Abstract

Studies on Minimum Quantity Lubrication in Turning Process

-Simplified and practical evaluation of lubricating and cooling effects of oil mist by means of Finite Element Method-

旋削加工における MQL（最少量潤滑）に関する研究

−有限要素法によるオイルミストの潤滑および冷却効果の簡易的かつ実践的評価法−

Graduate School of Natural Science & Technology

Kanazawa University

Division of Mechanical Science and Engineering

Student ID Number : 1424032001

Name : Ahmad Shahir bin Jamaludin

Chief advisor : Prof. Akira Hosokawa

Abstract

In the examination of Minimum Quantity Lubrication (MQL) in cutting process, it is necessary to understand exactly the tribological characteristics of tool-work/chip interface, because it reflects the cutting performance such as cutting force, cutting temperature, chip geometry and/or morphology, and tool life. In the simplified cutting model, the friction coefficient between the tool and chip is one of the fundamental parameters involving tribological phenomenon. The study deals with the appropriate Finite Element Method to analyze the capability of the Minimum Quantity Lubrication in turning process of mild steel base on the experimental data. FEM analytical models are designed and executed using the application package software DEFORM™-3D. In the meantime, orthogonal cutting tests of medium steel JIS S45C is executed with the TiCN-coated cermet tool in order to obtain the involved parameter to reduce speculation. Three significant variables: average Coulomb friction coefficient; chip thickness and contact length: are obtained from the experiment. It is proven that the DEFORM™-3D software is capable to evaluating the influence of MQL with a good degree of accuracy through the proposed FEM process. The influence of MQL onto turning process of difficult-to-cut materials SUS316 is also covered by the thesis. New type of MQL system is proposed. It is found that Extreme Cold Mist capable to improve the machinability of SUS316 in term of cutting force, surface roughness and cutting tool temperature compared to cutting process with dry method.

1.0 Introduction

Conventional wet cutting method has tended to shift to dry or semi-dry cutting due to a large amount of cutting fluid leads to the increment of power consumption and processing cost. In addition, the cutting fluid by-product obtained from the process pollutes the working environment that affected the health of the machine operators. Therefore, the development of Minimum Quantity Lubrication (MQL) machining is emphasized in solving and containing these matters [1].

In MQL cutting, a very small amount of cutting fluid is turned into fine oil mist, and supplied onto the cutting point as semi-dry processing, expecting the promotion of the cutting performance of tools in terms of tool integrity, product finish and power consumption. Approximately only 1/10000 fluid volume of that in the ordinary wet cutting is consumed during MQL, which leads to cleaning the working environment and reduction of waste liquid that lessen the overall processing cost [1]. Several researchers have been done in identifying the effect of Minimum Quantity Lubrication (MQL) during cutting process [1]. It is proven that MQL method can reduce the cutting force and cutting temperature, which leads to improvement of the surface finish and increment of tool life. However, it is still yet hard to be understood on how lubrication works during the cutting process because the frictional contact mechanism between cutting tool and workpiece/chip is considered as complex

Previous researchers did several studies in order to identify the parameters involved during one cutting process and their relationships between cutting performances [2-7]. The finite element method analysis is an important research tool in improving manufacturing and industrial capability, especially in mold making. However, it is considered difficult to design a perfect simulation model as the actual cutting process because of its complexity.

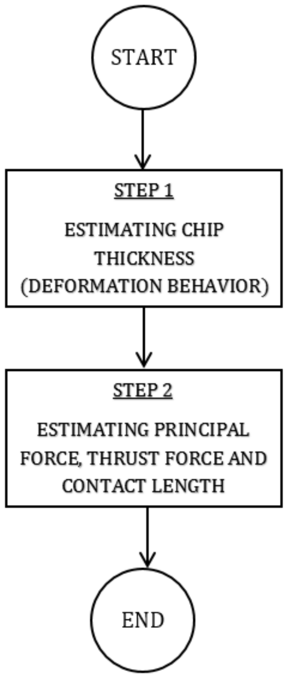

Fig. 1 Overview of main process in estimating influence of MQL by FEM

In recent years, application of finite element method (FEM) has become renowned in simulating high speed machining. Finite element method (FEM) is a numerical method that separates a problem into smaller regions. It is proven useful in saving the research cost and time. In addition, it is capable to forecast effects of cutting parameter such as cutting force and cutting edge temperature [8].

This thesis touches about the evaluation on the effect of MQL during cutting process with the application of FEM, as well as its efficiency in cutting difficult-to-cut material.

2.0 Methodology

The methodology is divided into two parts. The first part involves the application of FEM in evaluating MQL, while the second part explains the experimental procedure on conventional turning process where several MQL systems is applied and analyzed.

Fig. 1 shows the overview of main process in estimating the influence of MQL process specifically by FEM, regardless to the lack of accurate information of material deformation behavior. It is found in the study that, FEM is incapable to estimate whole parameter accurately simultaneously, whereas it is found that it is not enough to simulate the cutting under MQL behavior with just frictional coefficient measured experimentally. The process involves mathematical model in calculating frictional coefficient to estimate chip thickness, which is validated experimentally and resemble the actual lubrication phenomenon of MQL.

Based on the estimated chip thickness by the first step, the actual simulation on MQL will be executed with an appropriate FEM model that applies frictional coefficient and chip thickness. The accuracy of estimating the deformation is important whereas mechanical behavior of material is significantly related to the thermal behavior in actual cutting process.

2.1A Orthogonal cutting experiment on the effect of MQL

In this study, a pseudo orthogonal cutting tests of mild steel, JIS-S45C are carried out by OKUMA turning center, as shown in **Figs. 2a and 2b.** The insert has 0° rake angle and 10° clearance angle. In the orthogonal cutting tests, cutting speed range of 50, 100 and 200 m/min and depth of cut of *a*=0.3 mm (feed rate iny-direction is 0.3.mm/rev) are applied. The depth-of-cut (feed rate) is more than 10 times larger than the tool edge radius of 0.013 mm, which is assumed enough to neglect the effect of tool edge radius.

The orthogonal cutting conditions and material properties are shown in **Tables I and II**. The cutting forces are measured by a strain gauge type dynamometer. Chip thickness, t_c and contact length, l_c between chip and tool are also measured from the scratch mark left on the rake face of the tool for each cutting speed condition as shown in **Figs. 3 and 4**.

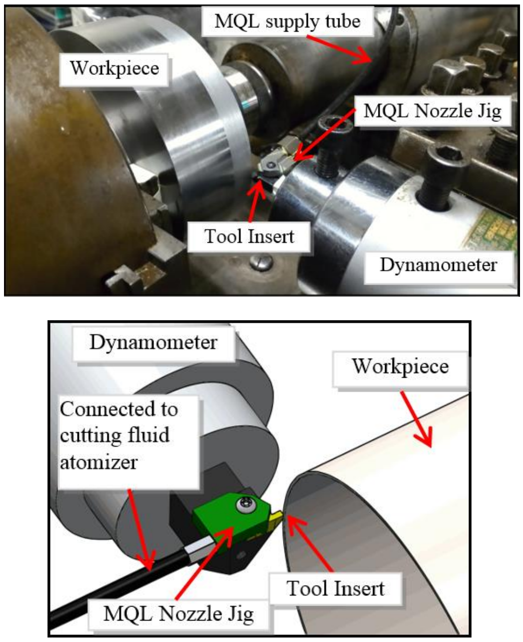

Fig. 2 Pseudo orthogonal cutting tests of mild steel, JIS-S45C are carried out by OKUMA turning center

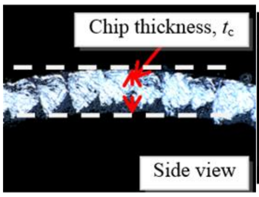

Fig. 3 Measurement of chip thickness

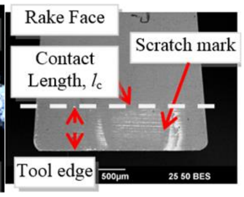

Fig.4 Measurement of tool-chip contact

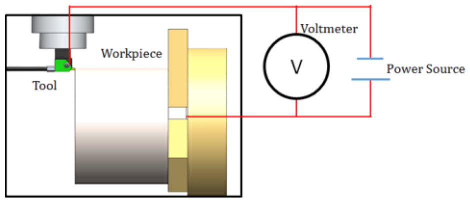

Fig. 5 Thermocouple method

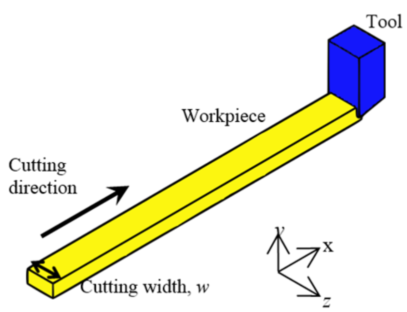

Fig. 6 Simplified FEM orthogonal cutting model in DEFORM-3D™

In the experiments, both dry and MQL assisted cutting tests are executed in order to obtain the parameter variation. The MQL outlet nozzle for orthogonal cutting is designed so as to supply oil mist onto the cutting edge accurately as shown in **Fig. 2b**. Two types of oil mist are used based on the variable composition between nontoxic vegetable oil and water. The composition of Oil-A is 99% vegetable oil and 1%water, while the composition of Oil-B is 30% vegetable oil and 70% water. Oil-A is supplied at 30 mL/h, while Oil-B is supplied 100 mL/h onto the tool rake face during the cutting process to ensure equivalent lubrication property, while Oil-B has additional coolant property. The properties of the oil mist applied in the study are summarized in **Table III.**

In the study, mean cutting temperature for each cutting conditions is measured with the application of tool-work thermocouple method, as shown in **Figs. 5.**

2.1B Finite Element Analysis on the effect of MQL

In this study, FEM simulation models in orthogonal cutting of mild steel, JIS-S45C is designed on the application software DEFORM™-3D, whereby the workpiece and cutting tool geometries are designed and simplified by the application of Computer-Aided Design (CAD), as shown in **Fig. 6**. DEFORM™ is a well-known commercially available FEM tool, with one of the best in graphical-user-interface (GUI), specialized in simulating metal forming.

In addition, the FEM tool employs Lagrangian formulation suitable for large deformation, as well as capable of generating specific mesh density for severe deformation zone on the workpiece. In the simulation, the FEM cutting tool is designed to resemble the actual orthogonal cutting-tool geometry at the cutting zone, with 0° rake angle and 10° clearance angle. The effect of tool edge radius is neglected, as the orthogonal cutting depth is

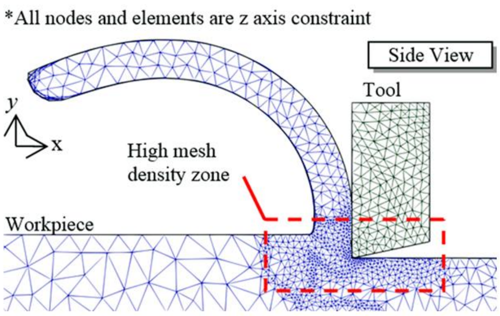

Fig. 7 Mesh structure in FEM model

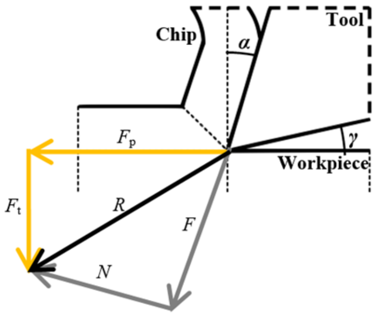

Fig. 8 Force vectors during typical cutting process

$$\mu_{\text{avg}} = \frac{F}{N} = \left(\frac{F_t + F_p \tan\alpha}{F_p - F_t \tan\alpha}\right) \quad \textbf{(Eq. 1)}$$

Table I Cutting condition for orthogonal cutting and FEM

Cuting tool			TiCN-coated Cermet
Workpiece			JIS S45C
Cutting width	w	[mm]	1.0
Depth of cut	a	[mm]	0.5
Cutting speed	v_c	[m/min]	50, 100, 200

Table II Properties of workpiece materials for FEM application

Material			JIS S45C
Young modulus	E	[GPa]	212
Density	ρ	[kg/m^3]	7850
Vickers hardness	HV0.3	[GPa]	1.96

Table III Properties of MQL oil and supply conditions

Cuting oil			A	B
Type			Vegetable oil	
Viscosity	v	[mm^2/s]	37	
Oil content		[%]	99	30
Flow rate	q	[cc/h]	30	100
Oil pressure	p	[MPa]	0.6	

more than 10 times larger than the tool edge radius in the equivalent experimental procedure. In the analysis, workpiece is designed to deform plastically, while elastic-deformation of cutting tool is neglected due to its large ratio of Young Modulus between the tool and workpiece materials, thus cutting tool is designed to be rigid. In the analysis, denser mesh is formed at the tool-workpiece contact where significant plastic deformation occurs. Adaptive meshing, ability to re-mesh whenever tool and workpiece's mesh overlapping occurred is applied, and the initial maximum number of elements in the tool is 10,000 elements, 50,000 elements for the workpiece.

Fig. 7 shows mesh structure in FEM model and all elements are constraints from distorting on Z-axis for the workpiece to deform in two-dimensional directions (X and Y axes). The cutting condition and material properties for FEM application are similar to the orthogonal cutting experiment, as shown in **Table I** and **Table II**, respectively. In term of designing a FEM model that can describes the actual cutting process, Previous researchers had applied average frictional coefficients, μ_{avg}, based on Coulomb's law of friction calculated by **Eq. (1)** from experimentally measured cutting forces, into their FEM model, referring to **Fig. 8**. It is assumed that the friction coefficient has a direct relationship to the actual friction phenomenon on the contact zone during the cutting process [9].

In evaluating the effect of coolant, two out of three zones of heat source are taken into consideration in the FEM model. These zones are primary zone (shearing deformation) and secondary zone (frictional contact between tool rake face and chip), as shown in **Fig. 9** [25]. As the ratio between tool edge and cutting depth are significantly large, the heat generation on tertiary zone (frictional contact between tool flank face and machined surface) is neglected. Although the mechanism of MQL during the cutting process is not yet fully

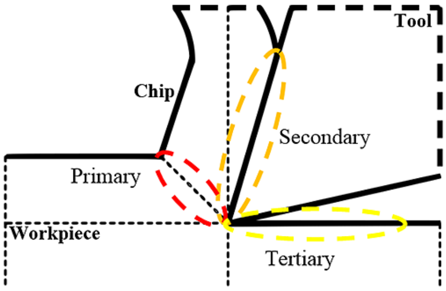

Fig. 9 Main sources of heat generation during orthogonal cutting

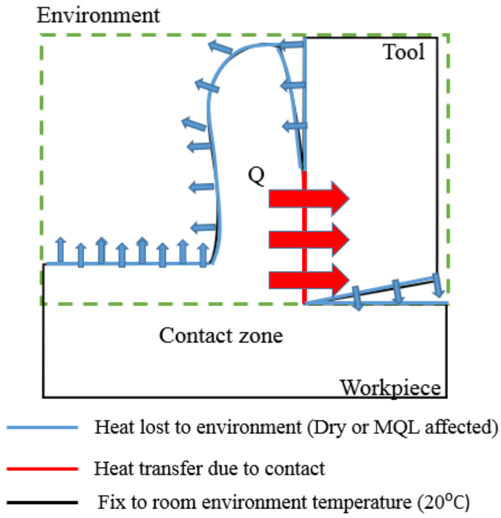

Fig. 10 Boundary condition for temperature analysis on MQL influence

understood and it is still incapable to simulate the inhomogeneous properties of MQL mist, following assumptions are made in order to examine the influence of MQL during the cutting process:

- Oil mist is completely covered the open surface of tool, chip and workpiece to the environment.
- MQL affects heat convection rate to the environment properties during the cutting process.
- The contacts between tool and chip and tool and workpiece are thermally perfect, having a large heat transfer coefficient (1000 kW/ (m^2·K)).
- Thermal softening and hardening, as well as phase transformation of chip and workpiece are neglected.

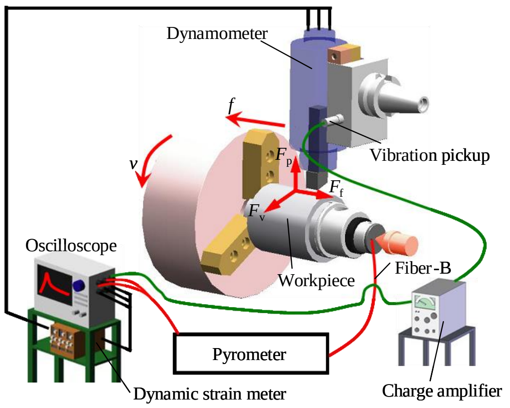

Fig. 11 Experimental setup for conventional turning with temperature measurement with pyrometer

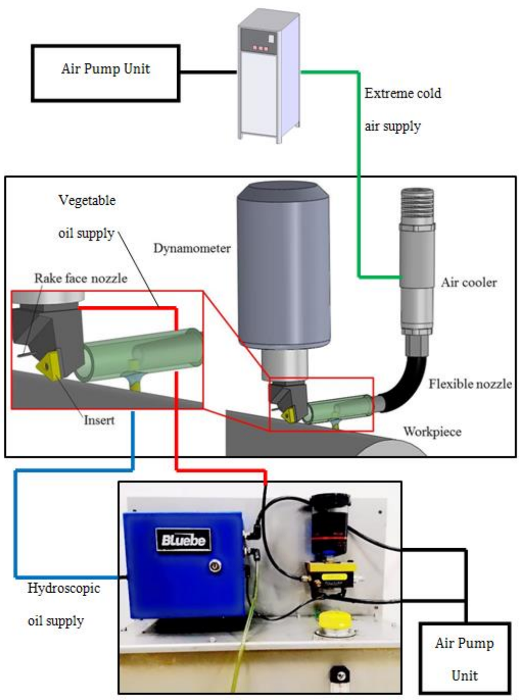

Fig. 12 MQL supplying system in conventional turning

Table IV: Heat transfer coefficients in FEM analysis

Heat Transfer Coefficient			Dry	Oil-A	Oil-B
Tool-Chip Boundary	h_c	[kW/(m².K)]	1000	1000	1000
Environment	h	[kW/(m².K)]	0.02	0.35	30

- The mean temperature estimated from the contact zone, l_c between tool and chip is calculated and compared to the experimental results.

The boundary conditions and involved coefficients for temperature analysis are summarized in **Fig. 10** and **Table IV**,

Table V: Material properties stainless steel, SUS316

Materials	SUS316
Young Modulus, E (GPa)	**205**
Poisson Ratio, ε	0.30
Thermal Conductivity, k (W/(m·K))	**17**
Density, ρ (kg/m^3)	**8070**
Volumetric Heat Capacity, c (10^6 J/(m^3·K))	**2.78**
Hardness Vickers, HV$_{0.3}$ (GPa)	**2.2**

Table VI: Main experimental cutting condition

Cutting Speed	:	50 ~ 200(m/min)
Depth of Cut	:	0.5(mm)
Feed	:	0.3(mm/rev)
Cutting Style	:	Dry, Various types of dual spray MQL, MQL and cold air

Table VII Variation of MQL supplying system applied

System Type	MQL type for rake face	Fluid rate (mL/h)	MQL type for flank face	Fluid rate (mL/h)	Total fluid rate (mL/h)
Dry	**Dry**	**-**	**Dry**	**-**	**-**
A	**Oil A**	**30**	**Dry**	**-**	**30**
B	Oil B	100	Dry	-	100
C	**Oil A**	**30**	**Cold air**	**-**	**30**
D	Oil A	30	Oil B	100	130
E	**Oil A**	**30**	**Cold air +Oil B**	**100**	**130**

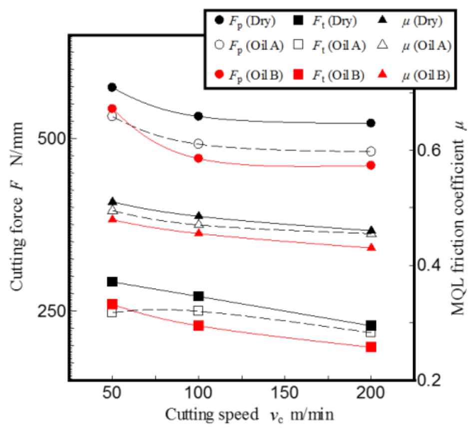

Fig. 13 Relationship between cutting speed v_c and cutting force F in various MQL methods

respectively.

2.2 Conventional turning process on stainless steel SUS316 with Extreme Cold Mist

In this study, specially designed workpiece for optical fiber application in temperature measurement is prepared, as shown in **Fig. 11**. Cutting forces is measured by a strain gauge dynamometer while cutting temperature is measured by the two-color pyrometer. In this study, stainless steel SUS316 is selected as workpiece. Material properties and main experimental conditions are shown in **Table V and Table VI.**

In this study, a system capable in supplying several types of heterogeneous Minimum Quantity Lubrication (MQL) cutting fluids to the rake and flank surface of the cutting tool are designed (**Fig. 12**). MQL with lubrication characteristic is supplied onto rake face of the tool by rake face nozzle. The characteristics of cutting fluids applied in the study and MQL systems are shown in **Table III** and **Table VII.**

3.1 Influence of MQL onto cutting force, chip thickness and contact length behavior in orthogonal cutting

It is observed in orthogonal cutting process that both principal and thrust force

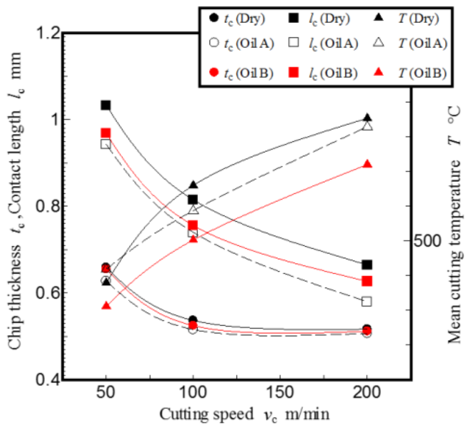

Fig. 14 Relationship between cutting speed v_c and chip thickness t_c and contact length l_c in various MQL methods

decreases as the cutting speed increases in general (Dry, LB1-MQL (Oil A) and LB70-MQL(Oil B)) as shown in **Fig. 13**. Similar

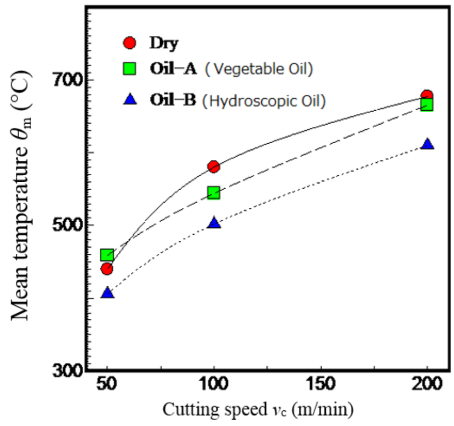

Fig. 15 Relationship between cutting speed v_c and experimentally measured mean cutting temperature θ_m

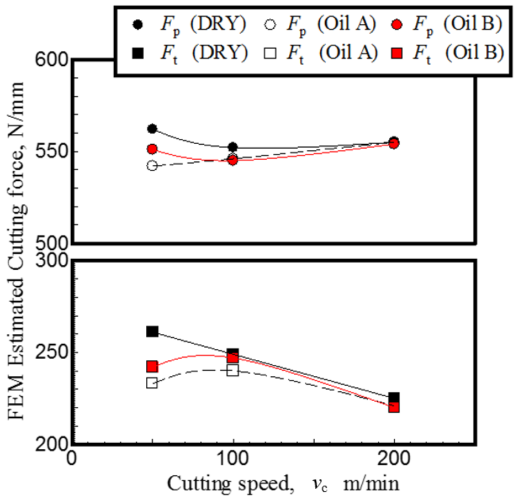

Fig. 16 Relationship between cutting speed v_c and cutting force F estimated by FEM

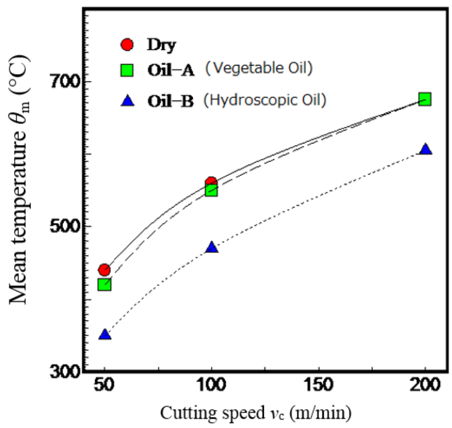

Fig 17 Relationship between cutting speed v_c and mean cutting temperature θ_m estimated by FEM with μ_{exp} and chip thickness t_c input.

trend is observed for the relationship between cutting speed and tool-chip contact length l_c and chip thickness t_c as shown in **Fig. 14**. It is observed that both l_c and t_c decrease as the cutting speed increases for dry and both MQL cutting conditions. It is understood that cutting force has a direct relationship to the cutting load and contact characteristic, where lower magnitude of cutting forces and size of contact length and chip thickness is observed on the application of MQL during the cutting process, as shown in **Figs. 13** and **14**. It is assumed that the existence of MQL molecule between tool and chip contact zone is capable in reducing the frictional stress, whereas the MQL molecule is assumed to act as a roller or spring like element.

Fig. 15 shows the relationship between cutting speed and mean cutting temperature measured by the tool-work thermocouple method during dry and MQL conditions. It can be observed that the cutting temperature increases with the increasing of cutting speed due to increasing cutting energy regardless with the decreasing cutting force. Meanwhile, cutting temperature in MQL assisted cutting (Oil-A and Oil-B) is lower than that in the dry cutting. It can be assumed that, the existence of foreign substance (oil or water molecule) between chip and tool surface is capable to absorb or conduct the heat away from the cutting zone.

Additionally, MQL assisted cutting with Oil-B shows significantly lower cutting temperature than Oil-A due to its water composition as coolant, is assumed being able to conduct the heat away with higher efficiency. The experimental results will be utilized in analyzing the efficiency of the FEM model later in this study.

3.2 Validation of the influence of MQL by FEM

MQL estimation FEM model is executed with similar frictional coefficient input, $\mu_n = \mu_{exp}$. It is observed that the FEM Model-B, as shown in **Fig 16**, estimates both principal force F_p and thrust force F_t with a good degree of accuracy.

Fig. 17 shows the relationship between cutting speed and mean temperature at tool-chip contact estimated by the FEM analysis. It can be observed that cutting temperature increases as the cutting speed increases, which has similar tendency to the experimental results. It can be justified that the FEM is capable to estimate the cutting temperature in the orthogonal cutting process with a good degree of accuracy when the appropriate heat convection coefficient to the environment with respect to the type of mist is used as a cooling parameter.

This shows that *MQL estimation FEM model* is capable to estimate the behavior of MQL in term of lubrication and cooling effect with higher accuracy when the MQL related chip thickness data is available. However, the method of limiting the node deformation mathematically is considered invalid in term of actual cutting process. Due to several limitations such as accurate material deformation model and contact heat transfer coefficient, it is considered agreeable in approximating the cutting behavior under MQL influence.

3.3 Influence of MQL onto machinability of Stainless Steel, SUS316

Figs. 18(a), 18(b) and 18(c) show the relationship between cutting speed v_c and cutting force components: principal force F_p, thrust force F_t, and feed force F_f: during the cutting process of stainless steel (SUS316) with TiCN-coated cermet cutting tool, respectively. The cutting process involves several types of MQL systems, for depth of cut a=0.5 mm, and feed rate f=0.3 mm/rev conventional turning process.

It is observed that the cutting force decreases as the cutting speed increases. The principal force F_p decreases up to approximately 50N with the application of MQL Type A and E. Meanwhile, feed force F_f and thrust force F_t decrease up to nearly 30N and 60N, respectively with the application of MQL Type E. It is assumed that the oil mist is able to penetrate the contact zone between chip and cutting tool with high efficiency for MQL system Type A and Type E, where the systems are able to reduce principal force, F_p.

However, only MQL system Type E is able to reduce feed force F_f and thrust force F_t with higher efficiency due to its ability in reducing the temperature at the tool flank with its extremely low temperature cold mist and higher total fluid rate.

Fig. 19 shows the relationship between cutting speed v_c and mean surface roughness, Ra (during the cutting process of stainless steel (SUS 316) with TiCN-coated cermet cutting tool in dry and MQL system Type A, C and E under the cutting conditions that depth of cut a=0.5 mm, feed rate f=0.3 mm/rev.

It is observed that the mean surface roughness decreases as cutting speed increases, meanwhile MQL system Type E shows the lowest mean surface roughness followed by MQL system Type C. It can be understood that low temperature cutting tool with MQL possible to increase the rigidity of tool by lowering the temperature, mixed with lubrication properties in MQL system Type E, surface roughness can be improved.

Fig. 20 shows the relationship between cutting speed v_c and tool edge temperature, θ (during the cutting process of stainless steel (SUS 316) with TiCN-coated cermet cutting tool in dry and MQL system Type A, C and E under the cutting conditions that depth of cut a=0.5 mm, feed rate f=0.3 mm/rev.

It is observed that the cutting temperature of Extreme Cold Mist system shows the lowest tool edge temperature, up to 100~150°C compared to dry cutting condition, and up to 50°C compared to MQL system Type C. It can be assumed that during the

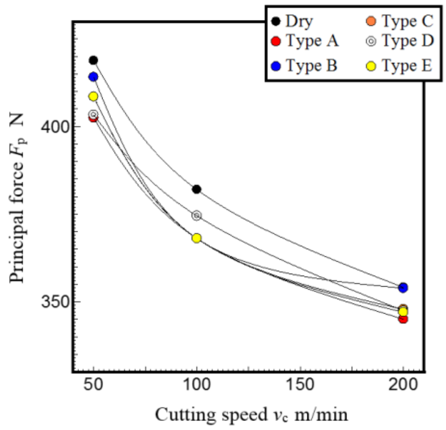

Fig. 18 (a) Relationship between cutting speed v_c and principal force F_p for various MQL systems

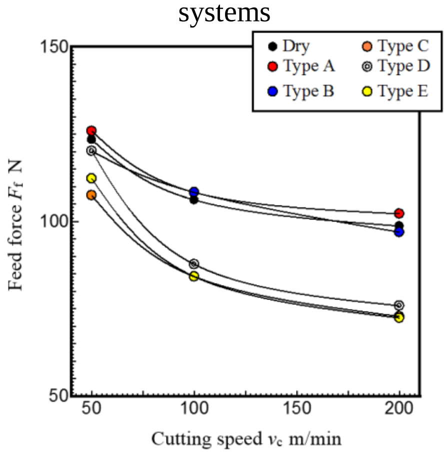

Fig. 18 (b) Relationship between cutting speed v_c and feed force F_f for various MQL systems

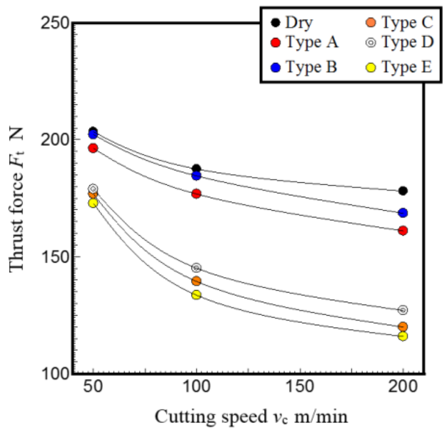

Fig. 18 (c) Relationship between cutting speed v_c and thrust force F_t for various MQL systems

Extreme Cold Mist system, the tool edge is cooled by forced heat convection of extreme cold air, plus with latent heat of oil mist (Hydroscopic oil).

Additionally, in Extreme Cold Mist system, the lubrication is improved and cutting chip is discharge smoothly. Thus, it is assumed that the temperature is reduced further by stable cutting process, supported by tool edge temperature results by MQL System Type A, where only vegetable oil is supplied onto rake face. In term of cutting efficiency, by taken into consideration of the tool edge temperature for cutting speed 200 m/min for MQL system Type E (Extreme Cold Mist system), which is 700°C, the equivalent temperature for dry cutting process is at the cutting speed of 50 m/min. Thus, the cutting efficiency with the

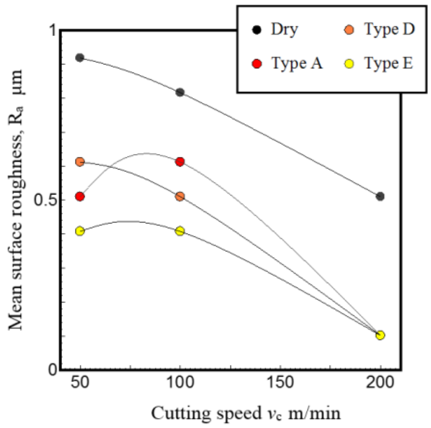

Fig. 19 Relationship between cutting speed v_c and mean surface roughness *R*a for various MQL systems

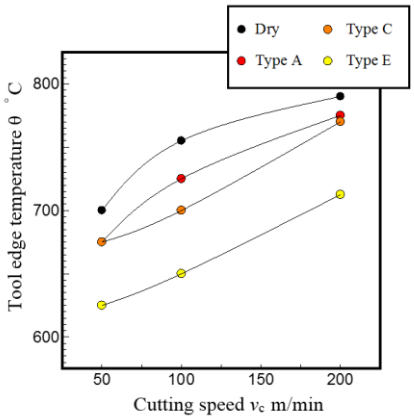

Fig 20 Relationship between cutting speed v_c and tool edge temperature θ

application of MQL system Type E (Extreme Cold Mist system) is 200/50 = 4.0 times higher than dry cutting.

Together with the results of cutting resistance, finish surface roughness, and tool flank temperature, the best results are obtained when Extreme Cold Mist system is applied during the cutting process, where vegetable oil is supplied on the rake face and combination of Hydroscopic oil with Extreme cold air onto the flank face.

Thus, it can be considered that MQL system Type E (Extreme Cold Mist system) is the best MQL system based on current study.

4.0 Conclusions

The conclusions in this thesis are written in 2 parts, FEM evaluation of MQL and Influence of MQL onto difficult-to-cut material turning process.

4.1 FEM evaluation of MQL

A FEM model is designed in order to simulate the cutting process with the application of SFTC DEFORM™-3D and orthogonal cutting process of the medium carbon steel, JIS S45C.

1. Experimentally obtained data such as the cutting force; average Coulomb friction coefficient, μ_{avg}; contact length, l_c and chip thickness, t_c are utilized in validating the FEM model accuracy.
2. The FEM model applied Arbitrary Lagrangian-Eulerian (ALE) formulations in estimating the chip deformations, where pre-determined chip thickness equivalent to the experimentally obtained data along with Coulomb friction coefficient is applied.
3. It is found that cutting force has a direct relationship with Coulomb friction coefficient and chip thickness. This phenomenon is proven by FEM where the various Coulomb friction coefficient input obtained from the experimental procedure

on various type of MQL, affected the estimated cutting force.

4. The FEM shows significant accuracy with the experimental results. The study shows that FEM is able to aid in understanding the influence of MQL during the cutting process.

4.2.1 Influence of MQL onto turning process

In this study, turning processing experiments were conducted on stainless steel (SUS316) with the application of various MQL conditions. Cutting force was measured and the effect of cold air was studied. Several conclusions can be made as following.

1. Supplying vegetable oil to the rake face is able to reduce principal cutting force component F_p up to 50N compared to the dry type, whereas the vegetable oil mist able to lubricate the contact surface between tool and chip.
2. By supplying cold air (–13.6°C) + hydroscopic oil (Extreme Cold Mist system) at 100mL/h volume rate, the system is able to decrease feed force F_f and thrust force F_t component up to 30N and 60N compared to dry type, respectively.
3. By supplying cold air (–13.6°C) to the flank face (Extreme Cold Mist system); the finished surface roughness is greatly improved compared with the dry type.
4. By supplying cold air (–13.6°C) to the flank face (Extreme Cold Mist system), cutting temperature is reduced up to 100~150°C compared to dry cutting condition.
5. Application of Extreme Cold Mist system, the effectiveness of cutting process is 4.0 times higher than dry cutting.
6. Based on the information obtained from cutting force, finish surface roughness and tool flank temperature, it can be concluded that Extreme Cold Mist system is the best MQL system in current study.

References:

[1] S. Debnath, M. M. Reddy, and Q. S. Yi, “Environmental friendly cutting fluids and cooling techniques in machining: a review,” Journal of Cleaner Production, Volume 83, Pages 33-47, (2014).

[2] E.M. Kopalinsky, P.L.B. Oxley, “An Investigation of the influence of feed and rake angle on the ratio of feed force to cutting force when machining with negative rake angle tools,” Annals of the CIRP, Vol. 33, Issue 1, pp. 43-46 (1984).

[3] G. Sutter, “Chip geometries during high-speed machining for orthogonal cutting conditions,” International Journal of Machine Tools & Manufacture, 45, pp. 719-726, (2005).

[4] T.H.C. Childs, “Friction modelling in metal cutting,” Wear, Vol. 260, Issue 3, pp. 310-318 (2006).

[5] C. J. Rao, D. Nageswara Rao, P. Srihari, “Influence of cutting parameters on cutting force and surface finish in turning operation,” Procedia Engineering, Vol. 64, pp. 1405-1415 (2013).

[6] B. de Agustina, C. Bernal, A. M. Camacho, E. M. Rubio, “Experimental Analysis of the Cutting Forces Obtained in Dry Turning Processes of UNS A97075 Aluminum Alloys,” Procedia Engineering, Vol. 63, pp. 694-699 (2013).

[7] B. Denkena, J. Kohler, R. Meyer, J-H Stiffel, “Modification of the tool-workpiece contact conditions to influence the tool wear and workpiece loading during hard turning”, Int. J. Automation Technol., Vol. 5 No. 3, pp. 353-361 (2011).

[8] N. A. Abukhshim, P. T. Mativenga, M. A. Sheikh, “Heat generation and temperature prediction in metal cutting: Review and implications for high speed machining,” International Journal of Machine Tools &Manufacture,Vol. 46, pp. 782-800 (2006).

[9] M. Abouridouane, F. Klocke, D. Lung, D. Veselovac, “The Mechanics of Cutting: In-situ Measurement and Modelling,” Procedia CIRP, Vol. 31, pp. 246-251 (2015).

平成29年1月31日

学位論文審査報告書（甲）

1．学位論文題目（外国語の場合は和訳を付けること。）

Studies on Minimum Quantity Lubrication in Turning Process —Simplified and practical evaluation of lubricating and cooling effects of oil mist by means of Finite Element Method—

（邦題訳又は英訳）旋削加工におけるMQL（最少量潤滑）に関する研究　—有限要素法によるオイルミストの潤滑および冷却効果の簡易的かつ実践的評価法—

2．論文提出者　(1) 所　　属　機械科学　専攻

(2) 氏（ふりがな）　名　Ahmad Shahir Bin Jamaludin（アハマド シャヒルビン ジャマルディン）

3．審査結果の要旨（600～650字）

当該学位論文に関し，平成29年1月31日に第1回学位論文審査委員会を開催し，提出された学位論文および関連資料について詳細に検討した．更に，平成29年1月31日の口頭発表の後，第2回審査委員会を開催し慎重に協議した結果，以下の通り判定した．

本論文は，旋削加工におけるMQL(最少量潤滑)の効果を，汎用FEMソフトに簡易的かつ実践的な手法を導入することによって容易に評価できることを示したものである．切削加工における加工液の潤滑および冷却効果を解析によって評価するためには，切削抵抗，工具-切り屑接触長さ，切り屑厚さ，切削点近傍の工具温度などすべてを正確に推定しなければならず，現実的には極めて難しい．本研究は解析ソフトDEFROM™-3Dにおいて，工具すくい面の摩擦係数を“非拘束単純モデル”で解析した切削抵抗より推定し，その値を用いて算出した切り屑厚さを拘束条件とする“自由表面拘束モデル”によって，切削抵抗，工具-切り屑接触長さ，工具すくい面温度を正確に算出可能なことを，２次元切削実験によって検証している．そしてこの解析手法を用いることで，潤滑効果によって切削抵抗を小さくして発生熱を抑制するとともに，冷却作用によって切削温度を低下させる条件をみいだし，工具すくい面には粘性に富んだオイルミスト，逃げ面にはおよそ–15°Cの冷風ミストを供給する新しいMQL切削法を提案し，その有効性を旋削実験によって実証している．

以上のように，本論文はMQL切削の潤滑および冷却効果を正確に評価できる解析手法を提案するとともに，冷風ミスト法という斬新な手法を示してその効果を実証したことは工学的・工業的にも価値がある．その内容は博士（工学）論文に値すると判定する．

4．審査結果　(1) 判　　定（いずれかに○印）　（合　格）・　不合格

(2) 授与学位　博　士（工　学）