An experimental and simulation study of chip transportation behaviour in gundrilling

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NANYANG
TECHNOLOGICAL
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**AN EXPERIMENTAL AND SIMULATION STUDY OF CHIP
TRANSPORTATION BEHAVIOUR IN GUNDRILLING**

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**SCHOOL OF MECHANICAL AND AEROSPACE
ENGINEERING**

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Abstract

Gundrilling is a machining process to produce deep holes with length to diameter ratios greater than 10. The material removed by the gun drill known as chips have to be evacuated from the cutting zone as fast as possible, in order to prevent the chip clogging. The failure in chip evacuation will lead to intense thermal and mechanical loading. To improve chips evacuation, a thorough understanding of coolant flow characteristics and chip transportation behaviour is necessary. This project aimed to quantify these characteristics and behaviour via experiments and computational fluids dynamics (CFD) simulation study.

Studies of the chips flow behaviours in different concentration of fluids were carried out through drop test experiments. The experiments were conducted in vertical square tube filled with the water-glycerine solutions which have properties similar to the coolant properties with concentration of 85 % oil to 5 % oil. From the experiments, terminal velocities of typical gun drill chips at different range of particle Reynolds number were determined to construct the unique drag curve. Based on the findings, a computational fluid dynamic (CFD) numerical model was developed to predict the lateral drag forces with respect to the particle Reynolds number. The simulated results showed good agreement with the experimental findings.

With that, the CFD model was then applied to analyse the coolant and chip flow trajectories in the actual gun drill. The chip motions were determined based on the combination of CFD simulation and mathematical calculation. Coefficients of restitution as required to determine the rebound velocities after the chip collide to the wall were obtained via calibration against the experimental data. With that, detailed evaluation on the effects of drill geometries including coolant hole configuration, nose angles and shoulder deb-off angles were conducted. In the analysis, coolant streamlines and pressure drop profiles from the coolant supply to the rake face cutting zone were presented. Extensive set of gundrilling experiments for commercial gun drill designs were conducted, it was found that the tool life of

gun drills corresponds with the effectiveness of coolant and chip evacuation. Based on the CFD analysis and experimental results, a new gun drill design that performs better than most commercial design was proposed.

List of publications

1. K.S. Woon, S. Wan, and **G.L. Tnay**, An experimental and simulation study on deep hole gundrilling of Inconel-718," *Proceedings of the 13th Euspen International Conference*, vol 2, pp. 277-280, 2013.
2. **G.L. Tnay**, S. Wan, K.S. Woon and S.H. Yeo, "The effects of dub-off angle on chip evacuation in single-lip deep hole gun drilling," *International Journal of Machine Tools and Manufacture*, vol. 108, pp. 66-73, 2016
3. K.S. Woon, **G.L. Tnay**, M. Rahman, S. Wan and S.H. Yeo, "A Computational Fluid Dynamic (CFD) model for effective coolant application in deep hole gundrilling," *International Journal of Machine Tools and Manufacture*, vol. 113, pp 10-18, 2017

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List of symbols

Re	Reynolds number
F_D	Drag force
g	Acceleration due to gravity
ρ_f	Fluid density
μ	Fluid viscosity
C_D	Drag coefficient
d_{sph}	Volume equivalent sphere diameter
ϕ	Sphericity
$\phi_{\perp}$	Cross-wise sphericity
$\phi_{\parallel}$	Lengthwise sphericity
A_o	Surface area
$A_{o,sphere}$	Surface area of the volume equivalent sphere
$A_{\perp}$	Projected cross sectional area
$A_{\perp,sphere}$	Cross-sectional area of the volume equivalent sphere
$A_{\parallel,sphere}$	Projector longitudinal sectional area of the volume equivalent sphere
F	Fluid force
v	Velocity
s	Displacement
e	Coefficient of restitution
T	Torque
ω	Angular velocity
θ	Angle of rotation
f	Feed rate
BCZ	Bottom clearance zone
DOZ	Dub-off zone
VB	Flank wear
K_t	Crater wear

1 Overview

1.1 Introduction

Gundrilling is a machining process that produces deep holes with length to diameter ratios greater than 10. It was first invented for drilling solid gun barrels approximately a century ago [1]. In recent years, the process was heavily used in many engineering industries, such as oil and gas, aerospace and medical sectors. One of the key challenges involves the manufacture of advanced downhole equipment for the Oil and Gas industries in which the drilling of extremely high length to diameter ratio (more than 400) holes on high yield strength superalloys material, such as Inconel 718.

Deep hole gundrilling with the hole diameter ranging from 0.5 to 40 mm are usually constructed by gun drill tool with single lip design (SLD). The drill consists of 3 major sections- carbide tip, shank and driver. The detailed geometry of SLD gun drill is shown in figure 1. The drill tip is designed as asymmetrical with two cutting edge which is called outer and inner edge. The location of the drill tip formed by the outer and inner edge is designed depending on the type of workpiece material. The clearance angles provided on the flank face allow the coolant to reach to the cutting edges. And the oil clearance angle on the shoulder deb-off allows the coolant to remove the chips and to cool the rake face.

The gun drill shank and driver are made of heat-treated alloy steel. The shank, driver and carbide tip are joined together using brazing processes. The shank is designed in v-shaped channel to allow more space for the chips to be evacuated from the drilled hole.

(a) Top view

(b) Front view

Figure 1: Gun drill geometry (a) Top view (b) Front view

The basic setup of a gundrilling process is shown in figure 2. During the process, whip guide and drill bush are required to guide the drill to produce a straight hole, at the same time high pressure coolant is supplied through the driver and internal passage of the drill. When the coolant reached the bottom drilled hole, the coolant flow diverts rapidly towards the dub-off angle and chips are removed along the flute to the chip box and then return to the coolant tank.

Figure 2: Basic setup of gundrilling process [1]

1.2 Motivation

Application of high pressure coolant in gundrilling is necessary. It provides cooling and lubricating to the drill tip, breaking and evacuating the chips from the cutting edge. The effectiveness of coolant application was reportedly governed by a number of critical drill geometries including the dub-off angle, clearance angle, inner/outer angle, and orifice of the drill design. Osman and Chahil [2] have previously proven that the drop in coolant pressure depends on the configuration of the supply passage. Following that, Astakhov *et al.* [3] found that the coolant pressure distributions can be improved by changing the shoulder dub-off angle of the gun drill. Despite the progress made in the past, improvements on coolant performance were largely conducted without sufficient understanding of the coolant flow characteristics and chip transportation behaviour.

In recent study, the experimental and simulation study of Woon *et al.* [4] showed that efficiency to evacuate the chips from the drilling point has a direct impact on the wear rate, failure mode and life span of the drill. In the analysis, chip formations block the coolant to reach the cutting zone (figure 3) and resulted in a

rapid increase in surface temperatures (660°C) on the rake and flank faces due to the heat generated from plastic deformation and frictional heating. Until the chip is broken and evacuated, coolant is then able to bring down the temperature rapidly to 470°C . With such cyclical thermal loading repeatedly in the drilling cycle (figure 4a), aggressive expansion and stress concentration on the cutting edges is resulted, and subsequently leading to crack propagation. As a consequence, gun drills degrade and fail under extreme thermal loading as shown in figure 4b.

Figure 3: Accessibility of coolant supply to the cutting edges is affected by the growing chip produced continuously in the process [4]

Figure 4: (a) Cyclical thermal loading (b) Catastrophic drill failure [4]

1.3 Objectives and scope

In order to optimize coolant performance and thus the life span of drills, a thorough understanding of the coolant flow and chip transportation behaviour in gun drilling is critical. The main objective of this project is to quantify the chip transportation and evacuation behaviour via computational fluid dynamic (CFD) simulation and experiments. The following are the objectives:

- Characterise and quantify the chips shapes and size.
- Understand the chips flow behaviour in different fluid concentration.
- Develop a base CFD model to simulate the drag coefficient of gun drilling chips.
- Develop a practical CFD model to simulate coolant flow and chips transportation behaviour.
- Characterise the effects of critical drill geometries on chip transportation efficiency.
- Determine optimum drill design for gun drilling of Inconel 718.

In the first part of the project, chip transport behaviour over a wide range of Reynolds number is determined through an experimental and CFD numerical study. Typical gun drill chips are characterized and modelled in terms of shape and size for numerical studies. A vertical flow apparatus is designed and fabricated to determine the drag coefficients of typical gun drill chips.

In the second part of this project, a CFD numerical model that is capable to simulate the coolant flow and chip transport behaviour on the gun drill is developed. The model is used to analyse the coolant performance and chip flow behaviours for different drill design and geometry such as tool edge angle, dub-off angle and coolant hole configuration.

2 Literature Review

Evacuation of chips from the cutting edge is one of the major challenges in gun drilling, especially drilling of high yield strength materials. Proper evacuation of the chips is necessary to avoid excessive rubbing of the chips against the internal hole surface and to ensure adequate exposure of the chip production zones (where high heat fluxes are generated) to the coolant. Moreover, entrapment of chips at the cutting edge would lead to an increase in torsional load, resulted in catastrophic drill failure [5]. To improve chip evacuation in gun drilling an in depth understanding of chip transportation behaviour is important.

In the following section, the methods to characterize and evaluate the coolant flow and chips transportation behaviour are explained.

2.1 Methods to characterize drag values of chip

Determination of drag coefficient can be obtained by particle settling experiments at low Reynolds numbers and at high Reynolds numbers in wind tunnels. The expressions used to calculate the drag and Reynolds numbers are [6]:

$$\text{Re}_p = \frac{d_{sph} u \rho_f}{\mu} \quad (2-1)$$

and,

$$C_D = \frac{F_D}{\frac{1}{2} \rho_f u^2 \frac{\pi}{4} d_{sph}^2} \quad (2-2)$$

where d_{sph} is the diameter of sphere having the same volume as the particle, u is the particle settling velocity, F_D , the drag force and ρ_f and μ are the fluid density and viscosity, respectively. Taking in the account of bouyancy, the drag coefficient, C_D may be expressed as:

$$C_D = \frac{4}{3} \frac{g d_{sph} (\rho_s - \rho_f)}{u^2 \rho_f} \quad (2-3)$$

where g is the acceleration due to gravity, u is the terminal velocity of particle and ρ_s is the particle density.

Over the years, empirical correlations for drag coefficients have been developed for different particle shape and size. For example, the correlations for spherical and non-spherical particles can be found in Haider and Levenspiel [6]; Pettyjohn and Christiansen [7] for various isometric and polyhedral particle; Ricther and Nikrityuk [8] for ellipsoidal and cubic particles; Unnikrishan and Chhabra [9] for cylinders; Jayaweera and Mason [10] for cones. In contrast, there were very few studies on irregular shaped particles. A few recent case studies were conducted by Hartman et al [11], Tran-Cong *et al.* [12] and Holzer and Sommerfeld [13].

In emperical correction expression, the most commonly used shape factor is the sphericity, ϕ , which is defined as the ratio of the surface area of the sphere, s , having the same volume (equivalent volume sphere) of the particle to the actual surface area of the particle. However, the sphericity, ϕ cannot be used to determine the particle orientation especially for non- spherical and irregular shape particles.

To accurately capture the particle flow behaviour, cross-wise sphericity, $\phi_{\perp}$ is included, which is defined as the ratio of the cross-sectional area of the volume equivalent sphere to the projected cross sectional area of the particle. Tran-Cong *et al.* [12] indeed found a good correlation between the drag coefficients based on the cross-wise sphericity, $\phi_{\perp}$ and the Reynolds particle number based on d_{sph} for the irregular particles considered in their study. The proposed correlation is valid within the range of Reynolds numbers from 0.15 to 1500.

After which, a more comprehensive correlation formula was developed by Holzer and Sommerfeld [13]. The authors included the lengthwise sphericity, $\phi_{\parallel}$ in the correlated formula, which is defined as the ratio between the cross-sectional

area of the volume equivalent sphere to the difference between half the surface area and the mean longitudinal projected area of the particle. The new correlation formula was established by integrating the Leith [14] correlation at low Reynolds number (Stokes region) and Ganser [15] correlation at critical Reynolds number (Newton region), and calibrating it against an extensive set of experimental data culled from the literature and their own numerical studies. Finally the correlated formula is derived as:

$$C_D = \frac{8}{Re} \frac{1}{\sqrt{\phi_{\parallel}}} + \frac{16}{Re} \frac{1}{\sqrt{\phi}} + \frac{3}{\sqrt{Re}} \frac{1}{\phi^{3/4}} + 0.4210^{0.4(-\log \phi)^{0.2}} \frac{1}{\phi_{\perp}} \quad (2-4)$$

For convenient determination, the lengthwise sphericity, $\phi_{\parallel}$ in equation (2-4) can be replaced by the cross-wise sphericity, $\phi_{\perp}$ and yielding:

$$C_D = \frac{8}{Re} \frac{1}{\sqrt{\phi_{\perp}}} + \frac{16}{Re} \frac{1}{\sqrt{\phi}} + \frac{3}{\sqrt{Re}} \frac{1}{\phi^{3/4}} + 0.4210^{0.4(-\log \phi)^{0.2}} \frac{1}{\phi_{\perp}} \quad (2-5)$$

In the section 3, the drag coefficient of a typical gun drill chip shape will be determined through a free-fall technique. The experimental drag data of the typical gun drill chip will be compared to different particle shapes which is reported in Holzer and Sommerfeld [13] experimental study.

2.2 Methods to evaluate coolant and chips flow behaviour

Evacuation of chips from the cutting edge is one of the major challenges in gundrilling, especially drilling on high yield strength materials. Proper evacuation of the chips is necessary to avoid excessive rubbing of the chips against the internal hole surface and ensure adequate exposure of the chip production zones (where high heat fluxes are generated) to the coolant. Moreover, large volume of chip is trapped at the cutting edge and would lead to an increase in torsional load, resulted in catastrophic drill failure [5]. Thus, high pressure coolant application on proper tool design is critical. To improve chip evacuation in gundrilling through drill design and process parameter optimization, an in depth understanding of chip transportation behaviour is important.

In the past, Osman and Chahil [2] studied on the gun drills geometry of cross sectional area at the interface of the drill tip and v-shank. Three types of coolant hole designs namely, Single-hole, Two-hole & Kidney-shaped were investigated. It was found that, internal coolant passage between the v-shank and drill tip was not completely covered and hence affected the coolant performance. The results show Two-hole coolant design provided the best performance due to the least pressure loss as compared to other designs.

Following that, Astakhov *et al.* [16] developed an apparatus to measure the coolant pressure profile at the bottom hole and drill tip regions. In the experiments, the effects of the drill geometry on the tool life were studied. It was found that the drill geometry with cutting angles, flank angles and drill point offset have major effects to the coolant flow at the cutting zone. Through these experiments, an optimum drill design with outer angle of 30°, inner angle of 20°, outer flank angle of 10°, inner flank angle of 20° and drill point offset with the ratio of diameter over 4 was proposed. By using the same experiments setup, Astakhov *et al.* [3] focused the experiments on the effects of shoulder deb-off. The experiments were conducted on single-lip gun drills with different deb-off angle (-9° to +20°) as shown in figure

5. It was reported that the coolant pressure can be improved by decreasing the commercial dub-off angle (20°). Although the analyses were sound, the actual increase in chip evacuation efficiency was not known since all the experiments were conducted without chips.

Figure 5: The effects of single-lip gun drill dub-off angle

Since the actual gundrilling process is operated in a closed zone and it is difficult to observe the chip flow behaviour inside the drilled hole. With that, Chin and Wu [17] developed two models for the prediction of chip length based on the cutting signals while Klocke *et al.* [18] implemented a new sensor on the outside of the hole to detect the chips length and velocities. However, these two methods are still unable to provide a better understanding on the chip breaking and the evacuation behaviour near the cutting zone. With that, D. Biermann *et al.* [19] observed the chip formation of drilling process in a transparent tube with high speed camera. It was proven that coolant can affect chip formations for different type of materials.

As experimental methods are costly and time consuming, therefore, researchers have employed the CFD simulation method to evaluate and optimize coolant performance in the drilling process. CFD method is able to resolve flow velocity, pressure, streamline, density, temperature and etc. For example, N. Beer *et al.* [20] investigated the complex coolant flow of the standard and modified twist

drill design based on CFD analyses. It was revealed that the twist drill with a small groove on the flank face can improve the cooling to the flank area thus improve the tool life. F. Fallenstein and J.C. Aurich [21] investigated the thermal conditions on the cutting tool and found that, flow rate and the coolant hole position have significant impact on the heat flux between tool and fluid.

Despite the progress made in the past, so far, no detailed study on the transportation of chip in gundrilling has been carried out. In the ensuing section, the method to quantify chip flow in gun drill will be discussed.

3 Prediction of drag and lateral forces of chip

Understanding of gun drill chips flow behaviour and drag coefficients over wide range of Reynolds number is characterized through free-fall drop test technique and computational fluid dynamic (CFD) simulation. In this chapter, the methods to characterize and quantify gun drill chips with different shapes and sizes, selection of the fluids and experimental setup are discussed. Based on the experimental findings, a CFD numerical model to determine the upward drag force and lateral forces acting on the gun drill chip is developed. The method for creation of geometry, meshing strategy and quantifies the terminal velocity of the gun drill chip are discussed.

3.1 Classification of gun drill chips

The shape of gun drill chip is complex largely defined by the drill geometry and other drilling parameters such as cutting speed and feed rate. As illustrated in figure 6, a backbone or ridge divides the chip into a smaller portion generated by the inner cutting edge and another larger portion generated by the outer cutting edge of the gun drill. The overall size of a chip is largely determined by the size of the drill.

Figure 6: Chip formation in gun drilling

Samples of actual gun drill chips are shown in figure 7. The gun drill geometry and drilling parameters are shown in table 1. The chips are classified into two categories: i) short chips (single petal); and ii) long chip (multiple petal) as shown in figure 7a & 7b.

Based on the drilling conditions in table 1, 90 % of the short chips and 10 % of the long chips were found. Short chips (single petal) are the desired chip in gun drilling as it can be easily evacuated from the cutting edge. Long chips (multiple petals) are undesirable chips, as they will prevent the coolant to cool the rake face leading to increase in surface temperature, and consequently the drill degrades and fails rapidly [4].

Table 1: Drilling parameters and drill geometry for gun drilling of Inconel 718

Drill diameter	8 mm
Outer angle	30°
Inner angle	20°
Dub-off angle	20°
Coolant pressure	60 bar
Spindle speed	700 rpm
Feed rate	3.5 mm/s

(a) Short chip (single petal)

(b) Long chip (multiple petals)

Figure 7: Type of gun drill chips (a) Short chip (single petal), (b) Long chip (multiple petals)

3.1.1 Characterization of Single petal chips

At first, characterization of 15 pieces of single petal gun drill chips was randomly selected. In the study, the curve length of the chips was measured with KEYENCE Digital Microscope VH-1000 as shown in figure 8b. With these curve length, the angle and the area of chip can be determined. For example, the chip generated from the 8 mm gun drill will have a radius of 4 mm. The angle of the chip is calculated as, $S = r\theta$ and the area of the chip is, $A = (\theta^\circ \cdot \pi r^2) / 360^\circ$, as shown in figure 8d. Following that, the chips are classified based on the wedge angle of the chip sector, θ° . As shown in the table 2, the wedge angle of the single petal chip is between 80° to 120° .

Figure 8: A sample of single petal chip generated from 8 mm gun drill

The weight of the chips is measured with the Mettler Toledo precise digital weighing scale. Based on the density (Inconel 718 density= 8200 kg/m³) and weight of the chip, the volume of the chips can be determined. With the particular chip volume, Sphericity (Φ) of the chips can be calculated which is determined based on the ratio of the surface area of a sphere (with the same volume as the chip) to the surface area of the chip:

$$\Phi = \frac{A_{o,sphere}}{A_o} = \frac{\pi^{\frac{1}{3}}(6V_o)^{2/3}}{A_o} \quad (3-1)$$

where A_o is the surface area, $A_{o,sphere}$ is the surface area of the volume equivalent sphere.

From table 2, three typical gun drill chips (given in figure 9) with the equivalent volume of 0.35 mm³ and Sphericity of 0.17 are used repeatedly in the free fall drop test experiments.

Table 2: Detail dimension of single petal chip

Chip Number	Weight (mg)	Curved Length (mm)	Wedge angle (θ)	Area of chip, A (mm ²)	Volume, V (mm ³)	Sphericity, Φ
1	2.67	6.55	93.77	13.09	0.33	0.17
2	1.82	5.59	80.05	11.18	0.22	0.16
3	2.87	6.63	94.93	13.26	0.35	0.18
4	2.77	7.42	106.21	14.83	0.34	0.16
5	3.08	7.76	111.12	15.52	0.38	0.16
6	2.62	6.34	90.81	12.68	0.32	0.18
7*	2.88	7.08	101.37	14.16	0.35	0.17
8*	2.84	6.91	99.00	13.82	0.35	0.17
9	2.96	7.23	103.60	14.47	0.36	0.17
10	3.07	7.91	113.28	15.82	0.37	0.16
11	3.08	6.32	90.45	12.63	0.38	0.20
12	3.05	6.44	92.20	12.88	0.37	0.19
13	2.96	7.86	112.63	15.73	0.36	0.16
14*	2.83	6.90	98.77	13.79	0.35	0.17
15	2.84	6.43	92.05	12.85	0.35	0.19

* Three typical gun drill chips were selected for the experiments

Figure 9: Typical gun drill chips with the equivalent volume, V of 0.35 mm^3 and Sphericity, $\Phi= 0.17$

Besides that, the projected area for three typical chips is measured in order to calculate the Crosswise and Lengthwise Sphericity of the chips. The Crosswise Sphericity ($\Phi_{\perp}$) is defined as the ratio of the cross-sectional area of the volume equivalent sphere to the projected cross sectional area of the chip:

$$\Phi_{\perp} = \frac{A_{\perp, \text{sphere}}}{A_{\perp}} \quad (3-2)$$

where $A_{\perp}$ is the projected cross sectional area, $A_{\perp, \text{sphere}}$ is the cross-sectional area of the volume equivalent sphere.

And Lengthwise Sphericity ($\Phi_{\parallel}$) is defined as the ratio between the projected longitudinal sectional area of the volume equivalent sphere to the difference between half the surface area and the mean longitudinal projected area of the particle:

$$\Phi_{\parallel} = \frac{A_{\parallel, \text{sphere}}}{0.5A_0 - A_{\parallel}} \quad (3-3)$$

where $A_{\parallel, \text{sphere}}$ is the projected longitudinal sectional area of the volume equivalent sphere

Once the details of the chips shape parameters (table 3) are determined, the chip can then be accurately model in Ansys Design Modeler for numerical studies.

Table 3: Data for Sphericity (Φ), Lengthwise Sphericity ($\Phi_{||}$), and Crosswise Sphericity ($\Phi_{\perp}$)

	Surface area (mm ²)	Projected area (mm ²)	Volume (mm ³)	Spherical Diameter (mm)	Lengthwise Sphericity, $\Phi_{ }$	Crosswise Sphericity, $\Phi_{\perp}$	Sphericity, Φ
Chip 1	13.82	12.10	0.35	0.90	0.115	0.049	0.174
Chip 2	14.16	11.80	0.35	0.90	0.102	0.051	0.170
Chip 3	13.79	12.90	0.35	0.90	0.100	0.046	0.174
Chip model	15.80	14.00	0.41	0.90	0.106	0.053	0.172

3.2 Free fall drop test experiments

To gain understanding of the gun drill chip flow behaviour in different fluid viscosities, the first approach of this project is to carry out the vertical drop test experiments.

The free fall drop test experiments are conducted in a transparent vertical square tube with the dimension of 0.1 m x 0.1 m x 1 m. The vertical apparatus is filled with different fluid viscosity and density for each experimental run. The temperature of the fluid is monitored constantly. A high speed camera is placed near to the bottom of the tube, to capture the falling chip. The chips are dropped from the top of the tube. When the falling chip is reached the terminal velocity, the timing and settling behaviour are captured by the high speed camera (Photron Fastcam SA5) that has a frame rate of 500 fps. The actual experimental setup is shown in figure 10.

Figure 10: Experimental setup for freefall drop test

3.2.1 Experimental setup and procedures

The procedure to carry out the free fall drop tests are:

- 1.Fill the tube with glycerine mixture.
- 2.Wait for all the air bubbles to escape
- 3.Drop the chip from the top of the tube
- 4.Record the trajectory of the chip using high speed camera and saving it for calculation of terminal velocity
- 5.Repeat steps 3 & 4 for the next two chips
- 6.Repeat steps 1 to 5 for different concentration of glycerine mixture. (Water-glycerine mixtures method is discussed in the section 3.2.2)

3.2.2 Fluid selection in tube

The initial plan was to study the gun drill chip flow behaviour in different viscosity of the water soluble cutting fluid (coolant), but as the coolant is opaque, an alternative solution is simulated by the water-glycerine mixtures during the free fall experiments.

Figure 11: (a) Water soluble cutting fluid (Coolant), (b) Water- Glycerine mixture

By varying the concentration of the water soluble cutting fluids and water-glycerine mixture, the viscosity and density can be measured and calculated respectively. The viscosities of the fluids were measured with the Anton Paar Physica MCR301 Rheometer at constant temperature of 25 °C as shown in tables 4 and 5.

Table 4: Viscosities of water-glycerine mixture

Shear rate (1/s)	3000
Temperature	25 °C
Percentage of Glycerine (%)	Viscosity (Pa.s.)
85	0.096
75	0.044
65	0.024
55	0.013
45	0.006
35	0.004
25	0.003
15	0.002
5	0.001

Table 5: Viscosities of water soluble cutting fluid mixture (coolant)

Shear rate (1/s)	3000
Temperature	25 °C
Percentage of Oil (%)	Viscosity (Pa.s.)
100	0.198
75	0.027
50	0.011
25	0.002
20	0.002
15	0.002
10	0.002

Once all the viscosities of the fluids have been determined, the comparison between 2 types of fluids is plotted in figure 12. With this curve, the coolant can be replaced by the water-glycerine mixture with the specified concentration.

Figure 12: Viscosity against the concentration curve for water soluble cutting fluid and water glycerine mixture

3.3 CFD numerical model setup

The second step is to develop the numerical model that is capable to quantify the fluid forces acting on the chips at different viscosities. With the forces obtained, terminal velocities of chip can be calculated when the drag force equal to the gravity force.

A steady state CFD numerical model to determine the upward forces and lateral forces of the gun drill chips over a wide range of Reynolds number were set up in ANSYS Workbench CFX 14.0 as shown in figure 13. The geometry of the typical gun drill chip and the flow domain were created according to the actual experimental setup. Meshing methods on the complex chip shape is described in the section 3.3.1.

Figure 13: CFD simulation setup in ANSYS Workbench CFX 14.0

3.3.1 Creation of geometry

The geometry of a typical gun drill chip and the flow domain with the same square tube of 0.1 m x 0.1 m x 1 m was created in ANSYS Design Modeler V14.0 as shown in figure 14.

Figure 14: Dimension of flow domain integrate with the gun drill chip

In order to provide proper mesh control, the flow domain was sliced into six blocks, with one small cuboidal block content of gun drill chip, after that, grouping the six blocks into single part by using the Form New Part functionality in the Design Modeler application as shown in figure 15, this is to ensure the conformal meshing between the interfaces.

Figure 15: Sliced geometry for better mesh control

3.3.2 Meshing setup

In the meshing process, combination of the structured hexahedral and unstructured tetrahedral meshes was applied as shown in figure 16. Hexahedral meshes were assigned on the six blocks through sweep method. Due to the geometric complexity of gun drill chip, the tetrahedral meshes with Patch Confirming Method were applied.

In order to accurately capture the boundary layer region, face sizing and five prismatic layers on the chip surfaces were introduced.

Figure 16: Meshing technique with combination of hexahedral and tetrahedral meshes on complexity geometries.

3.3.3 Grid Independence Test

The grid independence test was carried out by varying the mesh size (1.4×10^{-4} m to 0.2×10^{-4} m) on the chip surfaces as shown in figure 17. The results show the independence mesh size was reached when the mesh size is lesser than 0.4×10^{-4} m; hence this mesh size (0.4×10^{-4} m) was applied in the numerical study.

Figure 17: Grit independence test on gun drill chip

3.3.4 Method to quantify terminal velocity and lateral forces in numerical model

In CFX Pre-Processor, velocity boundary condition for inlet, pressure boundary condition for outlet and no slip wall boundary condition for the flow domain and chip surfaces were defined as shown in figure 18.

Figure 18: Boundary conditions for the flow domain

In order to determine the terminal velocity of chip, setting up of buoyancy model and net upward force equation (Drag force – Gravity force) was defined in the CFX pre-processor expression. As shown in figure 19, the terminal velocity is achieved when the drag force equal to the downward force of gravity.

Figure 19: Determination of terminal velocity

By varying the inlet velocity in a particular fluid viscosity, a range of net upward force and lateral forces can be calculated. After that, by interpolation of a range of inflow velocities and net upward force, the terminal velocity of the chip can be calculated while net upward force equal to zero, as shown in figure 20. Finally, lateral forces can be calculated while net upward force equals to zero as shown in figure 21.

Figure 20: Inlet velocities against net upward force curve to determine the terminal velocity (Dynamic Viscosity of the fluid= 0.096 Pa.s)

Figure 21: Lateral forces against net upward force curve to determine the lateral forces (Dynamic Viscosity of the fluid= 0.096 Pa.s)

3.4 Results & Discussion

Through the free fall drop test experiments, terminal velocities of three typical gun drill chips with sphericity (Φ) of 0.17 were determined to construct the unique drag curve. In the CFD numerical model, terminal velocities of the gun drill chip with sphericity (Φ) of 0.17 and 0.14 were simulated. The CFD results were compared with the experimental results for Reynolds numbers ranging from 0.06 to 36. In order to gain a better understanding on the drag of the gun drill chips, the drag curve of the chips was compared with the drag curve of generic shape obtained in the literature. Besides that, lateral motions of chip quantified by the CFD model were also compared.

3.4.1 Terminal velocity of gun drill chip

Based on the experimental and numerical study, the terminal velocity of gun drill chips in different viscosity and density of the fluids were determined as shown in table 6. Comparison between the experimental and simulated data is plotted as shown in figure 22. The result shows that as the sphericity increases, the terminal velocity of gun drill chip also increases. And simulated results of the 0.17 sphericity chip show good agreement is achieved, as the simulated trend line follow the experimental data.

Table 6: Comparison of the measured and simulated terminal velocity of the gun drill chips

Glycerine Concentration (%)	Density (kg/m ³)	Dynamic Viscosity (Pa.S)	Experimental Data (m/s)			Numerical Data (m/s)	
			Chip 1	Chip 2	Chip 3	Chip model ($\Phi=0.17$)	Chip model ($\Phi=0.14$)
85	1228.3	0.096	0.006	0.006	0.007	0.004	0.003
80	1218.0	0.070	0.006	0.006	0.008	0.005	0.004
75	1205.6	0.041	0.008	0.009	0.010	0.008	0.006
58	1164.6	0.011	0.013	0.013	0.014	0.018	0.015
26	1054.6	0.002	0.042	0.046	0.046	0.040	0.036
12	1016.7	0.001	0.046	0.048	0.053	0.044	0.043

Figure 22: Comparison of terminal velocities between experimental and simulated results

3.4.2 Drag curve of gun drill chip

With the determination of the terminal velocity, drag coefficients and particle Reynolds numbers were calculated as shown in tables 7 (Experimental data) and 8 (Simulated data). The experimental and simulated drag curve for gun drill chips was plotted as shown in figures 23 and 24.

Table 7: Reynolds number and drag coefficient results (Experimental data)

Glycerine Concentration (%)	Experimental Data					
	Chip 1		Chip 2		Chip 3	
	Re	C _D	Re	C _D	Re	C _D
85	0.062	2090.104	0.062	2072.173	0.078	1317.022
80	0.084	2150.945	0.086	2016.231	0.115	1138.329
75	0.203	1024.887	0.219	879.097	0.252	665.511
58	1.132	437.793	1.173	407.588	1.309	327.282
26	17.126	43.712	18.957	35.675	18.817	36.207
12	31.657	37.720	36.165	28.902	32.808	35.119

Table 8: Reynolds number and drag coefficient results (Simulated data)

Glycerine Concentration (%)	Numerical Data			
	Chip model ($\Phi = 0.17$)		Chip model ($\Phi = 0.14$)	
	Re	C_D	Re	C_D
85	0.033	7176.599	0.004	4308.466
80	0.061	4076.989	0.081	2784.844
75	0.152	1833.883	0.216	1100.970
26	14.679	59.494	17.408	51.433
12	29.484	43.483	32.200	44.324

Figure 23: Experimental drag curve of typical gun drill chip

Figure 24: Simulated drag curve of typical gun drill chip with sphericity of 0.14 and 0.17

3.4.3 Drag curve comparison

Comparison of the experimental and simulated data of gun drill chip is shown in table 9 and plotted in figure 25. As observed in figure 25, the simulated result shows similar trend to the experimental data. The result revealed that, as the sphericity of the chip increases, the drag coefficient of the chip increases.

In table 9, the relative errors between the experimental and simulated data are around 12 % to 40 %, and the average is 31 %. The error is mainly due to the oscillation of the chips as they were settling downwards. This behaviour will be discussed in the sections 3.4.4 and 3.4.5.

Table 9: Comparison of drag coefficients between experimental and simulated data

Average Re	Average Experimental C_D	Simulated C_D	Percentage error, %
0.067	2081.139	2900	39.35
0.095	1768.502	2500	41.36
0.224	856.498	750	12.43
19.947	38.531	50	29.77
30.772	33.914	45	32.69

Figure 25: Comparison between experimental and simulated drag curve

In order to have a better understanding on how the typical shape of gun drill chip behaviour as compared to generic shape, the experimental and simulated drag

data of gun drill chip were compared to different shape of particles from Holzer and Sommerfeld [13] as shown in figure 26. From the result, it was realized that the drag coefficients of gun drill chip are fall into the disk and plate region. And the drag curve shows similar trend.

Figure 26: Comparison between the drag data of gun drill chips and different shape of particles from the literature Holzer and Sommerfeld [13]

The gun drill chip with sphericity, ϕ of 0.17 is compared to the thin disk which has the same sphericity, ϕ of 0.18. From figure 27, the drag data of thin disk with sphericity of 0.18 fall into the drag data of experimental chip region and it has a similar trend. Through the comparison, the upward drag on gun drill chips can thus be approximated to thin disks.

Figure 27: Comparison between the experimental and simulated drag data of gun drill chips (Sphericity, $\phi = 0.17$) and simulated thin disk (Sphericity, $\phi = 0.18$)

Subsequently, the experimental drag data were also compared to the predicted drag data using the correlated equation (2-4) derived by the Holzer and Sommerfeld [13], the correlation equation (2-4) was determined based on the sphericity (Φ), crosswise sphericity ($\Phi_{\perp}$) and lengthwise sphericity ($\Phi_{\parallel}$) of the gun drill chip and Reynolds number of the particle.

The comparison between the predicted drag data and experimental data are shown in table 10 and the comparison drag curve was plotted in figure 28. The comparison shows that the predicted drag data follows the experimental drag data. The deviation between the experimental and predicted data is approximately 20 % to 66 % with an average is 49.3 %. The error is mainly due to the irregular shape of the chips, causing them to oscillate in lateral directions. The detailed analysis is shown in section 3.4.4.

Table 10: (a) Comparison of drag coefficients for experimental and predicted drag data using Holzer and Sommerfeld [13] correlation formula

Chip 1			Chip 2			Chip 3		
Re	Measured C_D	Predicted C_D	Re	Measured C_D	Predicted C_D	Re	Measured C_D	Predicted C_D
0.061	2090.10	1068.49	0.06	2072.17	1049.84	0.07	1317.02	878.89
0.083	2150.94	798.45	0.08	2016.23	764.17	0.11	1138.32	606.07
0.203	1024.88	345.94	0.21	879.09	318.97	0.25	665.51	292.47
17.126	43.71	20.02	18.95	35.67	20.27	18.81	36.20	21.79
31.657	37.72	17.63	36.17	28.90	18.01	32.80	35.11	19.72

(b) Percentage error between the experimental and predicted [13] drag coefficient

Reynolds Number	Percentage error, %		
	Chip 1	Chip 2	Chip 3
0.061	48.88	49.34	20.29
0.083	62.88	62.10	32.87
0.203	66.25	63.72	52.07
17.126	54.20	43.18	44.01
31.657	53.25	37.68	48.71

Figure 28: Comparison between the Holzer and Sommerfeld [13] correlation formula and experimental drag coefficient of gun drill chips

3.4.4 Settling behaviour of gun drill chip

Due to the irregular shapes of gun drill chips, the settling behaviour is different from the thin disks and plate. This settling behaviour of chip is captured with high speed photography. It is found that the chip oscillated in lateral motion as it settles downward. Figure 29a shows that the chip deviates noticeably from the imaginary straight line (indicated as a dashed line in the figure) when it settles down at the low Reynolds number. As compared to figure 29b, the deviations from the imaginary line increase when the Reynolds number increases.

Figure 29: Settling behaviour of typical gun drill chips captured from the high speed camera. (a) Settling in low Reynolds number ($Re= 0.08$), (b) Settling in high Reynolds number ($Re= 18$)

In addition to that, the vortices formed in the wake of the chip can also be seen clearly when the Reynolds number equals to 18 as shown in figure 30. These phenomena were also visible in the simulated results as well. Figure 31 show the vortices formation increase on the chip surface when the Reynolds number increases.

Figure 30: Vortices formed in the wake of the chip (Re= 18)

(a)

(b)

Figure 31: Vortices formation a) Streamline view b) Velocity contour view

3.4.5 Lateral forces acting on gun drill chips

Oscillations of chip were mainly caused by the vortices acting on it. This behaviour can be quantified in the numerical model as shown in table 11. It shows increase of particles Reynolds number leads to increase in the lateral force. However, the magnitude of the lateral forces appears to saturate beyond certain Reynolds number. As show in figure 32, maximum value of the lateral force at the saturate point is around 21 % of the chip weight.

Table 11: Determination of lateral forces in different range of Reynolds number

Water-Glycerine Mixture	Reynolds No.	F _x (N)	F _y (N)	Resultant	Percentage (%) of the chip weight
DI Water	48.675	5.00E-06	-5.00E-06	7.07E-06	21.44
12 %	29.345	5.00E-06	-4.80E-06	6.93E-06	21.01
26 %	14.611	4.50E-06	-4.10E-06	6.09E-06	18.47
75 %	0.151	1.40E-06	-1.20E-06	1.84E-06	5.58
80 %	0.061	1.30E-06	1.00E-06	1.64E-06	4.97
85 %	0.033	1.20E-06	-9.50E-7	1.53E-06	4.64

Figure 32: Lateral forces against the Reynolds number

4 Study of chip transportation behaviour in gun drilling

In this chapter, the method used to characterize the chip transportation behaviour along the gun drill tip is developed. Motions of the chip are predicted through CFD numerical simulations and mathematical method. In section 4.1, equations for calculating the linear and angular motions of chip are explained. With the chip contacting the wall, modelling of the contact model (wall effects) was also explained. In order to improve the accuracy of the CFD model, the method to calibrate the chip motion with experiments is shown in section 4.2.

4.1 Modelling of chip trajectories in gun drilling

Predictions of the chip trajectories in gun drilling were carry out through CFD numerical simulations and mathematical methods. The purpose of the CFD simulations is to estimate the fluid forces and torques on the chip. Once the net forces and torque values are calculated, the net displacement and rotational motion of the chip can be determined from the equations.

CFD simulations were carried out in a commercial CFD code, Ansys CFX version 14, which is based on the control volume method. In the geometry setup, a typical chip and 8 mm gun drill was imported into the code and prescribed as a stationary solid. The flow domain is extracted from the 8 mm drilling hole and gun drill. As shown in figure 33 a velocity boundary condition is defined on the two coolant hole of the flow domain (Inlet) and a pressure boundary condition on the outlet of gun drill. The outlet pressure was set to the ambient pressure (1 bar) and inlet pressure at 40 bar. No slip wall boundary conditions were applied to the rest of the flow domain, drill and the chip surfaces. The properties of coolant, drill and workpiece is shown in figure 33.

Figure 33: Boundary conditions and meshing control

4.1.1 Chip transportation in linear translation motion

The motion of the chip in the gun drill can be described based on the linear translation or combination with angular motion. In this section, equations for model the linear flow motion of gun drill chip are discussed.

Linear translation motion of the chip may be expressed in vector form as:

$$\sum F = ma = m \frac{dv}{dt} \quad (4-1)$$

or in three scalar equations,

$$F_x = ma_x \quad (4-1.1)$$

$$F_y = ma_y \quad (4-1.2)$$

$$F_z = ma_z \quad (4-1.3)$$

(where F is the net force, m is the mass of the body, and a is the acceleration of the body)

Once the force values were determined from the CFD simulation, the positions and velocities of the chip at the specific time step can be determined based on the equations:

Velocity equations express as:

$$dv = a dt \quad (4-2)$$

or in three scalar equations,

$$v_x = u_x + a_x \Delta t \quad (4-2.1)$$

$$v_y = u_y + a_y \Delta t \quad (4-2.2)$$

$$v_z = u_z + a_z \Delta t \quad (4-2.2)$$

(where v is final velocity, u is initial velocity, a is acceleration and t is time for each step)

Displacement equations express as:

$$v_p = \frac{ds}{dt} \quad (4-3)$$

or in three scalar equations,

$$s_x = (s_0)_x + v_x \Delta t \quad (4-3.1)$$

$$s_y = (s_0)_y + v_y \Delta t \quad (4-3.2)$$

$$s_z = (s_0)_z + v_z \Delta t \quad (4-3.3)$$

(where s is final displacement, s_0 is initial displacement, v is velocity and t is time for each step)

4.1.2 Contact model

Chip rebounding from the wall is not considered in Ansys Workbench. Due to this limitation, method to predict the velocity and position of the chip after collision from a wall (Inconel workpiece or carbide drill) was discussed in this chapter. In order to predict the velocity and position of the chip after rebounding from the wall, the values of coefficient of restitution were obtained via the experimental data, explained in section 4.2.

The coefficient of restitution, e is defined as the ratio of velocity after and before collision to the wall. A perfect elastic collision has a coefficient of restitution, e of 1. For coefficient of restitution, e equal to 0, chips will stop after collision, which means not bouncing at all. The normal and oblique impacts to the wall were described by the normal and tangential coefficients of restitution;

$$e_t = \frac{(v_t)_2}{(v_t)_1} \quad (4-4)$$

$$e_n = \frac{(v_n)_2}{(v_n)_1} \quad (4-5)$$

(where, e_t is tangential and e_n is normal coefficient of restitution, v_t is tangential and v_n is normal components of the velocity vector)

Prediction of the chip position before and after collision to the wall is shown in figure 34. The resultant speed before collision is indicated as V_{R1} , and after rebounding from the wall is V_{R2} . Tangential component of velocity to the wall and normal component of velocity to the wall is indicated as V_t and V_n .

Figure 34: Chip motion before and after wall collision

4.1.3 Procedures to solve the trajectory of chip in linear motions

The procedure to predict the trajectory of the chip (linear motions) is shown in figure 35.

Figure 35: Algorithm to solve the trajectory (linear motions) of the chip in gundrilling hole

4.1.4 Chip transportations in rotational motions

In this section, equations to derive the rotational motions of the chip were discussed. When the chip is rotating, a torque must be applied to change its angular momentum, which is given by:

$$T = \frac{dL}{dt} \quad (4-6)$$

where, T is the torque and L is the angular momentum

However, the above equation (4-6) is only valid for a fixed inertial frame, if the chip is rotating at the translation frame, then the equation (4-6) must account for rotation of the translation frame as measured from the inertial axes.

Hence, $\frac{dL}{dt}$ may be expressed as:

$$\frac{dL}{dt} = \frac{dL}{dt'} + \omega \times L \quad (4-7)$$

where, $\frac{dL}{dt}$ is referred to the time derivative in the fixed frame and $\frac{dL}{dt'}$ is referred to the time derivative in the translation frame

Combining equation (4-6) and (4-7) the following is obtained:

$$T = \frac{dL}{dt'} + \omega \times L \quad (4-8)$$

Taking translating frame as principal axes of inertia,

Let, $T = T_{x'}, T_{y'}, T_{z'}$ and $\omega = \omega_{x'}, \omega_{y'}, \omega_{z'}$

Angular momentum, $L = (I_{x'} \omega_{x'}), (I_{y'} \omega_{y'}), \& (I_{z'} \omega_{z'})$

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, and $\omega_{x'}, \omega_{y'}, \omega_{z'}$ are the angular velocities. All the values are acting around the principal axes.

We may express the equation (4-8) in three axes of components as:

$$\sum T_{x'} = I_{x'} \frac{dw_{x'}}{dt} + w_{y'} w_{z'} (I_{y'} - I_{z'}) \quad (4-8.1)$$

$$\sum T_{y'} = I_{y'} \frac{dw_{y'}}{dt} + w_{z'} w_{x'} (I_{z'} - I_{x'}) \quad (4-8.2)$$

$$\sum T_{z'} = I_{z'} \frac{dw_{z'}}{dt} + w_{x'} w_{y'} (I_{x'} - I_{y'}) \quad (4-8.3)$$

The above equations are known as the Euler equation of motion.

In order to determine the angle of rotation, θ between the principal axis of the chip and the inertial coordinate system, the angular velocities, $\omega_{x'}, \omega_{y'}, \omega_{z'}$ for each particular axis of the chip were calculated based on the Euler equations (4-8.1) to (4-8.3).

The torques $T_{x'}, T_{y'}, T_{z'}$ acting on the principal axis of the chip are simulated from the CFD numerical model, and the principal moment of inertia, $I_{x'}, I_{y'}, I_{z'}$ are measured from the Ansys Mechanical. With these values, the angular velocities for each particular axis of the chip can be determined. And angle of rotation θ can be calculated as:

$$\frac{d\theta}{dt} = \omega_p \quad (4-9)$$

4.1.3 Procedures to solve the trajectory of chip in rotational motions

The procedure to predict the trajectory of the chip (combination of translation and rotational motions) is shown in figure 36.

Figure 36: Algorithm to solve the trajectory (combination of translation and rotational motions) of the chip in gundrilling hole

Simulation of the chip motions is shown in figure 37. The forces and torques on the initial chip position (figure 37a) was first calculated from the CFD simulation. With these values, linear and angular displacement of chip to the second position (figure 37b) can be defined from the equation (4-1) to (4-3) and (4-8) to (4-9) at the specific time step. Once the new position of the chip is set, then forces and torques were re-calculated from the CFD simulation, so that the subsequent position of the chip can be determined (figure 37c).

Figure 37: Chip motions determination through combination of CFD simulation and mathematical calculation

4.2 Model Calibration

Calibration of the CFD numerical simulations was carried out with the gun drilling of Inconel workpiece. These experiments were conducted on the DMU 80p duoBLOCK® Five axis machine as shown in figure 38. The general commercial gun drill (N8) design with 30° outer angle, 20° inner angle, 20° shoulder deb-off angle and two outlets of the coolant hole was mounted on the spindle chuck. Fuchs Ecocool 701 with 12 % wt oil and 40 bar coolant pressure were used.

Figure 38: Experimental setup for analysing the chip transportations behaviour

The Inconel 718 workpiece (yield strength:-1058 MPa) with 8 mm diameter was housed in the transparent acryl tube and fixed on a vice clamp. First, gun drill was insert into the transparent acryl tube and drill on the workpiece to create a bottom hole shape. The feed rate (f) of 8 mm/min and cutting speed of 20 mm/min were used. An example of the chip used in the experiments is shown in figure 39. The chip is irregular in shape and is as thin as 0.04 mm. A backbone or ridge

divided the chip into a smaller portion generated by the inner cutting edge and another larger portion generated by the outer cutting edge of gun drill.

Figure 39: A typical Inconel chip generated from single-lip gun drill

After the chips were generated at the bottom drilled hole, the spindle was stopped and the high pressure coolant switched on to flush out the chip. The reason to stop the drill rotating is to allow the chip transportation behaviour to be observed along the drill tip. The images were recorded by a high speed camera (Photron fast cam SA5) that has a frame rate of 6000 fps.

The sequence of the chip flow behaviour with before contacting the wall and after rebounded off was recorded from high speed photography as shown in the figure 40. Each frame is about 1 ms. From the images, the before and after impact velocity can be estimated to calculate the coefficients of restitutions by using equations (4-4) and (4-5). Observations along the drill tip showed that the values of tangential, e_t and normal, e_n coefficient of restitution is about 0.92 to 0.98 and 0.47 to 0.52 respectively.

Figure 40: Sequence of frames recorded from the high speed photography (a) Before contact (b) contact to wall (c) after rebound

4.3 Results and discussions

4.3.1 Comparison between CFD prediction and experimental data

Comparison between experimentally observed and CFD calculated trajectory of a single chip being evacuated is shown in figure 41. Time step 0.1 ms was used in the calculation. The observation showed that as soon as the chip starts to break off (figure 41a), the coolant transports the chip towards the wall of the hole (figure 41b), causing it to contact the wall (figure 41c). The chip then rebounded off the wall of the hole and subsequently hit against the wall of the gun drill (figure 41d), after which it was successfully evacuated (figure 41e).

The experimentally observed and CFD calculated trajectory appear to be in good agreement. For completeness, the CFD calculated trajectory is shown in section 4.3.2.

Figure 41: Chip transportation behaviour captured by the high speed camera and CFD results

4.3.2 Comparison the chip trajectories between linear and rotational motion

The trajectory of the chip in gun drill can be plotted out based on the linear and rotational motions. The procedure to predict the trajectory can be found in figure 35 (linear motion) and figure 36 (linear & rotational motion). Once the positions are determined, the trajectory of the chip can be plotted as shown in figure 42. The path is defined in the y- z plane having the linear motion in blue path and the rotational motion in red path. The analysis started at point (y_0 , z_0) at which the chip started to break off from the cutting edge. The comparison showed that the path of the rotational and linear motion behaved in similar trend and the deviation in z axis is about 0.4 mm, this shows the chip has very little rotational motion in gun drill.

Figure 42: Comparison between the linear and rotational motion of chip in gun drill; Linear motion in blue path and rotational motion in red path

5 Optimization of gun drill geometries in high pressure flow

The objective in this chapter is to use the experimentally calibrated CFD model to evaluate the performance of commercial available gun drills. In section 5.1, drill geometric design that could affect coolant flow and chip transportation is studied. In section 5.2, the analysis of high pressure flow behaviour on various drill designs such as cutting angle, coolant hole configurations and shoulder deb-off angle are carried out. In section 5.3, a case study of chip evacuations and transportation on different shoulder deb-off angles are analysed. Comparison between the CFD results and drilling experiments are demonstrated in section 5.4. In the experiments, crater and flank wear to determine the tool life of the drills are discussed. Through CFD and experimental findings, a new gun drill design to prolong the tool life is developed. These results can be found in the last section of this chapter.

5.1 Characterization of commercial gun drill geometries designs

A variety of gun drill geometry designs can be found in the market. In order to ensure the efficiency of the cooling effects as well as chip evacuation, a thorough understanding of the commercial gun drill geometrical designs is necessary. In this section, characterization of the gun drill geometries such as cutting nose angle designs, coolant hole configurations, deb-off angles and the shape of the bottom drilled hole will be discussed.

5.1.1 Cutting nose angle designs

Three examples of popular commercial cutting nose angle configurations used in the industries are shown in figure 43. The outer cutting angle of 20° and

inner angle of 15° is labelled as N4 design. Outer cutting angle of 30° and inner angle of 20° is labelled as N8 design. Lastly the outer cutting angle of 40° and inner angle of 5° is labelled as N13 design.

Figure 43: Three different cutting nose angle designs

Different cutting angles design would create different shape of bottom drilled hole as shown in figure 44. Due to this, coolant flow behaviours on different nose angle configurations will be varied.

Figure 44: Bottom drilled hole shape created by different cutting nose angles design

The cavity at the bottom hole is divided into two zones: bottom clearance zone (*BCZ*) and dub-off zone (*DOZ*). *BCZ*, which is highlighted in yellow colour, is located at between the drill relief angles and the bottom drilled hole as shown in figure 45. The opening area between the oil clearance angle and the bottom drilled hole is defined as coolant exit area, *A*.

The coolant progress from the coolant exit area, *A* to reach the dub-off zone (*DOZ*) as shown in figure 46. This zone is defined at between the *ZX* plane (cutting edge plane) and the plane at 120° V channel (the oil dub-off region), highlighted in green colour. After that, the coolant will exit from the coolant exit area, *B* to the cutting edge zone.

Figure 45: Bottom clearance zone (*BCZ*) highlighted in yellow colour

Figure 46: Dub-off zone (DOZ) highlighted in green colour

The volume of the *BCZ*, *DOZ* and the area of the coolant exit *A* & *B* were measured from the 3D CAD model, as shown in table 12. The measurement results showed that when the outer cutting edge angle increased, then the space of the *BCZ*, *DOZ* and the coolant exit area *A* and *B* will decrease as shown in figures 47 and 48.

Table 12: Measurement results for *BCZ* and *DOZ* volume and area of coolant exit *A* and *B*

	Bottom clearance zone, <i>BCZ</i>	Dub-off zone, <i>DOZ</i>	Coolant exit, <i>A</i>	Coolant exit, <i>B</i>
	Volume (mm ³)		Area (mm ²)	
N4	23.336	13.431	4.9909	6.1529
N8	19.672	12.02	4.6108	5.7316
N13	15.631	7.3587	2.5216	3.5047

Figure 47: BCZ and DOZ volume for three types of cutting nose angle design

Figure 48: Coolant exit, A and B area for three types of cutting nose angle design

5.1.2 Coolant hole configuration

Three different types of coolant hole design are available commercially, Single-hole, Two-hole and Kidney-shaped hole as shown in figure 49.

Figure 49: Three different types of coolant hole design on the drill tip

The Single-hole configuration is designed with a diameter of 2 mm single hole on the gun drill tip. The hole is located at the angle of 123° from the cutting edge and 2 mm radius away from center of the drill tip. Total area of the coolant hole is 3.14 mm^2 .

The Two-hole configuration is designed with two different diameter hole. First hole with 1.9 mm diameter is located at the angle of 75° from the cutting edge. Second hole with 1.5 mm diameter is located at 164° from the cutting edge. The area for the 1.9 mm diameter coolant hole is 2.84 mm^2 and area for the 1.5 mm diameter coolant hole is 1.77 mm^2 .

The Kidney-shaped configuration is designed with a 2 mm slot starting from 89° to 178° from the cutting edge. The total area of the coolant hole is 13.39 mm^2 .

5.1.3 Shoulder dub-off designs

Changing of shoulder dub-off angle would influence the coolant flow pressure as reported by Astakhov *et al.* [3]. However, most of the manufacturers still using a fixed dub-off design of 20° for all the drilling application, perhaps due to the lacking of relevant knowledge. To gain a better understanding of the coolant and chip flow behaviour, five different dub-off angles (see figure 50) on N8 nose angle design was chosen in the study.

Figure 50: Five different dub-off angles

As shown in figure 51, by varying the dub-off angle, the volume of the dub-off zone, *DOZ* and the area of the coolant exit *B* will be altered. From the measurements shows given in table 13, increasing the dub-off angle of drill, the space of *DOZ* and the area of the coolant exit *B* will also increase.

Figure 51: Changing the dub-off angle leads to variation of dub-off zone (DOZ) area

Table 13: Measurement results for DOZ volume and area of coolant exit *B* in 5 different dub-off angles

Dub-off angle	Dub-off zone, mm ³	Coolant exit B, mm ²
0°	8.719	3.232
5°	9.529	3.831
10°	10.352	4.439
20°	12.020	5.731
30°	14.064	7.184

5.2. Visualization of high pressure coolant flow behaviour on various drill geometry design

In this section, evaluation of the coolant flow performance on various commercial gun drill geometries, such as cutting nose angle designs, coolant hole configurations and shoulder dub-off angles are analysed using CFD simulation. In the analysis, pressure drop profiles from the coolant supply to the rake are presented to determine the coolant performance. Streamline analyses are also performed to study the direction of the coolant flow.

5.2.1 CFD analysis on coolant hole configurations

The pressure coolant flow behaviour of three coolant hole design (Single-hole, Two-hole and Kidney-shaped) on N8 nose angle design is carried out. Figure 52 shows the high pressure coolant streamlines at the bottom drilled hole. It reveals that the location and the size of the coolant hole would determine the coolant performance. The results showed gun drill tip with the Single-hole design has the least efficient to cool the flank face as compared to Two-hole and Kidney-shaped. This is due to the location of the hole which is closer to the dub-off zone, *DOZ* (123° from the cutting edge), and hence majority of the coolant flow is diverted towards the shoulder dub-off angle and flow to the rake face leading to the significant pressure loss to the flank face. However, if the hole is repositioned closer to the outer flank, the coolant pressure at the rake face would reduce and as well as the chip evacuation efficiency.

Figure 52: High pressure coolant streamlines at bottom drilled hole for 3 different types of coolant hole design

To overcome these issues, Two-hole coolant configuration was designed (see figure 52). The main function of the lower hole (located at 75° from the cutting edge) is to provide the high pressure to outer flank face, and minor flow would go to the rake face as shown in figure 53a. The coolant flow exit from the upper hole (located at 164° from the cutting edge) directly goes to the v-channel without reaching the cutting zone as shown in figure 53b; this is due to the hole located near to the dub-off zone. This shows that the coolant from the upper hole would help to evacuate the chips more efficiently.

Figure 53: Coolant streamlines in Isometric view (a) Coolant flow from lower hole (b) Coolant flow from upper hole

However, the Two-hole design is still unable to provide high pressure coolant to the rake face, so the Kidney-shaped configuration was designed. The idea is to combine the Two-hole design into a big opening slot so that the high pressure coolant can reach the flank face (see figure 52) and at the same time given the high pressure to the rake face.

Coolant pressure profiles at the coolant exit area, *A* and *B*, and the cutting zone are shown in figure 54. As the coolant escaped from the drill tip, the coolant pressure began to loss significantly from the bottom clearance zone to the cutting zone. As observed from figure 54, Kidney-shaped design has the minimum pressure loss, and then followed by the Single-hole and lastly Two-hole. Kidney-shaped design can thus provide the best coolant performance at the cutting edge.

Figure 54: Coolant pressure profile for 3 different type of coolant hole design (a) at coolant exit area A (b) at coolant exit area B and (c) at cutting zone area

Figure 55 illustrates the coolant pressure distribution of the Kidney-shaped design at the coolant exit area, B . There is a drop in coolant pressure from 4 MPa (inlet pressure) to around 0.7 MPa. For the Two-hole design, coolant pressure dropped from 4 MPa (inlet pressure) to around 0.5 MPa. For the Single-hole design, coolant pressure dropped from 4 MPa (inlet pressure) to around 0.4 MPa.

Figure 55: Amounts of coolant pressure containing at the coolant exit area, B for coolant hole designs

The analysis of coolant streamline in isometric view is shown in figure 56. Results showed high pressure coolant flow will be deflected away from the cutting edge if the coolant hole is located near to the dub-off zone, *DOZ*. In order to improve the flow to cutting zone, drill tip with a Kidney-shaped hole can be designed.

Figure 56: Coolant streamlines analysis on three different types of coolant hole design

5.2.2 CFD analysis on nose angle design

Another drill geometry affects the coolant flow in the drilled hole is changing the nose angle design. As discussed in the section 5.1.1, changing of the nose angle geometry would influence the bottom drilled shape, volume of the bottom clearance zone, *BCZ*, deb-off zone, *DOZ* and the area of the coolant exit *A* and *B*.

The analysis of high pressure coolant streamlines at the bottom drilled hole is shown in figure 57. It shows gun drill with N13 nose angle design can provide better coolant flow to the flank face, and then followed by the N8 and N4. This revealed that increasing the outer cutting edge gun drill would lead to the increase in coolant pressure at the bottom clearance zone, *BCZ*. This is due mainly to the Bernoulli effects, where the outer cutting angle increase would cause the opening area at coolant exit area, *A* to reduce. This would cause the reduction of coolant flow rate at the coolant exit area, *A* and lead to the pressure at the bottom hole to increase.

Figure 57: High pressure coolant streamlines at bottom drilled hole for 3 different types of nose angle design

Although N13 design can provide better cooling to the flank area, but when coolant reaches the rake face cutting zone, pressure dropped is most significantly as compared to the other two designs as shown in figure 58.

Figure 58: Coolant pressure profile for 3 different type of nose angle design (a) at coolant exit area *A* (b) at coolant exit area *B* and (c) at cutting zone area

Figure 59 illustrates the coolant pressure distribution of the N13 design at the coolant exit area, *B*. There is a drop in coolant pressure from 4 MPa (inlet pressure) to 0.04 MPa. For the N8 design, coolant pressure dropped from 4 MPa (inlet pressure) to around 0.5 MPa. For the N4 design, coolant pressure dropped from 4 MPa (inlet pressure) to around 0.5 MPa.

Figure 59: Amounts of coolant pressure containing at the coolant exit area, B for nose angle designs

From the coolant streamlines in isometric views in figure 60, the coolant flow in N13 design is unable to reach the rake face. This is because the greatest outer cutting edge would create a steep bottom hole shape, so the coolant flow will follow the bottom hole shape all the way back without reaching the rake face. To overcome this, the outer angle is reduced to 20° (N4 design), which is found to improve the coolant pressure and the flow direction.

Figure 60: Coolant streamlines analysis on three different types of nose angle design

5.2.3 CFD analysis on shoulder dub-off designs

In this section, three types of shoulder dub-off angle (20° , 10° , 0°) are chosen in the analysis. As observed in figure 61, decreasing of dub-off angle would improve the coolant pressure at bottom clearance zone, *BCZ* and as well as the flow at the rake face. This is because the reduction of dub-off angle would cause the space of the dub-off zone, *DOZ* to reduce, which would cause the coolant flow rate to reduce at the coolant exit, *A* and *B*, and hence leading to pressure increase at *BCZ*.

Figure 61: High pressure coolant streamlines at bottom drilled hole for 3 different types of shoulder dub-off angle design

The coolant pressure profiles at the coolant exit area, *A* and *B* and cutting zone are shown in figure 62. The results show that the coolant pressure drop at the cutting zone can be minimised by decreasing the dub-off angle. With this improvement, the occurrence of vortices at the coolant exit area, *B* is eliminated. Vortex formation occurring at the coolant exit area *B* is mainly due to sudden expansion of flow at greater dub-off angles, resulting in greater pressure losses.

Figure 62: Coolant pressure profile for 3 different type of dub-off angle (a) at coolant exit area A (b) at coolant exit area B and (c) at cutting zone area

Figure 63 illustrates the coolant pressure distribution of the 0° dub-off angle design at the coolant exit area, B. There is a drop in coolant pressure from 4 MPa (inlet pressure) to 1 MPa. The second best design is dub-off angle with 10°, coolant pressure dropped from 4 MPa (inlet pressure) to around 1 MPa. Lastly, followed by the dub-off angle with 20°, coolant pressure dropped significantly from 4 MPa (inlet pressure) to less than 1MPa at coolant exit area, B, thus leading the formation vortices.

Figure 63: Amounts of coolant pressure containing at the coolant exit area, B for shoulder dub-off designs

From the coolant streamlines in isometric views in figure 64, the coolant flow at the rake face can be improved by decreasing the dub-off angle. By decreasing to 0° dub-off angle the flow can be properly guided to the rake face with a minimum pressure loss.

Figure 64: Coolant streamlines analysis on three different types of dub-off angle design

5.3 Effects of dub-off angle on chip evacuation

As discussed in section 5.2.3, changing of the shoulder dub-off angle has a significant influence on the coolant flow to the cutting zone. In this section, an analysis of the effects of dub-off angle on chip evacuation is carried out. Five different angles at 0° , 5° , 10° , 20° and 30° as shown in figure 65 are used to in the calibrated CFD model. The dub-off angles were modified on the N8 nose angle that has Two-hole coolant configuration.

Figure 65: N8 Gun drill nose angle design with various dub-off angles

A comparison of the chip trajectories in five different dub-off angles (figure 66) revealed that as the dub-off angle increases, the chip would travel deeper towards the bottom of the hole. Hence this would heighten the risks of the chip being stuck at the bottom. This is mainly due to the severity of the sudden expansion of the flow at greater dub-off angles, resulting in greater pressure losses and larger regions of flow separation.

Figure 66: Comparison of the chip trajectory with various dub-off angles

As observed in figure 67, 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 for the chip get stuck at the bottom of the hole increased. The results of velocity streamline view (figure 68) and pressure contour view (figure 69) showed 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 the cutting edge. This major finding suggests that designing the dub-off angle between 0° to 10° can facilitate chip evacuation effectively.

Figure 67: Pressure distributions at different dub-off angles

(a)

(b)

Figure 68: Flow behaviour at (a) 0° Dub-angle (b) 30° Dub-angle

Figure 69: Pressure contour views at (a) 0° Dub-angle (b) 30° Dub-angle

5.4 Drilling experiments with different gun drill geometries

Nine combinations of drill geometries are tested with 8 mm commercial gun drill as shown in table 14. The detailed gun drill geometries are shown in section 5.1. Drilling experiments on nickel-based alloy Inconel 718 workpiece (Yield strength 1058 MPa) are conducted on the DMU 80p duoBLOCK® Five axis machine. Constant feed rate of 8 mm/min, spindle speed of 800 rpm and cutting speed of 20 mm/min are used in the drilling process. The coolant pressure of the machine is fixed at 40 bar.

Experiments are conducted under unsupported guide bush condition, so pilot holes with the ratio of 1.5 D (12 mm) were created for all the gundrilling operations. The procedures to create the pilot hole were first using the 7.8 mm diameter twist drill to drill 1.5 D then follow by an endmill with 7.8 mm diameter to flatten the bottom hole and lastly use the 8 mm reamer to obtain the final hole.

Once the pilot holes are created, gun drill was inserted into the hole up to the length of 8 mm without drill rotation. After that, the spindle is activated and coolant supply is turned on to start the gundrilling operation. For each experimental run, drilling of up to 10 mm depth was made, and then the drill is retracted for tool wear inspection. Total drilling depth of 50 mm is conducted.

Table 14: Nine types of drill design combination

Drill no.	Nose angle	Coolant hole	Dub-off angle
1	N8	Two-hole	20°
2	N4	Two-hole	20°
3	N13	Two-hole	20°
4	N8	Single-hole	20°
5	N8	Two-hole	20°
6	N8	Kidney-shaped	20°
7	N8	Two-hole	20°
8	N8	Two-hole	10°
9	N8	Two-hole	5°

5.4.1 Results for commercial gun drill designs

Tool life of nine different combinations of designs were analysed based on the measurement value of maximum flank wear, $VB_{\max}$. The tool wears for every 10 mm of drilling depth were measured by the Keyence Digital Microscope Vh-1000. The flank wear was caused by the friction between the drilled hole surface and drill flank face as shown in figure 70.

Figure 70: Flank wear, VB measurement

At the rake face of the drill, crater wear, K_t was also measured. These values were measured by the Alicona optical 3D non-contact metrology system. The crater wear, was formed by the chips sliding on the rake face and results in a concave section as shown in figure 71.

Figure 71: Crater wear, K_t measurement

Tool wear comparisons between different types of coolant hole design are shown in figure 72 and figure 73 respectively. The results indicated that gun drill with Kidney-shaped design having the least amount of flank wear and as well as crater wear. This trend matches well with the CFD predictions. The CFD analysis also revealed that Kidney-shaped design is capable to deliver the highest coolant pressure and better coolant supply to the cutting edge (flank and rake face) as compared to other 2 designs. Therefore, the gun drill with Kidney-shaped design is found to have highest tool life.

Figure 72: Progressive flank wear, VB_{max} for 3 types of coolant hole design

Figure 73: Crater wear, K_t at 50 mm drilling depth for 3 types of coolant hole design

Tool life of the 3 different nose angles were compared as shown in figure 74. The result shows that tool life for N13 design in drilling of Inconel material can only able to sustain up to a depth of 20 mm. This is due to insufficient coolant at the rake face as revealed from the CFD simulation study. The result shows that coolant flow followed the bottom drilled hole shape and escape all the way back without reaching to the rake face, causing the cutting edge temperature increase rapidly and then leading to excessive crater wears, ultimately the drill will fail as shown in figure 75.

In order to improve tool life, the outer angle of the drill should have a smaller angle; this is to minimize the sudden expansion of the coolant flow at the bottom hole shaped. As observed from the CFD results, by reducing the outer angle of the drill (from 40° to 20°), the coolant flow can be properly guided to the rake face. Therefore, the K_t value is reduced as shown in figure 76.

Figure 74: Progressive flank wear, VB_{max} for 3 types of nose angle design

Figure 75: N13 drill design failure

Figure 76: Crater wear at 50 mm drilling depth for 3 types of nose angle design

Tool wear comparisons of three shoulder dub-off angles are shown in figure 77. The results revealed that flank wear was improved when the dub-off angle

decreases; this is because decreasing the dub-off angle would enhance the coolant pressure at the bottom clearance zone which was explained in the CFD analysis.

Moreover, it was also found that the flow quality at the coolant exit, *A* was improved. With this uniform flow, the flow can be guided properly to reach the rake face without vortex occurring, and hence improving the chip evacuation from the cutting edge. This explains why the crater wear (see figure 78) is drastically improved when the smaller dub-off angles is applied.

Figure 77: Progressive flank wear, VB_{max} for 3 types of dub-off angle design

Figure 78: Crater wear at 50 mm drilling depth for 3 types of dub-off angle design

5.4.2 Results for new drill design

Based on the previous CFD analysis and experimental findings, a new gun drill was designed and developed. The drill was designed based on the optimum design of coolant hole, dub-off angle and nose angle. A new drill with a Kidney-shaped coolant hole design, shoulder dub-off with 0° and N4 nose angle design was introduced in figure 79.

Tool life test were investigated for the new drill and compared to the nine different commercial drill designs as shown in figure 80. The results revealed an optimum drill has the least flank wear and the tool life in 50 mm drilling depth has improved near to 50 % as compared to the worst tool life drill design. Moreover, the value of crater wear, K_t was also improved to less than 1 μm as shown in figure 81.

Figure 79: New drill design; combination of Kidney-shaped hole, 0° dub-off angle and N4 (outer 20°, inner 10°) nose grind

Figure 80: Flank wear, VB_{max} comparison between 7 type of commercial drill and new concept drill designs

Figure 81: Crater wear, K_t at 50 mm drilling depth for 7 types of commercial drill and new concept drill design

6 Conclusions and suggestions for future work

The main objective of this project was to develop a computer fluid dynamic (CFD) numerical method to quantify the chip motions in gun drilling. At the onset of this study, a fundamental study on the gun chips flow motions was carried out through freefall drop test experiments and CFD simulation. In the experiments, terminal velocities of typical gun drill chips at different fluid concentrations were determined to calculate the drag coefficients in the Reynolds number ranging from 0.06 to 36. The results obtained from the CFD were compared with the experimental data and correlated formula predicted by Holzer and Sommerfeld [13].

Once the CFD model was verified, the next study of chip flow behaviour was carried out in the actual gun drilling. The method to predict the chip flow trajectories in gun drill was determined based on the combination of CFD simulation and mathematical calculation. The CFD model was performed to evaluating the coolant performance on various convectional drill designs such as coolant hole configurations, nose angle designs and shoulder deb-off angles were analysed. A case study of evaluating the efficacy of chip evacuation was carried out on different deb-off angles. To validate the CFD findings, gun drilling on Inconel 718 with a total of 9 different combinations of 8 mm commercial gun drill designs were performed. The main findings of the work were summarized as follows.

6.1 Conclusions

6.1.1 Chips flow behaviour in vertical drop test

- In the comparison of the drag curve between the typical gun drill chips and generic shape from the literature (Holzer and Sommerfeld [13]), it was found that the drag characteristics of chips could be approximated to thin disks that have the same sphericity to the chip.

- Comparing between the Holzer and Sommerfeld [13] correlation formula and the CFD model, the drag data computed from the CFD have better agreement with experimental results.
- Discrepancies of the CFD data was mainly due to the oscillation of the chip taking place when it settles downward. Oscillations in lateral motion were mainly caused by the vortices acting on it. This behaviour can be observed from the experiments and quantified with the CFD model.

6.1.2 Coolant and chip flow behaviour in gundrilling

- The results from the effects of coolant hole designs show that Kidney-shaped is the best design for coolant flow to reach the cutting edge and as well as minimum hydraulic pressure loss. This is followed by the Two-hole and lastly the Single-hole design. With the optimum coolant supply, the flank and crater wear would be reduced as tested from the drilling experiments.
- The results from the effects of nose angle designs show that with the greater the outer angle is, the greater the tendencies for the flow stagnate at the rake face cutting zone. A large region of flow stagnation at the cutting zone was occurred when the outer angle is more than 30° (N13 design). Therefore, N13 design has the shortest tool life for gundrilling of Inconel material. To improve the tool life, the outer angle should decrease to 20° like the N4 design, so that coolant flow can be properly guided to the rake face.
- The results from the effects of shoulder deb-off designs show that increase the deb-off angle would increase the pressure loss at the bottom clearance and rake face cutting zone. This is due to the sudden expansion of the flow at the shoulder deb-off. With deb-off angle at 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, chips would get stuck to the bottom of the hole. Therefore it is suggested dub-off angles ranging from 0° to 10° can facilitate chip evacuation much more effectively. This result explained why the tool life was better on the drill with 0° dub-off angle.

Finally, based on the CFD analysis and experimental findings, a new concept gun drill was designed and developed to prolong the tool life for gundrilling of Inconel material.

6.2 Suggestion for future work

In this project, a novel computational fluid dynamics (CFD) model that is capable to simulate and quantify the coolant flow and chip transportation behaviours was developed. The CFD model successfully determines the optimum drill geometric from the wide range of commercial drill designs for drilling on the Inconel 718. This study found that the performance of coolant flow to the cutting zone is highly dependent on the drill geometries and profile of the bottom drilled hole which can affect the change of coolant pressure, flow rate and the direction of the flow.

With the understanding gained in this project, a mathematical model can be further developed to predict the coolant and chip evacuation performance. The mathematical model can be included with a set of parameters such as cutting edge angles, dub-off angles, coolant hole designs, relief angles, inlet coolant pressure, and coolant properties. To study the effects of inlet coolant pressure and coolant properties, a special custom made flow loop system as shown in figure 82 was proposed. With this apparatus, experimental studies on the effects of coolant pressure, cutting tool materials, cutting temperature, coolant foaming, chip breaking in different coolant concentrations can be analysed.

Figure 82: Experimental flow apparatus

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