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Investigations on The Effects of Different Heat Transfer Coefficients in The Metal Machining

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ABSTRACT: In the metal machining, the cutting fluid has become a tough problem in term of the health of works and environmental protection. The heat transfer coefficients of the water-based fluid, mineral oil and plant oil are distinct. An investigation focused on the effects of different heat transfer coefficients (**h**) on the cutting thickness compression ratio, chip formation, stress distribution and specific cutting energy is presented and discussed. In this study, three heat transfer coefficients have been simulated by Third WaveAdvantedge in machining AISI 1045 steel during different cutting speeds.It has been shown that the Mises stress and temperature are both affected by the heat transfer coefficient. When the h reaches higher, the Mises stress increases and the temperature shows the opposite trend. Also, the results can be found that the chip compression ratio decreases and shear angle increases when **h**rises. The relationship between specific cutting energy and heat transfer coefficients can be found in this paper.
Keywords: heat transfer coefficient, finite element method, chip formation, chip compression ratio, shear angle, specific cutting energy

I. INTRODUCTION

Currently, the increasing development in metal machining has heightened the need for the cleaner, healthy and environmental mode of production. The machining process is expected to be more efficient to save energy and cutting fluids, especially in some emerging countries which do not have superior working condition and perfect environmental law. The coolants have become a great enemy of the environment, because they contain many chemicals which are harmful to the workers and surroundings.

Industries are looking for ways to reduce the waste of lubricants. Minimum quantity lubrication (MQL) technique has been proposed. In MQL, a small quantity of cutting fluid(5~600mL/h) mixed with pressurized air is injected in the cutting zone [1]. Khan and Mithu [2] conducted experiments on turning AISI 9310 alloy steel at different cutting velocities and feeds under dry, wet, MQL by vegetable oil conditions. The test equipment consists of a mixing chamber used to mix fluid from fluid chamber and compressed air. The purpose of investigations was conducted to explore the role of MQL on the machinability characteristics of that work material mainly in terms of cutting temperature, chip formation, tool wear and surface roughness. After comparing three above turning conditions, MQL leads to more reduction in average chip-tool interface temperature, lower chip reduction coefficient, better surface roughness and longer tool life. Godlevski et al. [3] proposed a new model of cutting fluid penetration in the interface zone. They assumed that a single capillary, with one closed, running along the full contact area of the tool-chip interface. It has a cylindrical form with dimension r and l. There are three phases of lubricant penetration into a single interface capillary: (1) penetration in the liquid phase;(2) micro-droplet explosion;(3) the quasi-equilibrium state. Godlevski et al. [6] also descripted the lubricating action of the tribo-active components of cutting fluids. Sérgio Luiz Moni Ribeiro Filho et al.[4] analyzed the effect of different vegetable fluids used in the tapping process of cast aluminum alloy, found that the MQL system is sufficient to reduce the friction of tool and surface roughness. Their tests show the torque was lower with MQL applications (using fluid PLANTO and fluid ECO) when compared to conventional cooling emulsions. Nilanjan Banerjee et al. [1] studied that the friction coefficient is significantly affected due to changes in process parameters while MQL machining of Ti -6Al-4V. Sliding speed is the most dominant factor followed by MQL parameters that affect the friction coefficient during the tribological test and actual machining operations as well.

Meanwhile, the increase in air pressure reduces the droplet size and increases the number flux. Bruce L. Tai et al. [5] summarized the advancements and challenges of MQL technology in automotive powertrain machining from both industrial and academic perspectives. Shibo Wang et al. [17] proposed a fluid penetration into flank zone model, after compared five metal working fluids, they found that $scCO_2$ spray and N_2 spray have excellent penetration capacity.

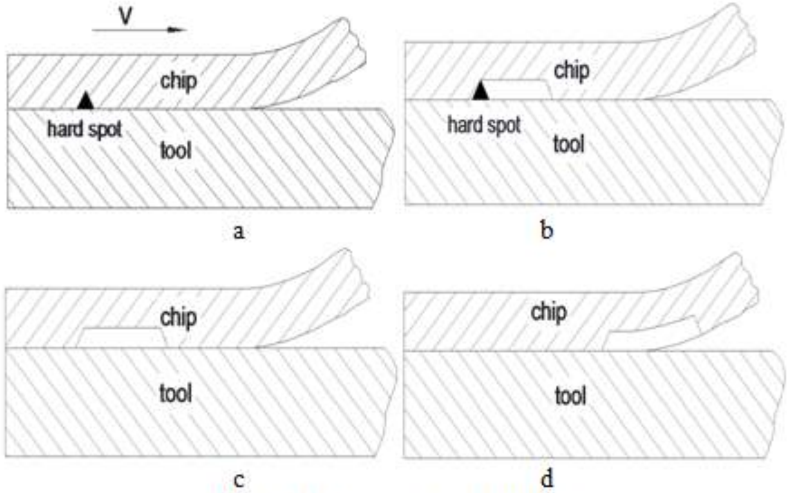


Fig. 1. The formation of capillary

Some researchers pay more attention to the friction in tool-chip-workpiece interface. H.BenAbdelali et al. [7] analyzed the friction coefficient during dry cutting with 9, 13 and 17 mm diameters pins in the range 5-300m/min. They found that the apparent friction coefficient is strongly influenced by sliding velocity. T.H.C. Childs [8] developed the friction theory in metal cutting, it consists of three conditions of turning, the lubricants still can penetrate into the chip-tool contact zone to reduce friction at lower velocities; at middle speeds, some solid falling off from work material exists in contact region to be solid lubricant; thermal softening will achieve self-lubrication. To obtain the differences among several lubricants, O. Pereira et al. [15] investigated the effects of N_2 and CO_2 as MQL, they found that the CryoMQL-LN2 has more 55% tool life compared to dry machining and the CryoMQL-CO2 has even double tool life.Researchers begin to focus on the heat flux and heat transfer, this is key process to improve tool life and surface roughness. Ceretti et al. [18] concluded that heat transfer phenomena during orthogonal cutting with uncoated (WC) and coated (TiN) tool, the heat transfer coefficient (h_c) could be described by equations. Benkai Li et al. [20] analyzed the heat transfer performance of MQL grinding, found that the ZrO2 has lowest heat transfer coefficient (1000W/(m^2K)) and the CNT has the best heat transfer coefficient (13000W/(m^2K)). Jin Tan [20] proposed method to estimate surface heat transfer coefficient based on grinding temperature. According to his theory, h between grinding zone could be 290000W/(m^2K). Aluminum and its alloys are used in great scale in the metal machining industries. Ductile materials such as brass, aluminum and its alloy are the main materials to which form turning process can be applied.
The present work deals with emulational investigations of the heat transfer coefficient as a variate which affects the consequence such as formation of chip and Mise stress etc of machining.

II. FINITE ELEMENT ANALYSIS AND SIMULATION

1.1 Finite element modeling

The commercial software AdvantEdge is a powerful tool for designing, setting up, improving and optimizing machining processes. It enables users to determine optimal machining parameters and tooling configurations that can reduce cutting forces, temperatures, and part distortion, all off-line. This reduces the need for online testing, which costs money and valuable production time. In this paper, a 2D numerical simulation was conducted for modelling the MQL. Third Wave AdvantEdge was utilized for the plain turning operation simulations. The commercial software is a very convenient method to simulate metal cutting, because it possesses automatic mesh generation. It uses updated-Lagrangian finite element codes to simulate high unconstrained plastic flows, which generally occur during the machining operations, under constraint that the solid is remeshed continuously. The spray of MQL was considered to be jetted on the both rake and flank faces. The MQL cooling effect was assigned with heat transfer coefficient, the global heat transfer coefficient is a physical variable, which governs heat generated on the chip-tool interface transferred to MQL droplets. The transfer coefficients (5230, 7.14×10^4, 3.93×10^5) for this investigation were cited from data available from MQL oil and water in the literatures E. Ceretti et al. [18] and Jin tan [20]. Fig. 2 shows the simulation setup.

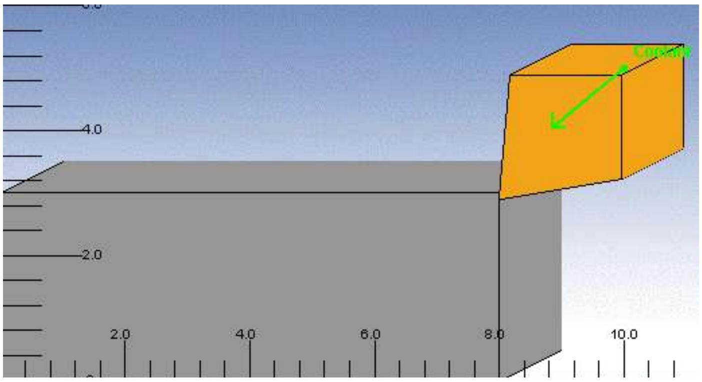


Fig. 2 The simulation setup

1.2 Constitutive model

Considering the influence of thermal effect on strain, strain rate, it is necessary to introduce the elastic-plastic constitutive model. In the finite element model, it is a model which relates the strain to plastic strain rate.

$$\boldsymbol{\sigma} = (\boldsymbol{A} + \boldsymbol{B}\boldsymbol{\varepsilon}^{\boldsymbol{n}})\left(\mathbf{1} + \boldsymbol{C}\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) \times \left(\mathbf{1} - \left(\frac{\boldsymbol{T} - \boldsymbol{T}_{\boldsymbol{room}}}{\boldsymbol{T}_{\boldsymbol{melt}} - \boldsymbol{T}_{\boldsymbol{room}}}\right)^{\boldsymbol{m}}\right) \qquad \textbf{(1)}$$

where $\boldsymbol{\sigma}$the equivalent flow stress, $\boldsymbol{\varepsilon}$ the equivalent plastic strain, $\dot{\boldsymbol{\varepsilon}}$the equivalent plastic strain rate, and $\dot{\boldsymbol{\varepsilon}}_{\mathbf{0}}$the reference strain rate was $1s^{-1}$. The parameters of the Johnson-Cook are listed in Table 1.

Table 1 Johnson-Cook flow stress model coefficients

A(MPa)	B (MPa)	n	C	m	T
553.1	600.8	0.234	0.0134	1.0	20

Table 2 shows the material properties for work-piece and tool, which are adopted from the reference [22].

Table 2 Material properties for work-piece and tool

Material properties	Workpiece	Tool
Material	AISI-1045	CBN
Young's modulus (GPa)	210	600
Poisson's ratio	0.3	0.22
Conductivity(Wm^{-1}°C^{-1})	53.9	44
Specific heat(Jkg^{-1}°C^{-1})	420	750
Thermal expansion Coefficient (°C^{-1})	1.2×10^{-6}	1.35×10^{-6}

1.3 Heat transfer model

As is shown in the Fig. 3, the heat generated at the chip-tool interface due to deformation and friction. The heat generation is modeled as a volume heat flux. Heat conduction isassumed to be the primary mode of heat transfer, whichoccurs in the work-piece and tool. The governing equation of heat transfer is as follows：

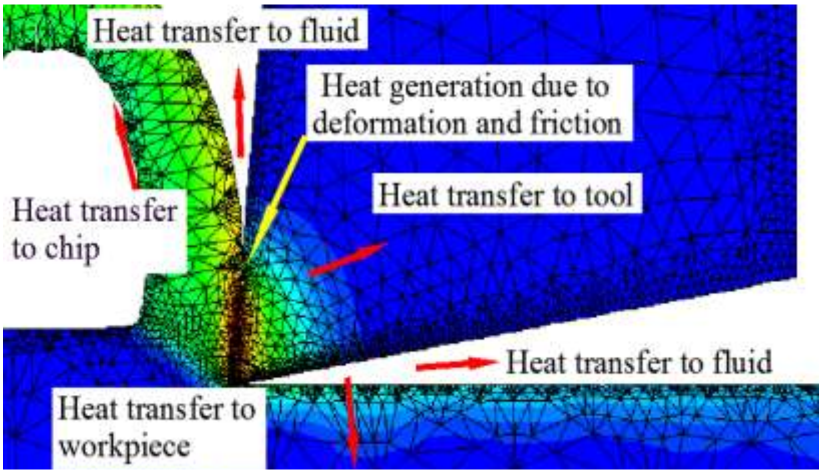


Fig. 3 The heat generation and flow

$$\int_V \rho_m \dot{U} dV = \int_s q dS + \int_V \dot{Q} dV \qquad (2)$$

Where V is the volume of solid material with surface area S, ρ_m the mass density, $\dot{U}$ the material time rate of internal energy, q the heat flux per unit area of the body flowing into the body and $\dot{Q}$ the heat supplied externally into the body per unit volume.

III. CUTTING SIMULATION EXPERIMENT SET UP

In this section, the macrograph of simulation configuration is shown in Fig. 1. The experiment was performed with turning AISI 1045 work-piece on the CA6140 machine. The CBN inserts with properties shown in table 2 were used in the tests. In the first tests, the chip load of 0.1mm, depth of cut of 1mm and the cutting speed (40, 100, 400, 560m/min) were adopted. After each test, the cutting chip formation, shear angle and cutting forces obtained from simulation were compared with each other under three heat transfer coefficients(5230, 7.14×10^4, 3.93×10^5 W/(m^2K)). In the second tests, the uncut chip thickness was 0.1mm, the depth of cut was 1mm and the cutting velocities were from 350 to 550 m/min. To obtain the specific cutting energy and discuss the size effect in metal cutting, the cutting forces and cutting power were recorded in simulation. Fig. 4 shows a 2D representation of the turning operation.

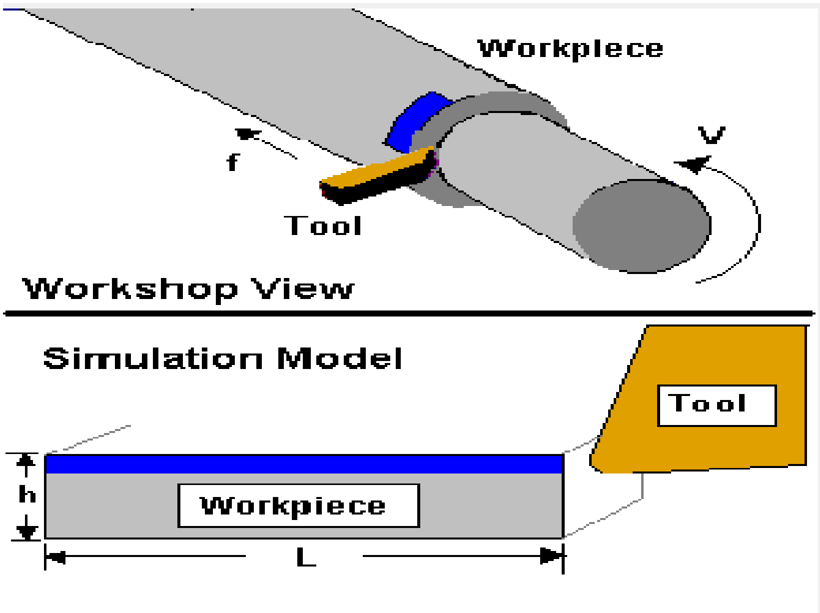
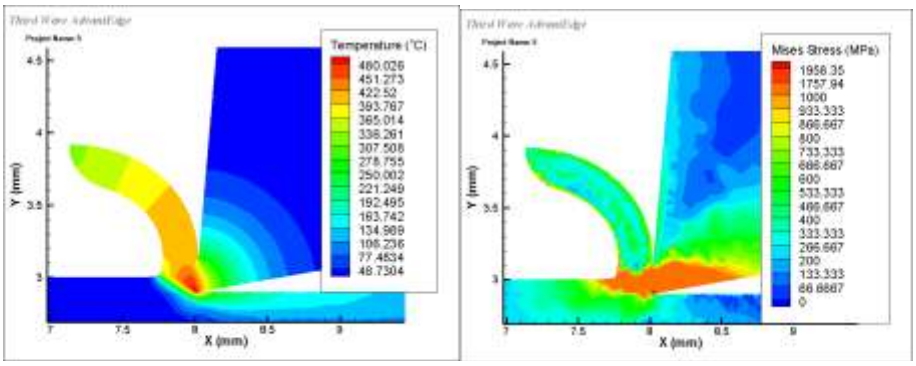


Fig. 4 Schematic representation of turning process in 2D

IV. RESULTS AND DISCUSSION

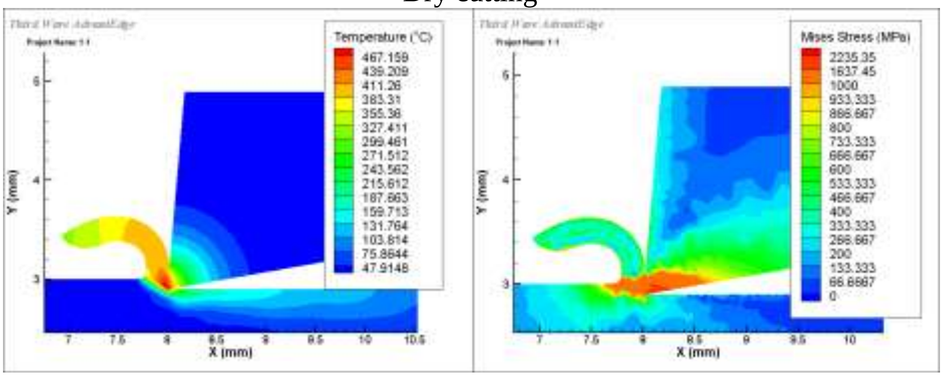
4.1The effects of heat transfer coefficient on chip shape

Duringthe metal machining, the chip form is a significant index to estimate the process of cutting. Especially the tool wear is small and machined surface quality is high when the chips appear long tubular or helical shapes. The "C" and "6" form chips are so necessary that they will not twine round the tools and work-piece, and the cutting forces are steady without any chip splashing. When the shear stress surpass the rupture strength on the whole shear region, there will be uniform size granular chip after the segmentation ofunit, this kind of chip represents low fluctuant cutting forces and fine machined surface quantity. The crack-chip reflects the unstable cutting condition when machine hard and brittle material, due to the metal layers after the elastic deformation process transforming into fragment directly, without plastic deformation. The avalanche crushed cutting could reduce the machined surface quantity and promote the tool failure.



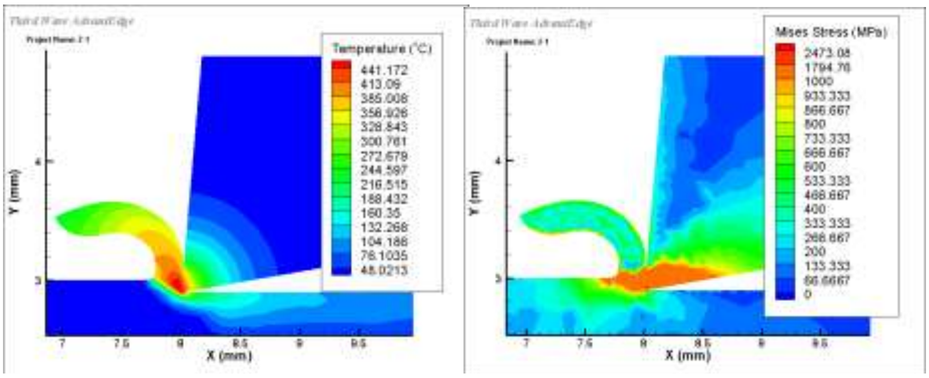
A_1 A_2

Dry cutting



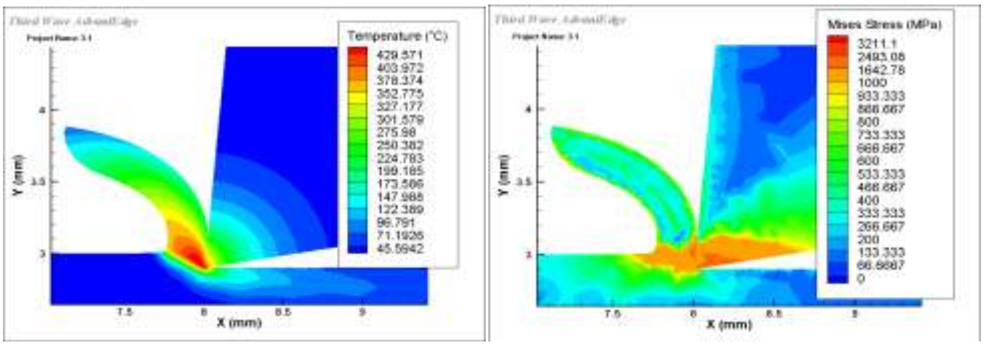
B_1 B_2

h=5230 W/(m^2K)



C_1 C_2

$h = 7.14\times10^4$ W/(m^2K)



D_1 D_2

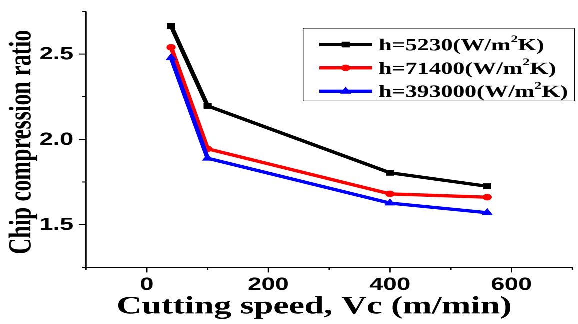
$h = 3.93\times10^5$ W/(m^2K)

Fig.5The temperature and stress distributions of material under different heat transfer coefficient (h) 5230, 7.14×10^4 and 3.93×10^5 W/(m^2K).

Fig. shows the distributions of temperature field and stress in the simulation of cutting process under heat transfer coefficient from low to high (5230, 7.14×10^4, 3.93×10^5 W/(m^2K)). The overall effect of heat transfer coefficient appears to be significant. As is depicted in Fig. 5a, at dry machining condition, the chip shape presents continuous circular. Temperature near the chip tool interface is about 480℃， which is due to the heat generated in shear zone and friction on chip tool interface. It is obviously shown in Fig. b, the chip shape has bigger curvature and the heat generation transfer from the chip tool interface to primary zone. Mainly because the simulated coolants take away heat flux coming from the effect of friction. Also, the experiments indicate that MQL reduces tribology behavior on the chip tool interface. However, the adiabatic bands on the chip can be found in Fig. c and d, because the cutting fluid with higher heat transfer coefficient appears more effective to take away heat flux. The stress variation shows reverse trend with temperature, due to coolant reducing the current temperature according to JC model.

4.2The effects of heat transfer coefficient on chip compression ratio and shear angle

Fig.6 a. shows the chip compression ratio Λ_h of material with three heat transfer coefficients under different speeds. It can be found in Fig. a that the chip compression ratio Λ_h of material goes down as the cutting speed and heat transfer coefficient increases. The value of Λ_h decreases with the increase in V particularly at its lower range because of plasticization and shrinkage of primary zone for reduction in friction and built-up edge at chip tool interface. High coefficient results in lower ratio Λ_h, because steel has excellent thermal conductance, the MQL droplets absorb heat flux more effective compared with other materials, reducing the thermal expansion. The variation in value of shear with cutting speed and heat transfer coefficient are shown in Fig.6 **b.** The shear angle goes up as cutting speed increase and it nearly goes up to 45°. The simulation results above are in accordance with the conclusion with Lei Wan [22]. The cutting temperature increasing with speed increases, reducing the internal friction on the chip tool interface, the shear angle changing as a result, besides, the chip flowing on the rake face of tool increasing with cutting speed up, the friction coefficient reduces correspondingly. Obviously, the shear increases with heat transfer coefficient increasing, it can be explained with the formula of chip compression ratio Λ_h.



a

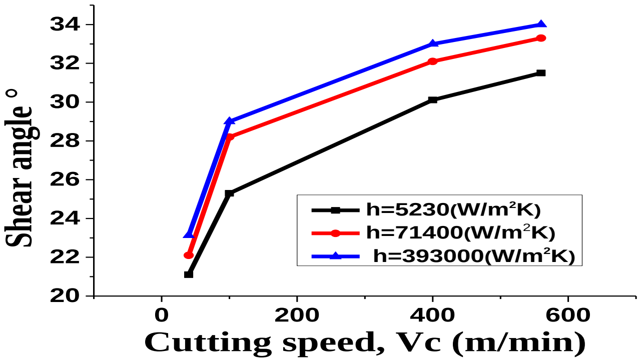


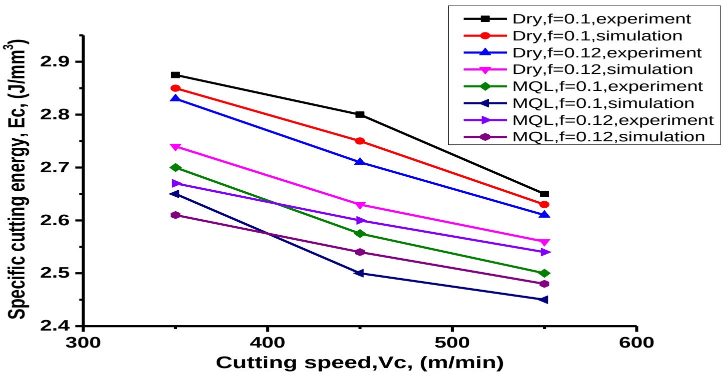
Fig. 6aThe chip compression ratio Λ_h of material and **b** shear angles of simulation under cutting speed from 40 to 560 m/min

4.3Specific cutting energy

The specific cutting energy is the energy which is used to remove unit volume material, it can be used to estimate the efficiency of energy utilization for material removing under metal cutting. The specific cutting energy can be expressed as follow:

$$E_c = \frac{P}{a_e v_w b} \tag{2}$$

Where a_e is the cutting depth, v_w is the cutting speed and b is the cutting width. Fig. 8 shows the comparison of specific cutting energy between MQL and dry condition.



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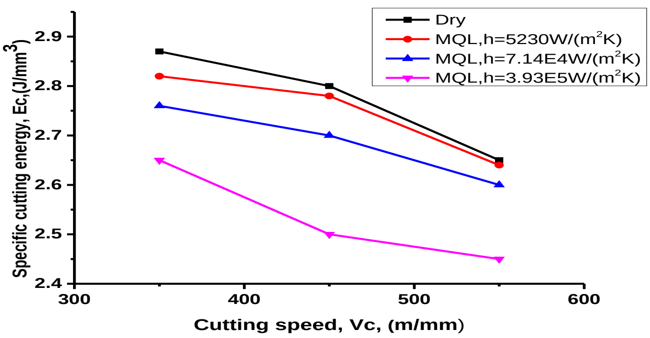

b

Fig. 7a Specific cutting energyobtained in experimentsand simulations and **b** the comparisons of specific cutting energy among different heat transfer coefficientsjius

Fig. 7a shows the specific cutting energy variation with the different cutting speeds and cutting conditions. It was observed that the specific cutting energy decreased as the feed rate and cutting speed increased under dry machining. It was notable that the specific cutting energy appears inverse tendency, the specific cutting energy increased as the feed rate increased under MQL condition. It was due to the size effect [21]. When material is cut by machining, there is increase in specific energy required with decrease in chip thickness. The shear stress in metal cutting is unusually higher than material yield stress, the shear stress presents enormous when thinner chip. The higher specific cutting energy is related to the thermal isolation during chip formation process, the most of energy consumed in metal-cutting transfers into heat, which is hard to spread under thick chip size and relative lower cutting speed, the thermal energy will transfer into melt energy. The softening material need less energy to be removed whichis remarkable as cutting speed increasing. The application of MQL at chip-tool interface is expected to improve the friction and thermal condition that decreases the specific cutting energy. The comparisons of specific cutting energy among three heat transfer coefficients can be found in Fig. 7b. The comparisons suggest that the specific cutting energy decreases as the cutting and heat transfer coefficient increase. Moreover, at a fixed cutting speed such as 450m/min, the energy consumption under 5230 W/(m^2K) is 11% larger than that under 3.93e5 W/(m^2K). While at the cutting speed of 550m/min, the energy consumption under the 5230 W/(m^2K) is 7.2% larger than that under 3.93e5 W/(m^2K).

V. CONCLUSIONS

In this paper work, the effect of MQL on chip formation, chip compression ratio, shear angle and specific cutting energy was studied. The conclusions can be drawn in this work:

a. There are three steps of metal cutting: initial step, elastic deformation and chips generated on the surface of work-piece, MWFs penetrated into the interface between chip and rake face in the form of droplet, improve the friction condition; plowing step, hard points squeeze into softer surface between chip and cutting tool to produce micro-cracks while cutting fluid adhering on the interface that near the tool edge begin to show lubrication failure caused by increasing shear stress and temperature; cutting step, the temperature and stress increasing with cutting process, the contact region between chip and rake face can be divided into two zone: sticking and sliding zones, the MWFs penetrate into sliding zone through capillaries;

b. The heat transfer coefficients have some influences on the formation of chip, the compression ratio and shear angle. The curvature of chip will be big, due to the heat loss caused by heat flux transfer. The shear angle is close to 34° influenced by ▯;

c. Specific cutting energy shows the size effect under dry condition while for the MQL reveals inverse trend. The comparisons with different h show that a bigger coefficient contributes to a small specific cutting energy. Finally, the simulation method is only applied to reveal the stress and temperature distribution, and can not be identical with experiments. So the chip shape under heat transfer coefficients is still worth to study in the future with experimental method.

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