A Simulation on Influence of Cooling at Rake Face to Tool Temperature

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Abstract. In this paper, heat balance equation at the tool is derived and modified. The equation covered heat generated at tool-chip interface and dissipation via rake face and flank face. Based on heat balance equation derived, heat removal from the tool can be improved by reducing rake face length exposed to ambient air. A cooling source from water is introduced at a fraction of exposed rake face with high heat transfer coefficient. Finite element study conducted shows tool temperature closed to cutting edge is reduced by 23% by increasing length of water cooling at rake face. In addition, increasing area of water cooling shows significant impact on tool temperature when tool temperature decent by 31% compared to without cooling from water. The presence of cooling source at a fraction of exposed rake face has remarkable effect on tool temperature.

Keywords; Orthogonal cutting, tool temperature

1. Introduction

In orthogonal cutting, there are three shearing zones which contributed to heat generation. They are namely primary shear zone, secondary shear zone and lastly tertiary shear zone. The energy from severe plastic deformation at primary shear zone during cutting is converted into heat and most of the heat generated is absorbed by the chip at secondary shear zone [1]. Therefore, at tool-chip contact zone, which is at secondary shear zone, the heat from the chip is transferred to the cutting tool as depicted in Figure 1 consequently increased the risk of thermally activated wear mechanism. To get rid of the heat from accumulating at tool-chip contact zone, cooling source has to be close to the cutting edge.

Poor heat distribution at tool-chip contact zone will promote increasing in sticking zone length consequently rising tool temperature. It is also reported in finite element modelling in cutting H13-hardened die steel when the highest temperature generated is located at tool-chip interface producing 500°C [2]. After some interval, the heat is propagated into the tool, consequently, increase tool temperature.

2. Plastic Deformation of Workmaterial

In metal cutting, the workmaterial undergo severe deformation at high strain-rate in the primary and secondary zones, which affect the plastic flow stress of the workmaterial. The plastic deformation in workmaterial is fundamentally accompanied by the heat generation which results in temperature rise in the work-material, mainly in the chip and the newly machined surface affecting the tool heating. The volumetric heat generation due to this phenomenon is given by:
\[ \dot{q}_p = \eta_p \bar{\sigma} \dot{\varepsilon}_eq \]  

(1)

where \( \eta_p \) is the plastic work conversion factor (Taylor–Quinney factor). It defines the fraction of the heat generation caused by mechanical dissipation associated with the plastic strain. Excessive tool heating by friction energy may accelerate tool wear if the contact/friction is not controlled. Friction at the tool–chip interface is described by the modified Coulomb friction law. This is defined by the relationship between the normal friction stress \( \sigma_n \) and the shear friction stress \( \tau_f \) as follow:

\[ \tau_f = \mu \sigma_n \]  

(2)

where \( \mu \) is the friction coefficient. Heat generation in the cutting zone has two origins, the friction at the tool–chip interface and the plastic strain of the workmaterial. The heat generated at the tool–chip interface by contact/friction is described according to the following relationship:

\[ \dot{q}_f = \eta_f \tau_f V_s \]  

(3)

where \( V_s \) is the sliding velocity, \( \tau_f \) the friction stress given by Eq. (2) and \( \eta_f \) the frictional work conversion factor. It is common to assume all the frictional work converted into heat, \( \eta_f = 1 \). Based on Figure 1, heat balance equations at the tool–chip interface by assuming a perfect contact, accounting of the frictional heat as at tool-chip interface can be written:

\[ \dot{q}_{tool} = \beta \dot{q}_f \]  

\[ \dot{q}_{chip} = (1 - \beta) \dot{q}_f \]  

(4)

where \( \beta \) defines the fraction of friction heat generated in the tool side.

3. Heat Energy Balance

Based on the first law of thermodynamics and the lumped parameter method, the heat energy balance equations of the tool can be written as follows:

\[ c \rho V \frac{dT_{tool}}{dt} = \dot{q}_{tool} A_{tc} - q_{ra} - q_{fa} \]  

\[ = \beta \dot{q}_f A_{tc} - h_{air} (T_{tool} - T_{air}) A_{ra} - h_{air} (T_{tool} - T_{air}) A_{fa} \]  

(5)

where \( c, \rho, V \) are the heat capacity, mass density and volume of the tool and \( A_{tc}, A_{ra}, A_{fa} \) are the contact area of tool-chip interface, contact. \( T_{tool} \) is the volume average temperature of the tool and \( h \) is the heat transfer coefficient of the area contact with air. \( q_{ra} \) is the heat that dissipates into air through the rake face via and \( q_{fa} \) is the heat emit into air through flank face. Both \( q_{ra} \) and \( q_{fa} \) dissipate heat via convection principal. Based on Eq. (5), a thermal circuit is generated to explain heat transfer process at tool-chip interface as shown in Figure 1. Fraction of heat at tool-chip contact length \( l_c \) is conducted to the tool as a result, heat flux, \( \dot{q}_{tool} \) generated increase tool temperature. At the rake face and flank face, heat is emitted to the air via convection.
Contact length of tool-chip, $l_c$ and exposed rake face, $l_{ra}$ can be related by Eq. (6) as follow:

$$l_{ra} = L - l_c$$

in which $l_c$ is determined by numerical approach. The fraction of two different conditions at exposed rake face is described by Eq. (7):

$$l_{cf} = l_{ra} - l_{air} = l_{ra} - \alpha l_{ra}$$

where $\alpha$ is fraction from total exposed rake face, $l_{ra}$. From Eq. (7), it is favorable to have minimum value of $\alpha$ to increase $A_{cf}$ for maximum heat dissipation via rake face. Therefore, a modified thermal circuit is derived as shown in Figure 2.

In order to enhance heat dissipation from tool, term $q_{ra}$ is modified by expanding the exposed length at rake face into two different environments. Modified of $q_{ra}$ leads to the following heat balance equation:

$$c_p V \frac{dT_{tool}}{dt} = \beta \dot{q}_f A_{ic} - \left[ h_{air}(l_{air}w_{air}) + h_{cf}(l_{cf}w_{cf}) \right] (T_{tool} - T_{air})$$

where $l_{air}$, $l_{cf}$, $w_{air}$, $w_{cf}$ are exposed rake face to the air, exposed rake face to cooling fluid, width of rake face to the air, and width of rake face to cooling fluid respectively. Based on Eq. (8) maximum heat dissipation at $q_{ra}$ can be achieved by increasing value of $h_{cf}$ and contact area of $A_{cf}$.
4. Numerical Modelling

4.1. Boundary Condition

Numerical modelling is conducted from simplified 2D model of cutting tool shown in Figure 3 to enlighten the influence of expansion of rake face into two different conditions. A full scale of cutting insert is used in the finite element modelling conducted in Abaqus 6.14. An assumption is applied for contact length of tool-chip, \( l_C \) which is equal to cutting depth, \( d \) while the rest of faces at cutting tool are considered thermally insulated. In this case, \( w_{\text{air}} \) and \( w_{\text{cf}} \) the software assumed the value is 1. At tool-chip, \( l_C \) cutting temperature, \( T \) is 300°C with depth of cut, \( d = 0.1 \) mm as in cutting Mg Alloy AZ31B-O [3]. Water is considered as cooling fluid attribute by its high specific heat capacity.

![Figure 3. Simplified tool model in orthogonal cutting](image)

Table 1 below describes the cutting condition applied in numerical model and Table 2 shows material properties of cutting tool and ambient properties. Four values of \( \alpha \) are used to simulate the influence of difference heat transfer coefficient, \( h \) at exposed rake face, \( l_{ra} \) to the tool temperature.

| Cutting condition                  | Values   |
|-----------------------------------|----------|
| Depth of cut, \( d \) (mm)        | 0.1      |
| Cutting temperature, \( T \) (°C) | 300      |
| Exposed rake face to cooling fluid, \( l_{cf} \) (mm) | \( \alpha = 0.1, 0.5, 0.7, 1.0 \) |

| Table 2: Material Properties [4] |
|----------------------------------|
| Density, \( \rho \) (kg/m\(^3\)) | Carbide Water at 20°C 15,000 998 |
| Thermal conductivity, \( k \) (W/mK) | Carbide Water at 20°C 46 0.598 |
| Specific heat, \( c_p \) (J/Kg °K) | Carbide Water at 20°C 203 4182 |
| Heat transfer coefficient, \( h \) (W/m\(^2\) K) | Air at 25°C Water at 20°C 5 10,000 |
Steady state condition modelling is considered in the finite element modelling which end after 10 second. In order to elucidate the influence of cooling fluid area on exposed rake face, \( l_{ra} \), same configuration of tool model is used with minor modification. Introduction of this configuration is to emulate a control volume of cooling fluid at the tool as in the real application, water need to be avoided to have contact with Mg alloy to prevent occurrence of explosion. Height of cooling fluid region is similar to the length of \( l_{cf} \). Cutting condition used are similar as in Table 1. It is a consideration the cooling fluid is constantly maintained at 20 °C through entire simulation in order to expedite the heat removal from the tool.

4.2. Result
Figure 4 shows the temperature distribution and specific temperature at a point (0.2, 0.1) mm from the cutting edge for respective \( \alpha \) value = 1 is equivalent to no cooling from cutting fluid entirely at exposed rake face. The cooling effect is only from the ambient air which have very low heat transfer coefficient. After 10 second, temperature at entire tool reach steady state condition which is 299°C. Nonetheless, the existence of cooling fluid at exposed rake face, has shown remarkable effect on tool temperature as depicted in Figure 5.

![Figure 4. Tool temperature with \( \alpha = 1 \).](image)

Compared to Figure. 6, presence of cooling fluid at a fraction of exposed rake face, \( l_{ra} \), the tool temperature at specified point (0.2, 0.1) dramatically reduces with the reduction of \( \alpha \) value as \( l_{cf} \) increase at rake face as denoted by Eq. (7). It can be explained by heat dissipation rate increment via convection to the cooling fluid which possessed high heat transfer coefficient even though the tool has low thermal conductivity. In Figure 6, temperature gradient shows the tool is cooling down with the aid of cooling fluid at \( l_{ra} \). Temperature reduction is very profound with \( \alpha = 0.1 \) when the recorded temperature reduces to 232°C which is 23% less than the tool with no presence of cooling fluid. High \( \alpha \) value retards heat dissipation from tool rake face to the ambient due to low heat transfer coefficient. Presence of cooling fluid at high \( \alpha \) value tends to limit its ability to absorb the heat from the tool.

![Figure 5. Tool temperature at location (0.2, 0.1) mm after 10 second; (a) \( \alpha = 0.7 \) (b) \( \alpha = 0.5 \) (c) \( \alpha = 0.3 \) (d) \( \alpha = 0.1 \).](image)
Trend of temperature rise is proportionally to $\alpha$ value. Therefore, in order to have a lower temperature of tool, the $\alpha$ value should be reduced as low as possible. In modified tool model, result of tool temperature at point $(0.2, 0.1)$ in steady state condition for every $\alpha$ value are depicted in Figure 6. Based on Figure 6, as expected the highest temperature is denoted for $\alpha = 0.7$ with $251^\circ C$ and remarkably the lowest temperature reduction is gained for $\alpha = 0.1$ which is $207^\circ C$ and coincide to the Eq. (8). It is denoted that influence of cooling fluid height is severe to tool temperature since temperature difference between original configuration and modified configuration for $\alpha = 0.1$ is $25^\circ C$ equivalent to 12% reducing in tool temperature. Therefore, it is an evidence that presence of cooling fluid at exposed rake face successfully led to decreasing in tool temperature.

Figure 6. Tool temperature at location $(0.2, 0.1)$ mm after 10 second in modified configuration. (a) $\alpha = 0.7$ (b) $\alpha = 0.5$ (c) $\alpha = 0.3$ (d) $\alpha = 0.1$

**Conclusion**

In order to further understand heat dissipation at tool rake face, heat balance equation is derived based on 2D model. A modification is introduced to the heat balance equation to improve heat dissipation at tool rake face by introducing cooling source with higher heat transfer coefficient. Numerical approach revealed reduction of exposed rake face length to the ambient by replacing with cooling source improved tool temperature close to cutting edge. Besides, area of cooling source has significant impact in reducing tool temperature.

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