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The effects of dub-off angle on chip evacuation in single-lip deep hole gun drilling

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Abstract

Without proper chip evacuation, gun drills will fail under intense thermal and mechanical loading during deep hole drilling of high temperature superalloys like Inconel 718. In gundrilling, the efficiency in evacuating chips is governed by the geometry of gun drills that defines the hydraulic boundary conditions for coolant and chip flow. In this paper, we propose a novel computational fluid dynamics (CFD) model that is capable to simulate and quantify the chip transportation behavior under high pressure coolant for drill geometry optimization. This is demonstrated through a case study on improving the shoulder dub-off design of commercial gun drills, which have a high tendency in trapping chips at the hole bottom. A more effective design criterion for shoulder dub-off is thus proposed.

Keywords: deep hole gundrilling; chip evacuation; dub-off angle; computational fluid dynamics; chip trajectories

1. Introduction

Gundrilling is a machining process to produce deep holes with length to diameter ratios greater than 10. The hole diameter range from 1 to 40 mm are usually constructed by gun drills with a single lip design, consists of an outer and inner cutting edges located asymmetrically over the drill diameter. Material removal achieved by the cutting edges will be breaking into smaller segments known as chips and evacuated by the high pressure coolant. As illustrated in Figure 1, high pressure coolant is supplied through internal conduits of the drill bit to the bottom of the hole, which will subsequently diverts rapidly towards the shoulder dub-off to facilitate the breaking of the chips and carry them out of the cutting zone through the v-channel flute.

Figure 1. High pressure coolant application in deep hole drilling using single-lip gun drill

Chip evacuation has a direct impact on wear rate, failure mode and life span of gun drills [1]. Chips that are not effectively evacuated will inhibit the cooling of cutting edges where heat is generated by continuous chip flow through friction. While, lubrication on the bearing surfaces will be detrimentally affected without adequate exposure of the chip formation zone - leading to excessive burnishing against the hole. As a result, the overall cutting performance will deteriorate with the drastic increase in torsional load and followed by rapid development of drill degradation [2]. To improve chip evacuation through drill design and process parameter, the understanding of chip transportation behavior is critical. Osman and Chahil [3] investigated the effects of the interface in between the drill tip and v-channel flute with an open hydraulic circuit. Three types of coolant hole configurations namely single-hole, two-hole and kidney-shaped were studied. The results showed that the two-hole design gave the best performance due to minimum hydraulic pressure loss as compared to other designs. Following that, Astakhov et al. [4]

developed a close circuit apparatus that was capable to measure coolant pressure at the bottom of the hole. It was discovered that pressure distribution around the drill tip is strongly influenced by the bottom hole geometries. As the shape bottom hole is defined by the designs of the drills, the authors concluded that the respective chip transportation behavior is also directly governed by the various drill designs. In a more detailed study, Astakhov et al. [5] focused their investigation on the effects of shoulder dub-off ranging from -9° to $+20^\circ$ as shown in Figure 2. It was reported that the lost in coolant pressure can be improved by increasing the dub-off angle to $+20^\circ$. Although the results were sound, the actual increase in chip evacuation efficiency was not known since all the experiments were conducted without chips.

Figure 2: Study of the effects of shoulder dub-off on coolant flow behavior. (a) Components overview of a single-lip gun drill; and (b) Varying dub-off angle from -9° to $+20^\circ$

Realizing the constraints of experimental techniques from the literature, the present study is focused on the development of a realistic computational fluid dynamics (CFD) model to study chip flow trajectory of chips in gundrilling. Our goal was aimed to establish qualitative

understanding of the effects of drill geometries through CFD simulations, which enables the improvement of chip evacuation efficiency through drill geometric optimization. In this paper, such capabilities are demonstrated with a focused case study on shoulder deb-off design for its significant influence on coolant flow in the vicinity of the cutting zone, as motivated by its significance in previous studies [4, 5].

2. Methodology

To simulate chip flow trajectory, the force and torque acting on the chips in high pressure coolant are computed based on the control volume method [6]. During the setup, a typical gun drill chip and gun drill bit are imported into ANSYS CFX 14.0 and prescribed as stationary solids. The flow domain is then extracted from the hole, gun drill and chip and subsequently meshed by the CFX solver. In order to accurately capture the boundary layer region, face sizing with 0.1mm element size and five inflation layers on the chip surfaces are introduced. Following that, boundary conditions of pressure at the inlet and outlet of the domain are defined, as shown in Figure 3. No slip wall boundary conditions were applied to the flow domain and drill surfaces.

Figure 3. Meshing of chip, gun drill bit, boundary and inflation layers

After the force and torque values are computed, the lateral displacement and rotation of the chip are then determined from the equations of motion:

$$\sum F = ma = m \frac{dv}{dt}; \quad \frac{dx}{dt} = v \quad (1)$$

where, F is the net force, m is the mass of the body, a is the acceleration of the chip, $\frac{dv}{dt}$ is the derivative of velocity with respect to the each time step, v is the velocity of the chip, and $\frac{dx}{dt}$ is the derivative of displacement with respect to the each time step.

Equation (1) can also be expressed in three axes of components as follows:

$$\sum T_{x'} = I_{x'} \frac{d\omega_{x'}}{dt} - \omega_{y'} \omega_{z'} (I_{y'} - I_{z'}) \quad (2-1)$$

$$\sum T_{y'} = I_{y'} \frac{d\omega_{y'}}{dt} - \omega_{z'} \omega_{x'} (I_{z'} - I_{x'}) \quad (2-2)$$

$$\sum T_{z'} = I_{z'} \frac{d\omega_{z'}}{dt} - \omega_{x'} \omega_{y'} (I_{x'} - I_{y'}) \quad (2-3)$$

where, $T_{x'}, T_{y'}, T_{z'}$ are the torques acting on the particle, $I_{x'}, I_{y'}, I_{z'}$ are the principal moments of inertia, $\omega_{x'}, \omega_{y'}, \omega_{z'}$ are the angular velocities, and $\frac{d\omega_{x'}}{dt}, \frac{d\omega_{y'}}{dt}, \frac{d\omega_{z'}}{dt}$ are the derivative of the angular velocities with respect to the each time step. All the values are acting around the principal axes. The new position and orientation of the chip are then updated. With that, a new cycle of force and torque computation is invoked to determine the next position and orientation of the chip. A three-step sample is shown in Figure 4.

Figure 4. Chip motion determination through CFD simulations. (i) Computation of initial force and torque at $t=0$ ms; (ii) Determination of linear-angular motions with an update of force and torque computation at $t=1$ ms; and (iii) Repetitions of (i) and (ii) to determine new motion at $t=2$ ms

When the chip comes into contact with the wall (Figure 5), the re-bound velocities are calculated from the coefficients of restitution:

$$e_t = \frac{(v_t)_2}{(v_t)_1} \quad (3)$$

$$e_n = \frac{(v_n)_2}{(v_n)_1} \quad (4)$$

where e_t and e_n are the tangential and normal coefficients of restitution while v_t and v_n are tangential and normal components of the velocity vector.

The coefficient of restitution, e , is defined as the ratio of velocity after and before impact. A perfect elastic collision will give e equals to 1 but if the chip stops after a collision then e is equal to 0. The values of the coefficient of restitution are obtained via calibration against experimental data is explained in the section 3. The overall procedure is summarized in Figure 6.

Figure 5. Chip motion before and after wall collision

Figure 6. Computational procedure for chip flow trajectory

3. Model Calibration

To improve the accuracy of the CFD model, it is calibrated with actual drilling experiments using commercial gun drills mainly to determine the coefficient of restitution. Fuchs Ecocool 701 with 12 % wt oil was applied at 40 bar while drilling speed and feed rate are set at 800 rpm and 8 mm/min respectively. All the experiments are conducted on the DMU 80p duoBLOCK as shown in Figure 7. Inconel 718 rods with 8 mm diameter are housed in transparent acrylic tubes and mounted on the machine with a vice clamp. 8 mm gun drills are

then brought into the acrylic tubes from the other side to perform drilling at the aforementioned conditions. After several chips, like the one in Figure 8 are generated, the process is stopped the spindle and the coolant is applied to flush the chips from the cutting zone. The flow motion of the chips is captured with a Photron Fastcam SA5 at a frame rate of 6000 fps. A sample that illustrates collision of the chip against the wall during its evacuation by the flushing coolant is shown in Figure 9. Each frame has an interval of 1 ms. The speed and directional change of the chip before and after collision are derived from the high speed photography and the findings are used to compute the coefficients of restitution. With more than 8 drilling cycles, the tangential e_t and normal e_n coefficients of restitution are approximated to 0.92 to 0.98 and 0.47 to 0.52 using with Eq. 3 and 4 respectively.

Figure 7. Experimental setup for model calibration. (a) High speed camera setup; and (b) Inconel rod housed in transparent acrylic tube

Figure 8. A typical Inconel chip generated from single-lip gun drill.

Figure 9. Chip motion involving wall collision captured with high speed photography. (a) Before collision; (b) During collision; and (c) After collision

4. Results and Discussions

Figure 10 depicts the trajectory of a gun drill chip. As soon as the chip breaks away from the cutting edges (Figure 10a), it is carried by the coolant towards the wall of the hole (Figure 10b), resulted in the first collision (Figure 10c). The chip is then rebounded from the wall (Figure

10d) and collides against the wall of the gun drill (Figure 10e), after which it is successfully evacuated (Figure 10f). The aforementioned is plotted in Figure 11. The results produced from the CFD model appeared to be in reasonably good agreement with the experiments.

Figure 10. Comparisons of chip transportation behavior between actual flow experiments and CFD simulations

Figure 11. Chip flow trajectory at a shoulder dub-off angle of 20°

Although shoulder dub-off on gun drills has significant influence on chip transportation behavior, most commercial gun drills adhere to a fixed design of 20° that has limited scientific basis. To determine the effects of shoulder dub-off on chip evacuation, 5 different angles ranging from 0° to 30° as shown in Figure 12 was studied with the developed CFD model. As the value of dub-off angle increases, the chip would travel deeper towards the bottom of the hole (Figure 13). Hence, this would heighten the risks of the chip being stuck at the bottom. This happens due to the severity of the sudden expansion of the flow at greater dub-off angles, resulted in greater pressure losses and larger regions of flow separation when the dub-off angle is greater than 10° , vacuum pressures begin to appear, and with such a pressure difference between front and rear surfaces of the chip, the tendency is for the chip evacuation gets blocked on bottom of the hole increased (Figure 14). From the velocity streamline view (Figure 15) and pressure contour view (Figure 16), the flow can be guided properly at the cutting edge with 0° dub-off angle. Whereas, at 30° dub-off angle, the flow is deflected away from the cutting edge and leading to the generation of vortices in the vicinity of cutting edge. This finding suggests that shoulder dub-off

between 0° to 10° can facilitate chip evacuation much more effectively than the conventional 20° .

Figure 12: N8 single-lip gun drill nose grind design with five different deburr angles.

Figure 13: Chip evacuation performance comparisons for five ranges of shoulder dub-off

Figure 14. Pressure distribution at five ranges of shoulder dub-off

(a)

(b)

Figure 15. Coolant flow behavior at the drill tip for (a) 0° dub-off angle; and (b) 30° dub-off angle

(a)

(b)

Figure 16. Pressure distribution at the drill tip for (a) 0° dub-off angle; and (b) 30° dub-off angle

5. Conclusions

In this study, an experimentally calibrated computational fluids dynamic model to quantify the linear and rotational flow motion of gun drill chips under high pressure coolant has been developed. With such capabilities, transportation behavior of the chip from the cutting zone can be simulated and thus enable a realistic evaluation of chip evacuation efficiency of a gun drilling process, which is largely governed by the design of gun drills. Based on this study on the effects of dub-off angles, the following conclusions are drawn:

- The greater the deb-off angle is, the greater the tendency for the chip being trapped on the bottom of the hole. This happens due to the severity of the sudden expansion of the flow at greater deb-off angles, resulted in greater pressure loss and larger regions of flow separation.
- With conventional 20° or larger, vacuum pressure (suction) begins to form at the bottom of a drilled hole. With such a pressure difference between front and rear surfaces of the chip, would cause chips to get stuck to the bottom of the hole.
- With deb-off angles ranging from 0° to 10°, the coolant flow can be guided properly at the cutting edge and resulting lesser pressure loss. Therefore, small shoulder deb-offs can facilitate chip evacuation much more effectively.

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References

- [1] K.S.Woon, S.Wan and G.L.Tnay, "An Experimental and Simulation Study on Deep Hole Gun drilling of Inconel-718," in *Proceedings of the 13th euspen International Conference*, Berlin, 2013.
- [2] J.Jung and J.Ni, "Prediction of Coolant Pressure and Volume Flow Rate in the Gun drilling Process," *Journal of Manufacturing Science and Engineering*, vol. 125, p. 696, 2003.
- [3] M.O.M.Osman and G.S.Chahil, "A Theoretical and Experimental Investigation of Coolant Flow in Gun drilling," *Int.J. Mach. Tools Manufact.*, vol. 19, pp. 143-155, 1979.
- [4] V.P.Astakhov, V.V.Galitsky and M.O.M.Osman, "A Novel Approach to the Design of Self-Piloting Drills with External Chip Removal, Part 2: Bottom Clearance Topology and Experimental Results," *Journal of Engineering for Industry*, vol. 117, p. 464, 1995.

- [5] V.P.Astakhov, J.Frazao and M.O.M.Osman., "On the Experimental Optimization of Tool Geometry for Uniform Pressure Distribution in Single Edge Gundeilling," *Journal of Engineering for Industry*, vol. 116, p. 449, November 1994.
- [6] S. V. Patankar, Numerical Heat Transfer and Fluid Flow, Hemisphere Publishing Corporation, 1980.