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Bold Approach in Finite Element Simulation on Minimum Quantity Lubrication Effect during Machining

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ABSTRACT

Application of Minimum Quantity Lubrication (MQL) in cutting process is becoming widespread, whereas manufacturers had gradually turns to the utilization of dry and semi dry cutting during the machining process. Compared to the conventional wet cutting method, utilization of MQL can be considered as parameter sensitive, whereas only a very small amount of cutting fluid is utilized during the process to cater similar or better performance as conventional wet cutting. Thus, it is necessary to understand precisely the characteristic of MQL applied cutting process, where behavior of tool-work/chip interface need to be observed sufficiently, due to its relationship with the cutting performance such as cutting force, cutting temperature, chip morphology, and surface finish. In this paper, bold approach of Finite Element Method (FEM) modelling is proposed in simulating the characteristic of the MQL in machining process. Two interrelated FEM analytical models are designed and executed using the application package software DEFORM™-3D. As a validation, orthogonal cutting tests of medium steel JIS S45C is executed with the TiCN-coated cermet tool in order to evaluate the involved parameter during the application of Minimum Quantity Lubrication in parallel. During the application of MQL in the orthogonal cutting process, three significant variables are observable, which are cutting force, chip thickness and contact length. In this paper, comparison of appearance friction and FEM input friction is done, where it is found that both parameter is related but not similar. Additionally, it is proven that FEM is capable in assessing MQL characteristic with a good degree of accuracy through FEM input friction and chip morphology modelling, thus it is easier to distinguish between contact condition and environmental condition through the proposed FEM validation process.

INTRODUCTION

In recent manufacturing trend, conventional wet cutting method has tended to shift to dry or semi-dry cutting processes in optimizing the power consumption and processing cost. In addition, the chemical by-product from conventional wet cutting process increases the pollution rate of working environment, possibility to affect the health quality of the machine operators. Therefore, application of Minimum Quantity Lubrication (MQL) is proposed during machining process to solve and contain the conventional wet cutting problem [1-3]. In MQL assisted cutting, a very small amount of cutting fluid is turned into fine oil mist and supplied onto cutting point, expecting to increase the cutting performance of tools, product quality finish and machining power consumption. Approximately only 1/10000 fluid volume of that in the ordinary wet cutting is consumed during MQL application make it easier to manage and leads to cleaner working environment and overall processing cost [1-3]. However, it is still yet hard to be understood on how lubrication works during the cutting process. This is due to contact mechanism between cutting tool and workpiece/chip is considered as complex even during conventional dry cutting, whereas it is extremely sensitive to parameters [3]. Although it is proven that supplying MQL during cutting process is able to reduce the principal forces and cutting temperature, improving the surface finish and increment of tool life, a lot of study is yet need to be done [1-3].

This paper is dealing with designing FEM models in simulating the effect of Minimum Quantity Lubrication (MQL) application during metal cutting. Several FEM models are designed and along with that, equivalent experimental process is also being executed. In the experimental process, dry and MQL cutting process are carried out, whereas the output parameters such as cutting force F_c, chip thickness t_c and contact length l_c are measured experimentally and compared with the FEM results.

METHODOLOGY

In recent years, Finite Element Method (FEM) has become a familiar method to simulate the cutting process and to obtain various information beforehand [11-22]. Several studies on cutting process had been done through FEM analysis in order to estimate the principal forces and/or cutting temperature, in which appropriate simplified or complex model is proposed and assumed in nearly analogous to the actual cutting process. However, it is still consider to be difficult in modelling inhomogeneous property of MQL mist, along with its lubrication and cooling effects onto the cutting process simulation [3, 11-22].

In current study, FEM simulation models in orthogonal cutting of mild steel, JIS-S45C are proposed and designed with the application software DEFORM™-3D, as shown in Fig. 1. This FEM tool employs Lagrangian formulation that is suitable for large deformation, as well as adaptive meshing, an ability to re-mesh whenever distortion occurred. In the FEM analysis, the FEM cutting tool is designed resembling the standard orthogonal cutting-tool geometry at the cutting edge, with 0° rake angle and 10° clearance angle. The cutting tool is designed as rigid, while workpiece is designed to experience plastic deformation when in contact with cutting tool due to its large ratio of Young Modulus between the tool and workpiece materials to save computing time and power consumption.

In the analysis, denser mesh is formed around the tool-workpiece contact where large plastic deformation occurs. The initial maximum number of elements for the tool is 10,000 elements, 50,000 elements for the workpiece. Figure 2 shows the example of model meshing, where all elements are fixed to deform in two-dimensional directions (X and Y axes). The chip formation from the simulated cutting process is assumed continuous, where no chip breaking is considered. The cutting condition is shown in Table 1, while the material properties for FEM application are shown in Table 2.

Table 1 Cutting conditions

Cutting Tool	TiCN-Coated Cermet
Workpiece	JIS-S45C
Cutting width w [mm]	1.0
Depth of cut a [mm]	0.3
Cutting speed v_c [m/min]	50, 100, 200

Table 2 Material properties [23]

Cutting Tool	TiCN-Coated Cermet	JIS-S45C
FEM Element type	Rigid	Plastic
Young modulus E [GPa]	650	212
Density ρ [kg/m^3]	14900	7850
Vickers hardness $HV_{0.3}$ [GPa]	13.7	1.96

Two interrelated FEM models are designed to simulate the MQL condition, which called as Dynamic FEM Model-A, and Semi-Static FEM Model-B, respectively. Different types of chip separation/formation criterions applied in each FEM model, and explained as following.

A. Dynamic FEM Model-A

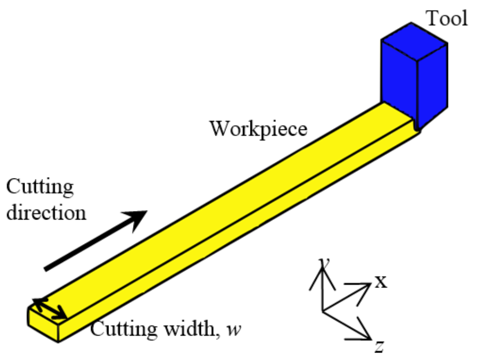

Fig. 1 Simplified FEM orthogonal cutting model for DEFORM-3D™.

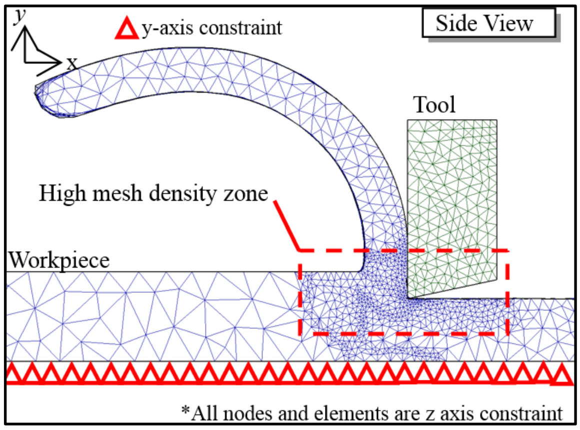

Fig. 2 Mesh structure in FEM model.

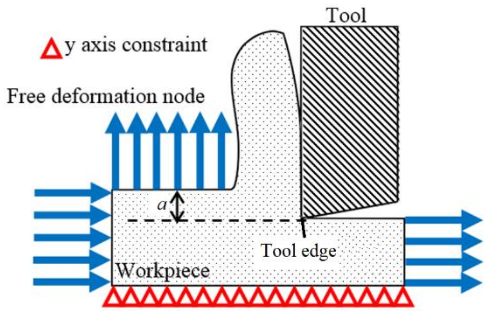

Fig. 3 Dynamic FEM Model-A

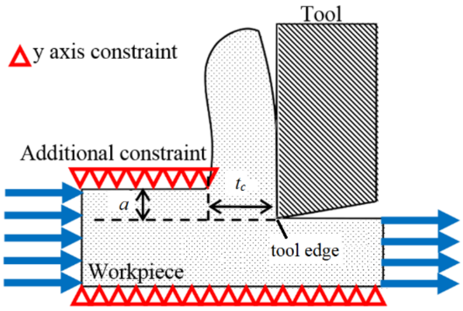

Fig. 4 Semi-static FEM Model-B

In Dynamic FEM Model-A (**Fig.** 3), MQL friction coefficient μ_{MQL} is assumed constant, occurring over the whole tool-chip interface, where the length of sticking and sliding zones are not taken into consideration. In this model, the chip thickness t_c and contact length l_c are estimated by FEM, based on various input friction coefficients.

B. Semi-Static FEM Model-B

Meanwhile, in Semi-Static FEM Model-B (Fig. 4), pre-determined chip formation criterion is utilized through Arbitrary Lagrangian Eulerian (ALE) formulation. The FEM model is designed with additional deformation constraint (Eulerian boundary) to pre-determine the end chip formation when the workpiece element displace or deformed (Lagrangian formulation). The gap size between the deformation boundary and the tool is equivalent to the measured chip thickness, t_{exp} for each cutting speed v_c condition. However, the purpose of this model is to simplified the MQL process and resemble the deformation in examining the effect of MQL itself. The parameters similar parameters observed in Dynamic FEM Model-A (estimated chip thickness t_{cal} and MQL friction coefficient μ_{MQL}), and the lubrication effect (current study) and cooling effect (future study) of MQL is analyzed.

Experimental Setup

In this study, a pseudo-orthogonal cutting test of mild steel, JIS-S45C are carried out by OKUMA turning lathe, as shown in Figs. 5 and 6. The cutting insert has 0° rake angle and 10° clearance angle. 0° rake angle tool insert is chosen to nullify the effect of rake angle and the analysis is focused on the effect of MQL onto cutting process. The orthogonal cutting is generated through designing the diameter of the tube shape workpiece to be as large as possible, to ensure cutting chip to deform orthogonally. Tube shape workpiece with external and internal diameter of 145.0 and 144.0 (mm), respectively is utilized, making the width-of-cut, w of 1.0 (mm). In the orthogonal cutting tests, cutting speed v_c range of 50, 100 and 200 m/min and depth of cut a = 0.3 mm (= feed rate, f in y-direction) are applied. The depth-of-cut (feed rate f) is chosen to be more than 10 times larger from tool edge radius of 0.013 mm, to neglect the effect of tool

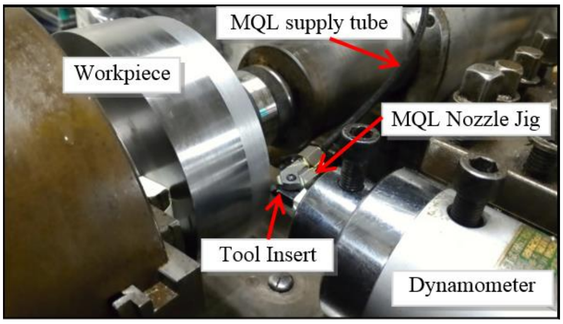

Fig. 5 Experimental setup

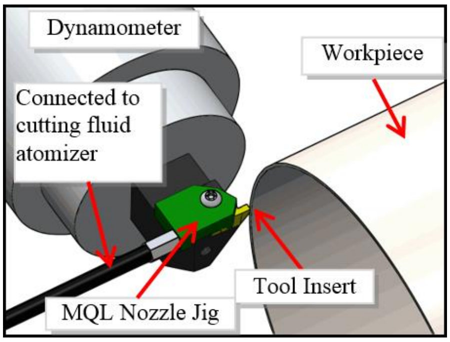

Fig. 6 MQL nozzle position

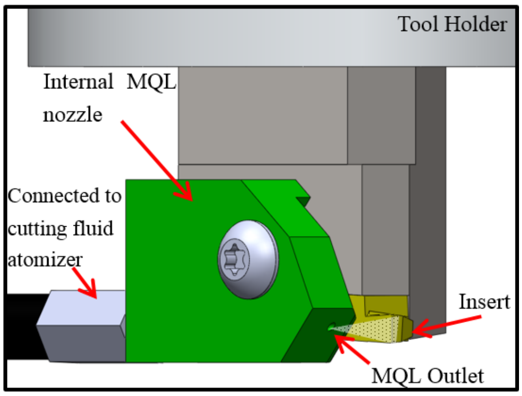

Fig. 7 MQL outlet position

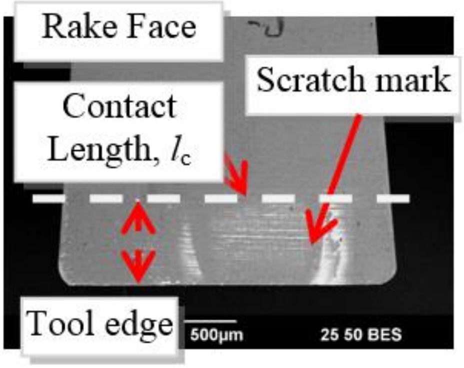

Fig. 8 Scratch mark on tool rake face

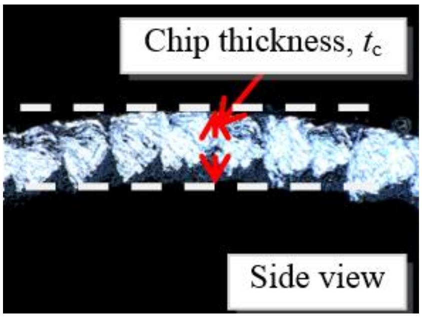

Fig. 9 Cutting chip side view and thickness measurement

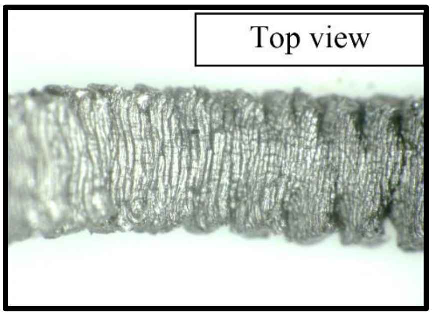

Fig. 10 Continuous flat centre of cutting chip

edge radius. The orthogonal cutting conditions and material properties are shown in Tables 1 and 2, similar to FEM simulation cutting conditions and material properties.

In the experiments, dry and MQL assisted cutting tests are executed in order to obtain the parameter variations (friction coefficient, chip thickness and contact length). The MQL outlet nozzle for orthogonal cutting is designed to supply oil mist onto the cutting edge accurately as shown in Figs. 6 and 7. Two types of oil mist are tested, Oil-L with 99% vegetable oil and 1% water, and Oil-C with 30% vegetable oil and 70% water (hydroscopic oil). Oil-L is supplied at 30 mL/h, while Oil-C is supplied at 100 mL/h onto the tool rake face during the cutting process, assuming to have equivalent lubrication property with Oil-L. Additionally, Oil-C has cooling property, whereas 70% of the oil mist composition is water. The properties of the oil mist utilized in the study are summarized in Table 3.

The principal forces, cutting force F_c and thrust force F_t are measured by a strain gauge type dynamometer. Meanwhile, contact length l_c between chip and tool are measured from the scratch mark left on the rake face of the tool for each cutting speed v_c condition (Fig. 8) with the application of digital microscope. In ensuring high precision of scratch mark measured, only new orthogonal tool insert is utilized for each cutting speed v_c and MQL conditions. Chip thickness t_c is measured with the application of micrometre, where the thickness of continuous deformation at the centre of the chip is taken into consideration (Figs. 9 and 10). In the study, MQL friction coefficient μ_{MQL} is estimated by means of average friction coefficient for the particular MQL assisted cutting process, as shown in Eq. 1 [11].

$$\mu_{MQL} = \left(\frac{F_t + F_p \tan\alpha}{F_p - F_t \tan\alpha} \right) \quad (1)$$

Table 3 Properties of cutting oil

Oil Type	Organic vegetable oil
Viscosity [mm²/s]	37
Oil contents [%]	
Oil A	99
Oil B	30
Supply rate [ml/h]	
Oil A	30
Oil B	100
Oil Pressure [MPa]	0.6

RESULTS AND DISCUSSIONS

Figure 11 shows the relationship between cutting speed v_c and cutting force F_c and thrust force F_t; obtained from dry and MQL assisted orthogonal cutting experiment. It is observed that both cutting force F_c and thrust force Ft decrease as the cutting speed v_c increases. Similar trend is 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 tool-chip contact length l_c and chip thickness t_c decrease as the cutting speed v_c increases. It is understood that, with the increasing cutting speed v_c, the shear angle θ increases, leads to decreasing chip thickness t_c. Additionally, with the increasing cutting speed v_c, contact time between chip and tool rake face decreases, leads to decreasing contact length l_c. These phenomena lead to the decreasing of principal forces F resulted from the cutting process. Additionally, both principal forces F_c and F_t, contact length l_c and chip thickness show lower magnitude during the application of MQL during the cutting process, as observed in Figs. 11. It is assumed that MQL affected the tool-chip contact behaviour, where it is observed that lower appearance friction coefficients μ are estimated during the MQL application, as shown in Fig. 11. Thus, this appearance friction coefficient is chosen as MQL friction coefficient in the study for the FEM analysis.

Figure 13 shows the relationship between cutting speed v_c, cutting force F_c and thrust force F_t estimated by Dynamic FEM Model-A with the MQL friction coefficient μ_{MQL} input. The relationship between cutting speed v_c and chip thickness t_c and contact length l_c are also shown in Fig. 14. It is observed from Fig. 13 that Dynamic FEM Model-A able to estimate principal forces with similar trend to the experimental results. However, only thrust force F_t is estimated accurately (<15%) to the experimental value, while cutting force F_c is over-estimated.

Furthermore, as it is observed from Fig. 14, contact length l_c and chip thickness t_c are also estimated with similar trend to the experimental results by Dynamic FEM Model-A. However, only contact length l_c is estimated accurately, while chip thickness t_c is over-estimated. Moreover, it is observed that when MQL friction coefficient μ_{MQL}= 0 is input into Dynamic FEM Model-A, FEM estimates thrust force F_t (frictional force) with zero value, but cutting force F_c is not zero. It is assumed that thrust force F_t is mainly caused by frictional contact characteristic, where it is needed to consider the frictional coefficient. However, cutting force F_c is highly related to material deformation behaviour (material stress-strain relationship) and frictional contact behaviour.

It is proven in current stage that, the MQL friction coefficient μ_{MQL} is considered as an important parameter in simulating the lubrication effect, as FEM is able to estimate thrust force F_t and contact length l_c with high accuracy. Additionally, it is in need to estimate accurate chip thickness t_c, to obtain accurate cutting load estimation for further understanding the effect of MQL. Due to limitation in assessing the appropriate material and mathematical model that leads to large error in estimating cutting force F_c in previous stage, optimization step is executed. In the optimization process, an imaginary friction coefficient μ_{cal} is calculated mathematically through Eq. (2) for each cutting speed v_c and MQL condition, with the assumption that cutting force F_c increases linearly with the increment of input friction coefficient μ. This

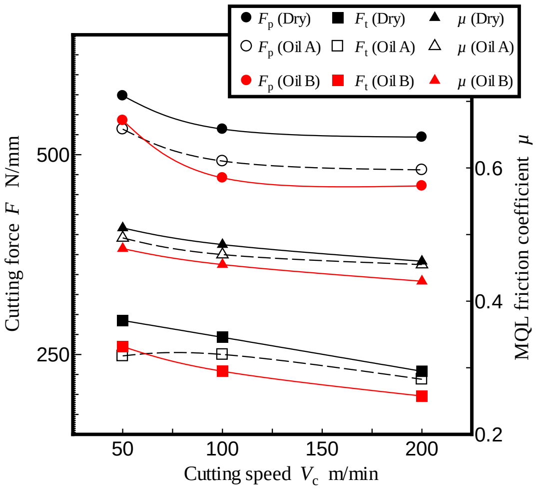

Fig. 11 Experimentally measured cutting force F_c, thrust force F_t and appearance frictional coefficient

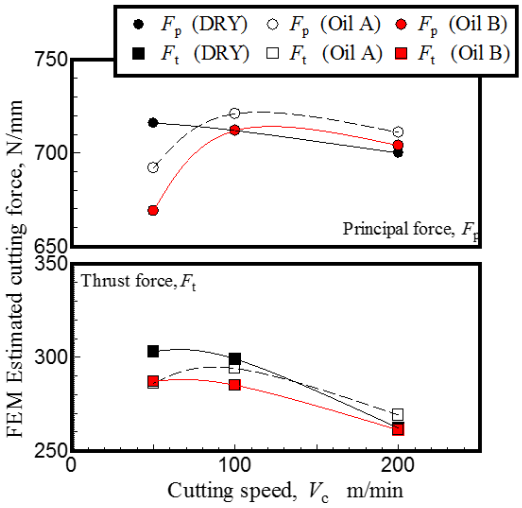

Fig. 13 Dynamic FEM Model A estimated cutting force F_c and thrust force F_t with μ_{MQL} input

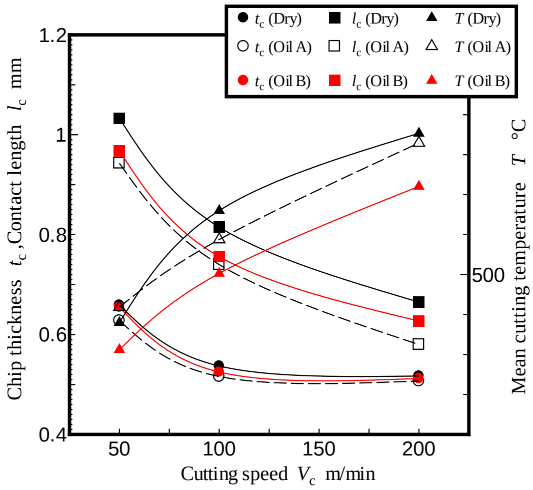

Fig. 12 Experimentally measured chip thickness t_c t_c, contact length l_c and cutting temperature T

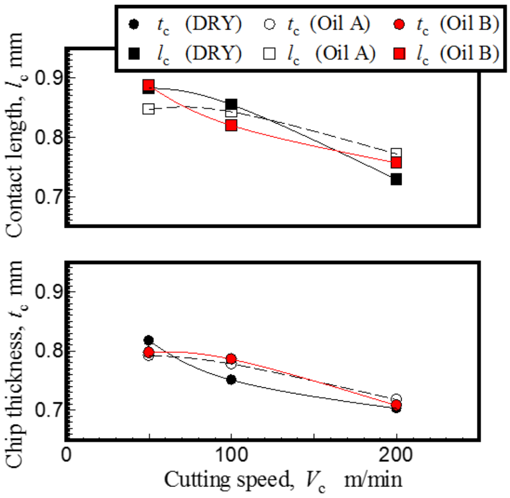

Fig. 14 Dynamic FEM Model A estimated contact length l_c and chip thickness t_c with μ_{MQL} input

process is purposely only to obtain a reliable chip thickness t_{cal} numerically and the simulation is re-run with Dynamic FEM Model-A, shown in Figs. 15 and 16. It is observed that, the estimation accuracy of cutting force F_c is significantly increases, as well as estimation of chip thickness t_c (Fig. 16). In contrary, thrust force F_t and contact length l_c are estimated with large error due to input friction coefficient optimization (Fig. 16).

$$\mu_{\text{cal}} = \mu_{\text{MQL}} \frac{F_{p(\exp)} - F_{p(\mu_n=0)}}{F_{p(\mu_n=\mu_{\text{MQL}})} - F_{p(\mu_n=0)}} \qquad (2)$$

Hence, it is known that the accurate chip thickness t_c modelling is important in estimating cutting force F_p, while accurate MQL friction coefficient, μ_{MQL} is important in estimating thrust force F_t. However, Dynamic FEM Model-A is incapable in estimating both cutting force F_c and thrust force F_t accurately in single-process. Therefore, Semi-Static FEM Model-B is utilized (Fig. 4); where Eulerian boundary is added with the gap between the deformation constraints to the cutting tool surface is equivalent to the size of experimentally measured chip thickness t_{exp} (≈ FEM estimated chip thickness,

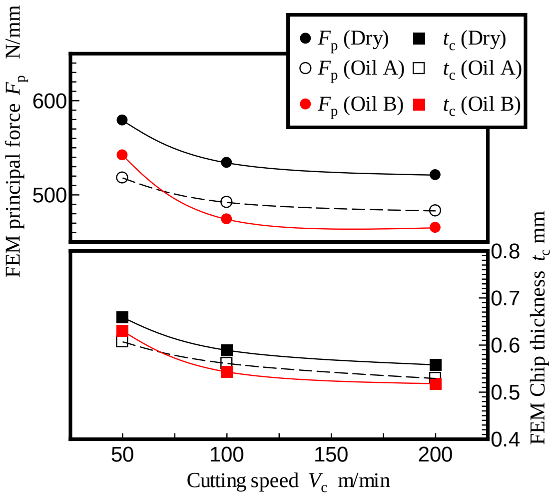

Fig. 15 Dynamic FEM Model A estimated cutting force F_c and thrust force F_t with μ_{cal} input

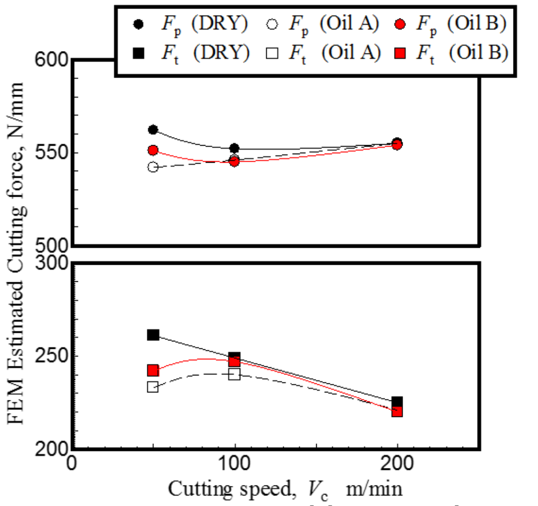

Fig. 17 Semi-static FEM Model B estimated cutting force F_c and thrust force F_t with μ_{MQL} input

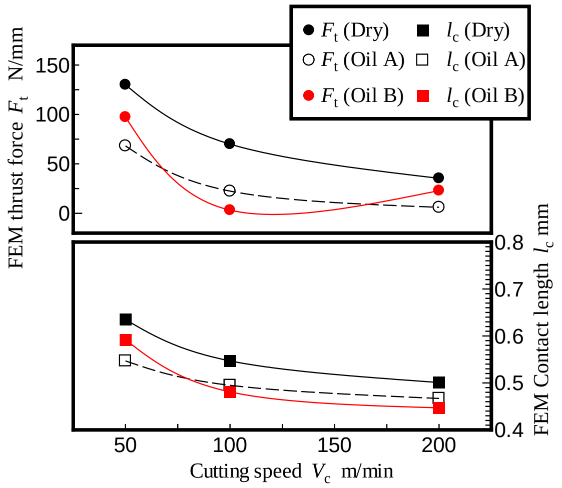

Fig. 16 Dynamic FEM Model A estimated contact length l_c and chip thickness t_c with μ_{cal} input

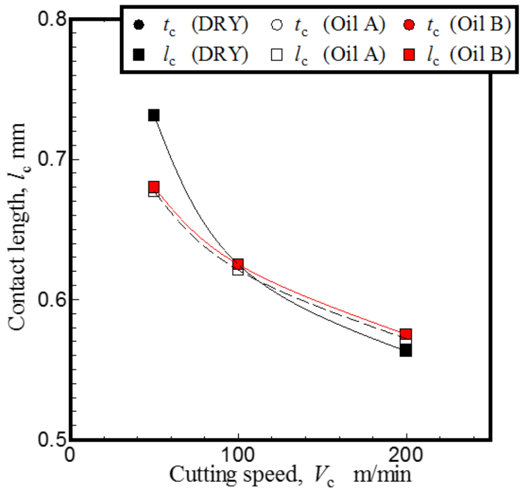

Fig. 18 Semi-static FEM Model B estimated contact length l_c and chip thickness t_c with μ_{MQL} input

t_{cal}). The friction coefficient input is similar to the Dynamic FEM Model-A input, where MQL friction coefficient μ_{MQL} is utilized. The estimated results by Semi-Static FEM Model-B are shown in Figs. 17 and 18. It is observed that the Semi-Static FEM Model-B is able to estimate cutting force F_c, thrust force F_t and contact length l_c with a good degree of accuracy.

It is observed from the previous stage, a combination of Dynamic FEM Model-A and Semi-Static FEM Model-B is capable in estimating the effect of MQL during cutting process. The proposed MQL estimation FEM process flow diagram is presented in Fig. 19. This process flow is limited to the equivalent experiment and FEM conditions to currently applied cutting conditions, including material properties and material flow stress model in the study. At the start of the process flow, empirical MQL friction coefficient μ_{MQL} is input. In the case of chip thickness data is not available, estimation of MQL chip thickness t_{cal} is done in the STEP 1 before proceeding to STEP 2. The paper is able to increase the understanding on performance of MQL assisted cutting process whereas analyzing the output principal forces, chip thickness, t_c and contact length l_c.

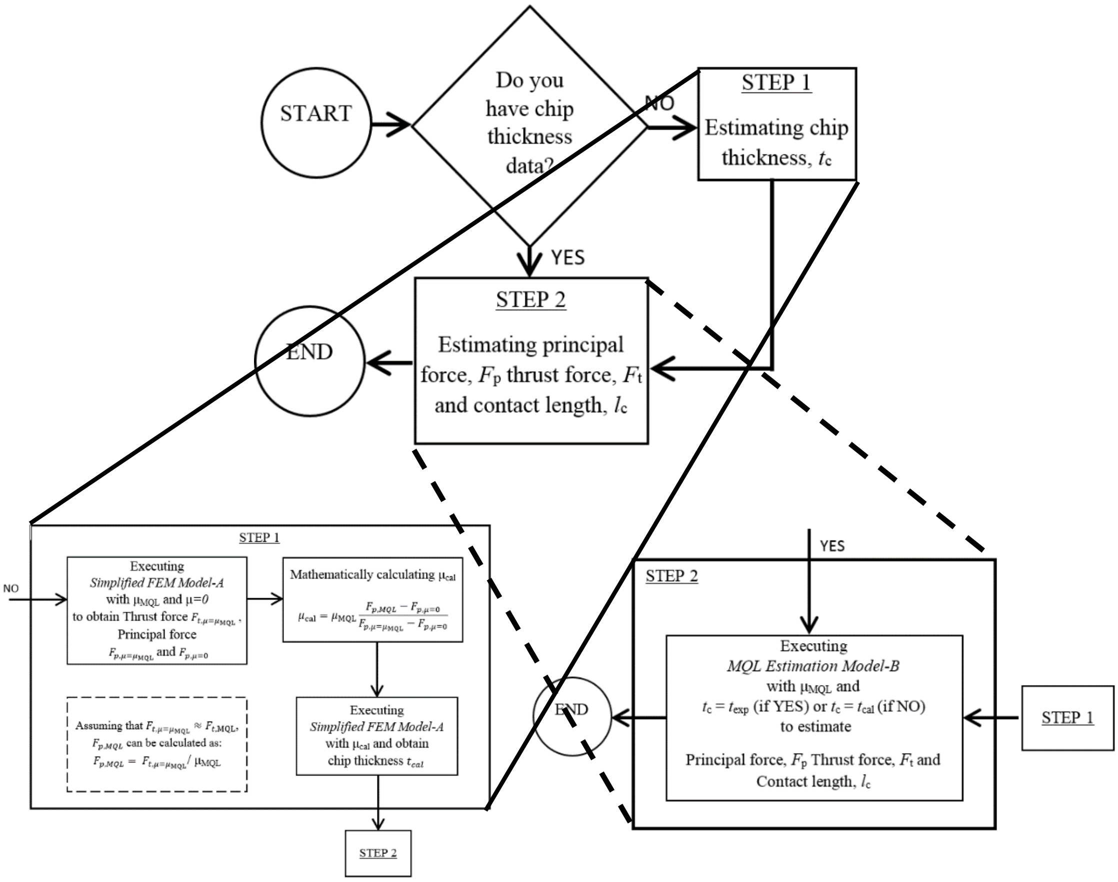

Fig. 19 Proposed MQL estimation FEM process flow diagram

CONCLUSIONS

In this paper, the study on the effective of MQL is dealt with application of FEM. Two FEM models are designed in order to simulate the effect of MQL during cutting process using the application of SFTC DEFORM™-3D. The validity of the models is verified by the equivalent experimental results on dry and MQL cutting tests. Effect of MQL onto principal forces; contact length l_c and chip thickness t_c is analyzed. Several conclusions are made, according to the FEM analysis, as following:

1. Thrust force F_t is highly related to the friction coefficient, which is related to effectiveness of MQL during cutting process in term of lubricated contact characteristic.
2. Cutting force F_c is highly related to chip characteristic (chip shape, shear angle), which is related to effectiveness of MQL in term of tool wear (tool shape integrity).
3. Lubrication plays minor role in temperature reduction during MQL application. It can be assumed that heat lost by principal force reduction by MQL application is not significant.
4. It is assumed that cooling effect in MQL (coolant property) is the one that have major role in temperature reduction in cutting tool, as well as extending the tool life. It is in need to take the cooling property such as heat transfer coefficient and mist temperature into consideration in the study of MQL application as coolant.

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