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Investigation of Chip Jamming and Drill Breakage in Deep-Hole Drilling using Smoothed Particle Hydrodynamics

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Abstract

Single-lip deep hole drilling is characterized by a high-quality hole and a high level of productivity achieved. It is performed using high feed rates in a single pass, and, therefore, chips must be removed by the cooling liquid. However, chip jamming is a significant problem when chips wrap around the tool, leading to marks on the borehole wall and an increased drilling torque, potentially causing sudden tool failure. The Smoothed Particle Hydrodynamics method is applied to simulate the challenging fluid flow and elastic bodies. A first approach is developed to model the effects of chip jamming and the possible consequence of drill breakage for a deeper understanding of the process behavior.

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Keywords: deep-hole drilling; smoothed particle hydrodynamics; SPH; cutting tool; chip removal

1. Introduction

Deep-hole drilling is characterized by the high-quality hole and the high level of productivity archived [24]. It is distinguished from conventional drilling by its length-to-diameter ratio larger than ten [5]. Deep-hole drilling is applied in the automotive, aerospace, and medical industries, and also in machine fabrication for the food industry. Different deep-hole drilling methods are available, ranging down to diameters less than one millimeter. This work focuses on a single-lip drill (SLD). However, its methodology can be applied to other deep-hole drilling methods. The SLD has a single asymmetrical cutting edge at the cutting head, resulting in large asymmetrical cutting forces countered by guide pads on the drill's backside. Thus, a high-quality surface is created as the guide pads constantly burnish the created hole [26].

Furthermore, single-lip drilling of deep holes enables high productivity by using high feed rates in a single pass [26]. Therefore, chips must be removed by the metalworking fluid (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. The tool shank that drives the cutting head has a smaller diameter than the cutting head to prevent further mechanical burnishing of the hole surface [26].

Further process improvement is, for example, driven by the goal of increased productivity and cost reduction, i.e., by increasing the material removal rate. Therefore, different investigations look into understanding the interaction of process parameters, such as feed rate or the cutting speed, by using finite element orthogonal cutting models [13] or full 3D simulation of the SLD process [6].

However, process reliability must also be considered for further improvement of the deep-hole drilling process. Especially, the shape and size of the produced chips play an important role in the reliable removal out of the borehole [19].

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While small chips are generally preferred, wear of the cutting edge or changing process parameters, especially, feed rate or fluid pressure, influence the shape and size of the chips [20]. Long and thin chips are problematic, as they can get stuck in the gap between the tool shank and the borehole wall and wrap around the tool. The jammed chip causes marks on the borehole wall and can block further chips from reliable evacuation. Furthermore, the congestion in the chip flute can cause an increased drilling torque, leading to sudden tool failure when the tool strength is exceeded [5]. To prevent chip jamming, the chip transport by the metalworking fluid is of significant interest for the process reliability in deep-hole drilling.

Previous investigations focused on transient chip evacuation and its improvement by drill design modifications [18][19]. Optimization of the cooling channel cross-section allowed a higher MWF flow at the same inflow pressure while maintaining the drill's structural strength. Furthermore, the cutting edge was modified to create a different chip form, improving its evacuation by increasing its flow resistance.

Other studies investigated the analytic calculation of drilling forces and torques required to evacuate chips under safe conditions [6][11][12]. Countermeasures, i.e., a pecking cycle (periodic drill retraction) or cutting parameter changes, are applied based on threshold values for the process forces to ensure a reliable process. Other approaches try to optimize chip form by in-process prediction, monitoring, or controllers [9][17]. These approaches aim to prevent chip jamming, which consequently causes drill breakage, by in-process actions. To the author's knowledge, numerical modeling of chip jamming and possible drill breakage does not exist. Further research is needed to improve the understanding of possible influence factors and their mitigation.

The modeling of chip evacuation often invoked inserting rigid chip forms obtained by digitalizing chips produced in experiments [18] into the flow. The comparison with elastic modeling showed that this approach is valid for the analyses of undisturbed chip evacuation [1]. However, an elastic modeling of the chips is needed for further modeling of chip jamming.

This publication aims to propose a model to study the process of chip jamming as a reason for drill breakage. In contrast to earlier works, an elastic chip is actively placed between the drill and the borehole impeding the drill's rotation and thereby allowing the process after the chip jamming to be examined. The gap between the drill and the borehole is artificially increased for the simulation to place the chip between them.

The simulation method Smoothed Particle Hydrodynamics (SPH) is applied to model the motion of the metalworking fluid and the elastic chip of the drill simulation. SPH is a method for describing fluids or solids by discrete moving interpolation points, the so-called particles. Therefore, the Navier-Stokes equations describing the fluid movement or the continuum equations describing solid bodies are represented by weighted sums over a set of neighbor particles [29]. Its Lagrangian and meshfree nature allows SPH 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.

This publication's novel contribution is the extension of existing models considering elastic chips to study the occurrence of chip jamming and its effect on the drill forces, which could possibly lead to drill breakage.

2. Smoothed Particle Hydrodynamics Method

SPH is a meshless Lagrangian method where the continuum medium is discretized by a collection of points called particles. In order to compute the physical attributes of fluid flow problems, SPH solves the Navier-Stokes (N-S) equations and approximates the partial differential equations at these integration points. Its mesh-free nature allows SPH to model changing surfaces and interfaces easily. This makes SPH advantageous in problems like the modeling of evolving fluid interfaces, as is the case for the modeling of chip evacuation in deep-hole drilling. Mesh-based methods may even be more computationally expensive to track the fluid interface compared to SPH.

For solving an arbitrary partial differential equation, SPH uses a smoothing function to summarize over a set of moving particles [27]. Starting from an identity of a property function $A(\boldsymbol{x})$ at a given position $\boldsymbol{x}$ in the simulation domain Ω,

$$A(\boldsymbol{x}) = \int_{\boldsymbol{x}' \in \Omega} A(\boldsymbol{x}')\delta(\boldsymbol{x}-\boldsymbol{x}')d\Omega,$$

the Dirac delta distribution $\delta(\boldsymbol{x}-\boldsymbol{x}')$ is replaced by a smoothing kernel function $W(\boldsymbol{x}-\boldsymbol{x}', h)$ with its smoothing length h. This results in an intermediary integral form

$$A(\boldsymbol{x}) \approx \langle A(\boldsymbol{x})\rangle = \int_{\boldsymbol{x} \in \Omega} A(\boldsymbol{x}')W(\boldsymbol{x}-\boldsymbol{x}', h)d\Omega.$$

To solve this equation numerically, the integral form is discretized by the weighted summation of a finite set of particles. The final particle approximation for $A(\boldsymbol{x})$ is given by

$$\langle A(\boldsymbol{x})\rangle = \sum_b \frac{m_b}{\rho_b} A_b W(\boldsymbol{x}-\boldsymbol{x}_b, h),$$

which is only evaluated over neighboring particles b instead of the complete domain's Ω entire particle set due to the compact support of the smoothing function. This reduces the required computational effort significantly. Each particle carries a set of properties, such as its assigned mass m_b, density ρ_b, velocity $\boldsymbol{v}_i$, and pressure p_b at its location. SPH implicitly fulfills the mass conservation as all mass is located at the finite set of particles.

The Navier-Stokes equations are applied to model fluid dynamics. They read in the Lagrangian form

$$\rho \frac{d\boldsymbol{v}}{dt} = \rho\left(\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v}\cdot\nabla)\boldsymbol{v}\right) = \rho\boldsymbol{g} - \nabla p + \mu\nabla^2\boldsymbol{v}$$

for the balance of momentum and for the conservation of mass through the continuity equation

$$\frac{d\rho}{dt} = -\rho\nabla \cdot \boldsymbol{v}.$$

The velocity is given by $\boldsymbol{v}$, time by t, gravity by $\boldsymbol{g}$, and pressure by p. Furthermore, an equation of state, which relates the density and the pressure, is required to solve the system of equations. Commonly, the Tait equation [7] is used in SPH, which reads

$$p = \frac{c_0^2\rho_0}{\gamma}\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right],$$

where c_0 denotes the numerical speed of sound, and ρ_0 is the reference density. The polytropic index γ is set to 7 for water [14].

The approach of using an equation of state to close the system of equations is called weakly compressible SPH (WCSPH) formulation. In contrast to the other commonly used, truly incompressible SPH (ISPH) formulation, which requires the additional solving of a Riemann equation, WCSPH is computationally less expensive. However, it faces the downside, which is that no pressure boundary condition can be applied due to the use of the equation of state. Further details about the SPH method and the application of the general SPH approximations on the Navier-Stokes equations are provided in [27].

For the description of solid materials, the equations describing the continuum are the same as for liquids. However, the momentum equation reads [10]

$$\frac{d\boldsymbol{v}}{dt} = \frac{1}{\rho}\nabla \cdot \boldsymbol{\sigma} + \boldsymbol{g},$$

using the Cauchy stress tensor $\boldsymbol{\sigma}$. The Cauchy stress tensor $\boldsymbol{\sigma}$ consists of the direction-independent hydrostatic stress σ_{hyd} and the direction-dependent deviatoric stress $\boldsymbol{\tau}$ as follows

$$\boldsymbol{\sigma} = \sigma_{\mathrm{hyd}}\boldsymbol{I} + \boldsymbol{\tau}.$$

Further details of applying of the SPH approximation for solids can be found in [23].

The description of rigid bodies, like the drill or the borehole, is derived from applying D'Alembert's principle on the Newton-Euler equations, resulting in

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{k} = \boldsymbol{q}$$

where $\boldsymbol{M}$ refers to the assembled mass matrix of the body, $\boldsymbol{k}$ containing the generalized gyroscopic forces, and $\boldsymbol{q}$ the generalized internal forces. A detailed overview of the dynamic description of rigid bodies can be found in [21].

The coupling of SPH and the rigid bodies, and between the fluid and solid SPH particles is achieved by the application of repulsive forces. Therefore, the modified Lennard-Jones-Potential [16] 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.

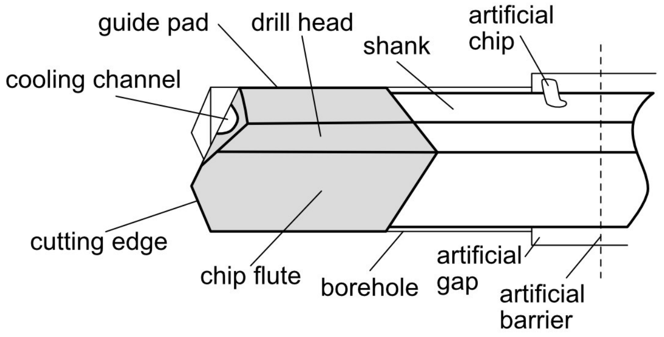

Figure 1: The geometry of the simulation model with an artificial semi-permeable barrier, blocking chips from their evacuation but allowing fluid to pass, an artificially increased gap between drill and borehole, in which an artificial chip is placed.

3. Modeling Deep-Hole Drilling

Having presented the essential numerical fundamentals of SPH, it is used to simulate the cutting fluid and the elastic chip bodies to investigate chip jamming and drill breakage. A single-lip drill with a diameter of $d = 2$ mm is used for the analysis. The inserted chips are obtained from experiments and digitalized for use in simulations. The process is described in previous publications [18]. The properties of the MWF are taken from the cutting oil Motorex Swisscut Ortho NF-X 10, which has a density of $\rho = 845\ \mathrm{kg/m^3}$ and a viscosity of $\nu = 10\ \mathrm{mm^2/s}$ [15].

The modeling of chip jamming and its potential consequence, drill breakage, includes modeling the fluid flow in combination with chip evacuation, forced chip jamming, and friction and torque modeling of the drill. To force the chip jamming, an artificial semi-permeable barrier is placed in the chip flute, which blocks the chips from their evacuation but allows the MWF to pass freely.

Furthermore, a chip is actively placed between the drill and the borehole to model the effect of the chip jamming into the drill's rotation. Therefore, the gap between the drill and the borehole is artificially increased. The chip is placed so that the edge of the chip flute catches it while the chip rubs against the borehole. The complete model is shown in Figure 1.

Between the chip and the borehole, both are the same material, Inconel 718, a Coulomb friction coefficient of 0.4 is assumed [24]. During the cutting of Inconel 718, high temperatures are observed. One source of this heat generation is the friction between the chips and the drill [1]. Therefore, sometimes drill coatings are applied to reduce the tool's friction and, consequently, the heat generation [28]. Hence, a significantly smaller conservative coefficient of friction is assumed between the drill and the chip.

In earlier investigations, the drill's rotation was forced onto the drill's body by assuming a constant rotational speed, neglecting any acting forces. This prevented measuring and analyzing the drill's forces and the required torque to drive the drill. In the following, the drill is driven by an active torque control. This is done by a proportional–integral–derivative (PID) controller, which calculates the error between the drill's desired rotational angle and the actual rotation of the drill in the

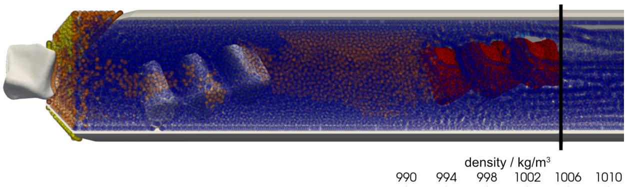

Figure 2: Fluid flow and chip evacuation under consideration of an artificial semi-permeable barrier, which blocks the chips from the evacuation but allows the MWF to pass [2]. An elastic chip colliding with the barrier is colored red. Further rigid chips during there are colored white and the fluid is colored according to its density. An transparance is applied to increase the visibilty of the chips.

simulation. Based on the error, the torque applied to the drill is changed based on proportional, integral, and derivative terms (denoted P, I, and D, respectively) to correct the rotational error. In the simulation the error derivative is calculated by a difference quotient and smoothed by a simple moving average using the last error derivative. Using this approach, the torque to reach a constant rotational velocity is given and this torque changes with friction.

4. Preliminary Results

The application of SPH enables the modeling of systems with free surfaces and changing interfaces due to its mesh-less nature, which can be only limitedly modeled with mesh-based methods. However, this comes with the prize of an increased computational effort.

As described, modeling of chip jamming and drill breakage includes multiple parts. The fluid flow during the chip evacuation and the jamming of the chips by an artificial barrier is shown in Figure 2. More details can be found in [2].

However, these results do not include friction between the chips and the drill. Therefore, the focus of this publication is on friction and its influence on the torque acting on the drill. A dry simulation model without any MWF inflow is tested to evaluate its capability to describe the jamming of chips and the subsequent increased torque onto the drill. In a later state, the fluid inflow and the insertion of chips from the bore ground will be added based on previous works [2].

The torque acting on the drill over time and the controller parameters, specifically the controller's control variable and the rotational error, are shown in Figure 3. The lower plot shows the rotational error taken as input for the controller and torque output applied by the controller onto the drill. As the drill starts from rest, the rotational error increases at the simulation start. This is compensated by a high torque, which decreases shortly after the drill starts to rotate and the rotational error declines. Over time, the rotational error oscillates between $\pm 2 \cdot 10^{-4}$ degree, and the controller's torque output shows the same oscillation, which could be reduced by an increased derivative term in the controller's design. Nevertheless, the achieved rotational error is relatively small and shows no continuous control error despite the constantly changing setpoint value of the drill's rotating orientation.

However, the rotational error shows a second higher frequency oscillation, which still needs to be understood. The same oscillation is also visible in the controller's torque output graph. Nevertheless, the drill's conservative torque does not show the same low-frequency oscillation. Moreover, the drill's conservative torque is not identical to the controller's output as it is around ten times smaller despite showing the same initial decline after the simulation starts.

Similarly, the drill's dissipative torque is only partially comprehensible. Some explanations of the deflections can be found in the visualization of the chip and drill movement. Around the timepoint $3.4 \cdot 10^{-5}$ seconds, the drill comes in contact with the chip for the first time. This causes an increase in the conservative and dissipative torque acting on the drill. The same can be seen around $6.2 \cdot 10^{-4}$ seconds when the chip scratches along the drill and around $8 \cdot 10^{-4}$ seconds when the drill collides with the chip again. However, the other excitations visible in the dissipative torque acting on the drill between these events cannot be explained at the moment.

Furthermore, the acting dissipative torques on the drill are small. Thus, the occurring friction between the chip and the drill is small. For the actual drill breakage, higher forces are assumed. For the readers' reference, two views in between the mentioned timepoints are provided to follow the movement of the chip and the drill.

5. Conclusions

The modeling of chip jamming and potential drill breakage includes modeling the fluid flow during chip evacuation, the forced chip jamming, and the friction and torque modeling of the drill. The goal of this publication was to find a simulation model that extends the modeling of chip jamming to allow the investigation of increasing drill torque loads and consequently caused drill breakages. Therefore, the drill was equipped with a torque controller to achieve the drilling rotation and allow the measurement of the torque acting on the drill caused by the chips instead of an applied fixed rotation, as done in earlier works. The existing simulation model was extended with an artificial chip placed in the gap between the drill and the wall of the borehole, which was artificially extended.

First only the dry simulation model was analyzed. The results showed the collision of the chip with the drill and the friction between them. A PID controller was applied which controlled the drill's torque to achieve the desired drill's rotation. The collisions and friction of the chip with the drill effected the torque acting on the drill. If the drill's torque exceeds the drill's strength, the drill could consequently break. Therefore, the model is well able to model chip jamming and the potential drill breakage following.

However, the measured conservative torque acting on the drill did not match the controller's torque output. Furthermore, it showed some yet unexplained deflections that could not be attributed to the drill's collisions with the artificial chip. Further work is needed to analyze these effects of the simulation model.

The friction forces between the drill and the chip are small. For the actual drill breakage, higher forces are required. Therefore, the modeling of the normal forces and friction forces between the chip and the drill and between the chip and borehole needs to be revisited.

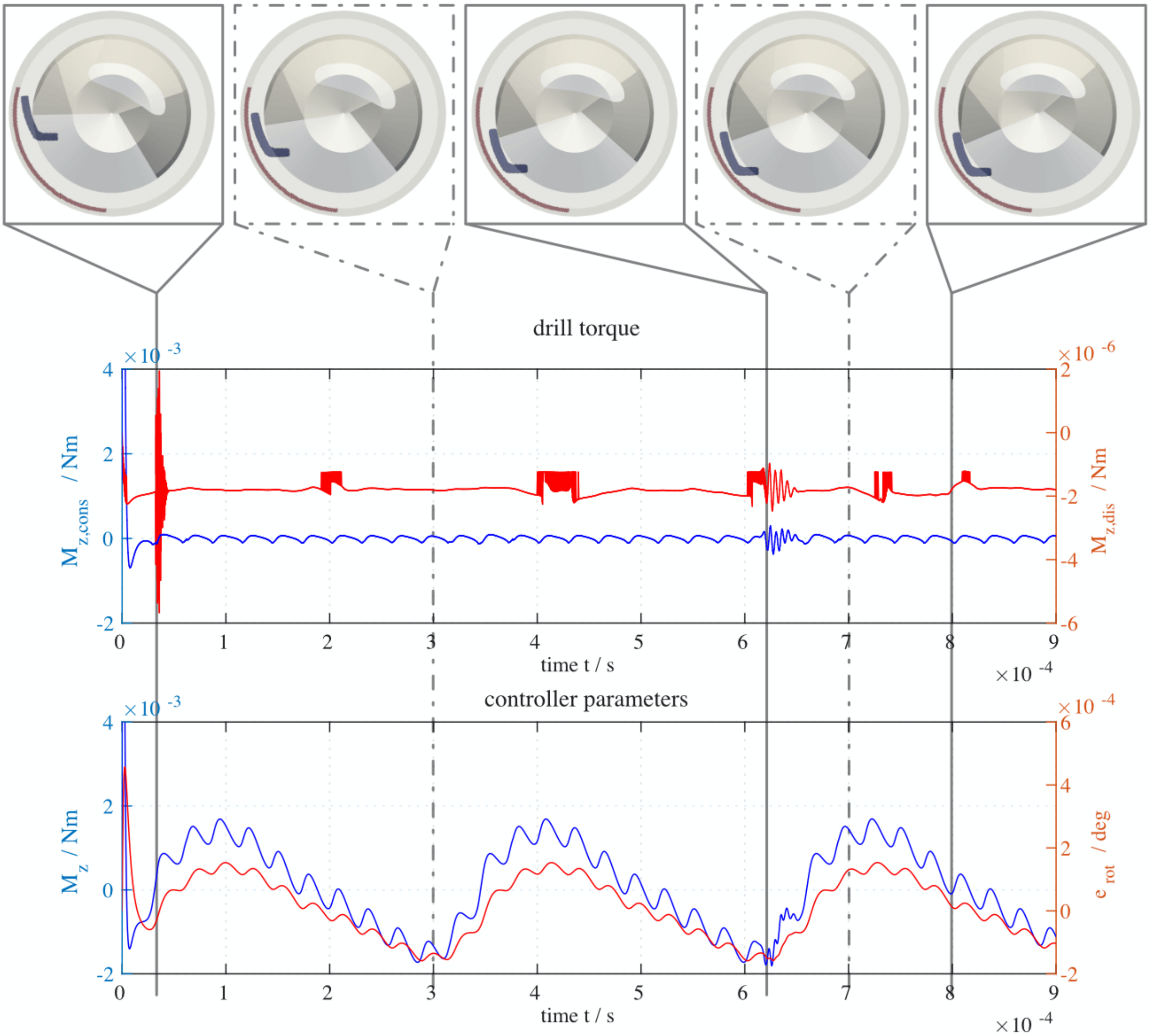

Figure 3: Visualization of the torque acting on the drill, the controller's parameters torque output and rotational error, and simulation views at selected time points. The lower plot shows the drill's rotational controller's torque output (blue) and rotational error input (red). The conservative torque (blue) and the dissipative torque (red) acting on the drill are shown in the middle plot. Visualizations of the simulation viewed from the borehead down the chip flute at selected time points are given above the plots.

To summarize, for the modeling of chip jamming and the potential drill breakage, the required modeling of the fluid flow, chip evacuation and chip jamming by an artificial barrier have been shown in previous publications. The presented model enables modeling the forces and torques caused by the jammed chips onto the drill. The next step is to combine fluid flow and chip evacuation with chip jamming and torque modeling to predict possible drill breakage for a deeper understanding of the process behavior.

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