Evaluation of the Minimum Quantity Lubrication in Orthogonal Cutting with the Application of Finite Element Method

Ahmad Shahir Jamaludin, Akira Hosokawa, Tatsuaki Furumoto, Tomohiro Koyano, Yohei Hashimoto

***Abstract*— In order to evaluate the performance of Minimum Quantity Lubrication (MQL) in cutting, it is necessary to understand the tribological and thermal effects of MQL during cutting process. This paper proposes a Finite Element Method to analyze the influence of the Minimum Quantity Lubrication in turning process of mild steel in terms of cutting force and cutting temperature. In the meantime, orthogonal cutting tests of medium steel JIS S45C is executed with the TiCN-coated cermet tool in order to obtain suitable parameter to verify the simulation model. Minimum quantity lubrication friction coefficient and chip thickness are obtained from the cutting experiment. Heat convection coefficients based on the MQL types are utilized in the proposed model. It is proven that the FEM is capable of estimating the cutting process with a good degree of accuracy. The model applied in the study enables to evaluate MQL assisted cutting characteristics in which cutting force and cutting temperature can be estimated.**

***Index Terms*— Minimum quantity lubrication; Orthogonal cutting; Cutting force; Cutting temperature; Finite Element Method.**

I. Introduction

In the process of cutting difficult to cut materials, excessive heat generation due to high cutting force and thermal properties of workpiece material is one of the main problem with respect to tool wear, deterioration of finished surface. In order to understand the heat generation and temperature increment during machining process, the tribological and thermal effects at rake and flank faces must be examined [1-8]

Previous researchers proposed several lubricating and cooling methods during the cutting process. It is needed for the cutting fluid to be supplied onto the contact zone of cutting tool-chip and cutting tool-workpiece interfaces, thus greater amount of lubricant were used [9-12]. However, this particular method had increases the total cost for maintaining and disposing of the cutting fluid, as well as health and environmental issues. Thus, an economically and environmentally friendly conception of machining is proposed, whereas the application of excessive cutting fluid is reduced if possible, eliminates it together. These matters lead to the application of dry machining and invention of minimum quantity lubrication (MQL) machining or near dry machining [9-12].

There are several types of cutting fluids applied during the MQL process, in which oil-based cutting fluid for lubrication, water-soluble or emulsion-based fluids as coolant are used. It is revealed that MQL system is able to reduce the frictional contact between tool, chip and workpiece during lubrication, the water-based cutting fluid is effective in reducing cutting temperature through conduction due to its higher specific heat capacity compared to oil based cutting fluid [10]. Previous studies have shown the relationship between cutting temperature and cutting parameters such as cutting speed, depth of cut, feed rate for various workpiece and tool materials. The geometry of tool and coolant type must be taken into consideration as part of important parameters for the application of cutting fluid during machining process [9-12].

It is important to utilize Finite Element Method (FEM) in obtaining more understanding on the mechanism of MQL and improving the efficiency of MQL application during cutting process. However, not much study had been done in analyzing MQL with the application of FEM method, as it is still considered difficult due to inhomogeneous properties of MQL mist [12-21]. This study deals with the appropriate FEM model in MQL cutting process in which lubricating and cooling effects of oil mist are taken into account. Additionally, equivalent orthogonal cutting processes supplied with various types of MQL are carried out to verify the FEM model.

II. Methodology

A. Experimental Procedure

In this study, a pseudo orthogonal cutting tests of medium carbon steel, JIS-S45C with TiCN-coated cermet cutting tool are carried out by OKUMA turning center, as shown in Fig. 1. 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, f in y-direction is 0.3 mm/rev) are applied. The depth-of-cut (feed

Ahmad Shahir Jamaludin: Graduate School of Natural Science and Technology, Kanazawa University, Kakuma-machi, Kanazawa, Ishikawa 920-1192, Japan (e-mail: shahiru@stu.kanazawa-u.ac.jp)

A. Hosokawa: Department of Mechanical Engineering, Institute of Science and Technology, Kanazawa University, Kakuma-machi, Kanazawa, Ishikawa 920-1192, Japan (e-mail: hosokawa@se.kanazawa-u.ac.jp)

T. Furumoto: Department of Mechanical Engineering, Institute of Science and Technology, Kanazawa University, Kakuma-machi, Kanazawa, Ishikawa 920-1192, Japan (e-mail: furumoto@se.kanazawa-u.ac.jp)

T. Koyano: Department of Mechanical Engineering, Institute of Science and Technology, Kanazawa University, Kakuma-machi, Kanazawa, Ishikawa 920-1192, Japan (e-mail: koyano@se.kanazawa-u.ac.jp)

Y. Hashimoto: Department of Mechanical Engineering, Institute of Science and Technology, Kanazawa University, Kakuma-machi, Kanazawa, Ishikawa 920-1192, Japan (e-mail: hashimoto@se.kanazawa-u.ac.jp)

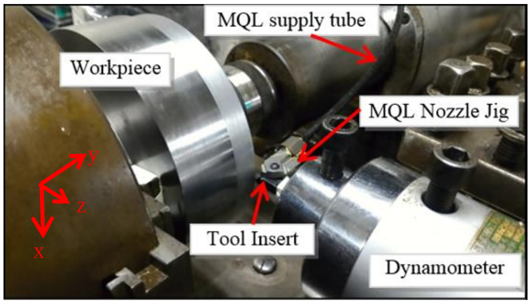

Fig. 1. Experimental setup for MQL assisted orthogonal cutting

Table I
Cutting conditions

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
Mechanical properties of work material

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

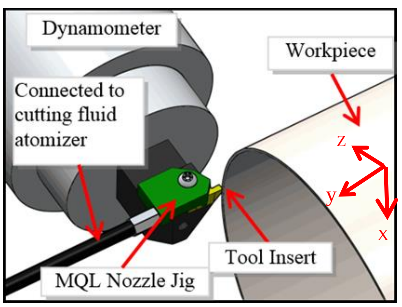

Fig. 2. Schematic illustration of orthogonal cutting

rate) is chosen to be 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.

In the experiments, both dry and MQL assisted cutting tests are executed, where the MQL outlet nozzle for orthogonal cutting is designed so as to supply oil mist onto the cutting edge accurately through the rake face as shown in Fig. 2. Two types of oil mist are used, based on the variable composition between non-toxic 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 with Oil-A with additional cooling property.

The properties of the oil mist applied in this study are summarized in Table III. Cutting forces are measured by a strain gauge type dynamometer. Chip thickness, t_c is measured with micrometer and contact length, l_c between

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	

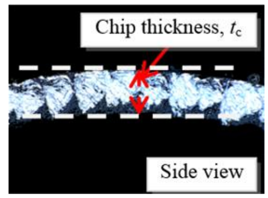

Fig. 3. Measurement of chip thickness

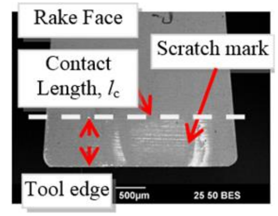

Fig. 4. Measurement of tool-chip contact length on the rake face

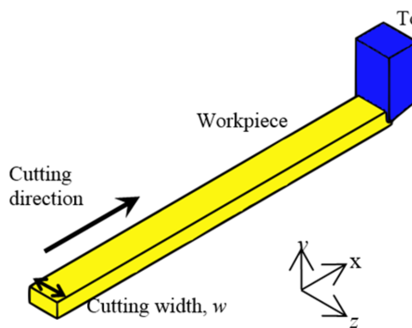

Fig. 5. Simplified FEM orthogonal cutting model in DEFORM-3D™

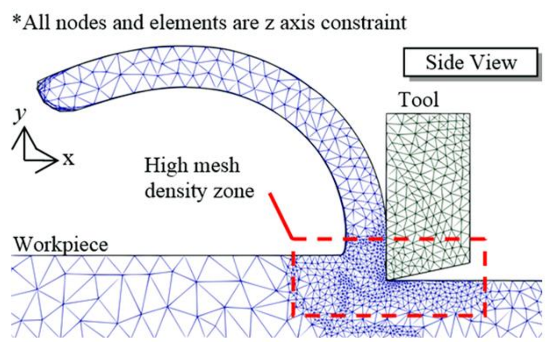

Fig. 6. Mesh structure in FEM model

chip and tool are 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. Mean cutting temperature for each cutting conditions is measured with the application of tool-work thermocouple method.

B. Finite Element Method

In this study, hybrid thermo-mechanical FEM model that capable of estimating mechanical deformation along with heat generation and temperature distribution is employed. Orthogonal cutting FEM simulation model is also designed with the application of DEFORM™-3D, whereby the workpiece and cutting tool geometries are designed and

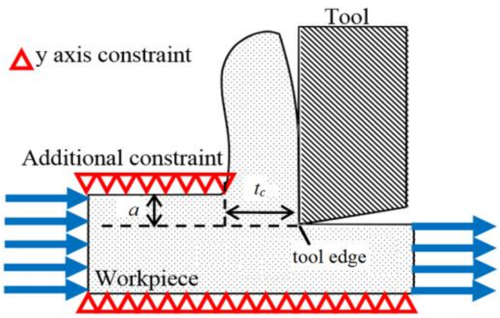

Fig. 7. Boundary conditions for material deformation

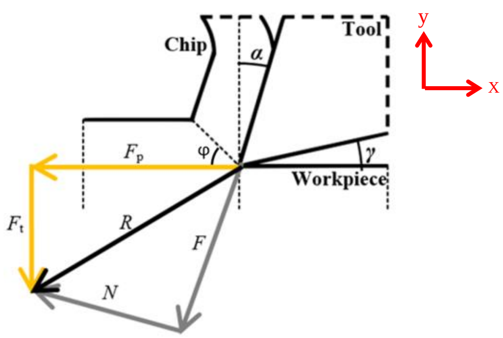

Fig. 8. Force vectors during orthogonal cutting process

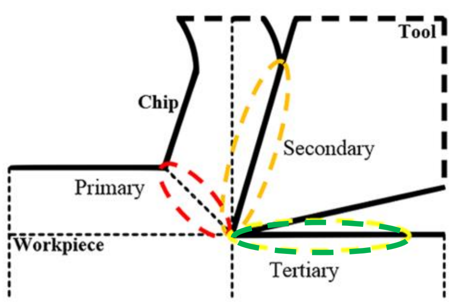

Fig. 9. Main sources of heat generation during orthogonal cutting

simplified with the application of Computer Aided Design (CAD) software, as shown in Fig. 5, similarly to the method had been done by previous by studies [12-20].

In the simulation, the FEM cutting tool is designed to resemble the actual geometry of the orthogonal cutting-tool 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 more than 10 times larger than the tool edge radius, similar to the equivalent experimental procedure, thus the tool edge is modeled as sharp.

Fig. 6 shows the initial overall model meshing, where high mesh density is modeled around the tool-workpiece contact region where large plastic deformation occurs. All elements are constraints from deforming on *z*-axis for the workpiece to deform in orthogonally (*x* and *y*-axes). Adaptive meshing, ability to re-mesh whenever tool and workpiece's mesh overlapping occurred is also applied, and the initial maximum number of elements for the tool is 10,000 elements, 50,000 elements for the workpiece. Here, arbitrary Lagrangian-Eulerian (ALE) method is employed in term of workpiece material deformation, as it is capable of simulating deformation with high accuracy [20]. In this model, the gap size between the Eulerian boundary and the tool is equivalent to the experimentally measured size of the chip thickness t_c

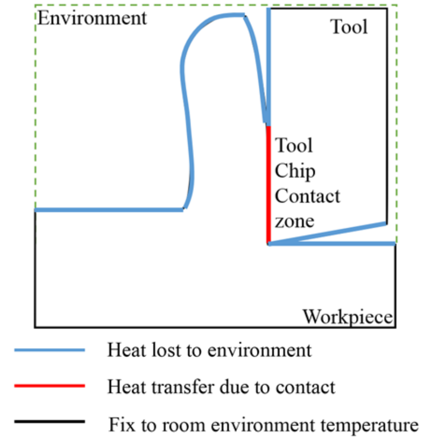

Fig. 10. Boundary condition for thermal analysis

Table IV
Heat transfer coefficients in FEM analysis

Heat transfer coefficient			Dry	Oil-A	Oil-B
Tool-chip boundaty	h_c	[kW/(m^2·K)]		1000	
Environment	h	[kW/(m^2·K)]	0.02	0.035	30

for each cutting conditions (cutting speed and type of MQL supplied), as shown in Fig. 7 and continuous chip is assumed throughout the simulation process.

As for the cutting force estimation during MQL conditions, it is assumed that oil mist enters the contact zone between tool and chip effectively, affecting the frictional behavior on the zone. Thus, simulation is run with the exact MQL friction coefficient, μ_{MQL} obtained by Eq. (1) based on the experimental results, according to Fig. 8, for each cutting and MQL conditions. In the analysis, workpiece is designed to deform plastically, while cutting tool is designed to be rigid due to its large ratio of Young Modulus between the tool and workpiece materials.

$$\mu_{MQL} = F / N = (F_t + F_p \cdot \tan\alpha) / (F_p + F_t \cdot \tan\alpha) \quad (1)$$

In addition to the boundary conditions for material deformation, those for the temperature analysis are also designed to the FEM model. In the FEM models, two out of three zones of heat source are taken into consideration, which are primary zone (shearing deformation) and secondary zone (frictional contact between tool rake face and chip), as shown in Fig. 9 [6]. 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 well understood and it is still incapable of estimating the inhomogeneous properties of MQL mist, following assumptions are made in order to examine the influence of MQL during the cutting process:

- Oil mist completely covers the open surface of tool, chip and workpiece to the environment.
- MQL affects convective heat transfer coefficient, *h* properties during the cutting process.
- The contacts between tool and chip and tool and workpiece are thermally perfect, having a large thermal contact conductance coefficient, h_c (1000 kW/(m^2·K)).

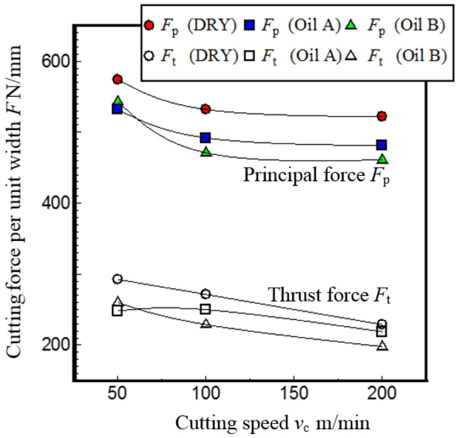

Fig. 11. Relationship between cutting speed v_c and cutting force F

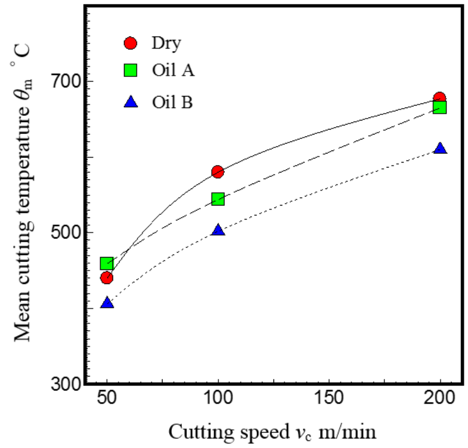

Fig. 13. Relationship between cutting speed v_c and mean cutting temperature θ_m

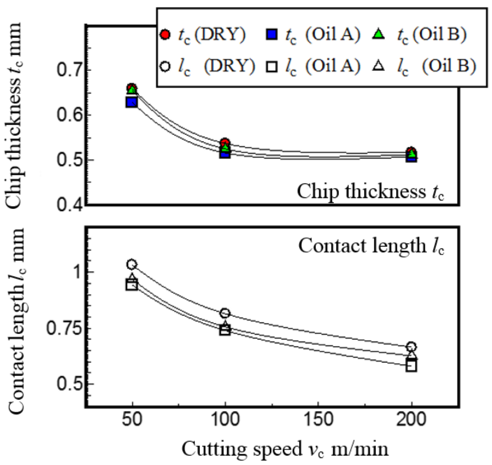

Fig. 12. Relationship between cutting speed v_c chip thickness t_c and contact length l_c

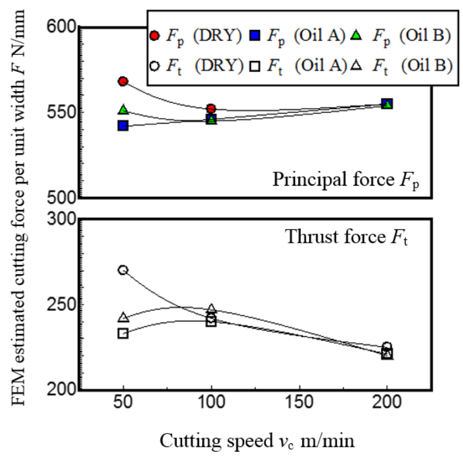

Fig. 14. Relationship between cutting speed v_c and cutting force estimated by FEM with μ_{MQL} and chip thickness t_c input

- Thermal softening, hardening, and phase transformation of chip and workpiece are neglected in the FEM analysis.
- The mean temperature θ_m estimated from the contact zone, l_c between tool and chip is calculated and compared to the experimental results.

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

III. Results and Discussion

A. *Mechanical analysis on Dry and MQL assisted orthogonal cutting process*

Fig. 11 shows the relationship between cutting speed v_c and principal force F_p and thrust force F_t in dry and MQL processes by the orthogonal cutting experiments. It is observed that both principal force F_p and thrust force F_t decrease as the cutting speed v_c increases. Similar tendency can be observed for the relationship between cutting speed v_c and tool-chip contact length l_c and chip thickness t_c as shown in Fig. 12, where both l_c and t_c decrease as the cutting speed v_c increases. It is understood that the decreasing of cutting force F with cutting speed v_c is due to the increment of the shear angle φ, which leads to lighter chip thickness t_c as well as contact time between tool rake face and chip becomes decreasing.

In addition to the lower principal force F_p, thrust force F_t and shorter tool-chip contact length l_c, lower chip thickness t_c is observed with the application of MQL during the cutting process, as shown in Fig. 12. It is understood that, MQL decreases the contact friction between tool and chip, μ_{MQL} as estimated by Eq. (1).

B. *Thermal analysis on Dry and MQL assisted orthogonal cutting process*

Fig. 13 shows the relationship between cutting speed v_c and mean cutting temperature θ_m measured by the tool-work thermocouple method during dry and MQL conditions. It is observed that the mean cutting temperature θ_m increases with the increasing of cutting speed v_c due to increasing cutting energy.

Meanwhile, mean cutting temperature θ_m in MQL assisted cutting (Oil-A and Oil-B) is lower than that in the dry cutting. It is assumed that, the existence of foreign substance (oil or water molecule) between chip and tool surface is capable of absorbing or conducting the heat away from the tool and chip. Additionally, MQL assisted cutting with Oil-B shows significantly lower mean cutting temperature θ_m than Oil-A

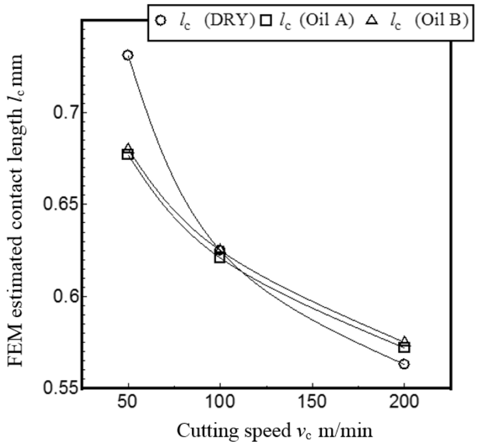

Fig. 15. Relationship between cutting speed v_c and contact length l_c estimated by FEM with μ_{MQL} chip thickness t_c input

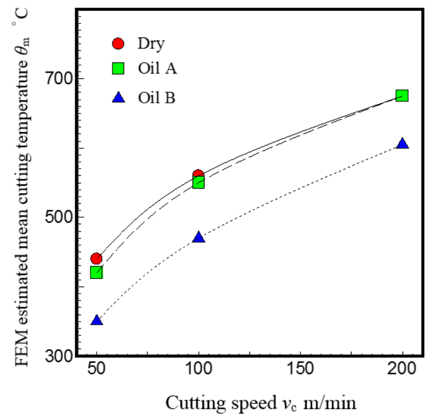

Fig. 16. Relationship between cutting speed and mean cutting temperature θ_m estimated by FEM with μ_{MQL} and chip thickness t_c input.

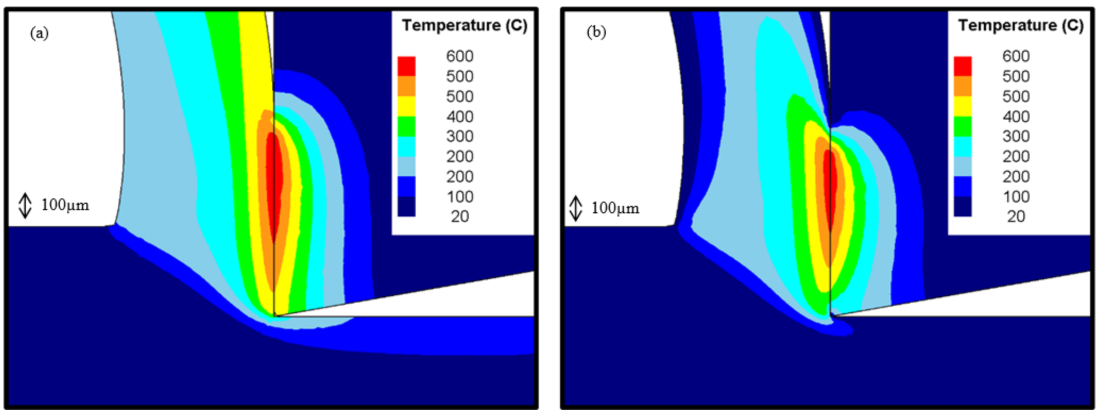

Fig. 17. Temperature distribution on tool and chip for cutting speed v_c=100 m/min for (a) dry and (b) Oil-B MQL conditions at saturation

due to its water composition as coolant, is assumed able to conduct the heat away with higher efficiency. The experimental results is utilized in verifying the FEM model later in this study.

C. MQL process validation by FEM

Figs. 14 and 15 show the analytical results by FEM model on the relationship between cutting speed v_c and cutting forces F and tool-chip contact length l_c respectively. It is observed that the FEM model is capable of estimating cutting force F and tool-chip contact length l_c with a good degree of accuracy (~12%). Although, lower cutting force is obtained by the FEM analysis under the MQL conditions, it is still unable to simulate MQL mist accurately in term of physical properties. Then the frictional coefficient μ_{MQL} and chip thickness t_c are taken into consideration as MQL parameters in the analysis of MQL cutting. Estimated cutting force, F and tool-chip contact length l_c from each cutting and MQL condition will be utilized in analyzing the effect of MQL onto heat generation and temperature distribution during the cutting process.

D. Analysis on the influence of MQL by FEM on cutting temperature

Fig. 16 shows the relationship between cutting speed v_c and mean temperature θ_m at tool-chip contact zone, estimated by the FEM. The FEM estimates similar tendency to the

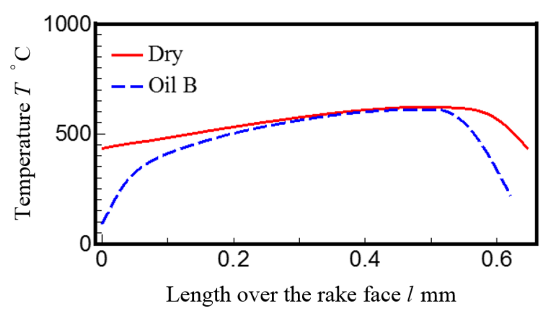

Fig. 18. Estimated temperature profile by FEM model for v_c=100 m/min for dry and Oil-B MQL conditions at saturation (0: Tool edge)

experimental results. Thus, it is proven that FEM is capable of estimating the mean cutting temperature θ_m in the orthogonal cutting process with a good degree of accuracy when the appropriate convective heat transfer coefficient, h with respect to the type of oil mist, is taken into consideration as MQL cooling parameter.

For more understanding on the effect of MQL during cutting process, temperature distribution comparison on cutting tool and chip estimated by FEM between dry and Oil-B is analyzed for cutting speed v_c =100 m/min, as shown in Fig. 17. It is observed that estimated temperature distribution for orthogonal cutting process supplied with Oil-B is smaller than that in the dry process. It is also observed that smaller size of highest temperature zone (red color zone) is estimated in the middle of tool-chip interface for the orthogonal cutting process with Oil B than that in the dry process. Furthermore, the temperature at the tool edge for orthogonal cutting process with Oil-B is lower than that in the dry orthogonal cutting, as shown in Fig. 18. It is estimated that, the MQL is taken into effect instantaneously as the chip separated from the tool rake surface. It is proven from the FEM analysis in the study that MQL is able to enhance the tool life during the cutting process by suppressing the size of the thermal affected zone in tool body and magnitude of temperature on the tool surface.

IV. Conclusions

This paper proposed a FEM model in order to evaluate the effectiveness of MQL by simulating the cutting process using the application of SFTC DEFORM™-3D. The FEM model applied Arbitrary Lagrangian-Eulerian (ALE) where chip thickness t_c is taken as MQL parameter along with MQL friction coefficient, μ_{MQL} in term of lubrication property. Convective heat transfer coefficient, h is taken into consideration as MQL parameter in term of cooling property.

The FEM analysis shows significant accuracy with the experimental results. The study shows that FEM is able to aid in evaluating and improving the understanding of the influence of MQL during cutting process. Further study can be done in various type of MQL such as high-pressure coolant and cryogenic coolant.

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