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Development of Thermomechanical Model for the Analysis of Effects of Friction and Cutting Speed on Temperature Distribution Around AISI 316L During Orthogonal Machining

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Abstract

In metal cutting, severe deformation takes place in the vicinity of the cutting edge of the high strain-rate and an increase in temperature is observed. Deformation behaviour of the work material in the primary and secondary zones is highly sensitive to the cutting conditions. Also, the frictional conditions between the tool and the chip and tool and the workpiece are highly complex and sensitive to the cutting conditions. As a result, the stresses and temperatures at tool-chip interface and around the cutting edge can be critically high in some cutting conditions and can cause excessive tool wear or premature tool failure. This research work focuses on the accurate prediction of the distribution of the process variables such as stresses and temperatures with the Finite Element (FE) Analysis to identify optimum cutting conditions, tool material, edge geometry and coating in order to help improve productivity and quality of machining operations. Effects of work material flow stress and interfacial friction at chip-tool interface on the accuracy of the predicated process variables in FE simulations are also analyzed. Specifically, friction models and cutting speed are varied to predict the effect on the temperature distribution, stresses and strain on the workpiece and tool chip during orthogonal cutting process. The result showed that an increase in coefficient of friction will cause an increase in thermal, force and mechanical variables during machining. Thus, the higher the coefficient of friction, the higher, the cutting forces, temperature, stress, and strain.

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1. Introduction

One of the commonest operations in manufacturing process is metal cutting. This is a complex phenomenon of multi-physics, where elasticity and plasticity, fracture, contact, heat transfer, among others takes place simultaneously.

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The frictional conditions between the tool and the chip and the tool and the workpiece are highly complex and also sensitive to the cutting conditions. As a result of these, the stresses and temperature at tool-chip interface and around the cutting edge can be critically high in some cutting conditions. The most significant factors in tool wear are temperature and the degree of chemical affinity between the tool and the workpiece.

The increase in temperature of the workpiece material in the primary deformation zone softens the material, thereby decreases cutting forces and the energy required to cause further shear. Temperature at the tool-chip interface affects the contact phenomena by changing the friction conditions, which in turn affects the shape and location of the primary and secondary deformation zones, maximum temperature location, heat partition and the diffusion of the tool material into the chip. Subsequently, the high cutting temperature strongly influence tool wear, tool life, workpiece surface integrity, chip formation mechanism and contribute to thermal deformation of the cutting tool.

In orthogonal machining process, majority of the input energy is converted into heat by the deformation of the chip and by the effect of the friction between chip and workpiece on the tool [1 – 3].

The experimental measurement of the temperature and heat distribution in metal cutting is extremely difficult due to the narrow shear band, chip obstacles, and the nature of the contact phenomena where the tool and chip, are in continuous contact, moving with respect to each other. Due to this difficulty, the development of analytical and numerical models of temperature distribution can aid in addressing important metal cutting issues such as tool life and dimensional tolerance under practical operating conditions. These models aid in the determination of temperature distribution on the tool rake face, the investigation of the heat partition and obtaining the temperature field within the cutting tool, chip and workpiece.

Various analytical studies have been done on the temperature distribution around the workpiece-tool interface. For instance, Young and Chou [4] presented an analytical model to predict the tool-chip interface temperature distribution during orthogonal metal cutting. It assumed plain strain and steady-state conditions. The shear plane and frictional heat source were assumed as plain heat sources of uniform strength. It was also assumed that the shear plane was inclined to the chip velocity, while heat conduction in the direction of motion was neglected and the heat generated along the shear plane was at a uniform rate. The results showed that the maximum temperature occur along the interface where the chip starts to separate from the tool face as a consequence of the assumption of a plane source of uniform strength at the tip interface. Komanduri and Hou [5] developed an analytical model for the temperature distribution at the tool-chip interface in metal cutting. The combined effect of shear and frictional heat sources were considered. The results showed the combined effects of the shear and frictional heat sources on the temperature rise. It was concluded that, although, the contribution of the friction heat source is predominant, the shear plane heat source accounts for an increase in the temperature at the interface of about 200ºC.

Moreover, studies on the machining of AISI 316L steel have mostly focused on the use of coated and/or uncoated carbide as cutting tool [6 – 12]. Whereas, the workpiece-tool materials interactions bring necessary implications to the thermal and mechanical behaviour of the machining processes as well as the machined product, different combination of workpiece-tool materials will have different thermomechanical behaviours. Hence, the need to study the impact of other cutting tool materials on the machining of AISI 316L steel. This is partly the focus of this study. Further to this, it also focused on investigating the effect of varying friction parameter on the temperature distribution around the workpiece-tool interface. Thus, the study developed thermomechanical model to analyze the effects of friction and cutting speed on cutting force, stress, strain and the temperature distribution around the cutting tool during orthogonal machining using the Finite Element method. The cutting tool material is high speed steel and that of the workpiece is AISI 316L steel. AISI 316L steel is an extra low carbon grade of 316, with high resistance to corrosion. It is useful for stainless steel watches, fabrication of marine vessels and other marine applications, and in the fabrication of reactor pressure vessels for boiling water reactors.

2. **Model Development**

The model developed is to give a clear understanding of the temperature distribution with cutting tools inserts embedded with heat pipes to eliminate the use of cutting fluid and reduce tool wear in machining. During machining, heat is generated at the cutting point from three sources. These are the primary shear zone where the major part of energy is converted into heat, the secondary deformation zone which is at the chip-tool interface where further heat is generated due to rubbing and/or shear and at the worn out flanks, where there is rubbing between the tool and the finished surfaces. Thus, the energy equation is given as:

$$\frac{\partial(\rho C_p T)}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial y}{\partial z} = \frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right) + Q_g \tag{1}$$

The workpiece is assumed to be stationary during the cutting operation, we have

$$\frac{\partial(\rho C_p T)}{\partial t} = \frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right) + Q_g \tag{2}$$

$$u = v = w = 0 \tag{3}$$

where u, v and w are the components of speed in the xyz directions; k = thermal conductivity; ρ = density; c_p = specific heat of workpiece; T = temperature and Q_g = internal heat generated. Assuming the material is homogenous isotropic, then

$$k_x = k_y = k_z = k \tag{4}$$

Therefore

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{Q_g}{k} \tag{5}$$

Where $\frac{1}{\alpha}$ is inverse of $\frac{\rho C_p}{k}$

where α = thermal diffusivity and ρc_p = volumetric heat capacity

Modelling the internal heat generation in the workpiece:

$$Q_g = Q_f + Q_s \tag{6}$$

where: Q_f = friction heat generation, Q_s = heat generation due to plastic deformation,

$$Q_f = F_f V_c = \frac{\tau h V sin\beta_n}{cos(\varphi_n+\beta_n-\alpha_n)sin(\varphi_n-\alpha_n)} \tag{7}$$

$$Q_s = F_s V_c = \frac{\tau h V cos\alpha_n}{sins\alpha_n\ cos(\varphi_n-\alpha_n)} \tag{8}$$

$$\therefore Q_g = \eta\tau\ \ V \tag{9}$$

Where: $$\eta = \frac{sin\beta_n sin\alpha_n cos(\alpha_n-\alpha_n)+cos\alpha_n \cos(\varphi_n+\beta_n-\alpha_n) sin(\varphi_n-\alpha_n)}{sin\alpha_n sin(\varphi_n-\alpha_n)cos(\varphi_n-\alpha_n)cos(\varphi_n+\beta_n-\alpha_n)} \tag{10}$$

where η = frictional work conversion factor

For frictional heat flow rate into the tool, according to Dinc *et al.* [6] and Haddag *et al.* [7], is given as:

$$Q_t = \frac{BQ_f\partial x}{l_{cn}k_t} \tag{11}$$

where: B = partition heat value at the nodal point, ∂x= grid length along the x-axis, l_{cn} = chip-tool length, k_t = tool's thermal conductivity

$$Q_t = BQ_f = \frac{B\tau h V sin\beta_n}{[cos(\varphi_n+\beta_n-\alpha_n)sin(\varphi_n-\alpha_n)]l_{cn}k_t} \tag{12}$$

Therefore, the heat balance at the tool-workpiece interface, taking to cognisance the thermal contact resistance is given by Haddag et al. [7] as:

$$Q_{tool} = \beta Q_g + \mu(T_w \quad T_t) \tag{13}$$

$$Q_{workpiece} = (1 \quad \beta)Q_g \quad H(T_w \quad T_t) \tag{14}$$

where: β = heat generation coefficient, μ = H = heat transfer coefficient for the tool-workpiece interface and the contact length is expressed as Huang and Liang [8] and Budak and Ozlu [9]:

$$l_{cn} = \frac{tsin\theta}{cos\lambda\, \mathrm{si\ n}\varphi}\left[1 + \frac{\grave{c}\gamma_{AB}I}{3[1+2\left(\frac{\pi}{4}-\varphi\right)-\frac{\grave{c}\gamma_{AB}I}{k_{AB}}}\right] \tag{15}$$

where: $$\gamma_{AB} = \frac{sin\alpha}{2sin\varphi\cos(\varphi-\alpha)} \tag{16}$$

$$K_{AB} = \frac{1}{\sqrt{3}}\left(A + B\left(\frac{\gamma_{AB}}{\sqrt{3}}\right)^n\left(1 + C\ l\ og\frac{\gamma_{AB}}{\sqrt{3}\varepsilon_0}\right)\right)\left[D \quad E\left(\frac{T-T_r}{T_m-T_r}\right)^m\right] \tag{17}$$

$$I = \left(\frac{dk}{d\gamma}\right)_{AB} \tag{18}$$

$$\left(\frac{dk}{d\gamma}\right)_{AB} = \frac{1}{3}B_n\left(\frac{\gamma}{\sqrt{3}}\right)^{n-1}\left(1 + C\ l\ og\left(\frac{\gamma_{AB}}{\sqrt{3}\varepsilon_0}\right)\right)\left[D \quad E\left(\frac{T-T_r}{T_m-T_r}\right)^m\right] + \left[\frac{1}{\sqrt{3}}(\sigma_0 + B\left(\frac{\gamma}{\sqrt{3}}\right)^n\left\{1 + C\log\left(\frac{\gamma}{\sqrt{3}\varepsilon_0}\right)\right\}\right]\left[\quad m\left(\frac{T-T_r}{T_m-T_r}\right)^{m-1}\right]\frac{\partial T}{\partial\gamma} \tag{19}$$

where γ_{AB} = shear strain; $\gamma_{AB} = s\ ear\ strain\ rate$; $\varepsilon_o = reference\ s\ ear\ straın\ rate$; T = absolute temperature; T_r = reference temperature; T_m = melting temperature; T_w = workpiece temperature; α = rake angle; φ = shear angle; λ = tool-workpiece contact angle; subscript n refers to normal component and β_n = normal friction angle. A, B, C, D, E, n and m are material constants explained in Outeiro [6].

The boundary conditions were adopted from Chiou et al. [10] and Ojolo et al. [11] as:

1. The heat source is considered as a plane heat source on the top face of the insert with the following expression.

$$k\frac{\partial T}{\partial z}(x,y,z,t)\Big|_{z=0} = \begin{cases} q_c \ \ for \ \ 0\le x\le L_x,\ \ 0\le y\le L_y \\ h(T-T_\infty)\ otherwise \end{cases} \tag{20}$$

Where q_c is the heat fluxes flowing into the tool insert.

2. The adiabatic boundary conditions are assumed for the two surfaces which are close to the heat source (x=0, y=0) and the bottom surface (z=c) are the following

$$\frac{\partial T(0,y,0\le z\le c,t)}{\partial x} = 0 \tag{21}$$

$$\frac{\partial T(x,0,0\le z\le c,t)}{\partial y} = 0 \tag{22}$$

$$\frac{\partial T(x,y,z,t)}{\partial z}\ \ _{z=c} = 0 \tag{23}$$

3. The ambient boundary conditions are assumed for the two surfaces and considered to be far away from the heat source (x=a, y=b) can be describe as:

$$T(a,y,z,t) = T_\infty \tag{24}$$

$$T(x,b,z,t) = T_\infty \tag{25}$$

2.1 Modelling and simulation

A finite element analysis solver was employed for the geometric modelling and simulation procedures. Fig. 1 shows the geometric model and the simulation results are captured in Figs. 2 to 5. The dimensions of the workpiece as modelled is (0.02 x 0.02) m and 0.04 m high. Constant feed rate and depth of cut of 19.1 mm/rev. and 1 mm respectively were used. The workpiece material is of AISI 316L steel grade and the cutting tool is of high speed steel.

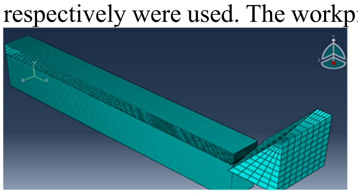

Fig 1: Mesh Image of the Work-piece and tool

The simulation was carried out by varying the coefficient of friction within the range 0.1 (0.1) 0.5 and the cutting speed V_C within the range 50 (100) 450 respectively. The test procedure involves varying the speed while the friction coefficient was held constant.

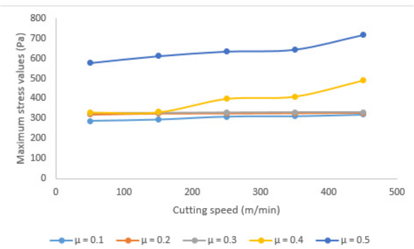

Fig. 2: Variation of maximum cutting stress with speed

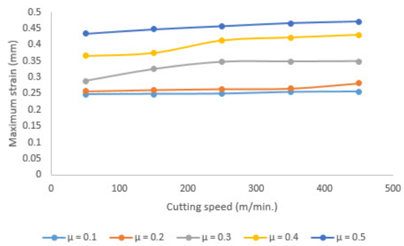

Fig. 3: Variation of the maximum strain with speed

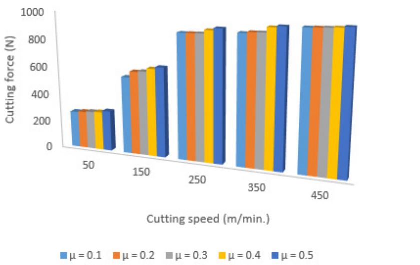

Fig. 4: Variation of cutting force with cutting speed

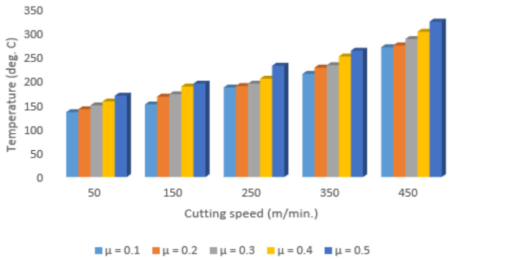

Fig. 5: Variation of tool-chip interface temperature with speed

3. Results and Discussion

Figs. 2 and 3 show that the maximum stresses and strains increase with cutting speeds at constant friction. Moreover, Fig. 3 shows that there is close relationship between the maximum strain values obtained when the friction coefficients (μ) were 0.1 and 0.2. This further suggest that at low friction, the maximum stress and strain are minimal. Figs. 4 and 5, on the other hand, show that increase in cutting speed leads to increase in cutting forces and tool-chip temperatures. However, Fig. 4 shows that at very low and very high speeds, the values of cutting forces are closely related and around 277 and 987 N across the different μ values.

4. Conclusion

Finite element simulation of orthogonal cutting of AISI 316L steel at different cutting speeds and coefficient of friction were investigated. The outcome showed the effects of varying cutting speeds and friction on process variables such as forces, stress/strain and temperatures at the chip-tool interface and stress distributions on the tool rake face. The results showed that an increase in coefficient of friction will cause an increase in thermal, force and mechanical variables during machining. Thus, the higher the coefficient of friction, the higher, the cutting forces, and thermomechanical properties. The chip formation tends to change from discontinuous to continuous as the coefficient of friction and cutting speed increases. The material properties show tendency towards ductility at higher values of coefficient of friction and high cutting speed.

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