MODELLING IMPROVEMENTS IN THE FINITE VOLUME METHOD FOR TEMPERATURE DISTRIBUTIONS CALCULATIONS IN ORTHOGONAL METAL CUTTING

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Abstract. *The fields of temperature distributions in the orthogonal metal cutting by the Finite Volume Method, FVM, were implemented in a numerical code and are presented. The field of isothermal distributions in the tool, chip and work-piece were obtained, using the rate of energy and material flow balance equations, the heat sources from the plastic shear deformation rate at the shear plane and by friction on the tool face. Thus, the energy conservation laws for the steady state conditions of metal machining were applied to each control volume of the structured mesh of piece, chip and tool. Shear stress friction factor* $\tau = mk$ *were employed to model friction and calculate the friction heat source on the tool face, instead of Coulomb friction model. Additionally, the shear plastic deformation power due to the heat source in the cutting shear plane was calculate by* $F_{shear}.V_{shear}$ *(shear force x shear velocity). The field of temperature distributions in the machining of AISI 1020 steel with hard metal insert are presented for velocities of 29.6, 78.0 and 155.4 m/min and compared with the results of Finite Element Method from Tay et al. (1974). The maximum temperature calculated at tool face for each velocity is shown to be in good agreement with the FEM results for a specific calibrated friction factor m. However, the temperatures in the shear plane were different. The effects of material and machining parameters on the temperature distributions are also discussed.*

Key-words: *FVM, Temperature distributions, SAE 1020.*

1. INTRODUCTION

Accurate and repeatable measurements and calculations of the maximum temperature at the cutting tool face and at the workpiece-chip shear zone are important and current topics in metal machining research and practice on the shop floor. Tool life and tool wear are directly linked to the tool face temperature. Consequently, the surface roughness of the workpiece is affected by a worn tool with implications in machining productivity and economy. In addition, the surface quality of machined workpiece, machining accuracy and its surface integrity are also influenced by the temperature generated on the machined surface. Thus, experimental methods, analytical models and numerical methods are intensive research topic and have been developed by several researchers and academics to measure and predict the maximum temperature on the tool face and machined surface in metal cutting. Measurement of tool-chip interface temperature have been carried out by implanted thermocouples, tool-chip hot junction thermocouple, infrared thermal camera, infrared pyrometer, tool microstructural change at region of maximum temperature.

Various experimental methods and reviews on metal cutting temperatures have been presented in the literature. Early works with experimental results are in the books by Trent and Wright (2000), Boothroyd and Shaw (1984). More recently, reviews in metal cutting temperatures are seen in the work by Bacci da Silva et al. (1999), the articles by Komanduri et al. (2001), Abukhshim et al. (2006) and Han et al. (2021). On the other hand, numerical simulation methods have been also employed to model and predict the field of temperature distribution in metal cutting. One first work, applying the FEM method to model orthogonal metal cutting, which is usually cited, is the article by Tay et al. (1974). Later, the authors published a second article with the experimental results for machining steel and comparison with the predicted maximum temperature by Tay et al. (1974), which is seen in the work by Stevenson et al. (1983). The authors stated that finite element modelling showed good agreement with the experimental tool temperature measurements.

Bressan et al. (1992) have also applied the finite difference method, FDM, to calculate the distributions of temperature in the bidimensional orthogonal metal cutting. Assuming the material properties of AISI 1020 steel constant with temperature, the results compared well with the FEM results of Tay et al. (1974), however, the results depended on the assumed boundary conditions, Biot number and friction forces.

The aim of present work is to apply the finite volume method, FVM, and examine the modelling of the heat sources and cutting velocities and its influences on the temperature distributions in the orthogonal machining of AISI 1020 steel. In the FVM approach, the balance of energy flowing into and out plus the heat source in each control volume is assumed zero, therefore the energy conservation law is imposed on each control volume. The modelling of the heat sources was carried out firstly in the friction zone, the friction on the tool-chip interface by assuming the friction factor "*m*" as *shear stress friction factor,* $\tau = mk$, were τ is the shear stress and k is the shear stress limit. Secondly, in the primary plastic deformation zone, examine the modelling of the heat source at the shear plane by the generation of shear strain rate power, *shear force x shear velocity,* $F_{shear}.V_{shear}$. Considering that the mechanical power is used for both plastic strain and friction, an efficiency factor η of heat conversion from mechanical energy was assumed for both heat sources.

2. METAL CUTTING ANALYSIS BY THE FINITE VOLUME METHOD

During the metal cutting operation, the chip is formed by severe shear deformations and friction on tool face, nearly 90% of total mechanical energy is converted into heat. Therefore, the temperatures of the tool, the chip and the workpiece are increased from room temperature to high temperatures, which mainly depend on the material properties, the cutting speed and time. The heat sources occur in two main regions: the primary plastic shear deformation zone around the principal shear plane and the secondary plastic shear deformation and friction zone on the tool face (Bressan et al, 1992; Shaw, 1984). A third source of heat is friction between the tool tip and the new workpiece surface. Thus, neglecting the third source of heat, the total rate of heat generated $\dot{Q}_{total}$ during metal cutting process can be calculated by,

$$\dot{Q}_{total} \cong 0.9 F_c . V_c = \dot{q}_{sh} + \dot{q}_f \qquad \text{[watt]} \tag{1}$$

where F_c is the cutting force [N], V_c the work velocity [m/s], $\dot{q}_{sh}$ is the rate of heat due to plastic shear strain in the primary region and $\dot{q}_f$ is the rate of heat in the secondary region, which is due to both the material plastic shear strain and friction on the tool face. The rate of heat generation in the secondary zone of tool friction can be evaluated by,

$$\dot{q}_f = \eta . F_f . V_{cav} \qquad \text{[watt]} \tag{2}$$

where F_f is the friction force [N], V_{cav} chip velocity [m/s] and η the efficiency factor of heat conversion from mechanical energy. The velocities of chip and at the principal shear plane V_ϕ were calculated by the mathematical vector relations,

$$V_{cav} = \frac{V_c \, sin(\phi)}{cos(\phi - \gamma)} \qquad \text{and} \qquad V_\phi = \frac{V_c \, cos(\gamma)}{cos(\phi - \gamma)} \tag{3a,b}$$

where ϕ is the shear angle of the primary shear plane which has area $A = t_\phi . \ell$, and γ is the tool rake angle or tool attack angle. The friction force F_f was evaluated by assuming a shear stress modelling of friction, using the well-kown equation of friction factor, $\tau = mk$, where m is the friction factor and k the material current plastic shear stress: $0 \le m \le 1$. Hence, $F_f = \tau . A_f$ and then, $F_f = m . A_f . k$, where A_f is the area of friction contact of chip with tool, $A_f = \ell_f . \ell$, where ℓ_f is contact length. Therefore, substituting into Eq. (2), the rate of heat generation by friction on the tool face was calculated by,

$$\dot{q}_f = \eta . m . k . \ell_f . \ell \frac{V \, sin(\phi)}{cos(\phi - \gamma)} \qquad \text{[watt]} \tag{4}$$

The rate of heat generation due to plastic shear strain at the principal shear plane was obtained by,

$$\dot{q}_{sh} = \eta . F_\phi . V_\phi = \eta . \tau_\phi . t_\phi . \ell . V_\phi \qquad \text{[watt]} \tag{5}$$

where F_ϕ is the shear force [N] acting on the shear plane, V_ϕ is the shear velocity [m/s], t_ϕ and ℓ are the length of primary shear area and chip width, respectively ($t_\phi = t_1 / sin\phi$). τ_ϕ is the material current plastic shear stress which depend on the shear strain rate and temperature. The shear velocity was calculated by the mathematical vector relation.

Therefore, substituting Eq. (3b) into Eq. (5) and assuming $\tau_\phi = k$ and the factor η of heat conversion efficiency, the rate of heat generation by plastic shear strain at the principal shear plane was calculated by,

$$\dot{q}_{sh} = \eta . k . \ell \frac{t_1}{sin\phi} \frac{V \, cos(\gamma)}{cos(\phi - \gamma)} \qquad \text{[watt]} \tag{6}$$

where t_1 is the depth of cut or the thickness of undeformed chip. Assuming N as the number of control volume containing the heat source, the generated heat in each control volume of mesh is computed as,

$$\dot{q}_f * = \dot{q}_f / N_f \qquad \text{and} \qquad \dot{q}_{sh} * = \dot{q}_{sh} / N_{sh} \tag{7a,b}$$

2.1 The Finite Volume Method

The bi-dimensional field of isothermal in the tool, chip and workpiece were calculated numerically by employing the FVM method or the control-volume method and a structured and fixed mesh of control volumes. Metal cutting was investigated for 2D heat and mass flows conditions and the orthogonal cutting process conditions.

Applying the first law of thermodynamics for a generic control volume, the rate of energy flowing into the volume minus the rate of energy flowing out plus the generate rate of energy within the control volume is equal to the rate of change of internal energy. Thus, the balance of rate of energy in a control volume for transient condition is calculated by,

$$\sum \dot{q}_{in} - \sum \dot{q}_{out} + \dot{Q}_g = \frac{\partial U}{\partial t} \tag{8}$$

where $\dot{q}$ is the rate of heat flow (conduction, convection and by mass transport), $\dot{Q}_g$ $(= \dot{q}_g.dx.dy.\ell)$ is the rate of generated energy by the heat sources and U is the internal energy of control volume. Assuming the machining process in steady state condition ($\partial U/\partial t = 0$) and Δt = 1s, also assuming that the workpiece is moving with work velocity V_c and the tool is fixed, for a control volume situated in the workpiece and chip domains, see in Fig. (1), the balance of energy of Eq. (8) is reduced to,

$$q_{cW} + q_{kW} - q_{kS} - q_{cE} - q_{kE} + q_{kN} = 0 \tag{9}$$

where: $q_{cW} = \rho V_c\, c\, \Delta y\left(\left(T_p + T_W\right)/2\right)$ thermal energy transfer by mass transport (10)

$q_{kW} = -K\, \Delta y\left(\left(T_p - T_W\right)/\Delta x\right)$ heat transfer by conduction, Fourier equation (11)

$q_h = -h\, \Delta x\left(T_p - T_{amb}\right)$ heat by convection for control volumes at workpiece and tool boundaries (12)

ρ = mass density [kg/m^3] ; K = coefficient of thermal conductivity [w/(m.^{o}C)]
c = specific heat [J/(Kg.^{o}C)] ; h = coefficient of heat transfer by convection [w/(m^2.^{o}C)]

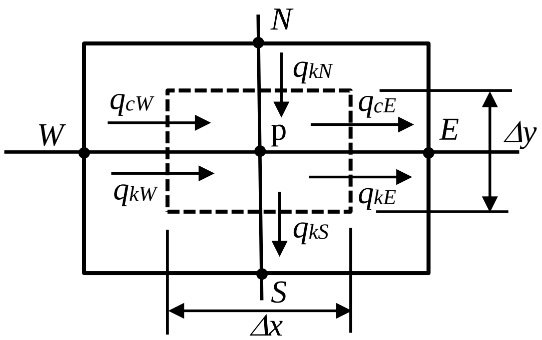

Figure 1. Heat and mass rate fluxes in a control volume situated in the mesh domain and without heat source.

Alternatively, for control volumes situated in the primary zone and containing the principal shear plane, Eq. (10) is modified to account for the plastic shear deformation heat source, q_{sh} ,

$$q_{cW} + q_{kW} - q_{kS} - q_{cE} - q_{kE} + q_{kN} + q_{sh} = 0 \tag{13}$$

Similar equation for friction source. Replacing Eq. (11), Eq. (12) into Eq. (10), and similar equations for neighbouring points on the mesh E, N, S and, after rearranging, the temperature at point p in the mesh domains is calculated by,

$$T_p = \left\{\left(\frac{\rho c V_c}{2K} + \frac{1}{\Delta x}\right)\frac{\Delta y^2}{\Delta x}T_W - \left(\frac{\rho c V_c}{2K} - \frac{1}{\Delta x}\right)\frac{\Delta y^2}{\Delta x}T_E + T_S + T_N\right\} \Big/ \left[2\left(1 + \left(\frac{\Delta y}{\Delta x}\right)^2\right)\right] \tag{14}$$

The temperature for points in the mesh domain of tool, the velocity V_c have to be set to zero, and for chip by V_{cav} .

The boundary conditions adopted in the present mathematical modelling of orthogonal metal cutting were:

a) Temperature gradient at chip end and far from the tool face was very small ($\partial T/\partial n = 0$),
b) The heat transfer from the workpiece, chip and tool to the air was done by convection. No coolant was used.
c) Heat source due to plastic shear strain in the principal shear plane, q_{sh} , according to Eq. (6).
d) Heat source due to friction on the tool face, q_f , according to Eq. (4).
e) The temperature at the bottom of the workpiece was assumed the room temperature of 25 °C.

3. RESULTS AND DISCUSSIONS

The field of isothermals of dry orthogonal machining of AISI 1020 steel were carried out by numerical simulations, using a numerical code with the FVM approach for the work speeds of 29.6, 78.0 and 155.4 m/min, according to Tay et al. (1974). The tool material was the tungsten carbide, Tay et al. (1974). The Gauss-Seidel method was used for the numerical convergence. The material and machining parameters of the orthogonal cutting are seen in Tab. (1) (Tay et al., 1974). Numerical convergence was attained after 20000 numerical iteration loops.

In Fig. 2a, the bidimensional mesh of FVM modelling of the present orthogonal cutting process is shown. In Fig. 2b, the field of temperature distributions in the tool, chip and workpiece are displayed for the work speed of 78.0 m/min, assuming the friction factor m =0.35 and efficiency factor of heat conversion η =0.60, in order to attain equal maximum tool temperature by Tay et al. The corresponding machining and material parameters are in Tab. (1). The maximum temperature attained on the tool face was 620 °C, which is very close to the value of 615 °C obtained by Tay et al. (1974), using FEM approach. However, temperature near the principal shear plane is approximately 480 °C, which is different of the value 200 °C by Tay et al. (1974). This difference is due to the assumption of heat source occurs exclusively on the control volumes in the principal shear plane. Tay et al. assumed that the shear zone is large and occurs around the principal shear plane. Thus, the heat source occurred in several control volumes distributed around the main shear plane.

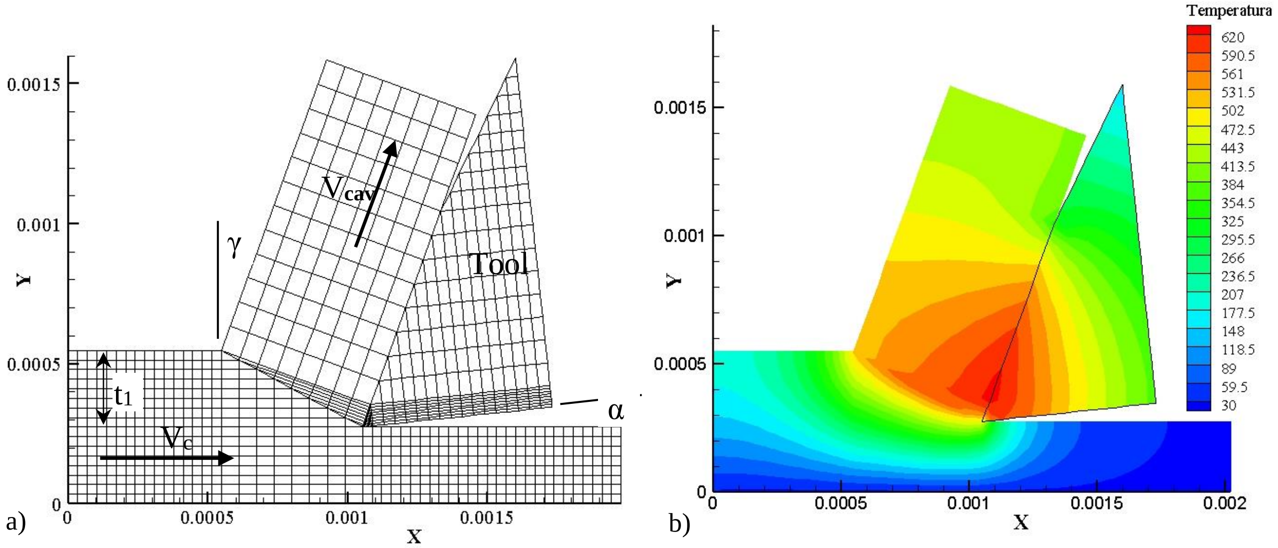

Figure 2. Numerical simulation of orthogonal cutting of AISI 1020 steel by FVM. a) mesh of control volumes.
b) isothermal distributions for work speed of 78 m/min. The maximum temperature reached on the tool face was 620°C.

Table 1. Parameters of orthogonal cutting of AISI 1020 steel (mass density ρ = 7800 Kg/m^3). (1)Tay et al. (1974). (2)Metals Handbook.

Cutting parameters	1	2	3	Cutting parameters	1	2	3
(1) tool speed, V_c [m/min]	29.6	78.0	155.4	(1) depth of cut, t_1 x10^{-3} [m]	0.274	0.274	0.274
(1) shear angle, ϕ	30°	30°	30°	(1) tool contact length, ℓ_f x10^{-3} [m]	0.68	0.82	0.91
(1) rake angle, γ	20°	20°	20°	(2) thermal conductivity K of workpiece [w/(m.°C)]	77	77	77
(1) clearance angle, α	6°	6°	6°	(2) thermal conductivity K of tool [w/(m.°C)]	35	35	35
(1) room temperature	22 °C	22 °C	22 °C	(2) limit plastic shear stress, k [Pa]	600x10^6	415x10^6	418x10^6
coefficient of heat transfer by convection, h [w/(m^2.°C)]	5700	5700	5700	friction factor, m	0.52	0.35	0.30
(2) specific heat, c [J/(Kg.°C)]	470	470	470	heat conversion factor, η	0.60	0.60	0.60

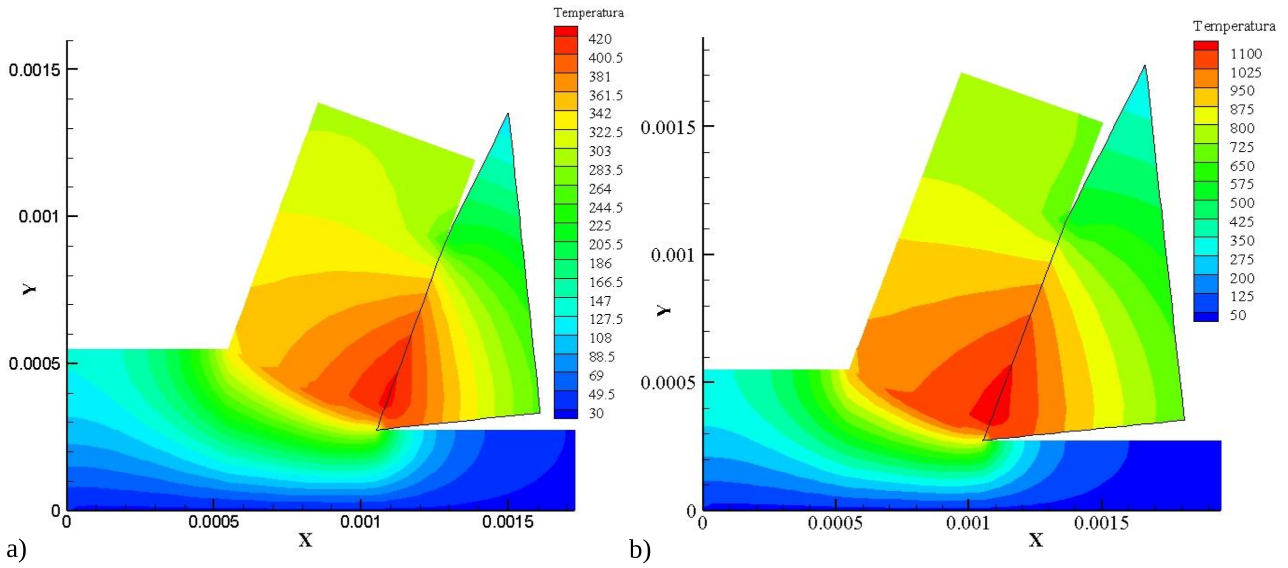

Figure 3. Field of temperature distributions in numerical simulation of orthogonal cutting of AISI 1020 steel by FVM. a) work speed of 29.6 m/min. The maximum temperature reached on the tool face was 420 ºC. b) work speed of 155.4 m/min. The maximum temperature reached on the tool face was 1100 ºC.

In Fig. 3a,b, the field of temperature distributions in the tool, chip and workpiece are shown for the work speeds of 29.6 and 155.4 m/min, assuming the friction factor m =0.52 and 0.30, respectively. The maximum temperature attained for work speeds of 29.6 m/min on the tool face was 420 ºC, which is very close to 424 ºC obtained by Tay et al. (1974). For work speeds of 155.4 m/min, maximum temperature was 1100 ºC, which is close to 1016 ºC obtained by Tay et al.

4. CONCLUSIONS

The maximum temperatures calculated by the Finite Volume Method for the tool face for each velocity are shown to be in good agreement with the FEM results obtained by Tay et al. (1974), for a specific calibrated friction factor m. For the work speeds of 29.6, 78 and 155.4 m/min, the calibrated friction factors were m = 0.52, 0.35 and 0.30, respectively. The maximum temperature reached on the tool face for work speeds of 29.6, 78 and 155.4 m/min were 420 ºC, 620 ºC and 1100 ºC respectively. However, the temperatures in the shear plane are different from those obtained by Tay et al.. This difference is due to the assumption of heat source occurs exclusively on the control volumes in the principal shear plane. Tay et al. assumed that the shear zone is large and occurs around the principal shear plane. Thus, the heat source should be assumed to occur in several control volumes distributed around the main shear plane.

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6. RESONSABILITY FOR THE INFORMATION

The authors are solely responsible for the information included in this work.