Improving Coolant Effectiveness through Drill Design Optimization in Gundrilling

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Abstract. Effective coolant application is essential to prevent thermo-mechanical failures of gun drills. This paper presents a novel study that enhances coolant effectiveness in evacuating chips from the cutting zone using a computational fluid dynamic (CFD) method. Drag coefficients and transport behaviour over a wide range of Reynolds numbers were first established through a series of vertical drop tests. With these, a CFD model was then developed and calibrated with a set of horizontal drilling tests. Using this CFD model, critical drill geometries that lead to poor chip evacuation including the nose grind contour, coolant hole configuration and shoulder dub-off angle in commercial gun drills are identified. From this study, a new design that consists a 20° inner edge, 15° outer edge, 0° shoulder dub-off and kidney-shaped coolant channel is proposed and experimentally proven to be more superior than all other commercial designs.

1. Introduction

Gundrilling is an invaluable deep hole drilling technology to produce aerospace components made of exotic materials like Inconel and titanium alloys. Successful implementation of gundrilling relies on effective coolant application, especially in evacuating chips from the cutting zone. With continuous production of chips from the process, failure to evacuate chips effectively leads to chip packing, recutting of chips, build-up of intense heat and increase in cutting force. Ultimately, the drills will fail [1] and the parts will be damaged - resulted in costly material scrap and down time. Such issue calls for a total chip control system [2] where effective chip evacuation begins with adequate chip breaking.

Simple techniques like peck drilling [3] have long been a popular choice while coupling vibration to gundrilling [4] is also recently attempted. Nevertheless, the abruptness nature of pecking has adverse impacts on tool life especially when difficult materials are involved. Vibration-assisted drilling requires rigid carbide drills to transfer vibration energy effectively, which makes it impossible for depths of drilling beyond 1 meter.

To avoid auxiliary processes, high-pressure delivery of coolant through drill shafts is still a standard practice. Be it oil-based or water-based, an ideal coolant evacuates chips from the drill path while lubricates bearing surfaces and cools cutting edges. Essentially, these abilities are derived from optimum concentration of the base medium special additives, in view of the Rehbinder effect, surface energy and Marangoni effect [5]; as well as the flow behaviour and rheological properties governed by drill designs. Initial attempt to understand the latter began with the study of flow energy loss with a closed pressurized hydraulic circuit [6]. Later, a new concept known as ‘hydraulic diameter’ was introduced to predict friction loss in drill shanks. Further losses at the bottom hole clearance due to
flow interaction and hydraulic resistance [7] were detected from pressure measurement. An analytical method was then proposed to improve drill design for better chip evacuation and tool life [8]. Nevertheless, previous studies based on pressure measurement have several drawbacks. Firstly, unavailability of miniature gauges limited most investigations to big drills. Secondly, construction of pressure conduits and mounts artificially alters the coolant flow and chip transport behaviour. Thirdly, measuring pressure discretely on the drill describes scalar quantities of the coolant flow but not its rheological characteristics in vector. These, perhaps, explain the limited success in tackling more extreme deep-hole applications of this era [9] with existing knowledge in gundrilling.

In this paper, a novel CFD model that reveals the actual behaviour of coolant flow and chip transport is presented. The governing geometries of a gun drill including the nose grind contour, coolant hole configuration and shoulder dub-off angle were subjected to fluid flow, mass transfer and heat exchange analyses. All findings were validated with drilling experiments.

2. Methodology

Three distinct stages are involved in developing the model: (i) Determine drag coefficient of gundrilling chips with vertical drop test; (ii) Set up CFD model and simulate the drop tests for comparison; (iii) Calibrate chip motion with drilling experiments.

2.1. Empirical drag coefficient

Chip transport behaviour is governed by a dimensionless parameter known as drag coefficient \( C_D \), which measures resistance of chips within a particular coolant. To quantify \( C_D \) of gundrilling chips comprehensively in water-miscible coolants, a series of drop tests was conducted with Fuchs Ecocool 701 (5%-85%) using a 0.1m×0.1m×1.0m transparent tube. The corresponding dynamic viscosity \( \mu_f \) was measured with the Anton Paar MCR301 rheometer.

Coolants were filled and rested in the tube until no air bubble was visible, before the drop of a gundrilling chip was made. Travel distance and time duration for the chips to reach zero acceleration were recorded with the Photron Fastcam SA5 to compute terminal velocity \( U_t \). This occurs when the weight of the chip \( F_g \) equals the drag force \( F_d \). Hence, the net force \( F_g-F_d \) acting on the chip is zero. With \( V_{tor} \), the particle Reynolds number \( Re_p \) and drag coefficient \( C_D \) are determined as follows:

\[
Re_p = \frac{d_{sph} u_t \rho_c}{\mu_f}
\]

\[
C_D = \frac{4 g d_{sph} (\rho_c - \rho_f)}{3 \rho_f u_t^2}
\]

where \( d_{sph} = 2 \left( \frac{3V_c}{4\pi} \right)^{\frac{1}{3}} \) is the equivalent spherical diameter of the chip [10], \( V_c \) is chip volume; \( A_c \) is chip surface area; \( u_t \) is chip terminal velocity; \( g \) is gravity acceleration; \( \rho_c \) is chip density; \( \rho_f \) is coolant density; and \( \mu_f \) is coolant dynamic viscosity.

Each condition was repeated for three times with different chip samples. The resultant \( Re_p \) and \( C_D \) for water-miscible coolants 5%-85% in concentration are 0.06-36.1 and 28.9-2150.

2.2. CFD model development

Next, the CFD model was developed based on finite volume method and shear stress transport turbulence model in order to handle vortexes in compressible water-miscible coolant at high pressure [11]. Gundrilling chips were reproduced in the flow domain as static solids; and together with the physical properties of the coolants were input into ANSYS Workbench 14.0. Complex shape of the chips was meshed with 0.01mm tetrahedral elements, contained within the flow domain with hexahedral meshing. Five prismatic layers were included to capture the boundary flow. Refer to Fig. 1 for the model setup.
To simulate the drop test, the boundary condition of the flow outlet was set to 1 atm. boundary condition of flow outlet inflow velocity was varied for water-miscible coolants while the outlet. The drag force $F_d$ and net force $F_g - F_d$ can be derived from the CFD model. When $F_g - F_d$ for a particular coolant variant was reduced to zero, the corresponding $V_{wp}$ was determined and thus, the $Re_p$ and $C_D$ can be computed respectively. Fig. 2 shows the simulated and experimental results.

![Figure 1. Setup of the base CFD model for deep hole gundrilling.](image1)

**Figure 1.** Setup of the base CFD model for deep hole gundrilling.

![Figure 2. Drag coefficients of gundrilling chips for water-miscible coolants 5%-85% concentration.](image2)

**Figure 2.** Drag coefficients of gundrilling chips for water-miscible coolants 5%-85% concentration.

2.3. Chip motion calibration
As chips are flushed from the drill point, the general motion of chip flow across water-miscible coolant is governed by the conservation law of momentum [12]. In differential form, the translational and angular motions are expressed as:

\[
\frac{dx}{dt} = u_i; \quad m_c \frac{du_i}{dt} = \sum F_i
\]

\[
\frac{d\theta}{dt} = \omega_i; \quad I_c \frac{d\omega_i}{dt} = \sum T_i
\]

where \( x \) is the position vector, \( u_i \) is the initial chip translational velocity, \( m_c \) is the chip mass, \( F \) is the total force acting on the chip, \( \theta \) is the angle of rotation, \( \omega_i \) is the initial chip angular velocity, \( I_c \) is moment of inertia and \( T \) is the total torque acting on the chip.

Transporting from a blind hole, chips collide and rebound on the hole and V-channel of the gundrill along the course of evacuation to the chip collection box. For such impacts with minimum elastic deformation [13], the normal \( u_{nr} \) and tangential \( u_{tr} \) velocity components of the chip are:

\[
u_{nr} = e_n u_{ni}; \quad u_{tr} = e_t u_{ti}
\]

where \( e_n \) and \( e_t \) are the coefficients of restitution in the respective directions. The corresponding forces acting on the chip are essentially impulses from the impact:

\[
F_n = m_c(u_{ni} - u_{nr}); \quad F_t = m_c(u_{ni} - u_{nr})
\]

while the resultant angular velocity is

\[
\omega_r = \frac{F_t d_{sph}}{2m_c k^2} = \frac{5(u_{ni} - u_{nr})}{d_{sph}}
\]

where \( k = \sqrt{\frac{2d_{sph}}{5}} \) is the radius of gyration of the chip.

For the CFD model to predict chip motion accurately, a series of calibration drilling test was performed with commercial gun drills on the DMU 80 P duoBLOCK. Ø8mm Inconel 718 bars were mounted in hardened acryllic tubes of high transparency. Fuchs Ecocool 701 with 12%wt oil was applied at 20-40bar while drilling speeds and feeds were set at 700-1000rpm and 5-10mm/min respectively. Chip motion was recorded at 6000fps with the Photron Fastcam SA5. Then, by deriving the location and orientation discrepancies between the experimental and numerical results, governing parameters such as coefficients of restitution, numerical time step are refined accordingly. Such calibration was repeated until the error is reduced below 20%. A sample of the final outcome is shown in Fig. 3.

![Figure 3. Calibration of chip motion with horizontal drilling tests.](image-url)
3. Methodology

Gun drill design governs chip transportation efficiency through the influence of the coolant’s rheological behaviour and characteristics, alongside properties of the coolants. The gun drill geometries involved are nose grind contour, coolant hole configuration and shoulder dub-off angle. Using the CFD model derived from Sec. 2.3, evaluation of the governing geometries was conducted for Ø8mm drilling of Inconel 718 according to the scope in Fig. 4. In all cases, the drilling speed and feed were 800rpm and 8mm/min respectively, with water-miscible coolant 12% operating at 40bar.

3.1. Effects of nose grind contour

The nose grind contour defines the most prominent geometry of the gun drill that determines the mechanics and performance of the process. It consists of the outer cutting edge, inner cutting edge and drill apex. Different contour designs are classified according to their variations in the outer edge angle $\phi_o$, inner edge angle $\phi_i$ and drill apex offset $A_p$, as a combination. The most commonly found designs are N4 ($\phi_o=15^\circ$, $\phi_i=20^\circ$, $A_p = D/4$); N8 ($\phi_o=30^\circ$, $\phi_i=20^\circ$, $A_p = D/4$); and N13 ($\phi_o=40^\circ$, $\phi_i=5^\circ$, $A_p = D/4$). Different nosegrind contours are intended for different materials but the guidelines have never been clear. In this study, we evaluate the coolant flow characteristics of N4, N8 and N13 collectively with the two-hole coolant configuration and shoulder dub-off angle of 20°.

From the CFD results in Fig. 5a, it is noticeable that delivery of coolant to the drill point deteriorates significantly from N4 to N8 and N13. With N4 and N8, large amount of pressurized coolant is able to reach the vicinity of the drill point and penetrate the cutting edges on the rake faces. This posts a stark contrast to N13 where most of the coolant that rebounds from the bottom hole, escapes directly into V-channel without being able to access the cutting edges where chips are formed. The difference between the conditions of N4 and N8 is least significant.

3.2. Effects of coolant hole configuration

In gundrilling, coolant that is supplied under high pressure travels along the internal conduits of drill shafts and drill tips before ejected through coolant hole(s) on the face of a gun drill to reach the drill point. Configuration of the coolant holes thus plays an important role in through-shaft coolant delivery of the process chiefly, in regulating the coolant volume and pressure. Although three types of configuration namely one-hole, two-hole and kidney-shaped are commercially available, the two-hole gun drills are most frequently popular. In order to compare the coolant performance of these configurations, the N8 nose grind contour and shoulder dub-off angle of 20° were applied.
Fig. 5b depicts the results of the CFD analysis. In general, the performance involved in delivering high-pressure coolant to the drill point improves from 1-hole to 2-hole and with kidney-shaped being the best. Having the single largest orifice with an effective area $A_{orf}$ of 4.81mm$^2$, the kidney-shaped configuration is capable of ‘flooding’ the entire rake faces at high pressure. For the 2-hole configuration with a top and bottom $A_{orf}$ of 1.24mm$^2$ and 2.83mm$^2$ respectively, reasonable amount of coolant can be found at the drill point although pressure of the combined flow is reduced. As a comparison, one-hole configuration with a $A_{orf}$ of 3.78mm$^2$ produces a strong stream of coolant but the flow is deflected back into the V-channel, resulted in poor access of coolant to the cutting edges.

**Figure 5.** CFD analysis of gun drill geometries (a) nose grind contour: I-N4, II-N8, III-N13; (b) coolant hole configuration: I-One hole, II-Two hole, III-Kidney shaped; and (c) shoulder dub-off angle: I-0°, II-10°, III-20°.

3.3. **Effects of shoulder dub-off angle**

The shoulder dub-off of gun drills has two major roles in the process. Firstly, it is one of the relief geometries of the drill to prevent burnishing on the flank surfaces. Secondly, it diverts rebounding coolant from the bottom hole to the cutting edges. The latter contributes to the effectiveness of coolant application, to a great extent that the overall tool life is strongly governed. According to our experience, most of the commercial gun drills are shipped with a shoulder dub-off angle $\phi_d$ of 20°, disregard of the applications involved. The effects of shoulder dub-off was studied with the CFD model for $\phi_d$ ranging from 0° to 10° and 20°. The two-hole configuration and N8 nose grind contour were used.
As evidently found from the CFD analysis in Fig. 5c, the ability to deliver coolant to the drill point increases significantly by reducing $\phi_d$ from 20° to 10° and 0°. With small $\phi_d$ at 0°, delivery of the coolant is capable to penetrate deep into the inner and outer rake faces where heat is generated from chip formation and chip flow. Increasing $\phi_d$ to 10° and 20° leads to the drop in both hydraulic pressure and volume of the coolant flow and resulted in deterioration of cooling and chip evacuation.

4. Discussions
To improve the effectiveness of coolant application in gundrilling requires good knowledge of the coolant’s rheological properties and characteristics, in the context of commercially available solutions. First and foremost, one should understand the active role of nose grind contour is cutting. When materials are removed from the hole with the advancement of the drill, the bottom of the hole generated bears the same geometry of the drill’s nose grind contour, in a directly inverse manner. The bottom hole deflects high-pressure coolant onto the rake faces to evacuate chips and remove heats from the cutting edges. With the combination of a large inner edge angle ($\phi_i=20^\circ$) and a small outer edge angle ($\phi_o=15^\circ$) of the N4 nose grind contour, the large $\phi_i$ allows higher volume of coolant flow while the small $\phi_o$ deflects the coolant to the cutting zone. Therefore, chip evacuation and heat removal in N4 is superior.

Secondly, in order to achieve better results, N4 nose grind contour has to be coupled with the correct coolant hole configuration. Of the designs available in the market, the reason to use the kidney-shaped design is obvious. Having the largest, single orifice that spans across the drill face, high volume of coolant with good conservation of pressure is deflected uniformly over the rake face is an assurance for high effectiveness. Although the effective orifice area of the kidney-shaped and two-hole configurations is comparable, the difference in their performance is overwhelming due to the lost pressure and volume of the coolant supplied from the upper hole of the two-hole design.

![Figure 6](image.png)

**Figure 6.** Tool life validation for various combinations of drill geometries.
Thirdly, with N4 nose grind contour and kidney-shaped configuration, the shoulder dub-off angle $\phi_d$ of the optimum drill design is set at 0°. Using the smallest possible $\phi_d$, the narrow passage enables the build-up of sufficient hydraulic resistance for the deflected coolant to maintain its high pressure, according to the Bernoulli’s principle. This is especially critical for deep penetration of coolant delivery into the cutting zone to remove excessive heat from the rake faces. On the contrary, the wrongly use of a large $\phi_d$, 20° for instance in most commercial gun drills impairs the coolant performance with the loss of hydraulic pressure due to the sudden expansion of coolant flow that is deflected from the bottom hole.

With deeper understanding of the effects of commercial gun drill geometries on rheological properties and characteristics of high-pressure coolant, an optimum drill design for effective chip evacuation and cooling is proposed. Essentially, combining the N4 nose grind contour, kidney-shaped coolant hole configuration and shoulder dub-off angle $\phi_d$ of 0° as a whole, one should achieve better results with the salient merits of each geometry. To validate this hypothesis and the CFD analyses in Sec. 3, a series of gundrilling tests on Inconel 718 were carried out on the DMU 80 P duoBLOCK with the same operating conditions of the CFD simulations. All designs were subjected to the drilling of 50mm in depth. Each drilling cycle was 10mm. By the end of every cycle, the flank wear $VB$ was recorded. The results as summarized in Fig. 6 show apparent agreement with the CFD analyses.

5. Conclusions
In this paper, a CFD model that is capable to simulate rheological characteristics of coolant, flow transport behaviour of chips and heat exchange on rake face is proposed and experimentally substantiated. Based on the analyses of this model, the following conclusions are drawn:

- Tool life is governed by nose grind contour, coolant hole configuration and shoulder dub-off angle in gundrilling.
- Commercial drill designs with large outer angle and small inner angle, single coolant hole configuration and large shoulder dub-off angle adversely affects coolant delivery and deteriorates chip evacuation and cooling of cutting edges.
- An optimum design that combines small inner angle and large outer angle, kidney-shaped coolant hole configuration and small shoulder dub-off angle produces the best tool life.

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