

# Investigation of Reducing Metalworking Fluid Consumption in Deep-Hole Drilling using Smoothed Particle Hydrodynamics

Andreas Baumann and Peter Eberhard  
Institute of Engineering and Computational Mechanics  
University of Stuttgart  
Pfaffenwaldring 9, 70569 Stuttgart, Germany  
andreas.baumann@itm.uni-stuttgart.de

The reduction of metalworking fluid (MWF) in machining processes allows the reduction of costs and energy consumption. However, the process reliability, especially for deep-hole drilling, is influenced significantly by the MWF and its ability to evacuate the created chips out of the borehole. This work investigates the application of Smoothed Particle Hydrodynamics (SPH) in investigating the reduction of MWF for the drilling process. First results will be presented and an outlook on the further investigations will be provided.

## I. INTRODUCTION

The trend towards reducing costs and achieving more sustainable production continues. According to [4], cutting machine tools account for 1 to 3% of the global electrical energy demand. Applying metalworking fluid contributes significantly to energy consumption in production [3]. Depending on the machining center, the MWF supply accounts for up to a quarter of the total energy demand [4]. Accordingly, the reduction of MWF consumption is an obvious target.

In deep-hole drilling processes, the MWF supply significantly influences the chip evacuation, as shown in earlier investigations [1], [9], [10]. Deep-hole drilling is applied for drilling holes with a length-to-diameter ratio larger than ten [2]. The applications are in the automotive, aerospace, and medical industries, as well as machine fabrication for the food industry. Different deep-hole drilling methods are available, ranging down to diameters less than one millimeter. All methods are characterized by the high-quality hole and the high level of productivity archived [12].

This work focuses on a single-lip drill shown in Figure 1. The cutting head has a single asymmetrical cutting edge resulting in large asymmetrical cutting forces countered by guide pads on the drill's backside. Thus, the guide pads constantly burnish the created hole, contributing to the high-quality surface [13].

Furthermore, deep hole single-lip drilling is performed using high feed rates in a single pass [13]. Therefore, chips must be removed by the MWF, which is pumped under high pressure through an internal cooling channel to the cutting head. The MWF flushes the chips through the chip flute, which runs along the tool shank.

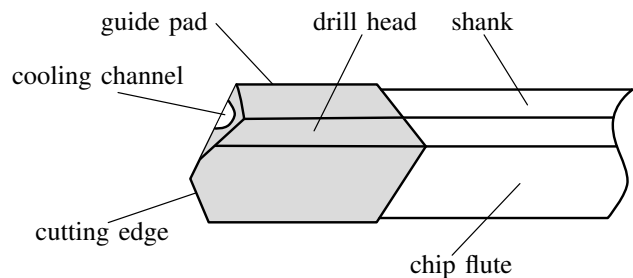


Fig. 1. Geometry of a single-lip drill.

In industry, the maximum MWF supply pressure is often applied to achieve a reliable chip evacuation and cutting process. Studies [5] suggest that the energy demand can be significantly reduced by applying a flow rate control for the MWF supply without negatively affecting the workpiece quality or the tool life.

This work investigates the modeling of complex processes like reducing the MWF supply considering a reliable evacuation of the chips using Smoothed Particle Hydrodynamics. Therefore, a coupled SPH/DEM simulation models the chip evacuation process. SPH is applied to model the motion of the metalworking fluid, whereas the Discrete Element Method (DEM) is used to describe the motion of the solid bodies such as chips, drill, and workpiece. The Lagrangian and mesh-free nature of SPH allows it to describe arbitrary moving surfaces and interfaces. Its application areas are especially when non-regular, moving free surfaces or dynamic fluid/structure interactions are present, like in the case of modeling deep-hole drilling.

In the following section, the modeling of the deep-hole drilling process is described before first results of the simulation with reduced MWF are presented. Finally, conclusions are drawn on the ability of SPH to model such complex processes, and future research questions will be presented in the talk.

## II. MODELING

As readers are assumed to be familiar with the basic SPH formulation, only a brief summary of selected topics is offered

in the following. The weakly-compressible SPH formulation is applied, which relates pressure and density by the equation of state. Therefore, no pressure boundary condition for the inflow can be applied. Instead, a finite volume simulation with the inflow pressure boundary condition of 100 bar [9] is carried out beforehand to evaluate the inflow velocity. Accordingly, a nominal velocity of 69 m/s is assigned to the inflowing SPH particles. The effect of gravity is insignificant compared to the fluid's inertia. Therefore, gravity is neglected here.

The artificial speed of sound is set to ten times the inflow velocity accordingly, so the density fluctuations remain less than 1%, according to [6]. Furthermore, the SPH-corrections of  $\delta$ -SPH, artificial viscosity, and artificial stress are applied to improve the SPH approximation of the MWF. The SPH particle size is chosen based on a simulation stability analysis while allowing a suitable discretization of the inflow in the kidney-shaped internal cooling channel. The particles are removed in the chip flute near the drill's end after they flow through the cutting channel. The required computational effort is minimized by discretizing the flow only from where it enters the drill tip until it reaches the drill's end. The simulation's fluid properties and SPH parameters are summarized in Table I.

TABLE I  
FLUID PROPERTIES AND SPH PARAMETERS.

| parameter                       | symbol           | value                 | unit              |
|---------------------------------|------------------|-----------------------|-------------------|
| fluid density (at 20°C) [7]     | $\rho_f$         | $8.45 \times 10^2$    | kg/m <sup>3</sup> |
| dynamic viscosity (at 40°C) [7] | $\mu$            | $8.45 \times 10^{-3}$ | kg/ms             |
| chip density [11]               | $\rho_s$         | $8.190 \times 10^3$   | kg/m <sup>3</sup> |
| artificial viscosity factors    | $\alpha$         | 0.2                   |                   |
|                                 | $\beta$          | 0.3                   |                   |
| artificial stress factor        |                  | $5.0 \times 10^{-2}$  |                   |
| diffuse density factor          | $\delta$         | $1.0 \times 10^{-1}$  |                   |
| artificial speed of sound       | $c_0$            | $6.9 \times 10^2$     | m/s               |
| CFL                             |                  | $7.5 \times 10^{-1}$  |                   |
| initial particle distance       | $\Delta$         | $8.0 \times 10^{-5}$  | m                 |
| smoothing length                | $h$              | $1.2 \times 10^{-4}$  | m                 |
| number of fluid particles       | $n_{pf}$         | $\approx 25,000$      |                   |
| inflow velocity                 | $v_{in}$         | $6.9 \times 10^1$     | m/s               |
| angular velocity                | $\omega_z^{SLD}$ | $5.0 \times 10^2$     | rad/s             |
| chip influx velocity            | $v_{chips}$      | 2.5                   | m/s               |

Instead of performing a computationally expensive chip formation simulation, the chips are modeled as rigid DEM bodies and inserted from the borehole ground into the chip flute. The forms are obtained by selecting typical chip forms from experiments and digitizing them using an optical 3D measurement system. The chips are only unilaterally coupled with the fluid while inserted, which means that the chips deflect the fluid while the fluid forces on the chips are neglected. Once the chips are completely within the chip flute, they are released, and their motion is described by the Newton-Euler equations. Then, a bilateral coupling of the chips and the fluid is performed.

Due to the complex geometries of the chips, a repulsive force boundary condition is applied for the fluid-structure interaction. Therefore, the modified Lennard-Jones-Potential [8] is applied,

which calculates the interaction force based on the particle's distance to the surface of the rigid bodies, respective their distance to each other.

The reduced MWF supply is modeled by a reduced inflow velocity, which corresponds linearly to a reduced flow rate. The analysis is carried out from a fluid dynamics point of view. Thereby, other functions of the MWF, like lubrication or heat transport, are neglected. However, the analysis provides a first assessment for later experimental investigation.

### III. RESULTS

Figure 2 presents some first results of the investigation of reducing the applied MWF supply for the evacuation of the chips. It shows the MWF flow for the different inflow velocities at  $t = 1.5$  ms. The faster inflow velocity corresponds directly with an increased flow rate and, thus, a higher fluid volume in the simulation domain. This can be seen by the faster progress of the inflowing MWF; for a higher inflow velocity, the fluid flows further in the borehole at the same time point. After passing the cutting tip, the flow velocity in the chip flute is also higher for a higher inflow velocity.

Furthermore, the separation between the chips depends on the inflow velocity. The chips have a larger distance and are evacuated faster from the borehole for higher inflow velocities. The chips come into contact with slower inflow velocities and are pushed by the following chips.

### IV. CONCLUSIONS

Smoothed Particle Hydrodynamics is applied to model the deep-hole drilling process to investigate the reduction of MWF supply. Reducing MWF in machining processes allows for reducing costs and energy consumption. However, the evacuation of the created chips, which is highly influenced by the MWF supply, is a key point for process reliability. This work investigates the ability to apply SPH for process modeling to investigate the reduction of MWF supply. The first results show that SPH is well able to capture the changing and dynamic interfaces between the fluid and the evacuated chips. The results indicate that the MWF supply can be reduced.

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### REFERENCES

- [1] Baumann, A.; Oezkaya, E.; Schnabel, D.; Biermann, D.; Eberhard, P.: Cutting-fluid flow with chip evacuation during deep-hole drilling with twist drills. *European Journal of Mechanics - B/Fluids*, Vol. 89, pp. 473–484, 2021.
- [2] Biermann, D.; Bleicher, F.; Heisel, U.; Klocke, F.; Möhring, H.C.; Shih, A.: Deep hole drilling. *CIRP Annals*, Vol. 67, No. 2, pp. 673–694, 2018.
- [3] Biermann, D.; Saelzer, J.; Bergmann, B.; Schenzel, J.; Menze, C.J.; Gerken, J.F.; Wolf, T.; Denkena, B.; Möhring, H.C.; Zabel, A.: Fundamental characterization of lubrication effects through various cooling lubricants in the chip formation zone. *Production Engineering*, 2024.

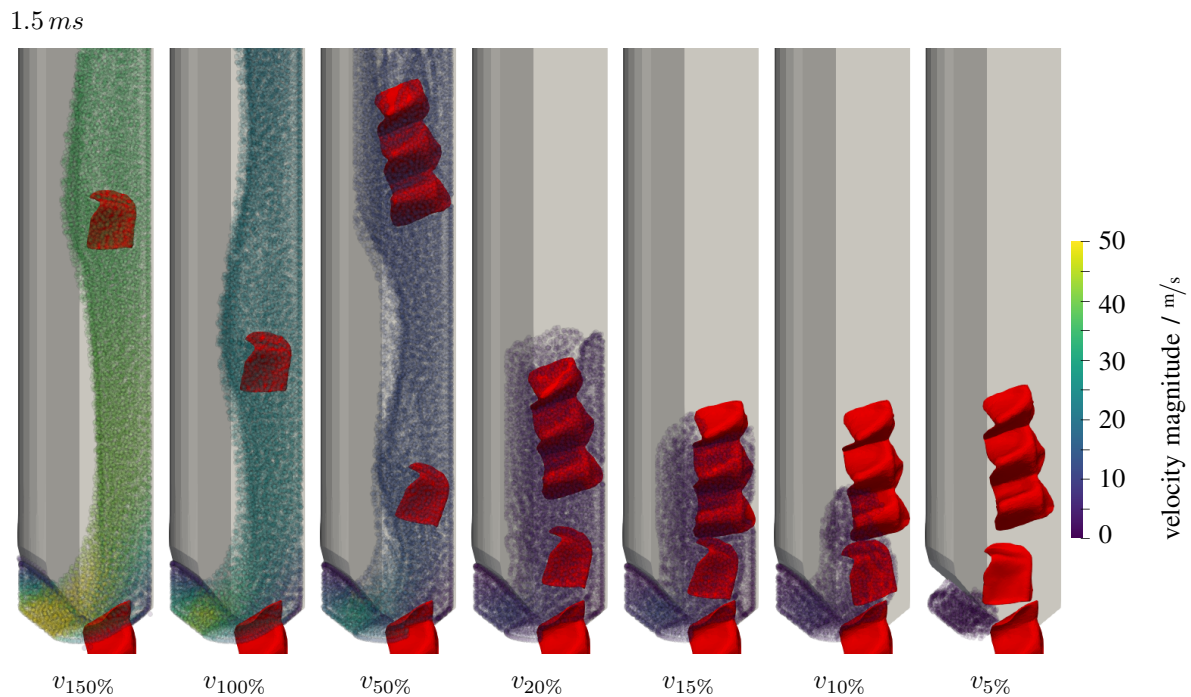


Fig. 2. Comparison of the flow for the different MWF flow rates at  $t = 1.5$  ms. The view is perpendicular to the chip flute while the drill rotates. The chips are colored red, and the MWF is partially transparent so that the chips can be recognized along the chip flute.

- [4] Denkena, B.; Abele, E.; Brecher, C.; Dittrich, M.A.; Kara, S.; Mori, M.: Energy efficient machine tools. *CIRP Annals*, Vol. 69, No. 2, pp. 646–667, 2020.
- [5] Denkena, B.; Mori, M.; Dittrich, M.A.; Klages, N.; Matthies, J.: Energy efficient supply of cutting fluids in machining by utilizing flow rate control. *CIRP Annals*, Vol. 72, No. 1, pp. 349–352, 2023.
- [6] Monaghan, J.: Simulating free surface flows with sph. *Journal of Computational Physics*, Vol. 110, No. 2, pp. 399–406, 1994.
- [7] Motorex: Technisches Datenblatt: Swisscut Ortho NF-X 10, 2023. [https://motorex.com/Pdf/TI/Motorex/Schneidoeel/SWISSCUT-ORTHO-NF-X-10/SWISSCUT-ORTHO-NF-X-10\\_1017181\\_DE\\_20230309-124926.pdf](https://motorex.com/Pdf/TI/Motorex/Schneidoeel/SWISSCUT-ORTHO-NF-X-10/SWISSCUT-ORTHO-NF-X-10_1017181_DE_20230309-124926.pdf), last accessed 31st December, 2024.
- [8] Müller, M.; Schirm, S.; Teschner, M.; Heidelberger, B.; Gross, M.: Interaction of fluids with deformable solids. *Computer Animation and Virtual Worlds*, Vol. 15, No. 3-4, pp. 159–171, 2004.
- [9] Oezkaya, E.; Baumann, A.; Michel, S.; Schnabel, D.; Eberhard, P.; Biermann, D.: Cutting fluid behavior under consideration of chip formation during micro single-lip deep hole drilling of Inconel 718. *International Journal of Modelling and Simulation*, Vol. 43, No. 2, pp. 49–63, 2022.
- [10] Oezkaya, E.; Baumann, A.; Eberhard, P.; Biermann, D.: Analysis of the cutting fluid behavior with a modified micro single-lip deep hole drilling tool. *CIRP Journal of Manufacturing Science and Technology*, Vol. 38, pp. 93–104, 2022.
- [11] Special Metals Corporation: SMC-045: INCONEL alloy 718, 2007. <https://www.specialmetals.com/documents/technical-bulletins/inconel/inconel-alloy-718.pdf>, last accessed 31st December, 2024.
- [12] Verein Deutscher Ingenieure (VDI): VDI 3210, Blatt 1: Tiefbohrverfahren (Deep-hole drilling), 2006.
- [13] Woon, K.S.; Tnay, G.L.; Yeo, S.H.: Deep hole gun drilling of nickel-based superalloys. In: Davim, J.P. (ed.) *Drilling Technology: Fundamentals and Recent Advances*, pp. 37–88. De Gruyter, 2018.