Investigation of Chip Jamming in Deep-Hole Drilling

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

***Abstract*—In this paper, we show the recent progress and first insights in modeling chip jamming in the deep-hole drilling process. Chip jamming is a significant problem when chips wrap around the tool, leading to marks on the borehole wall and an increased drilling torque causing sudden tool failure. Recent investigations focused on chip evacuation and fluid distribution along the cutting edge. This work extends the existing models by adding an artificial barrier in the chip flute. This barrier approximates a chip jammed between the drill shaft and the borehole wall. In the first approach, this barrier blocks the complete chip flute but allows fluid to pass, only blocking the chips from their evacuation. In the second approach presented, a non-permeable artificial barrier partially blocks the chip flute.**

Furthermore, we show the validation of the model and evaluate the assumption of rigid chips for the chip evacuation as they are applied in earlier investigations. Finally, we show the deformation of the chip as it blocks the fluid from its evacuation and the impact on the fluid flow during the process.

I. Introduction

Deep-Hole drilling is applied for drilling holes with a length-to-diameter ratio larger than ten [4]. The applications are in the automotive, aerospace, and medical industries, and also in machine fabrication for the food industry. Different deep-hole drilling methods are available, ranging to diameters less than one millimeter. All methods are characterized by the high-quality hole and the high level of productivity archived [10]. 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 [11].

Furthermore, single-lip drilling of deep holes is performed using high feed rates in a single pass [11]. Therefore, chips must be removed by the cooling liquid which is pumped under high pressure through an internal cooling channel to the cutting head. The cooling liquid flushes the chips through the chip flute, which runs along the tool shank. The tool shank which drives the cutting head has a minimal smaller diameter than the cutting head to prevent further mechanical burnishing of the hole surface [11].

Generally, small chips are preferred for a reliable removal out of the borehole. However, wear of the cutting edge or changing process parameters, especially, feed rate or fluid pressure, can also produce long and thin chips. These unfavorable chip forms can, e.g., get stuck in the gap between the tool shank and the borehole wall and wrap around the tool. This leads to marks on the borehole wall, further chip congestion in the chip flute, and an increased drilling torque causing sudden tool failure when the tool strength is exceeded [4].

Moreover, the single-lip drill has only a single straight flute for the chip evacuation. In contrast, a twist drill acts as an Archimedean screw, which supports the transport of the cutting fluid and the transport of the chips [1]. Therefore, chip evacuation is of significant interest for the process reliability of single-lip drills.

Previous investigations focused on the chip evacuation from the borehole and the fluid distribution, especially the fluid flow around the cutting edges. For single-lip drills, it was shown that the cutting edge is not sufficiently supplied with cutting fluid, and the chip transport has the potential for optimization [7]. Therefore, the cooling channel cross-section was optimized to allow a higher fluid flow with the same inflow pressure. The cutting edge design was changed to create a different chip form, offering better fluid flow resistance. Both modifications result in a faster chip evacuation and, thereby, an increase in process reliability [8]. Furthermore, different modifications by adding a second chip flute were tested [3], [9]. However, these showed no significant improvement in the fluid flow behind the cutting edge.

In our recent work, we aim to model the process of chip jamming in deep hole drilling to improve the understanding of the process and thereby increase its reliability. This contribution shall summarize the current state of our research and point out the next step in the 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 formulation is applied, which relates pressure and density by the equation of state

$$p = \frac{c_0^2 \rho_0}{\gamma} \big[\big(\frac{\rho}{\rho_0} \big)^{\gamma} - 1 \big].$$

The polytropic index $\gamma = 7$ and the reference density $\rho_0 = 1000\, kg/m^3$ are used for water. The speed of sound c_0 is selected as a numerical control parameter and set to be

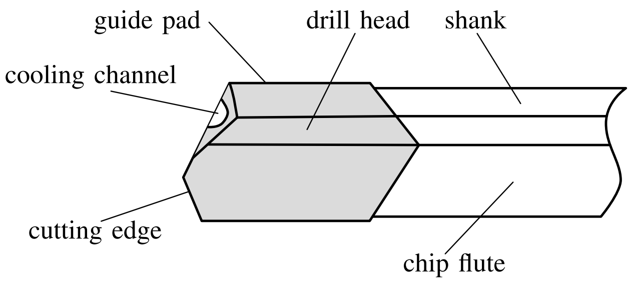

Fig. 1. Geometry of a single-lip drill.

ten times the maximum flow velocity. Thereby, a small compressibility of around 1% has to be expected while reducing the computational expanse significantly [5].

The boundary condition is applied by a modified Lennard-Jones potential [6], which also acts as coupling between the SPH particles and the DEM bodies. Any friction between the fluid and the solid bodies and between the solid bodies is neglected in the following modeling as the first approach but shall be added later in the following investigations.

II. Modelling

A. Modelling and Validation

The single-lip deep hole drill's modeling is based on a coupled SPH/DEM simulation. SPH describes the cooling liquid, and its properties are in Table I. The solid bodies, such as the drill, the borehole, and the chips are modeled by DEM. The DEM bodies are imported as non-convex polyhedral surface meshed. The coupling between them and the fluid is described by a repulsive force interaction given by a modified Lennard-Jones potential.

The model parameters correspond to the experimental setup with a fluid inflow pressure of 100 bar through the internal cooling channel of the drill [7]. No pressure boundary condition can be applied in the simulation as a weakly-compressible SPH formulation is used. Therefore, a CFD simulation with the inflow pressure boundary condition is carried out to evaluate the inflow velocity, which is used in the SPH simulation instead.

The experimental data is measured by our partners at the ISF at the TU Dortmund based on Particle-Image Velocimetry. Therefore, the drill is placed within a transparent resin cylinder which is rotated instead, resulting in the same relative movement as in the real application. Small physical particles are inserted in the cutting fluid, which can be tracked by digital image analysis through the resin cylinder. This allows the estimation of the fluid velocity. The comparison of the flow field in the chip flute is shown in Figure 2 for different time points. It can be seen that simulation results agree well with the experimental data. Further details about the experimental validation and the additional comparison with CFD simulations are given in our joint publication [7].

TABLE I
Model parameters for the SPH/DEM model.

parameter	symbol	value	unit
fluid density	ρ_f	999.3	kg/m^3
dynamic viscosity	μ	10^{-3}	Pa s
inflow velocity	v_f	69	m/s
fluid particle size	Δ_f	$8 \cdot 10^{-5}$	m
solid density	ρ_s	8190	kg/m^3
solid particle size	Δ_s	$9.5 \cdot 10^{-6}$	m
Youngs modulus	E	200	GPa
Poisson ratio	μ	0.3	-
smoothing length factor	h_f	1.5	-

III. Chip Jamming

The previously presented model is used in several investigations to model the fluid distribution and the chip evacuation for single-lip drills [7] and possible drill geometry modifications to improve the fluid flow along the cutting edge [3]. This model is extended here to include the jamming of chips in the chip flute.

A. Elastic chip behaviour

In the first setup, a semi-permeable barrier is introduced in the chip flute blocking the outlet for chips but allowing cutting fluid flow to pass. This can be seen as a single chip stuck, i.e., in the small gap between the drill shaft and the borehole wall, which prevents the next following chip from passing. However, the blocking chip's elastic deformation allows the fluid to flow freely around it, as first assumption.

The first chip is placed in the chip flute and is modeled elastically by applying SPH also for elastic bodies. Therefore, the chip can deform in contrast to previous investigations in which the chips were modeled as rigid DEM bodies. The properties for the solid SPH body are given in Table I. The model setup is shown in Figure 3. The elastic first chip is colored red for increased contrast. All following chips are colored white and are introduced from the drill tip. They are on a fixed trajectory while entering and are released once they are completely within the borehole. Furthermore, the following chips are modeled as rigid to reduce the simulation time.

Figure 4 shows the fluid flowing into the chip flute. The fluid flow starts at the beginning of the simulation when the borehole is assumed to be empty. Starting at the time point $t = 0.14\,\mathrm{ms}$, the chip has been caught by the fluid and is accelerated. Figure 5 shows the overlay of the chip form relative to its center of gravity with a low opacity allowing us to visualize the actual deformation of the chip along its transport in the chip flute for the time points $t = \{0.1, 0.14, 0.18, 0.22, 0.26, 0.3\}\,\mathrm{ms}$ and its main acceleration between $t = 0.14\,\mathrm{ms}$ and $t = 0.16\,\mathrm{ms}$.

It can be seen that the chip forms overlay well, showing that no significant deformation occurs during the chip's acceleration. This shows that the assumption of a rigid chip is a

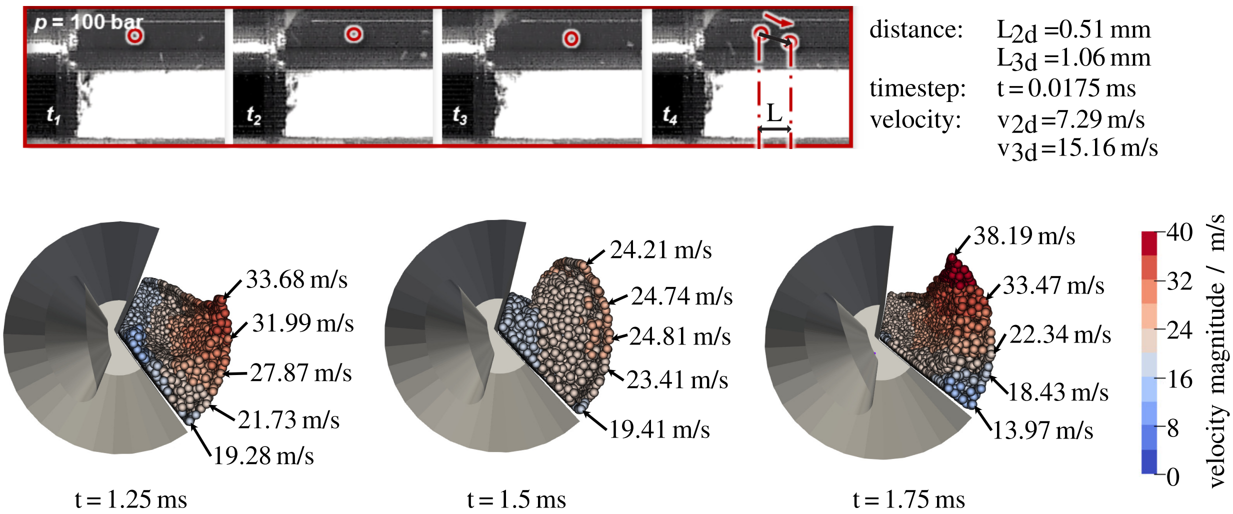

Fig. 2. Fluid velocity in the chip flute at different time points shown for SPH in the bottom row and the tracking of a tracer particle with the Particle-Image Velocimetry in the upper row for comparison. The experimental results are from [7].

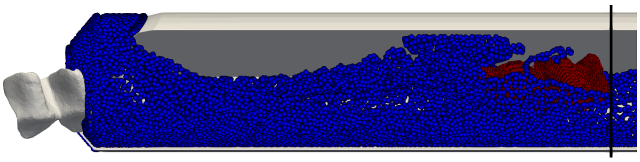

Fig. 3. Model setup with the artificial barrier on the right side, blocking the chips but allowing the fluid to pass. The fluid is colored blue, and the elastic chip in red for increased contrast.

good choice for the analysis of the fluid distribution and chip evacuation as it was already done in previous investigations.

Once the chip hits the barrier, it is repelled. The overlay of the chip form after impact is shown in Figure 5 for a short time range of 0.016 ms. It can be seen that the chip's deformation oscillates with a high frequency. In general, this deformation of the chip on impact and the possible deformation by the following liquid is only possible due to the elastic modeling of the chip. However, the high-frequency deformation decreases the step size when using an adaptive step size control.

This high-frequency response can be expected after the force excitation by the impact but is not of interest in this investigation. The focus is placed here on the actual low-frequency deformation of the chip instead.

Figure 6 shows the fluid density after the chip has hit the barrier. Although the chip blocks the outlet partially, which causes the fluid to flow back in the direction of the drill head, the fluid can still pass the chip. The density and fluid pressure rise when the borehole is completely filled, e.g., around $t = 0.8ms$. Moreover, the fluid density rises significantly when the second chip collides with the first chip and further blocks the outlet. Afterwards, the second chip and the fluid's force cause the elastic chip's deformation.

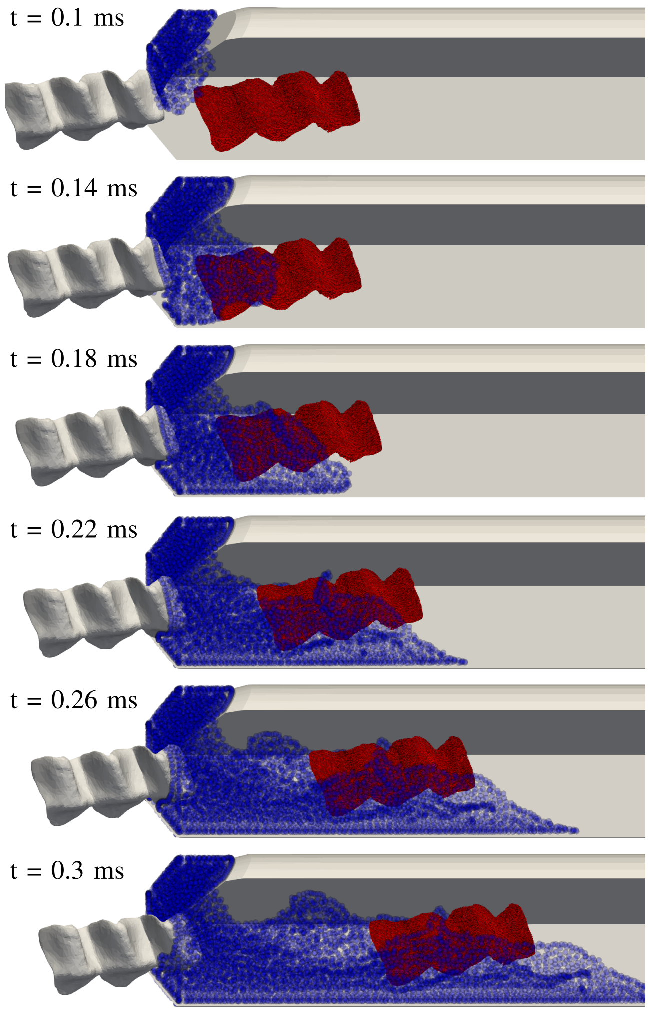

Fig. 4. Fluid flow into the empty chip flute and acceleration of the chip over time.

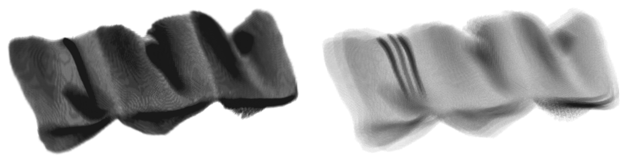

Fig. 5. Left: Overlay of the chip form during its acceleration and transport in the chip flute for the time points $t = \{0.1, 0.14, 0.18, 0.22, 0.26, 0.3\}$ ms and its main acceleration between $t = 0.14$ ms and $t = 0.16$ ms. Right: Overlay of the chip form after its impact into the artificial barrier for $t = \{0.426, 0.43, 0.434, 0.438, 0.442\}$ ms.

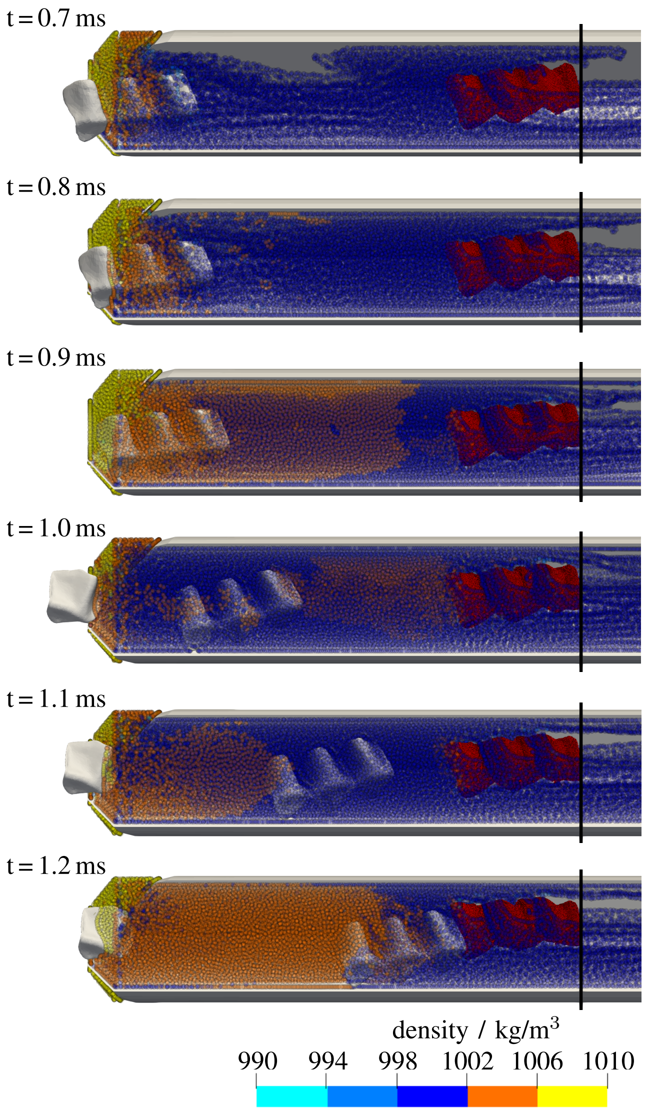

Fig. 6. Fluid density over time for semi-permeable blocked chip flute and deformation of elastic chip. The fluid is coloured transparent to increase the visibility of the chips.

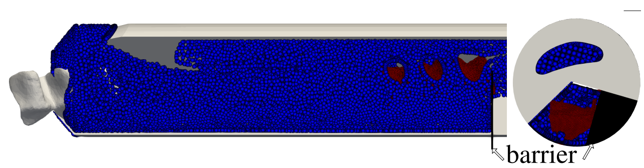

Fig. 7. Model setup with the artificial barrier in the chip flute, blocking the chips and the fluid, side view on the left, view on the drill tip on the right side.

B. Fluid flow for a partially blocked chip flute

The second simulation model contains a partial barrier in the chip flute, which is non-permeable for both chips and fluid in contrast to the previous setup. Figure 7 shows the setup with the flexible chip colored red, the fluid blue and other chips in white. The blockage is colored black and partially laps into the chip flute, as seen on the figure's right.

Figure 8 shows fluid distribution over time for the fluid flowing into the empty borehole, hitting the elastic chip placed in the chip flute, and dragging it along. The fluid flow hits the artificial barrier first around 0.35 ms after the simulation start, and the chip hits around 0.5 ms. Furthermore, the chip diverts the fluid flow and it even starts to flow back in the direction of the drill head as the chip hits the barrier and blocks the outflow further.

As can be seen, the partial blockage leads to an increase in the fluid density resulting in a rise in fluid pressure. Although water is nearly incompressible, this increase in density is due to the weakly-compressible SPH formulation, as described earlier. In contrast to the previous setup, the rise in density and pressure starts before the second chip is entirely within the borehole and reaches higher levels. However, the increase in density and respectively in pressure is not enough to deform the elastic chip significantly and press it through the gap next to the artificial barrier. This is achieved by the following (rigid) chip, which collides with the first chip at around 1.3 ms after the simulation starts and causes the chip to bend around the barrier and, consequently, later through the gap.

IV. Conclusion

In this paper, we showed the recent progress and first insights in modeling chip jamming in the deep-hole drilling process. Chip jamming is a significant problem when chips wrap around the tool, leading to marks on the borehole wall and an increased drilling torque causing sudden tool failure. Therefore, former models used to model the fluid distribution and chip evacuation in deep-hole drilling were extended to artificially block the chip evacuation. This was archived by introducing two artificial barriers in the chip flute, thereby modeling a chip stuck between the drills shaft and the borehole wall.

Two different setups are analyzed. For the first, a semi-permeable barrier in the chip flute blocks the chips from their evacuation but allows the fluid to pass. This was changed to a total blockage, which leaves a gap in the chip flute but blocks chips and fluid for the second setup.

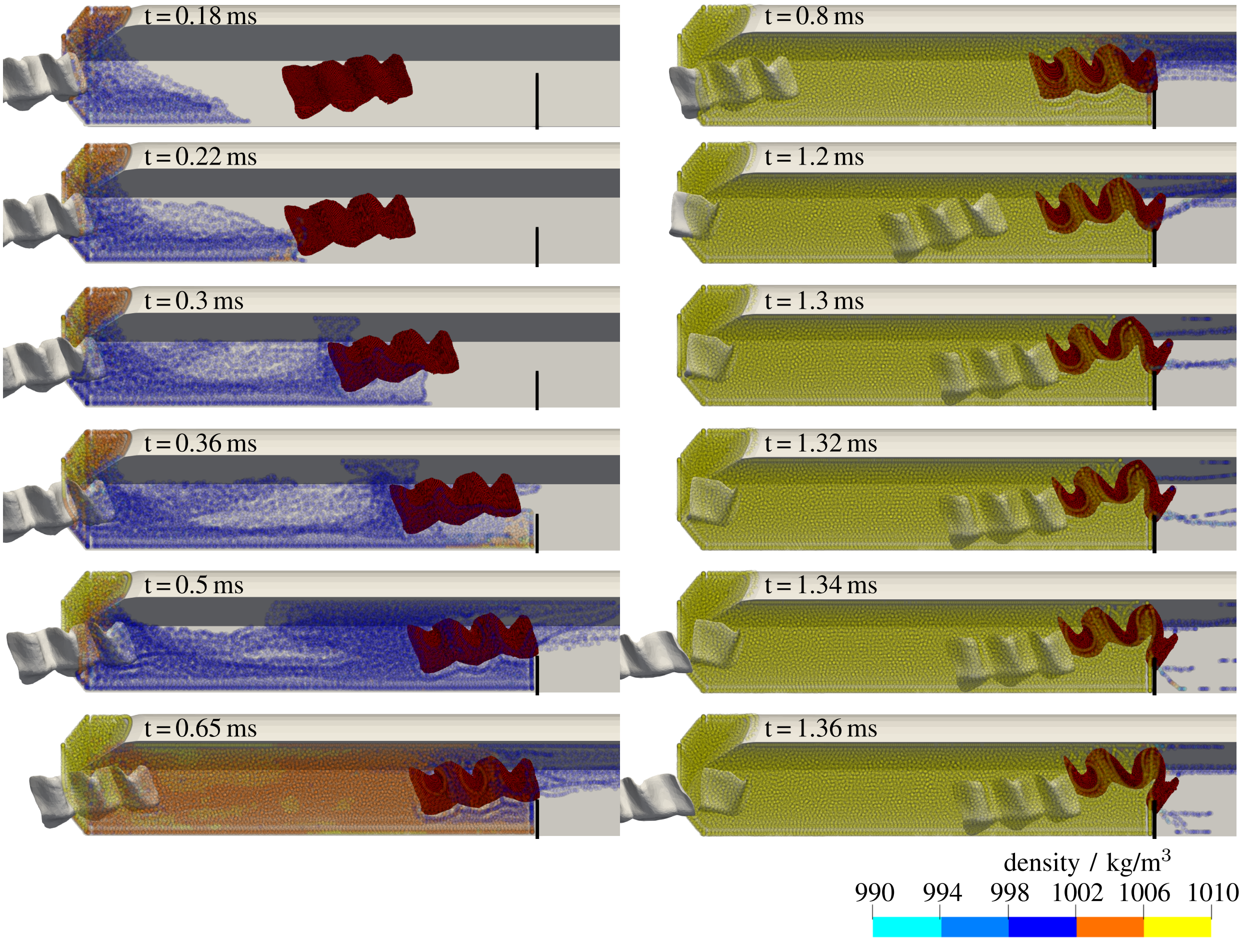

Fig. 8. Fluid density over time for partially blocked chip flute and deformation of the elastic chip. The fluid is colored transparent to increase the visibility of the chips.

The elastic chip was modeled using SPH for elastic bodies to allow its deformation. The chip form analysis showed that no deformation occurs during the acceleration by the fluid flow. Therefore, the assumption of rigid chips is sufficient for the sole investigation of their evacuation and the fluid distribution as done in earlier investigations of the authors, i.e., [7].

However, an oscillating high-frequency deformation occurs as the elastic chip hits the barrier. This is not of interest for further investigations as only the actual deformation of the chip is of interest. Furthermore, the high-frequency oscillation leads to a decrease in the simulation step size due to the high velocity of the solid particles. Thus, future work should neglect the high-frequency oscillation by applying modal model-order reduction techniques on a finite-element-based approximation of elastic bodies [2].

Additionally, first insights about the fluid flow during the starting of a chip jamming were shown. The fluid flows back to the tool head after the chip blocks the outlet until the initially empty borehole is filled. This leads to an increase in the fluid pressure in the outlet. However, this rising pressure is not enough for chip to pass through the gap between the drill and the artificial barrier. The following chip collides with the jammed chip, causing the elastic chip's significant deformation, and forces it afterwards through the gap. Further model improvement is required in this aspect as the increasing density exceeds the assumptions applied by the weakly-compressible SPH formulation.

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