Investigation of Temperature and Heat Transfer during Machining: Review

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Abstract— This study deals with the review of different researches done on the temperature and heat generation during machining process. Elevated temperatures generated in machining operations significantly influence the process efficiency and the surface quality of the machine part. Heat transfer between the chip, the tool, and the environment during the metal machining process has an impact on temperatures, wear mechanisms and hence on tool-life and on the accuracy of the machined component.

Key words: Temperature, Heat Transfer, Convection, Conduction

I. INTRODUCTION

A large amount of heat is generated during machining process as well as in different process where deformation of material occurs. The temperature that is generated at the surface of cutting tool (insert) when cutting tool comes in contact with the work piece is termed as cutting tool temperature. Heat is a parameter which strongly influences the tool performance during the operation. We know the power consumed in metal cutting is largely converted into heat. Several experimental attempts have been made to predict and measure the temperatures involved in the process. Over the past few decades, many academicians studied the characteristics of machining processes, using numerical, analytical and experimental techniques. Prediction and measurement of machining forces, temperatures, tool wear, residual stresses and many other characteristics are performed with substantial care, and many good agreements are found between numerical/analytical solutions and experimental data. Temperature field is one of the most important properties of a machining process; since the field can affect other characteristics such as residual stresses and tool wear.

Prediction of temperature distribution is generally engineered using finite element-based models, which takes long time. Another way used widespread is to employ curve fitting: relating temperature distribution to cutting parameters and tool and work piece properties by fitting a curve to temperature experiments. However, this method is not fully based on physical phenomena. Therefore, there is a need for rapid and accurate solution to the temperature prediction problem based fully on physical phenomena, which is found by using finite difference-based model proposed in this paper. Investigation of heat partition in high speed turning of high strength alloy steel. It is known that the most widespread way to predict cutting temperatures on chip, tool and work piece, in orthogonal machining, is FEM-based methods. Many studies on the issue are present on simulation of several process outputs such as cutting forces, stresses and temperature fields on chip, tool and work piece, employing FEM-based models [1].

The Temperature field in any region of tool and tool holder is calculated from heat flux estimation at the cutting surface. The determination of the temperature and of the heat flux at the chip-tool interface is done by using inverse heat condition problem technique. A great contribution of this work is the development of a technique that takes into account not just the insert tip but also the shim and tool holder. Heat balance equations were determined in partial differential equation forms for the chip and for the tool. The results for continuous machining processes agreed well with experimentally measured temperatures. The proposed algorithm can be utilized in selecting cutting speed, feed rate and tool rake and clearance angles in order to avoid excessive thermal loading of the tool, hence reducing the edge chipping and accelerated wear of the cutting tools[2].

Different approaches were carried out to predict quantitatively the temperature level and heat flux at the interface with cutting speed, feed rate, rake angle, tool geometry, tool material and work piece materials [3].

In this study average chip-tool interface temperatures have been experimentally studied using the tool-work thermocouple technique. The tool-work thermocouple technique is the best method for measuring the average chip-tool interface temperature during metal cutting. The benefits of using the tool-work thermocouple are its ease of implementation and its low cost as compared to other thermocouples [4] .

II. TEMPERATURE AND HEAT IN METAL CUTTING

During the metal cutting process, a considerable amount of the machine energy is transferred into heat through plastic deformation of the work piece surface, the friction of the chip on the tool face and the friction between the tool and the work piece. This results in an increase in the tool and work piece temperatures.

The temperature distribution depends on the heat conductivity and specific heat capacity of the tool and the work piece and finally the amount of heat loss based on radiation and convection. The maximum temperatures occur in the contact zone between the chip and the tool. There are three main sources of heat generation during the process of cutting metal with a machine tool.

A. Sources and Causes of Heat Generation and Development of Temperature in Machining:

In cutting, nearly all of energy dissipated in plastic deformation is converted into heat that in turn raises the temperature in the cutting zone. Since the heat generation is closely related to the plastic deformation and friction, we can specify three main sources of heat when cutting as shown in figure 1.

1) Plastic deformation by shearing in the primary shear zone (heat source Q1)
2) Plastic deformation by shearing and friction on the cutting face (heat source Q2)

3) Friction between chip and tool on the tool flank (heat source Q3)

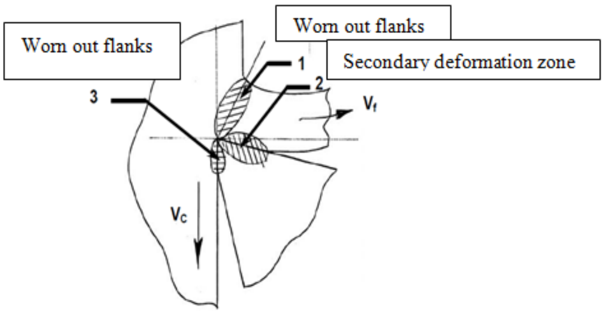

Fig. 1: Sources of Heat Generation In Machining

Heat is mostly dissipated by,

1) The discarded chip carries away about 60~80% of the total heat (q1)
2) The workpiece acts as a heat sink drawing away 10~20% heat (q2)
3) The cutting tool will also draw away ~10% heat (q3).

As the cutting action proceeds and the heat has been generated most of the heat is dissipated in the following manners (chip, work piece, cutting tool and cutting fluid).

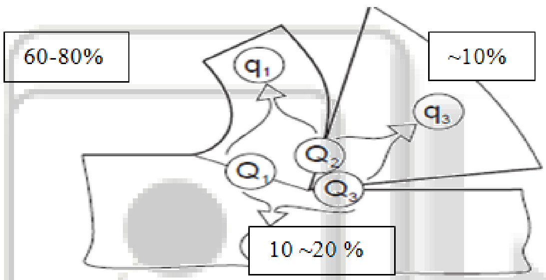

Fig. 2 : The Balance Of Heat Generation And Heat Dissipations In Metal Cutting

– The discarded chip carrying away the heat. The temperature decays along the length of the chip. Also, due to head convection and radiation at the outer surface of the chip, the temperature gradient is higher across the chip cross section than along the length of the chip.
– The work piece acts as a heat sink.
– The cutting tool acts as a heat sink.
– Coolant, where used, will help to draw away heat from all areas. There are different estimations of the amount of heat dispersed into the tool, chip and work piece. Any coolant will reduce the actual temperature of all three heat sinks [4].

B. *Effect of Cutting Temperature on Tool and Job:*

Heat phenomena occurring both in cutting zone, are directly related to the wear rate of tool, to the machinability of work piece material, to the tool stability and to many other characteristics of the machining process. Almost all work of cutting forces is turned into the thermal energy. Generated heat goes from the cutting zone into the chips, tool, and work piece and into the environment, causing decrease of hardness of tool's cutting elements, cutting wedge deformations, loss of tool cutting ability and its bluntness.

– The possible detrimental effects of high cutting temperature on cutting tool (edges) are: Rapid tool wear, which reduces tool life, Plastic deformation of the cutting edges if the tool material is not enough hot-hard and hot-strong, Thermal flaking and fracturing of the cutting edges due to thermal shocks, Built-up-edge formation.
– The possible detrimental effects of cutting temperature on the produced jobs are: Dimensional inaccuracy of the job due to thermal distortion and expansion contraction during and after cutting, Surface damage by oxidation, rapid corrosion, burning etc and Induction of tensile residual stresses and micro cracks at the surface/subsurface.

Generated heat distribution in work-piece, in tool and in chips, i.e. the temperature level at working elements of tool at processed surface and at chips depends on: work piece material (its mechanical and chemical characteristics), cutting speed, feed rate, depth of cut, tool geometry, lubricants type and other relevant parameters [5].

III. HEAT IN MACHINING

Heat has critical influence on machining; to some extent, it can increase tool wear and then reduce tool life due to thermal deformation and can add to environmental problems. Due to complexity of machining mechanics, it is hard to predict the intensity and distribution of heat sources in individual machining operations. Especially, because the properties of material used in machining vary with temperature, the mechanical process and the dynamic process are tightly coupled together [6].

A. *Heat Generation in Metal Cutting:*

The total heat generated Q during a machining operation is distributed between work piece, tool, and chips and surrounding.

$$Q_{total} = Q_w + Q_T + Q_c + Q_s. \dots (1)$$

Where $Q_w, Q_T, Q_c and\ Q_s$ the amount of heat is conducted into the work piece, tool, and chips is the amount of heat dissipated to surroundings respectively [7].

B. *Heat Generated in Primary Zone*

$$I_P = \frac{F_S V_S}{b t_1} \dots\dots\dots\dots\dots(2)$$

Where,

– I_P is the intensity of shear plane heat source
– b is the cutting width
– *t1* is the uncut depth [7]

C. *Heat Generated At the Interface between Chip and Tool:*

$$I_c = \frac{F V_x}{h b} \dots\dots\dots\dots(3)$$

Where,

– F is the friction velocity
– V_x is the sliding velocity of chip along the interface
– h is the plastic contact length [7]

IV. THERMAL MODEL OF INSERT-TOOL HOLDER ASSEMBLY

The figure 3 is described by transient three-dimensional heat diffusion equation. The equation considering temperature dependent thermal properties can be written as

$$\frac{\partial}{\partial x}\left(K_i \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_i \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_i \frac{\partial T}{\partial t}\right) = (\rho C_p)_i \frac{\partial T}{\partial t} \dots\dots .(4)$$

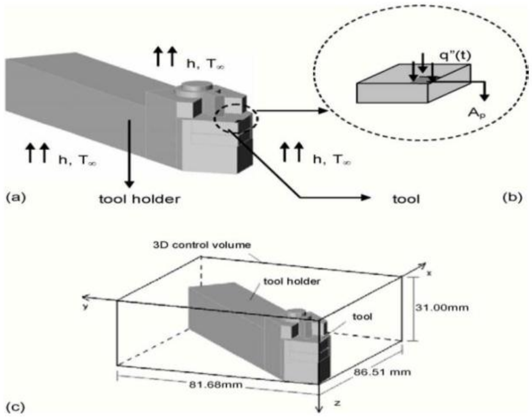

Fig. 3: Thermal Problem Scheme (A) Tool and Tool Holder Assembly (B) Interface Heat Flux Detail (C) 3D Control Volume [7]

Subjected to boundary conditions

- In the regions exposed to environment:

$$K_i \frac{\partial T}{\partial \eta} = h(T - T_\infty) \qquad \text{……… (5)}$$

- At chip tool work piece interface

$$K_i \frac{\partial T}{\partial \eta} = q(t) \qquad \text{…………...(6)}$$

- Initial condition $T(x, y, z, o)$

A. Heat Flux Estimation, Q(t):

One way to estimate the heat flux q(t) is to require that the traditional least square function, F_q, defined as the error between the computer generated temperature T_i and the measured temperature, Y_i is minimized with respect to the unknown q(t). F_q is then defined as

$$F_{qm} = \sum_{n=1}^{N} \{Y(r_n, t_m) - T(r_n, t_m, q_m)\}^2 \quad \text{…….(7)}$$

Where,

- r represents vector of the rectangular coordinate system (x,y,z)
- n denotes the thermocouple position
- m denotes the measurement time [7,8]

B. Heat Generated in the Primary and secondary Deformation zones:

$$Q_s = F_s V_s = \frac{\tau h_c V_w \cos(\alpha_n)}{\sin(\emptyset_n)\cos(\emptyset_n - \alpha_n)} Q_f = F_f V_c = \frac{\tau h_c V_w \sin(\beta_n)}{\cos(\emptyset_n + \beta_n - \alpha_n)} \quad \text{…….. (8)}$$

Where F_s, F_f, V_w, V_s *and* V_c are the shear force in the shear plane, the frictional force between the tool rake face and the chip contact zone, the cutting velocity, the cutting velocity component along the shear plane and the cutting velocity component along rake face, respectively $\tau, \emptyset_n, \alpha_n$ and β_n are the shear stress in the shear plane, shear angle, normal rake angle and normal friction angle, respectively. H is the instantaneous uncut chip thickness. The average temperature rise of the chip per unit depth of cut due to shearing is determined by Oxley's energy partition function.

$$\Delta \bar{T} = Q_s \frac{1 - x}{\rho C_c h_c V_w} \qquad \text{………. (9)}$$

Where ρ *and* C_c the mass density and specific heat capacity of the chip are, respectively x represents the proportion of the shearing flux entering into the work piece, and is defined by [7,8]:

$$x = 0.5 - 0.35 \log_{10}(R_t \tan \emptyset_n) for\ 0.004 \le R_t \tan \emptyset_n \le 10 \quad \text{…….(10)}$$

$$x = 0.3 - 0.15 \log_{10}(R_t \tan \emptyset_n)\ for\ R_t \tan \emptyset_n \ge 10 \quad \text{……… (11)}$$

$$(thermal\ number) R_t = \frac{h_c V_w}{\alpha}, (thermal\ diffusivity)\alpha = \frac{K_c}{\rho C_c}$$

C. Modeling and Computational algorithm for Steady-state chip-tool Temperature Fields;

Based on the first law of thermodynamics, the energy balance in two-dimensional differential control zone can be written as:

$$Q_x + Q_y + Q.dx.dy - Q_{x+dx} - Q_{y+dy} = \rho C_p \frac{\partial T}{\partial t}.dx.dy \quad \text{…….. (11)}$$

Where $dx.dy$ is the area of the infinitesimal element zone. $Q, (Q_x, Q_y)$ and (Q_{x+dx}, Q_{y+dy}) are the energy generation rates per unit area, the heat conduction input and output rates, respectively, which are perpendicular to the each control surface. ρ, C_p, t, T Represent mass density, specific heat capacity of medium, time and the temperature in the element, respectively.

The heat conduction rates (Q_x, Q_y) can be evaluated from Fourier's Heat conduction law,

$$Q_x = -k.dy.\frac{\partial T}{\partial x} \quad , Q_y = -k.dx.\frac{\partial T}{\partial y} \quad \text{……..} \quad (12)$$

Using Taylor series the heat flow rates in two orthogonal directions can be written as first order approximations:

$$Q_{x+dx} = Q_x + \frac{\partial Q_x}{\partial y} d \quad \text{………} \quad (13)$$

Assuming thermal conductivity does not vary in the medium

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{Q}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \quad \text{………… (14)}$$

D. Chip Temperature Model:

The heat balance equation [as shown in the above equation] for the discrete chip zone can be written in partial differential equation form in Cartesian coordinate as the following,

$$\left(\frac{\partial^2 T_c}{\partial x^2} + \frac{\partial^2 T_c}{\partial y^2}\right) + \frac{Q_c}{k_c} = \left(\frac{\rho C_c}{k_c}\right).\frac{\partial T_c}{\partial t} = \left(\frac{\rho C_c}{k_c}\right).V_c \frac{\partial T_c}{\partial x} \text{….} \left(\frac{\partial^2 T_c}{\partial x^2} + \frac{\partial^2 T_c}{\partial y^2}\right) + \frac{Q_c}{k_c} = \left(\frac{\rho C_c}{k_c}\right).\frac{\partial T_c}{\partial t} = \left(\frac{\rho C_c}{k_c}\right).V_c \frac{\partial T_c}{\partial x} \text{….(15)}$$

Where Q_c, k_c, C_c are the energy generation rate per unit area in the differential chip zone, thermal conductivity and specific heat capacity of the chip, respectively. In order to solve the partial differential equation using the finite difference method, the following approximation can be made

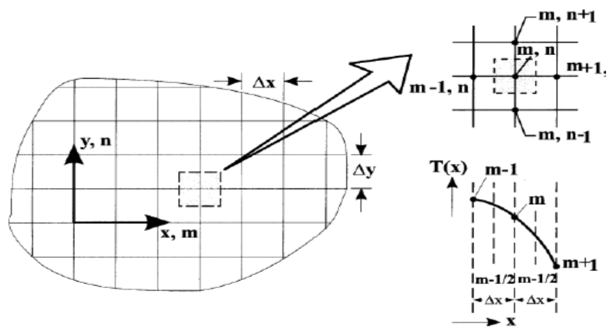

Fig. 4: Nodal Network In 2-D Control Volume And Finite Difference Approximation [9]

$$\left.\frac{\partial^2 T}{\partial x^2}\right|_{x,y} \cong \frac{T_{(x+\partial x,y)} + T_{(x-\partial x,y)} - 2T_{(x,y)}}{\partial x^2} \cong \frac{T_{(x,y+\partial y)} + T_{(x,y-\partial y)} - 2T_{(x,y)}}{\partial y^2} \quad \text{........ (16)}$$

Therefore, by using the above approximations, the governing equation in the partial differential equation form can be written as in the following finite form:

$$\frac{T_{(x+\partial x,y)} + T_{(x-\partial x,y)} - 2T_{(x,y)}}{\partial x^2} + \frac{T_{(x,y+\partial y)} + T_{(x,y-\partial y)} - 2T_{(x,y)}}{\partial y^2} + \frac{Q_{c(x,y)}}{k_c} = \left(\frac{\rho c_c}{k_c}\right).V_c \frac{\partial T_{c(x,y)}}{\partial x} \quad \text{...... (17)}$$

The chip geometry must be meshed into small discrete elements for the finite difference solution of the chip temperature field and the equilibrium equation above needs to be written for each nodal point. The aspect ratio of the mesh can be unity to simplify the solution, $x = \partial y$.

In the equilibrium equation, the heat flow into the differential chip control zone Q_c from the frictional heat source can be localized for each node along chip-tool contact length as [7,8,9]:

$$Q_{c(i)} = \left.\frac{(1-\Gamma_i).Q_f.dx}{l_{cn}}\right\} if\ and\ only\ 1 \le i \le N_x + 1 \quad \text{..(18)}$$

E. Tool Temperature Model:

Cartesian coordinates are used for the chip, whereas applying polar coordinates to the tool is advantageous due to mathematical accuracy and its convenience in the computational implementation of the model.

The heat transfer equilibrium equations for the control zone around the tool nodal points can be written in polar coordinates as,

$$\frac{\partial^2 T_t}{\partial r^2} + \frac{1}{r}\frac{\partial T_t}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T_t}{\partial \psi^2} + \frac{Q_t}{k_t} = 0 \quad \text{......... (19)}$$

In order to write the above partial differential equation in the form of finite difference, the following approximations can be made [7,8,9]:

$$\left.\frac{\partial^2 T}{\partial r^2}\right|_{r,\psi} \cong \frac{T_{(r+\partial r,\psi)} + T_{(r-\partial r,\psi)} - 2T_{(r,\psi)}}{\partial r^2},$$

$$\left.\frac{\partial^2 T}{\partial r}\right|_{r,\psi} \cong \frac{T_{(r+\partial r,\psi)} + T_{(r-\partial r,\psi)} - 2T_{(r,\psi)}}{2.r.\partial r} \quad \text{...... (20)}$$

V. CONCLUSION

The methods studies above study of temperatures and heat transfer. It enables investigation of influence of technological parameters (machining regime, tool material, cutting geometry etc.) on cutting temperature. Using developed method machinability of work-piece materials can be compared. The maximum temperature value through the work piece progresses with the tool movement, maximum value of temperature obtained at the contact region between the tool and work piece during the cutting process. Interface temperature is closely connected to cutting speed. With increase of cutting speed, an increase occurs in the interface temperature eventually the heat also increases. Interface temperature also increased with the feed rate However, the cutting speed appeared to have more pronounced effect on the cutting temperatures than the feed rate.

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