A Review of Abrasive Wear by Coupled Finite and Discrete Element Methods

Shegawu Hailemariam [1]***, István Oldal*** [1]***, Gábor Kalácska*** [1]

Abstract: *Abrasive wear is defined as a mode of material removal that is caused by hard asperities or hard particles sliding over soft materials. It is very important in several engineering applications. The goal contribution of this study focuses on the model of friction, wear, and fracture and the coupling model of finite element method /smooth particle hydrodynamic and discrete element method to abrasive wear to the mechanical machines. The study may help researchers to select an appropriate abrasive wear modeling software and wear model.*

Keywords: *Abrasive wear, DEM, FEM/SPH, Fracture*

1. INTRODUCTION

Nowadays, the existence of advanced technology has solved complex problems, but one of the existing complex phenomena in the world is the wear of machines. Researchers are using modern technology to study its evolution and evolution in space and time, such as finite element method with mesh smooth particle hydrodynamics and discrete element method at the contact points or lines.

Tribology is the science of interacting surfaces and it studies friction, wear, and lubrication. Wear is a continuous process that reduces the service life of the machine components and tools due to material stress(Sardar et al., 2020) and damage of contact surface when a relative motion happened. Abrasive wear is caused by hard asperities or hard particles sliding over a relatively softer surface, so that causes damage at the interface.

Due to wear out of machines, accidents occur, loss of money and time, machine exposited to regularly unnecessary maintenance, unwanted manufacturing cost and frictional heat enhanced may machine burns out. Therefore, studying abrasive wear is necessary to minimize and eliminate wear problems and to increase the service life of machines.

Dumper truck bodies, chutes, and conveyers of bulk material system machinery exposed abrasive wear (Forsström & Jonsén, 2016).To explore the fracture mechanism of rock materials, modeling and simulation technology are widely used(F. Wang et al., 2020). Solid particles exist when two surfaces with relative motion in dry friction due to this conditions the three-body friction interfaces, and thus affects the friction properties of whole friction pairs(W. Wang et al., 2014)

The mechanical behaviors of materials in service were strongly affected by microstructure and deformation, hardening, failure, and phase transformation of materials due to microstructural features during the mass removal processes (Seriacopi et al., 2020).

Mechanical properties of hardness, surface roughness, Young’s modulus, Poisson’s ratio, and working conditions including abrasive particle size, load, velocity, and sliding distance that influence the abrasive wear performance of the material and are one of the most effective materials testing methods under abrasive wear condition is the dry sand rubber wheel test (Katinas et al., 2021).

1.1. Literary background and foundation of the research

(Schramm et al., 2020) investigated tillage tools abrasive wear prediction using DEM and scratch test with a specific implementation of abrasive wear. The methods included are single asperity scratch test and wear simulation by both DEM and scratch test within these found closed outcomes wear volume. The limitation is an exclusive fracture and thermal effect.

Duan focused on diamond grit double scratching of SiC predication by a couple of DEM and SPH methods with a specific implementation of grit double scratching (Duan et al., 2017a). The methods included are performance parameters, and twice scratching experiments within comparisons of results of the error range is approximately 10–25%. The limitation is percentage error is too high and applied more input variables and parameters. Duan (Duan et al., 2017b) studied the removal mode of SiC prediction by a couple of SPH and FE with a specific implementation of single scratching. The methods included are cone shape diamond with mesh element (FE), SiC couple mesh (SPH) and (FE), and scratching experiment by single diamond grit within good result found contact pressure. The limitation is excluded wear depth and rate.

Du (Du et al., 2020) investigated the cutting quality of the abrasive waterjet prediction using a couple of SPH and DEM with a specific implementation of abrasive wear. The methods included a material model of waterjet, abrasive particle and workpiece, and experimental design within these found the abrasive mass flow rate is increased, more abrasives impact. The limitation is excluded in erosive and corrosion wear.

Wu focused on rock-breaking behavior (Wu et al., 2019) prediction using a couple of SPH-FEM/DEM with a specific implementation of waterjet impact. The methods included a model of SPH, cohesive element and waterjet, and Voronoi tessellation within this broken depth increase with increasing of the velocity of waterjet. The limitation is excluded crack and wear.

Beck and Eberhard (2015) studied abrasive wear prediction using a couple of DEM and SPH with a specific implementation of abrasive wear. The methods included are different types model of couple DEM-SPH and wear models within these found removed material decreasing due to decreasing of abrasive particle velocity. The limitation is exclusive erosive and corrosive.

2. AIM OF THE RESEARCH

The research aims to investigate advanced technology, software, modeling, and simulation of abrasive wear, friction, and fracture. My goal is to know the phenomenon of mass removed from surfaces and resistance to reduce the wear rate of material removal:

- To study failure analysis mode of materials like fracture, creep, yielding of material, and damage.
- To study mechanical properties and chemical properties that reduce friction, wear, and fracture.

By examining different modeling methods and results, we present the numerical modeling possibilities of abrasive wear.

3. MATERIAL AND METHOD

In this chapter, a finite element with smooth particle hydrodynamics and discrete element used to achieve my research goals will be presented, including the model of friction, wear, and fracture.

3.1. Abrasive particles material model

The discrete element method algorithm was adopted to characterize the behavior of discrete particle flow and the finite element with smooth particle hydrodynamic by automatic particles generation using specifying the particle injection time and velocity (Du et al., 2020).

In smooth particle hydrodynamics, a kernel approximation is used based on randomly distributed interpolation points. The properties of each particle are evaluated via the integrals or the sums over the values of its neighboring particles (Wu et al., 2019) a crucial point to visualization of SPH particles may mislead of interpolation point and smooth length of SPH particles with a center point and partially transparent sphere around it (Beck & Eberhard, 2015).The size influence on the high-speed steel wear rate model, orientation, and distribution into the oxide scale of chicken feet MC carbides and the rod was studied (Phan et al., 2017).

A single abrasive grain with the cutting of monocrystal silicon carbide was carried out with a couple of finite element methods and smooth particle hydrodynamic in the simulation (Duan et al., 2017). The continuous abrasive particle flow of abrasive parameters such as abrasive particle size distribution, abrasive mass flow rate, and abrasive materials was mode, water flow was modeled by the SPH method with the enhanced fluid formulation, the workpiece was modeled by FE incorporating the material failure response (Du et al., 2020)

3.2. Contact description

3.2.1 Particle to particle contact

The three types of contact particles such as SPH to DEM, DEM to DEM, and SPH to SPH, and penalty-based particle to particle interaction was realized by defining normal and tangential stiffness, damping coefficients, static, and rolling friction coefficients were presented by (Du et al., 2020).To model the abrasive wear input variables of sliding speed, contact pressure, contact time, and contact temperature and parameters of Archard wear coefficient, mass flow rate, particle size mode, and coefficient of friction. Figure 1 is a schematic diagram of the abrasive particle spatial distribution in the simulation model, while Figure 2 shows the Photograph of the experimental setup.

(Du et al., 2020)verification experiments were carried out by a KMT waterjet cutting system, as shown in fig.2. It has a streamlined waterjet intensifier high output pump, which provided water pressure upto 413.7 MPa (60,000 psi), speed of the robot position accuracy end-effector varied from 1 to 120,000 mm/min, and the repeat position accuracy was ± 0.05 mm.For all the trails,

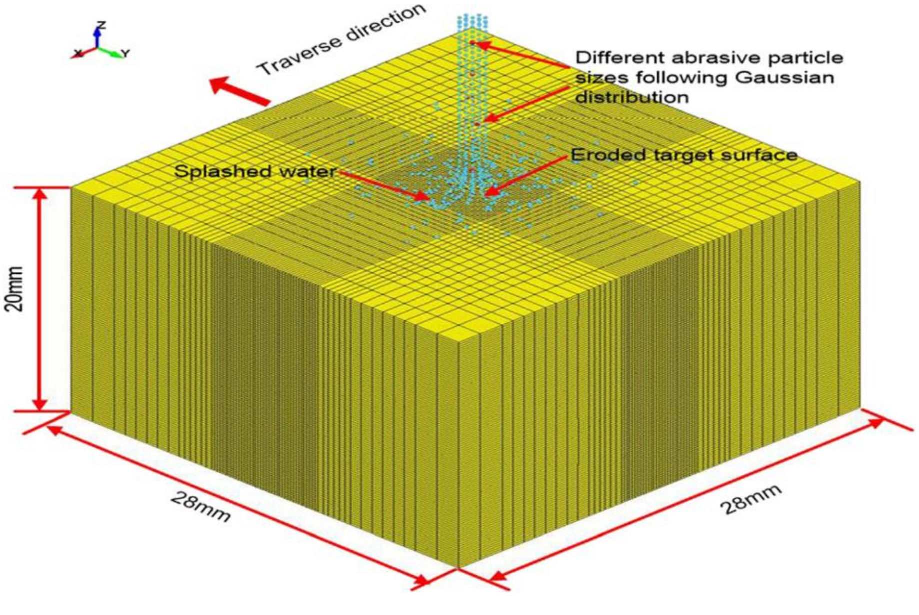

Fig. 1. *Abrasive particles spatial distribution in the simulation model* (Du et al., 2020)

the abrasive nozzle assembly parameters were kept constant as standard configurations, i.e., the orifice diameter (0.33 mm), the nozzle diameter(1.02 mm), and the nozzle length (76.2 mm). The specimens were C45 plates with 200 mm× 100 mm×20 mm dimensional sizes. The abrasive was 80 mesh alman-dinegarnet sand, which was the most commonly used in the abrasive waterjet machining process. Besides, an automatic abrasive metering system was used to ensure the accurate control of the abrasive mass flow rate throughout the experiments. Full factorial experiments were designed to verify the accuracy of the numerical simulation. The length of each slit was60 mm, and the cutting parameters could be referred to in Table 1. In the experiments, appropriate water pressure was considered at a 2-mm standoff distance between the nozzle and the specimen, while the abrasive mass flow rate was kept constant at 0.18 kg/min. Furthermore, five levels of the traverse speed and water pressure were selected within the equipment limitations and the typical ranges of AWJ machining.

Table 1 operation parameters in the AWJ cutting experiments.(Du et al., 2020)

Parameter's	description
Water pressure	200, 240, 20, 320, 36 (MP_a)
Transverse speed (mm/min)	80, 120, 160, 20mm240
Standoff distance	2 (mm)
Abrasive mass flow rate	kg.18 (kg/min)
Jet impact angle	90°

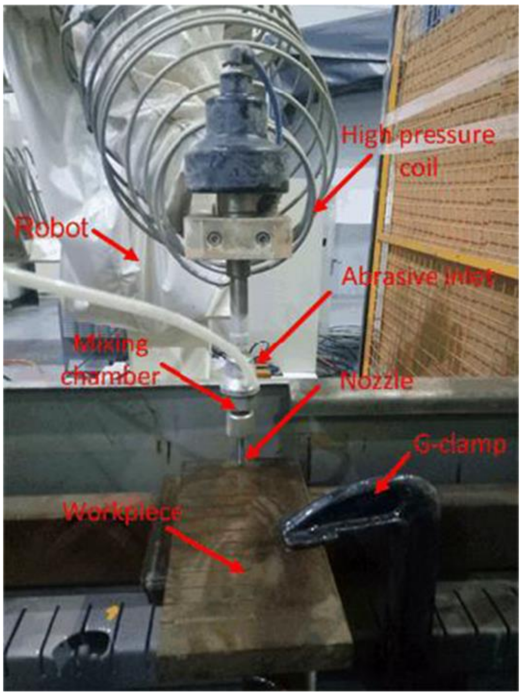

Fig. 2 Photo of the experimental setup (Du et al., 2020)

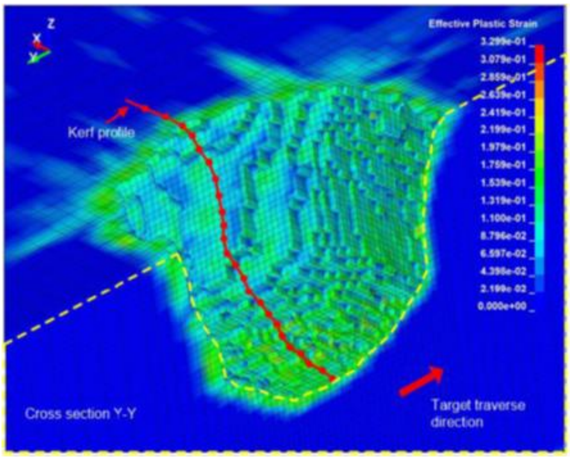

Fig. 3 Outputs in the centric cross-section Y-Y view of the FEM workpiece under the impact of abrasive waterjet(Du et al., 2020)

(Du et al., 2020) simulation and experimental results of the AWJ cutting process under different transverse speed and water pressures compared, the average velocity of the water flow and abrasive particles calculated according to the actual water pressure used in the experiments, the workpieces at to move in the opposite direction of traverse speed, and abrasive waterjet fixed in and then cutting depths under different traverse speeds and water pressures calculated, as shown in Fig.2.

3.2.2. Particle to structure contact

(Du et al., 2020) workpiece interaction to abrasive particles and waterjet refer to particle-structure contact. The SPH particles connected with the FEM structures could be defined by the penalty-based node to surface contact, where the slave part is the SPH node-set, and the master part is the FEM faces of the workpiece. As for the coupling method of the DEM particle sand the FEM structures, a non-tied coupling interface between particles and the surface is implemented, which controls the spherical discrete elements acting like non-spherical abrasive particles

3.3. Numerical model

3.3.1 *Basic theory of SPH*

Discretizing Navier -Stokes equations (Wu et al., 2019) two-dimensional SPH-FEM/DEM coupled model developed to investigate rock breaking behavior underwater jet impact based on the LS-DYNA software, where the SPH method was adopted to model the water jet and the FEM/DEM method was adopted to simulate rock breaking response. To better approximate the micro-structure of rock, a Voronoi tessellation technique was adopted to generate the random polygonal grains. A zero-thickness cohesive element is inserted along the boundaries of the Voronoi grains to model the mechanical interaction between grains as well as the breaking process of rock.

Numerical water jet impact tested on sandstone is firstly conducted to verify the proposed method as well as calibrate the corresponding micro-parameters. verified method, the effects of microstructure and micro-mechanical properties on the rock-breaking performance underwater jet impact systematically investigated. The numerical results showed that the rock-breaking performance is greatly affected by grain size and irregularity, ductility, microscopic strength, and the heterogeneity of micro-parameters, whereas the contact stiffness ratio has little effect on the rock-breaking performance of underwater jet impact (Du et al., 2020).

In the smooth particle hydrodynamic (SPH) method, a kernel approximation is used based on randomly distributed interpolation points (Wu et al., 2019). The properties of each particle are evaluated via the integrals or the sums over the values of its neighboring particles. Conservation of mass, momentum, and energy of the fluid to SPH formulation is based on discretizing the Navier-stokes equation.

3.2.3. Voronoi tessellation technique

A Voronoi tessellation technique is added to LS-DYNA by a FORTRAN program (Wu et al., 2019) to represent the microstructure of the rock generate granular rock model with different grain size and regularity, two control parameters that of the average distance between control points and the fluctuation amplitude of the distance between control points and With a fixed average distance, a larger value of the fluctuation amplitude of the distance between control points helped to a rock model with more irregular grains.

$$\frac{d\rho_i}{dt} = \sum_{j=1}^{N} m_j v_{ij}^{\beta} \frac{\partial W_{ij}}{\partial x_i^{\beta}}$$

Conservation of momentum:

$$\frac{dv_i^{\alpha}}{dt} = \sum_{j=1}^{N} m_j \left(\frac{\sigma_i^{\alpha\beta}}{\rho_i^2} + \frac{\sigma_j^{\alpha\beta}}{\rho_j^2} \right) \frac{\partial W_{ij}}{\partial x_i^{\beta}}$$

Conservation of energy:

$$\frac{de_i}{dt} = \frac{1}{2} \sum_{j=1}^{N} m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} \right) v_{ij}^{\beta} \frac{\partial W_{ij}}{\partial x_i^{\beta}} + \frac{\mu_i}{2\rho_i} \varepsilon_i^{\alpha\beta} \varepsilon_j^{\alpha\beta}$$

3.3.4. Numerical modeling of Rock failure model

To simulate the dynamic breaking behavior of rock underwater jet impact, the zero-thickness cohesive element inserted along the boundaries of the Voronoi grains, by simulating the failure of the cohesive element, the rock breaking process realized, such as crack initiation and propagation and numerical model of FEM-DEM established (Wu et al., 2019).

3.3.5. Coupling algorithm of Rock failure model

(Wu et al., 2019) based on the LS-DYNA platform. a node to surface contact algorithm adopted to implement the coupling of SPH and FEM/DEM, based on the penalty method, assuming a virtual spring existed between SPH particles and the face of finite elements and the penetration between them checked in every time step, contact force imposed when there occurs a penetration, whereas nothing done, FEM/DEM model based on Voronoi grains exerted a single surface contact algorithm and which allows automatic searching for penetrations of all grains after cohesive elements failed.

4. CONCLUSION

We can successfully model and simulate removal materials caused by abrasive particles and also resistance to abrasive wear by appropriate selecting parameters and input variables to minimize abrasive wear and enhanced resistance abrasive wear. In addition, the effect of temperature, fracture, and vibration on abrasive particles was studied.

Based on the results in the literature, it can be concluded that FEM can describe abrasion with a good approximation. DEM and FEM (SPH) are suitable for modeling abrasive material and its movement. The advantage of DEM is that it describes the motion conditions well and the shape of the particles can be easily adjusted. The disadvantage is that many parameters are required for the model, most of which are not physical characteristics. Therefore, validation of the entire model is required.

REFERENCES

1. Beck, F., & Eberhard, P. (2015). Predicting abrasive wear with coupled Lagrangian methods. *COMPUTATIONAL PARTICLE MECHANICS*, *2*(1), 51–62. https://doi.org/10.1007/s40571-015-0034-y
2. Du, M., Wang, H., Dong, H., Guo, Y., & Ke, Y. (2020). Numerical research on kerf characteristics

of abrasive waterjet machining based on the SPH-DEM-FEM approach. *International Journal of Advanced Manufacturing Technology*, *111*(11–12), 3519–3533. https://doi.org/10.1007/s00170-020-06340-4

3. Duan, N., Yu, Y., Wang, W., & Xu, X. (2017). SPH and FE coupled 3D simulation of monocrystal SiC scratching by single diamond grit. *International Journal of Refractory Metals and Hard Materials*, *64*, 279–293. https://doi.org/10.1016/j.ijrmhm.2016.09.016
4. Forsström, D., & Jonsén, P. (2016). Calibration and validation of a large-scale abrasive wear model by coupling DEM-FEM: Local failure prediction from abrasive wear of tipper bodies during unloading of granular material. *Engineering Failure Analysis*, *66*, 274–283. https://doi.org/10.1016/j.engfailanal.2016.04.007
5. Katinas, E., Chotěborský, R., Linda, M., & Kuře, J. (2021). Sensitivity analysis of the influence of particle dynamic friction, rolling resistance, and volume/shear work ratio on wear loss and friction force using DEM model of dry sand rubber wheel test. *Tribology International*, *156*, 106853. https://doi.org/10.1016/j.triboint.2021.106853
6. Phan, H. T., Tieu, A. K., Zhu, H., Kosasih, B., Zhu, Q., Grima, A., & Ta, T. D. (2017). A study of abrasive wear on high-speed steel surface in hot rolling by Discrete Element Method. *Tribology International*, *110*, 66–76. https://doi.org/10.1016/j.triboint.2017.01.034
7. Sardar, S., Karmakar, S. K., & Das, D. (2020). Identification and modeling of applicable wear conditions for stir cast Al-composite. *Friction*, *8*(5), 847–873. https://doi.org/10.1007/s40544-019-0302-6
8. Seriacopi, V., Prados, E. F., Fukumasu, N. K., Souza, R. M., & Machado, I. F. (2020). Mechanical behavior and abrasive mechanism mapping applied to micro-scratch tests on homogeneous and heterogeneous materials: FEM and experimental analyses. *Wear*, *450–451*, 203240. https://doi.org/10.1016/j.wear.2020.203240
9. Wang, F., Liu, S., & Ji, K. (2020). Numerical study on abrasive machining of rock using FDEM method. *Simulation Modelling Practice and Theory*, *104*, 102145. https://doi.org/10.1016/j.simpat.2020.102145
10. Wang, W., Liu, Y., Zhu, G., & Liu, K. (2014). Using FEM–DEM coupling method to study three-body friction behavior. *Wear*, *318*(1), 114–123. https://doi.org/10.1016/j.wear.2014.06.023
11. Wu, Z., Yu, F., Zhang, P., & Liu, X. (2019). Micro-mechanism study on rock breaking behavior underwater jet impact using coupled SPH-FEM/DEM method with Voronoi grains. *Engineering Analysis with Boundary Elements*, *108*, 472–483. https://doi.org/10.1016/j.enganabound.2019.08.026

Authors addresses

[1] *Hailemariam, Shegawu,Ph.D. student, Institute of Technology, Szent István Campus, MATE*
H-2100Gödöllő, Páter K. u. 1. Hungary
abebaw.hailemariam.shegawu@uni-mate.hu

[1] *Prof.Dr. Oldal István, Department of Mechanical, Institute of Technology, Szent István Campus, MATE*
H-2100 Gödöllő, Páter K. u. 1. Hungary
oldal.istvan@uni-mate.hu

[1]*Prof. Dr.Kalácska Gábor, Head of Doctoral School, Institute of Technology, Szent István Campus, MATE*
H-2100 Gödöllő, Páter K. u. 1. Hungary
kalacska.gabor@uni-mate.hu

Contact person

[1]*Hailemariam, Shegawu, PhD student, Institute of Technology, Szent István Campus, MATE*

H-2100 Gödöllő, Páter K. u. 1. Hungary
shegawh@yahoo.com,
abebaw.hailemariam.shegawu@uni-mate.hu