48%	23%	11%	13%	3%
Maccles	78%	53%	16%	14%	15%	2%
Irregular	89%	51%	20%	21%	16%	6%
All Diamonds	85%	50%	18%	18%	14%	3%

From this table it can be seen that Design B results in a lower risk of diamond damage than

Design A. It is also clear that Design C results in the lowest risk of diamond damage for all stone sizes. The only time when the model indicates that more than 25% diamond damage is experienced is for the 10 carat diamonds in Design A. 33% of all the big simulated diamonds in Design A will have more than 25% diamond damage. As expected, larger stones are at a greater risk of being damaged.

7 CONCLUSION

From our results in Table 3, it can be concluded that the possibility of diamond damage in the RhoVol machine is reduced with Design C because the impact velocities of diamond on diamond are reduced as shown in Figure 10. Design C was arrived at after considering the particle trajectories in Design A and B. These results illustrate that DEM simulation offers a quick and affordable method to enable making improved design decisions.

For future work we can explore the following:

- The effect of the mesh resolution on the particle dynamics. It is already known that the higher the resolution of the mesh representation of the diamond particle the longer the simulation time will be.
- We could also simulate the cube shaped diamonds to confirm that their trajectories do not differ dramatically from the shapes simulated in this work. We could also simulate more diamond examples.
- We could investigate the effect of changing the design of the sorting tube. As illustrated in Figure 5, the exit of the sorting tube has an effect on the trajectory of the particles into the sorting bin.

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