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# A Computational Fluid Dynamics Approach for Chip Evacuation Optimization in Deep Hole Drilling

K.S. Woon[1], G.L. Tnay[2]

[1]Department of Mechanical Engineering, National University of Singapore, 10 Kent Ridge Crescent, Singapore 119260.
[2]Machining Technology, Singapore Institute of Manufacturing Technology, 71 Nanyang Drive, Singapore 638075.

mpewks@nus.edu.sg

**Abstract**
Effective chip evacuation is critical in deep hole drilling. This is especially true when Ni-based superalloys with high temperature strength is involved where drills are failed catastrophically when the chips are not effectively evacuated. To prevent such costly failures, special drilling fluids is usually applied at high pressure in order to improve the effectiveness to evacuate chips. But the level of success varies greatly without a clear understanding of the chip transport characteristics at the narrow cutting zone. This paper presents a computational fluid dynamics (CFD) model to simulate the motion of such chips in drilling fluids. Firstly, hydrodynamic drag acting on the chips is numerically computed as force and torque to determine the lateral displacement and rotation of the chips. Secondly, as chips collide against the walls along evacuation channel, the respective rebounding motion is estimated with a set of restitution coefficients determined empirically with high speed videography. Finally, the chip trajectory and its transport behaviour under a particular operating condition can be realistically simulated. In this paper, the capabilities of this novel CFD model is demonstrated through a case study on the shoulder dub-off of deep hole drills - a key geometry that governs the effectiveness of chip evacuation. With the study of a wide range of design variations, it was discovered that the generous reliefs of the shoulder dub-off on most commercial drills have a high tendency in trapping chips at the cutting zone, despite registering higher volumetric flow of coolant on to the cutting zone. These observations were substantiated with an extensive set of drilling experiments, in which case it was also found that the tool life of deep hole drills corresponds with the effectiveness of chip evacuation. Lastly, an optimization solution is provided.

Chip evacuation, Shoulder dub-off angle, Deep hole drilling

## 1. Introduction

In deep hole drilling, evacuation of chips helps to prevent thermal-mechanical fatigue drill failures from intense building up of cutting temperature and accelerated increase in axial drilling force [1]. To ensure chip evacuation effectiveness, researchers developed instrumentation to monitor chip motions. For example, an optical sensor system was used to detect chip lengths and velocities on the outside of the hole [2]. But methodology of this kind is unable to provide sufficient insights on chip transport at the cutting zone, which is technically important to improve the evacuation mechanism. More useful experimental techniques involve the use of high speed camera to capture the chip formation mechanism as well as the subsequent chip transport mechanism within transparent tubes [3]. However, as both mechanisms are highly sensitive to test conditions and parameters, in-depth and exhaustive investigations are costly and time consuming. In this paper, we present a relatively cost effective method based on computational fluid dynamics (CFD) analyses.

## 2. Methodology

Our CFD model is developed in the ANSYS CFX 15.0 using the finite volume method and the Menter's shear stress transport turbulence model. Three critical steps are required to simulate chip motion in coolant: (i) calculation of drag force and torque acting on the chip from the ANSYS CFX post analysis; (ii) determination of consequential translational and angular motions and; (iii) computations of the coefficients of restitution to determine chip motion after collision along the passage.

### *2.1. CFD Setup*

Firstly, typical gun drill and gundrilling chip geometric models are imported into ANSYS and prescribed as stationary solids. The fluid domain in grey is extracted from the workpiece, chip and gun drill as shown in Figure 1. The inlet and outlet coolant channels as shown in blue are defined as velocity and pressure boundaries with prescribed conditions. The outlet pressure is set to the ambient pressure of 1 bar and the inlet pressure at 40 bar. To generate the meshing of gundrilling chips, unstructured tetrahedral elements that are able to accommodate highly irregular shapes are implemented. Lastly, inflation layers on the chip surface are also used to improve the accuracies of the flow boundaries.

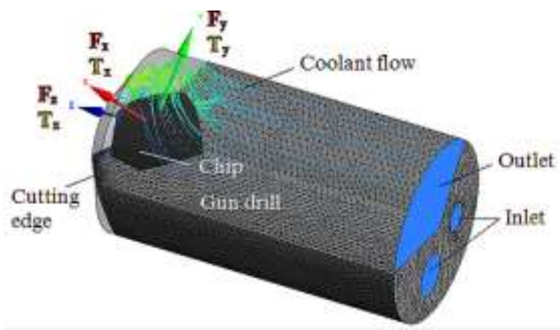


**Figure 1.** Model setup for force and torque computations.

### 2.2. Rebounding model

When chips collide along the transport passage, the rebounding motions are computed as: $(v_n)_2 = e_n.(v_n)_1$ and $(v_t)_2 = e_t.(v_t)_1$ the normal $v_n$ and tangential $v_t$ velocity components respectively, where $e_n$ and $e_t$ are the normal and tangential coefficients of restitution. The magnitudes of $e_n$ and $e_t$ are derived through actual drilling experiments using high speed photography. Cylindrical Inconel-718 workpieces of 8 mm in diameter are housed in transparent tubes prior to the drillings. Feed rate and cutting speed are set at 5 mm/min and 20 m/min. Coolants with 12%wt oil concentration and 40 bar coolant pressure are applied. Chip transport motion is captured with the Photron Fastcam SA5 high speed camera at a frame rate of 6000 fps. Figure 2 shows the transport of a chip while colliding on the walls of the passage during evacuation.

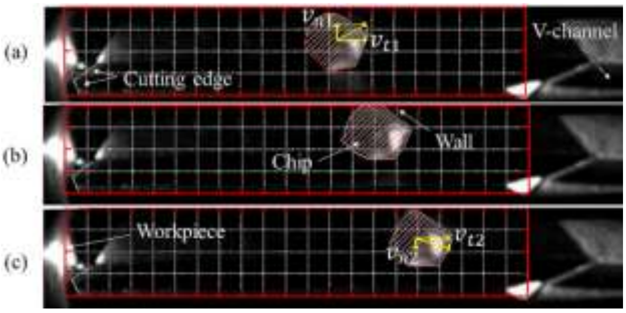


**Figure 2.** Chip motion captured with high speed photography. (a) Before; (b) During; and (c) After colliding on the passage [4].

### 3. Effects of dub-off angle on chip evacuation

Drilling experiments are performed on the DMU 80p duoBLOCK® five axis machine, using 4 different shoulder dub-off angles ranging from 0˚, 5°, 10° to 20˚ as shown in Figure 3. The Inconel-718 workpieces carry a mean yield strength of 1058 MPa. The drills have uniform cutting angles: outer edge angle of 30˚ and inner edge angle of 20˚ with the two-hole coolant configuration design. Constant cutting and coolant parameters in Sec. 2.2 are used.

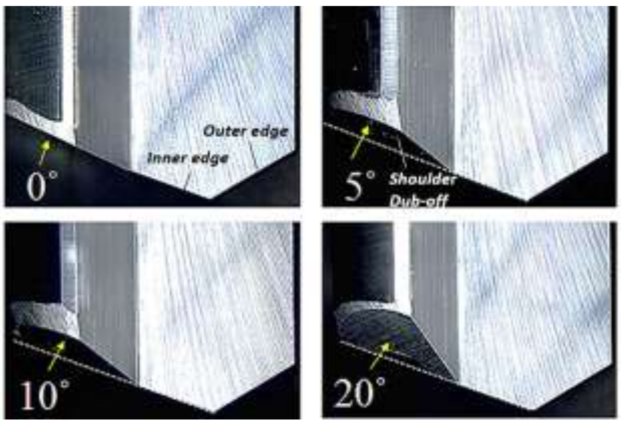


**Figure 3.** Evaluation of shoulder dub-off angles on chip evacuations.

Upon completion of drilling, flank wear developed on the commercial dub-off angle of 20˚ and modified dub-off angles 0˚, 5˚ and 10˚ are compared. The maximum flank wear $VB_{max}$ is measured at every 10 mm of drilling depth using the Keyence Digital Microscope VH-1000 and the maximum crater wear *Kt* is measured at the end of the drilling cycle using the Alicona optical 3D non-contact metrology system. From Figure 4, it is obvious that the reduction in shoulder dub-off angle helps to increase the tool life in deep hole gundrilling for Inconel-718.

This is mainly because coolant flow can be guided more accurately to the cutting edges using minor shoulder dub-off angles. With the improvement of coolant delivery, the effectiveness of chip evacuation increases progressively with the reduction of shoulder dub-off angle. On the contrary, increasing the shoulder dub-off angle up to 30° can cause flow stagnation zone near the cutting edge as shown in Figure 5.

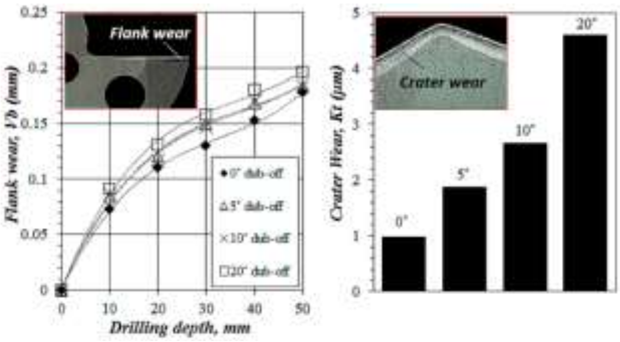


**Figure 4.** Tool life validation for various shoulder dub-off angles. (a) Flank wear; and (b) Crater wear.

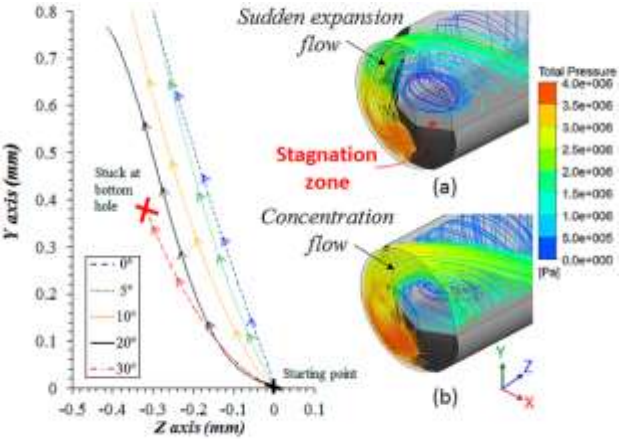


**Figure 5.** Chip evacuation trajectories for different shoulder dub-off angle. (a) Commercial dub-off angle, (b) Optimum dub-off angle [4].

### 4. Conclusions

Based on the CFD analyses and experimental results, the following conclusions are drawn:

i) Commercial shoulder dub-off angle design has high tendency to trap chips being at the bottom of deep holes.
ii) By reducing the shoulder dub-off angle, coolant can be delivered to the cutting edges for improved chip evacuation.
iii) Drills with 0˚ shoulder dub-off angle yields the best tool life performance in drilling Inconel-718.

#### References

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