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OSCILLATING DISC TECHNOLOGY FOR ROCK EXCAVATION

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Abstract Rock cutting is a challenging process. Heavy equipment, large cutting forces, high wear rates and large amounts of required energy are common challenges when cutting rock. Traditionally, rock cutting is based on a linear motion of the cutting tool. However, a significant improvement on the cutting performance is expected when using non-linear cutting techniques. Non-linear cutting can be achieved by using an actuator to create a vibrating or oscillating motion on top of the linear forward motion of the cutting tool. The focus in this paper is on the oscillating undercutting disc cutter. This disc attacks the rock like a chisel or pickpoint, aiming at a cutting process dominated by tensile failures.

Although the discrete element method has been successfully used for various rock cutting processes, all these processes are based on linear rock cutting tools and most of these researches are based on 2D simulations. The use of a 3D approach is necessary to enable the simulation of oscillatory rock cutting tools.

This paper utilizes discrete element method in 3D to investigate non-linear cutting processes, especially the effects of the design parameters such as frequency, velocity and eccentricity of the cutting tool. To resemble rock-like materials the particles are placed in a dense particle assembly and they are bonded together through perfect brittle elastic bonds. The bonds can fail in shear and in tension, allowing the dominant failure mechanisms, i.e. shear and tensile cracks, to occur. After failure of these bonds, particles can still interact through collisions.

The simulation results show the effect of the tested design parameters and is compared with analytical models and an actual experiment of the oscillating undercutting disc.

1 INTRODUCTION

In many offshore construction projects, it might be necessary to excavate rock. This is often the case in the construction and maintenance of ports, tunnelling and dredging trenches for pipelines. Nowadays the cutting of (hard) rock is an expensive business, due to high wear rates, heavy cutting equipment and the high amounts of energy that is needed to cut the rock. Reduction of wear rates, might be achieved by developing alternative cutting tools. Mechanical excavation tools often cut in a single linear (forward) motion. In various experiments it is shown that the cutting performance of the tool significantly improves when an oscillation is added perpendicular to the linear forward cutting motion, e.g. excentric ripper, oscillating disc cutter [1] and the vibrating cutter [2]. In the case of tough and/or intact rock, the oscillating disc cutter (ODC) is a promising new development. This type of cutting tool is quite similar to a chisel. The only difference is that the edges of the chisel are rounded, so that it looks like a disc. Models and experiments from literature suggest, that lower cutting forces can be achieved in case an eccentric oscillation is added to the disc, by means of an actuator or kinematics [1]. The motion of the disc therefore consists of two parts, forward velocity V (linear) and eccentric oscillation frequency ω (non-linear), see Figure 1. On top of these motions, some ODC can also rotate freely around the disc centre axis. This rotation is only created, due to the friction between the disc and the rock. In the simulations done in this paper this motion is neglected.

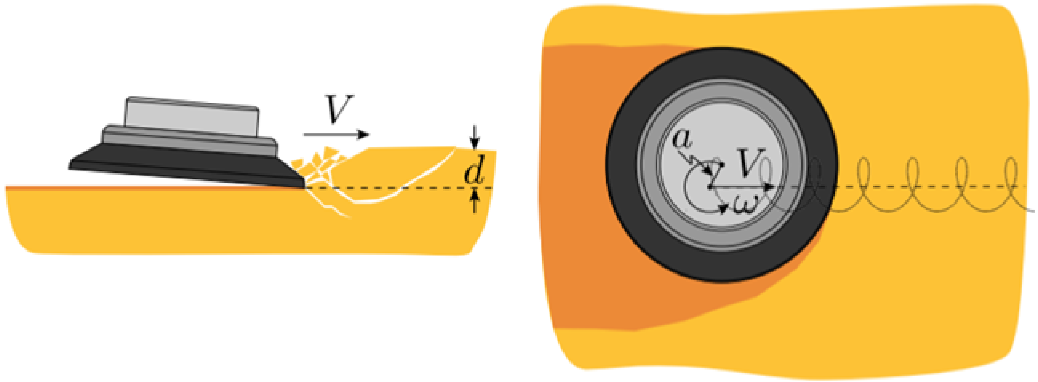

Figure 1: Oscillated disc cutter kinematics [1].

In this research the goal is, to provide more insight on the effects of the kinematic parameters of an ODC on the cutting forces. Various semi-analytical rock cutting models exist. These models however, assume a constant direction of the cutting force. This assumption is not valid for an ODC, since the direction of the force changes during cutting.

Besides, the semi-analytical models there are also analytical models created specifically for the ODC. This is done by Kovalyshen [1] and by Dehkhoda and Detournay [3]. However, these models are not able to solve the forces perpendicular to the cutting direction. Therefore, it is opted to use more advanced models. The DEM is proven to be successful in simulating rock cutting processes. The advantage of DEM is that particles can be bonded together to create a rock like structure. The software used in this research is EDEM 2018 [4].

2 DISCRETE ELEMENT METHOD WITH BONDING

The DEM model consists of a contact and bonded model, which will be explained in the first subsection. Afterwards the damping, which is added on the particles is explained.

2.1 Constitutive model

In case no bonds exist between two particles, collisions are modeled using the Hertz-Mindlin contact model [5]. The Hertz-Mindlin contact model, can model frictional, normal and rolling friction forces between two particles. However, since the goal is to create a solid material, the particles that contact each other at the start of a simulation will be connected using a bond. This bond is elastic and perfectly brittle. This bond between two particles is described by a stiffness matrix, according to the Timoshenko beam theory [6]. The radius of the bond, is set to be equal to the smallest radius of the two connected particles. If the tensile or shear strength in the bond reaches a certain criterion the bond will fail, and the bonded connection between the two particles is lost. After bond failure, a potential interaction between the particles is considered to be a collision. The stiffness matrix of the bond [7] used to calculate bond stresses from deflections is shown in Equation 1.

$$\begin{bmatrix} S_x \\ S_y \\ S_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} \frac{EA}{l} & & & & & \\ 0 & \frac{12EI_z}{l^3(1+\phi_z)} & \frac{12EI_y}{l^3(1+\phi_z)} & & & \\ 0 & 0 & 0 & Symmetric & & \\ 0 & 0 & 0 & \frac{GJ}{l} & & \\ 0 & 0 & \frac{-6EI_y}{l^2(1+\phi_z)} & 0 & \frac{EI_y(4+\phi_z)}{l(1+\phi_z)} & \\ 0 & \frac{6EI_z}{l^2(1+\phi_y)} & 0 & 0 & 0 & \frac{EI_z(4+\phi_y)}{l(1+\phi_y)} \end{bmatrix} \begin{bmatrix} u_x \\ u_y \\ u_z \\ \theta_x \\ \theta_y \\ \theta_z \end{bmatrix} \quad (1)$$

with, Young's modulus of the bond E, the cross-sectional bond area A, and the second moment area of the bond I, bond's shear modulus E, bond length l and Timoshenko shear coefficient ϕ . It is assumed that only small bond displacements/rotations are allowed.

2.2 Numerical damping

Numerical damping is added as a simplification to simulate energy lost to heat generation and wave scattering. The numerical damping term α_d used is 0.7, the damping equations are as following:

$$F_i^d = -\alpha_d \vee F_i \vee sign(V_i) \quad (2)$$

$$T_i^d = -\alpha_d \vee T_i \vee sign(\omega_i) \quad (3)$$

With, particle velocity V_i and particle angular velocity ω_i.

2.3 Assembly generation

A particle assembly needs to be generated before setting up a DEM simulation. The particle assembly is important because the model solution is driven by geometry. To simulate rock, it is necessary to have a tight packed assembly with low porosity, high connectivity number and should be isotropic and homogeneous. The particle assembly is generated using external software, as EDEM does not yet offer such functionality. GID 14.0 [8] is used to generate an assembly. In GID particles are generated by creating a mesh at which spheres are placed at the nodes. The size of the spheres is affected by the distance to the neighboring nodes and a random input factor. These spheres are allowed to overlap. This overlap is corrected by solving an algorithm that optimizes the distance between particles and the size of the particles.

3 MATERIAL CALIBRATION

To calibrate the particle assembly a Brazilian tensile strength (BTS) and uniaxial compressive strength (UCS) simulation test is done. These tests are common in rock engineering and give a measure of the material's strength. The UCS gives the compressive strength of a rightcylindrical sample of material, and the BTS gives a measure of the tensile strength of the material when the cylinder is compressed in diametrical direction, as seen in Figure 2.

The BTS and UCS of the particle assembly is calibrated until a strength of 1.8 and 16.5MPa respectively is found. These strength values are chosen, since experimental ODC data is available for the cutting of rock with these material properties. In the model the UCS and BTS (macro properties) are calibrated by adjusting the tensile and shear bond strength (micro properties). However, by focusing only on these two parameters, the failure pattern (cracks) and failure strain of the particle assembly is not representative of a UCS or BTS test on rock. Both the failure pattern and bulk modulus of elasticity (macro property) can be calibrated by changing the bond Young's modulus (micro property), as seen in Equation 1. Increasing the bond Young's modulus will lower strain at failure and increase the bulk Young's modulus. However, increasing the bond Young's modulus also affects the failure pattern.

In Figure 2 a slice of the cylinder, after failure during an UCS and BTS simulation is shown. In the Figures the damage property is shown, which is defined as the ratio of the damaged bonds over initially created bonds. In the graph the typical failure pattern for UCS and BTS tests on rock can be seen.

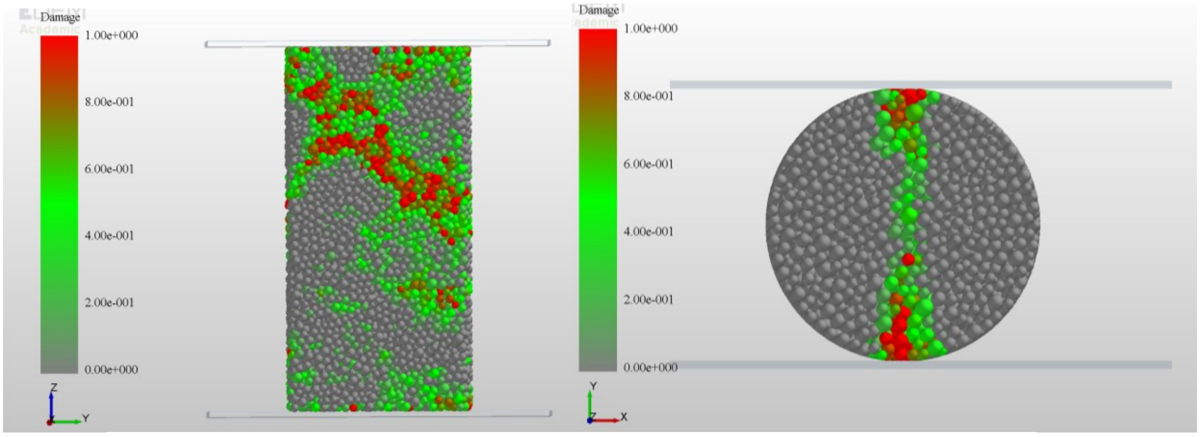

Figure 2 UCS test (left) simulation and BTS test (right) simulation after failure.

In this research, the calibration of both the UCS and BTS values with one set of micro-parameters is not possible. It is found not to be possible to create UCS/BTS ratios larger than seven. Since, tensile fracture is dominant during the ODC simulations, only the BTS is calibrated. The micro properties for a BTS of 1.79 MPa can be seen in table 1.

Table 1: BTS bond parameters

Tensile bond strength [MPa]	Shear bond strength [MPa]	Bond Young's Modulus [GPa]	Poisson ratio ν	Bulk strength [MPa]	Bulk Young's modulus [GPa]
23	23	15	0.3	1.79	4

After calibrating the BTS, the effect of the random assembly generation is tested by generating ten different seed numbers. Results are used to calculate the standard deviation on the BTS, results are given in table 2.

Table 2: Assembly generation randomness (BTS)

Seed numbers	Standard deviation, σ	BTS mean [MPa]
10	0.04	1.79

4 NUMERICAL ODC SIMULATIONS

For modelling, the ODC simulation computational time is found to be challenging. Since, the simulation time is far longer for the ODC simulations, than for the BTS and UCS test. The ODC simulations done in this research took between 4 and 13 days. The computational time is mainly affected by the size of the particle. A smaller particle radius, will increase the number of particles required to fill the assembly, and will reduce the timestep. For sake of computational time, the assembly size is chosen to be small (7x7x2 cm) and the particle size chosen is quite larger (1.3 mm on average).

Besides the restrictions required for the computational time, some assumptions are done to simplify the model. Firstly, gravity is neglected, since gravitational forces are negligible in comparison to the cutting forces. Secondly, the disc is not allowed to rotate around the centre axis, therefore an extra torsional moment is added on the disc cutter. In literature ODC's are able to rotate around the centre axis. To achieve this in the simulation, multi-body dynamics is to be added into the model. Instead of adding multi-body dynamics, it is chosen to vary the friction coefficient between the disc and the particles. Varying this friction coefficient, will give more insight in the effect of the torsional moment of the disc on the cutting forces. Besides friction, also different kinematics and geometrical properties, as for example the ODC's oscillation frequency, eccentricity and clearance angle are compared. In all ODC simulations the cutting depth is set constant at 4mm therefore, the disc will only cut a few particles deep. This small cutting depth is needed to limit computational expense. However, cutting only few particles deep, might prevent tensile cutting failure. Because of this reason, a simulation will be done containing smaller particles. This simulation will give more information on the effects of the particle size on the cutting forces.

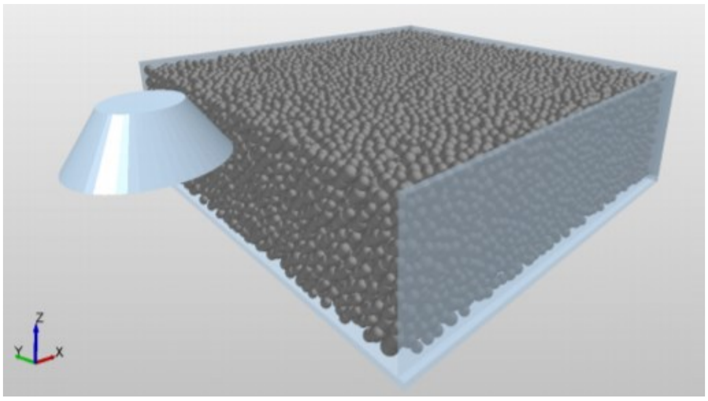

Figure 3 Simulation configuration. A box is created on the outside to keep the assembly into place.

4.1 Oscillation frequency

In Figure 4, the force (magnitude) is shown during ODC simulations for different oscillation speeds. The Figure suggests an asymptote, which is also seen in literature [1]. Still, more simulations with higher oscillation speed are required be done to be certain.

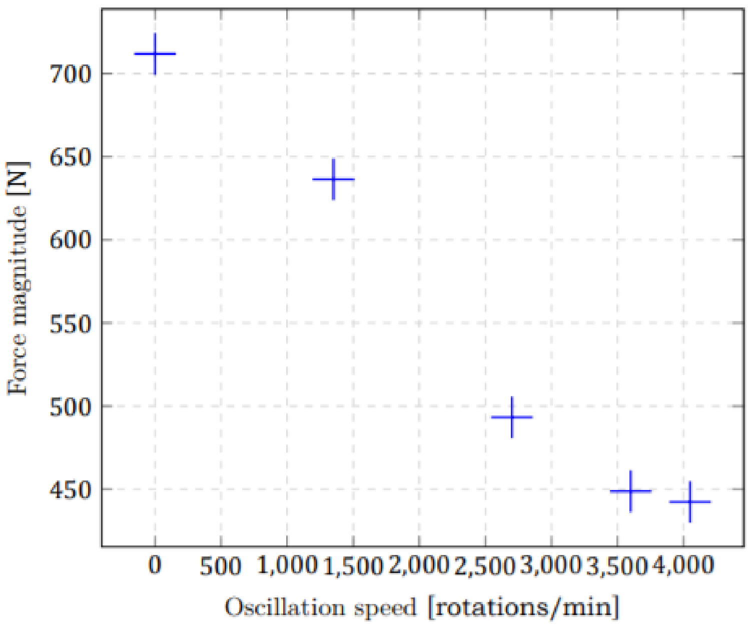

Figure 4 Force (magnitude) for different oscillation speed. Disc radius is 10mm, disc forward velocity is 0.5m/s, and eccentricity is 4mm.

The highest oscillation speed gives a reduction of 38% of the average force magnitude in comparison to linear cutting. The force drop is found to be approximately equal in X, Y and Z direction. Peak forces stay the same when oscillating speed increases, while the average force decreases. However, the frequency of this peak increases, due to the increase of rotations cycles, as seen in Figure 5.

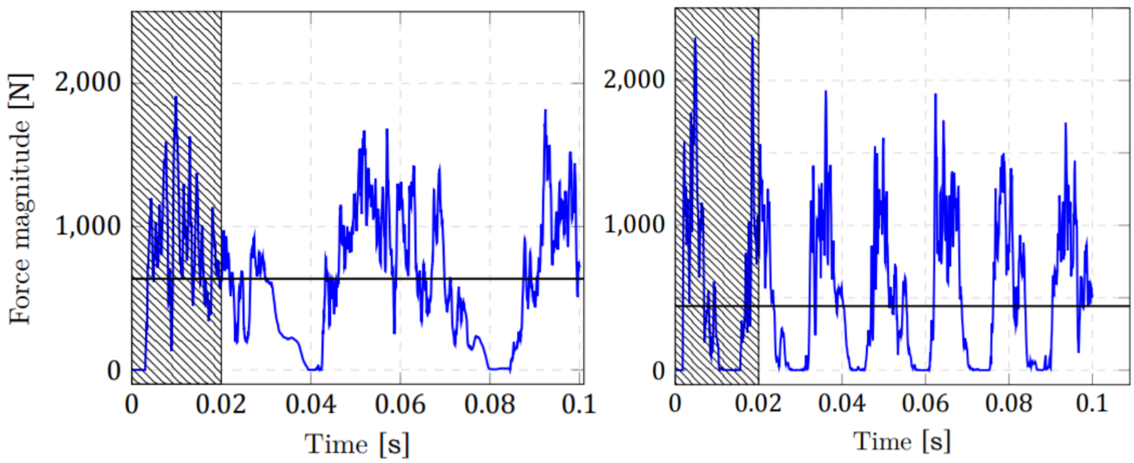

Figure 5 Force (magnitude) and average force, 1350 rpm (left) and 4050 rpm (right). Disc radius is 10mm,

forward velocity is 0.5m/s, and eccentricity is 4mm. (In case the disc is not fully penetrated the graph is shaded).

Still, more information can be gained by looking at the bond breakage. Bond breakage during ODC simulations is mainly found to be tensile (99%). Furthermore, more bonds tend to break, slightly before and at the peak force, during an oscillation cycle. It is found, that this peak force during an actuation cycle is crucial for initiating cracks in the particle assembly.

4.2 Eccentricity

The eccentricity describes the distance between the centre of the disc and the point of rotation. It is found that the eccentricity is mainly needed to acquire backwards motion of the disc during an oscillation cycle. Backward motion can occur during a rotation cycle, when the eccentricity multiplied by the disc radius and oscillation speed is larger than the disc's forward speed. Backward motion will decrease the contact area between the disc and the rock. The smaller contact area increases the stress in the bonds near the ODC, which is beneficial for creating bond failure.

4.3 Clearance angle

The clearance angle is the angle at which the cutter is positioned, as can be seen in Figure 6.

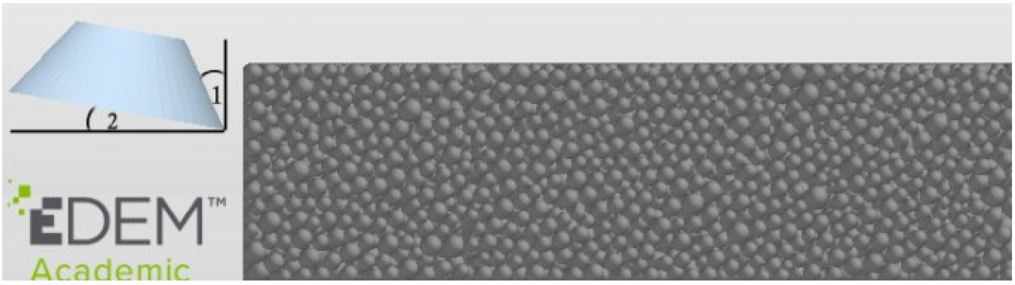

Figure 6 Clearance angle (2) and rake angle (1). (xz view, parallel to positive y axis)

It is found that the clearance angle affects the force in Z direction significantly. This can be seen in Figure 7, where the normal force is shown for a clearance angle of zero degrees and nine degrees. At a clearance angle of zero degrees, forces in the normal direction gradually increases, before reaching a more stable normal force. This occurs due to the particles being stuck beneath the tool and therefore particles are less likely to flow away from the cutter. with a clearance angle of 9 degrees the particles have more space and are less likely to be stuck. The main difference in normal force is therefore dependent on the contact area. At 9 degrees clearance angle the contact is mainly on the disc's edge instead of a contact plane, which exist at 0 degrees clearance angle.

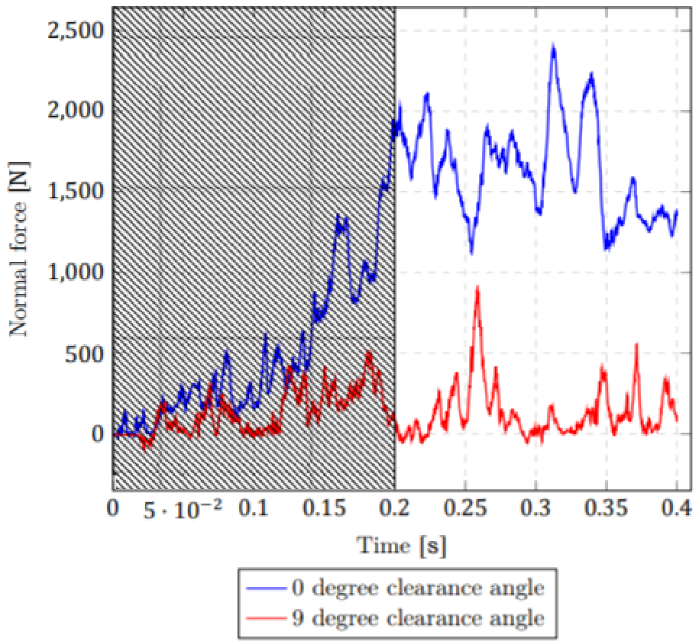

Figure 7 Normal force at different clearance angles. Disc radius is 10 mm, disc forward velocity is 0.1 m/s, oscillation frequency is 0 Hz (In case the disc is not fully penetrated the graph is shaded).

4.4 Model validation

Validation of the model is done by comparing the DEM results, with the analytical model of Detournay and Dehkhoda [3], which they validated with experimental data. Their model however, only calculates forces in X and Y direction. The comparison between the numerical model, explained in section 2 and the analytical mode is shown in Figures 8 and 9. The same BTS of the rock sample and kinematic parameters of the ODC are also used in the experiments done by Detorunay and Dehkhoda.

It can be seen, that on the end of the rotation cycle the force flattens out faster. The model of Detournay and Dehkhoda assumes that the rock only will be removed at the position of the disc cutter. In the simulations chips of rock are removed and therefore the contact time during a cycle between the rock and the disc cutter can be shorter. For this reason, the force in the simulation flattens out faster at the end of the actuation cycle. The same can be said of the beginning of the rotation cycle.

As said before, the bonded particle does not allow rotation around the disc centre. The influence of the extra (slip) moment, therefore is to be checked. This is done by running a simulation, where the friction coefficient of the disc's contact model between the disc and the particle is set to be zero. By doing this the moment is removed. However, it should be noted that the rotation and inertia of the disc is still not taken into account. From the simulation data it is found that the magnitude of the force is decreased by 29%.

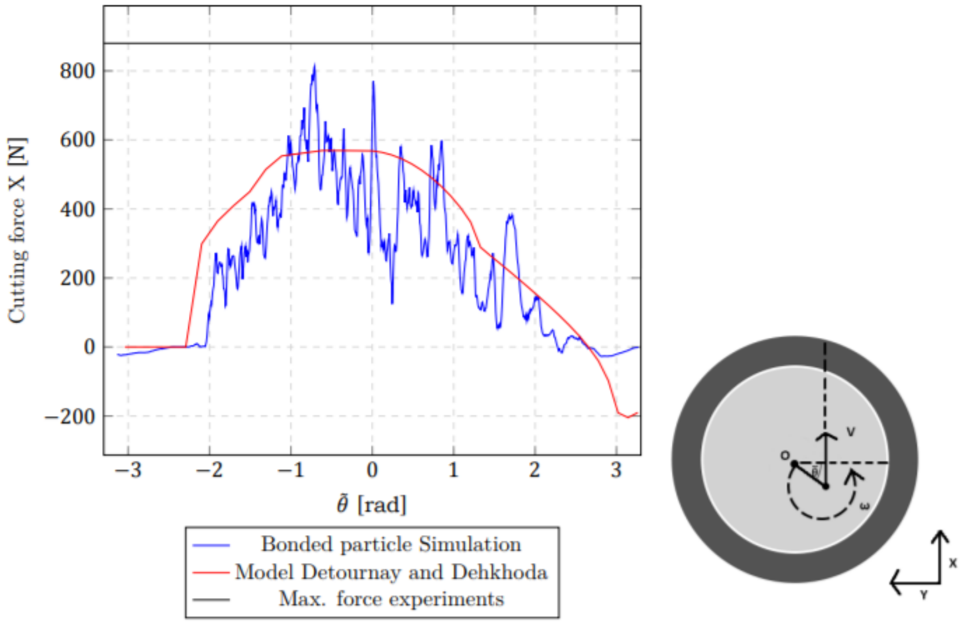

Figure 8 Comparison between model of Detournay and Dehkhoda and simulation results. Cutting forces (in X direction) are displayed over one actuation cycle. Disc radius is 10 mm, Eccentricity is 4mm, forward velocity is 0.1m/s, oscillation speed is 4.5 rotations/s.

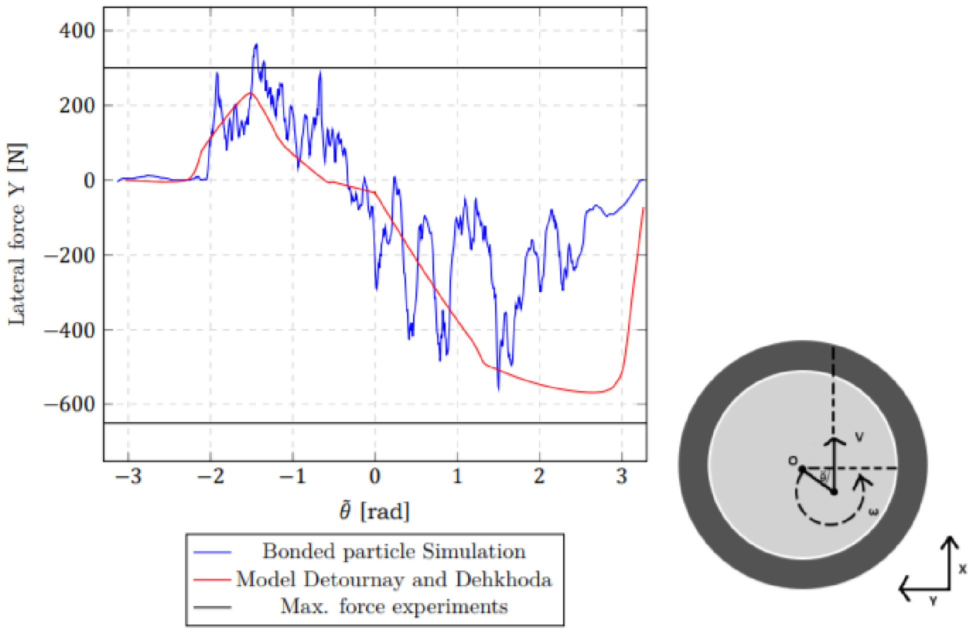

Figure 9 Comparison between model of Detournay and Dehkhoda and simulation results. Cutting forces (in Y direction) are displayed over one actuation cycle. Disc radius is 10 mm, Eccentricity is 4mm, forward velocity is 0.1m/s, oscillation speed is 4.5 rotations/s.

4.5 Particle size

The particle diameter chosen in the simulation is quite large (1.3mm on average). If the size of a particle is decreased, the time step will decrease and the number of particles will increase, resulting in a longer computational time. To give more insight in the effect of the particle radius on the cutting forces, the BTS is calibrated for an assembly consisting of smaller particles (1mm particle radius). However, no significant change in forces is found when using this particle assembly for ODC simulations, as can be seen in Figure 10. Still the data is found to be more accurate, as the forces during an oscillation cycle became more constant.

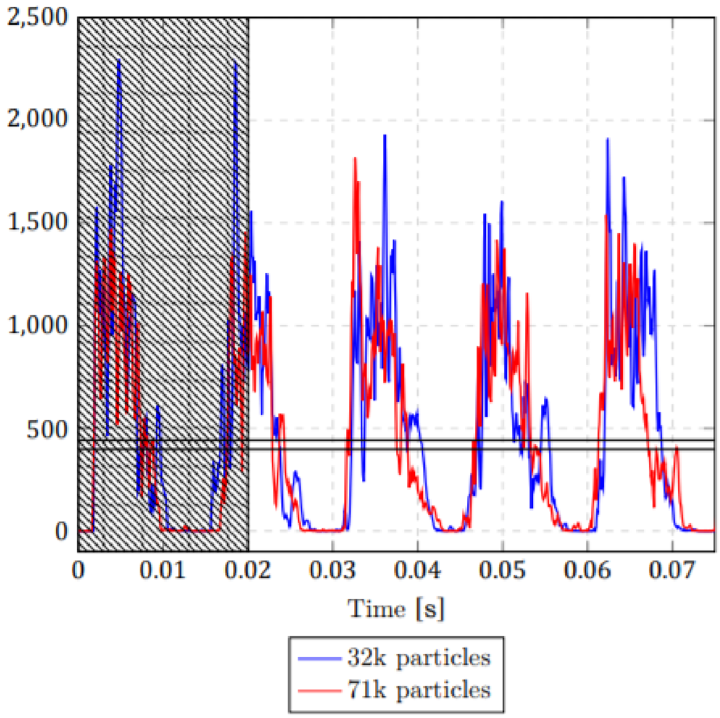

Figure 10 Force (magnitude) over simulation time for 4050 rotations/min, 32k particles (average 442N) and 71k particles (average 398N). Disc radius is 10mm, disc forward velocity is 0.5m/s, and eccentricity is 4mm

5 CONCLUSION

The bonded particle model simulations, found similar observations as seen in literature. Firstly, the bonded particle model, also shows a decrease in force for higher oscillation frequencies (as seen in Figure 5). This decrease in force is only found for the average force, the peak forces do not decrease. Furthermore, by comparing the ODC forces, with findings from literature, the forces in the ODC simulations are found to be comparable. However, more experimental data would be needed as only one experiment is used to validate the bonded particle model for oscillatory cutting.

Overall the bonded particle model is suitable for simulating the ODC. Most interesting is, that the forces and bond breakage (crack initiation) during an actuation cycle gave more insight in the working principle of the ODC. Most cracks are initiated slightly before and at the peak force of an actuation cycle. This means, that the smaller contact area, due to the eccentric oscillation, together with the high force resulted in an increase of crack initiation. The eccentricity is found also to be important in determining, whether average cutting forces might decrease. The eccentricity gives the possibility to provide backward motion of the disc during a rotation cycle, this motion is found to be crucial for lowering the average cutting forces.

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