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Modelling of Temperature Distribution During Micro End Milling of Ti-6Al-4V Alloy

Bhanupratap Gaur, Vipindas K*, Jose Mathew

Department of Mechanical Engineering
National Institute of Technology Calicut, Kozhikode, Kerala – 67360, India

Abstract

Titanium and its alloys are the materials which are challenging to cut due to their high toughness, high chemical reactivity, spring back action, and strain hardening under normal cutting conditions and low thermal conductivity. It causes dimensional inaccuracy, residual stresses, distortion in tool and workpiece along with rapid tool wear and breakage. Many times titanium and its alloys are used for making micro parts, for which micro machining is done and highly accurate dimensions are required. Due to this, it becomes necessary to predict temperature distribution and maximum temperature at tool-chip interface during micro machining of titanium and its alloys. When machining takes place, whole energy input finally converts to heat energy and raises the temperature of machining zone. In this paper, both shear plane and friction plane heat generations are considered and incorporated as heat generation sources. This paper uses the Finite Difference (FD) Technique for predicting temperature distribution between chip and tool rake face while micro machiningTi-6Al-4V alloy with two fluted, 1mm diameter, uncoated solid Tungsten Carbide tool. Analysis has been done for depth of cut of 4µm and 5µm with dry conditions and FD equations so obtained weresolvedusing theMATLAB software. For the formulation purpose, governing equation used is two-dimensional heat flow equation in Cartesian coordinate converted to partial differential equation form. The results have been compared with previously published work and are found to match with them.

Keywords: Ti-6Al-4V, End milling, Temperature Distribution, Finite Difference Method (FDM)

1 INTRODUCTION

Thermal analysis of machining processes is very significant because, temperature imparts limitations on process and tool selection. Heat produced during machining becomes responsible for phase change of tool and workpiece materials, distortion of thetool, tool wear, improper dimensions of finished components, residual mechanical and thermal stresses, tool deflection, etc. It is very significant to find temperature distribution at machining zone due to low thermal conductivity, high tool wear rate and spring back tendency of these materials. Tool wear increases drastically if temperature overshoots crystal binding limits of thetool. Temperature analysis of advanced material is also important as it is responsible for tool wear hence, productivity, surface finish and integrity.

Due to theadvancement of computers, numerical approaches got more popularity than analytical ones. For prediction of temperature distribution during machining generally Finite Element (FE) models are used. Using FE technique, complex geometries can beanalysed and approximate results can be achieved by iterations. In this paper, Finite Difference Method is used for the purpose of analysis with proper boundary conditions as it is a swift and accurate method for predicting temperature distribution during machining.

Due to thehigh melting point, low specific heat and low thermal conductivity, Titanium and its alloys become very hot even at moderate cutting speeds which in turn cause rapid tool wear and chemical reaction with tool material [1]. To mill Titanium alloys efficiently, theright combination of machining parameters, tool material and milling strategy should be selected [2]. Machining should be done in such a way that maximum temperature is minimised. Cutting speed raises temperature significantly and its effect is not linear. It was found that, for some cutting speed ranges, the increase of cutting speed resulted in asignificant increment in cutting temperature, this may be because of large heat generation rate which is larger than the heat dissipation rate from the cutting zone [3]. Many researchers have done temperature distribution analysis and modelling using FEM. Lin et al. [4] performed experiments and did Finite Element(FE) analysis of end milling, it was found that temperature during machining depends upon cutting conditions like spindle speed, feed rate, tool rotation angles, etc. Li et al. [5] conducted FEM analysis of 3D turning of Titanium and found that temperature during machining depends upon cutting speed.

Some researchers have proposed faster techniques for temperature field prediction. Mamedov et al. [6] did thermal analysis using semi analytical approach. Lazoglu et al. [7] predicted temperature fields using elliptic structural grid generation method for oblique cutting. Many researchers have done Finite Element analysis by considering heat generation at shear and friction planes both [8]-[10]. Chen et al. [11] conducted an experiment and validated with simulation, they found that more portion of heat goes to theworkpiece when cutting speed is increased as compared to that of increased feed. Ozelet al. [12] did experimental investigations and finite element analysis on coated and uncoated tungsten carbide tool and for micro end milling of theTi-6Al-4V workpiece. They found thetemperature of CBN coated tool was low as compared to that of theuncoated tool. Baharudinet al. [13] conducted finite element simulation using ABAQUS/Explicit software. Temperature distribution simulation for micro end milling of Ti-6Al-4V was done for different undeformed chip thicknesses. It was found that temperature increases with undeformed chip thickness. Also due to low thermal conductivity of Ti-6Al-4V highest temperature was concentrated at tool edge. Muller et al. [14] performed radiation thermometry experiment at a High speed turning process which showed that workpiece surface temperatures increase with the increment in cutting speed.

Author to whom correspondence should be made. Email: vipindas.k@gmail.com

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Due tohigh temperature gradients in the material and between thesurface and the surroundings, temperatures drop very fast. Vipindaset al. [15] conducted finite element simulation for the prediction of temperature distribution and highest temperature for micro machining of Ti-6Al-4V alloy using ABAQUS with different undeformed chip thicknesses under steady state condition.

2 OBJECTIVE AND RESEARCH SCOPE

Because of difficulties in measuring temperature in micro machining, limited work has been reported on thermal modelling of micro machining of Ti-6Al-4V. This paper presents aprediction of temperature distribution and highest temperature during micro machining of Ti-6Al-4V alloy using FDM considering 2D case. Further work can be done in temperature modelling by considering tool and chip as 3D geometries.

3 WORK MATERIAL AND CUTTING TOOL

For this work, Ti-6Al-4V has been selected as the workpiece material because of its superior properties such as high strength to weight ratio, resistance to heavy loads, low thermal and electrical conductivities resistance to corrosion, stress-corrosion resistance, bio-compatibility, high specific ultimate tensile strength, etc. Ti-6Al-4V alloy finds application in areas such as marine and aircraft structural components, submarine heat exchanger components, turbine blades, biomedical implants, parts of racing cars, etc. The cutting tool material used in this paper is uncoated Tungsten Carbide which is very much suitable for several micro machining operations.

4 SIMULATION METHOD

In this study developed model was simulated by using MATLAB. To simplify the micro end milling process, an orthogonal machining is assumed. It is reasonable to assume micro end milling as an orthogonal machining due to (a) small depth of cut used and hence effect of helix angle can be neglected (b) deformation area is much small compared to the tool and workpiece. Hence in this study simulation was done considering that machining is orthogonal. Simulation was done only for single tooth. Two different feed per tooth (4µm and 5 µm) was used for the simulation.

5 TEMPERATURE DISTRIBUTION MODELLING

5.1 Procedureand assumptions

Assumptions made for temperature modelling are as follows:

(1) Orthogonal machining
(2) Steady state conditions
(3) 2-dimensional heat flow
(4) Thermal conductivity of workpiece material is constant with respect to temperature.

Flowchart showing procedure for temperature distribution modelling has been shown below in Fig 1.

5.2 Temperature distribution formulation

The primary deformation zone from where shearing takes place is assumed as infinitely thin in this study. After getting sheared off in primary deformation zone, the chips flow over the rake face of the tool. Due to rubbing action between chip and tool rake face, heat gets generated due to friction. Heat generated in the primary and secondary deformation zones are expressed as follows [9].

$$\dot{Q}_s = F_s V_s = \frac{\tau h V_w \cos(\alpha)}{\sin(\phi)\cos(\phi-\alpha)}, \qquad (1)$$

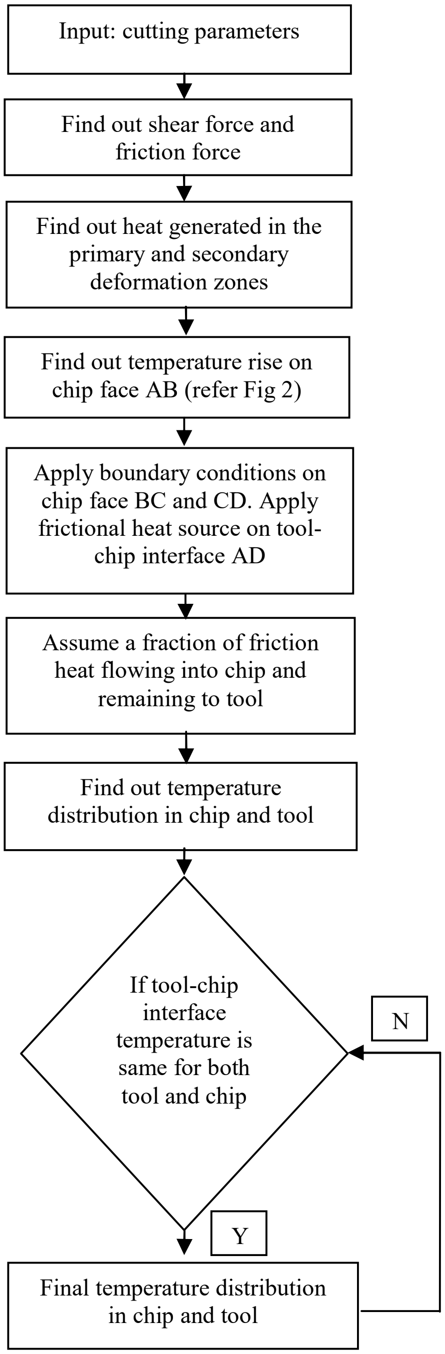

Fig. 1. Flowchart fortemperature distribution modelling [15]

$$\dot{Q}_f = F_f V_c = \frac{\tau h V_w \sin(\beta)}{\cos(\phi+\beta-\alpha)\sin(\phi-\alpha)}, \qquad (2)$$

Where, F_s, F_f, V_w, V_s, and V_c are the shear force in the shear plane (N), thefrictional force between tool rake face and chip (N), the cutting velocity (m/s), the cutting velocity component along the shear plane (m/s) and the cutting velocity component along the rake face (m/s) respectively. τ, φ, α and β are the shear stress in the shear plane (MPa), shear angle (degree), rake angle(degree) and friction angle (degree) respectively and h is the uncut chip thickness (UCT) in (μm).

Due to heat generation, the temperature of chip raises. This average temperature rise can be found analytically by employing Oxley's energy partition function, which has been given below.

$$\Delta\bar{T} = \dot{Q}_s \frac{1-\lambda}{\rho c h V_w}, \qquad (3)$$

Where, ρ is mass density of the chip (Kg/m^3), c_c is the specific heat capacity of the chip (Jkg^{-1} K^{-1}). λ is proportion of the shearing flux entering into the workpiece, and it can be found by following two expressions:

$\lambda=0.5-0.35\log_{10}(R_t.\tan(\phi))$; *for* $0.004 \leq R_t \tan(\phi) \leq 10$ *(4)*

$\lambda=0.3-0.15\log_{10}(R_t.\tan(\phi))$;*for* $R_t \tan(\phi) \geq 10$ *(5)*

Here, R_t is thermal number and ζ is thermal diffusivity, which are expressed as,$R_t = \frac{hV_w}{\xi}$ and $\xi = \frac{k}{\rho c}$. Here, $k$and c are the thermal conductivity and the specific heat capacity of chip respectively.

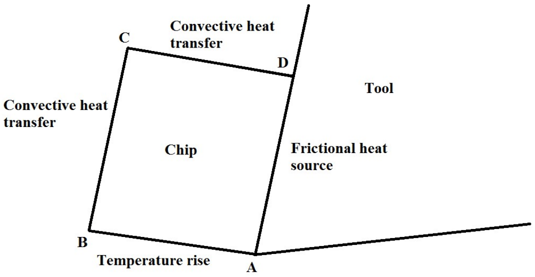

Fig. 2. Illustration of chip boundary conditions [15]

The average temperature rise hence found using Eqn(3) can be used as a boundary condition for temperature rise on the chip face AB in Fig2. Heat generated in the secondary deformation zone can be used as a heat source on the face AD. On the face, BC and CD are open to air for free convective heat transfer which is a boundary condition for these two faces.

5.3 Governing equation

During an infinitesimally small time, the chip can be considered as a medium which is in quasi-static thermal equilibrium. The 2D heat balance equation in Cartesian coordinates is as follows:

$$\frac{d^2T}{dx^2} + \frac{d^2T}{dy^2} + \frac{\dot{Q}}{k} = \frac{1}{\xi}\frac{dT}{dt}, \qquad (6)$$

For the discrete chip and tool zones, the equation can be written in partial differential form in Cartesian coordinates as,

$$\frac{\partial^2T}{\partial x^2} + \frac{\partial^2T}{\partial y^2} + \frac{\dot{Q}}{k} = \frac{\rho c}{k}\frac{\partial T}{\partial t}, \qquad (7)$$

For solving this equation using finite difference method, the term$\frac{\partial T}{\partial t}$ can be converted to $\frac{\partial T}{\partial x}$ form. So the equation takes the form,

$$\frac{\partial^2T}{\partial x^2} + \frac{\partial^2T}{\partial y^2} + \frac{\dot{Q}}{k} = \frac{\rho c}{k}V\frac{\partial T}{\partial x}, \qquad (8)$$

6 RESULTS AND DISCUSSION

The energy equations were solved for different nodal elements using FDM. The FDMEquations were solved using MATLAB. Cutting speed kept at 15.7 m/min and undeformed chip thickness (UCT) was varied and they were 4 and 5 μm, and the results obtained after various iterations are shown in Fig3and Fig 4.For 4μmUCT, the maximum temperature found is around 405 ^{o}C, which is at a distance of approximately 15 μmfrom the shear plane on the interface of tool and chip. Also, it can be seen that when the UCT is increased from 4 to 5μm, the maximum temperature at thetool-chip interface has also increased to 424^{o}C approximately and it's distance increases to 20 μm approximately, which shows the direct relation between undeformed chip thickness and temperature rise.

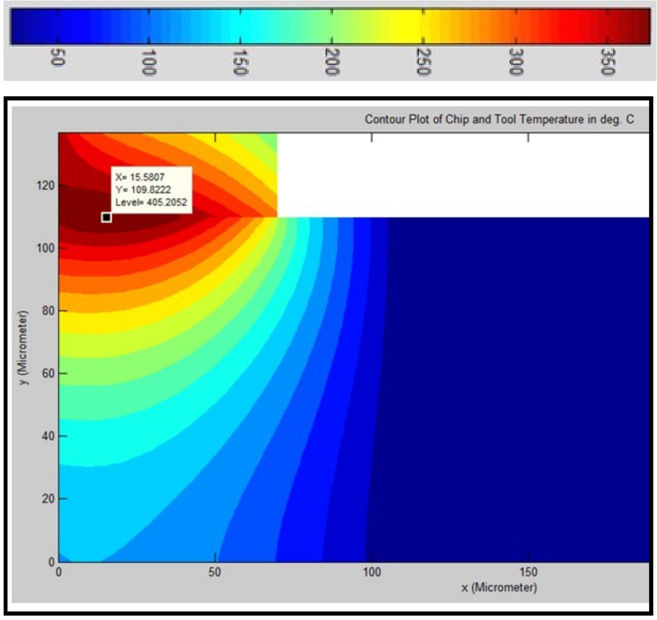

Fig. 3. Temperature distribution in chip and tool domains during machining simulation with 4 μm undeformed chip thickness

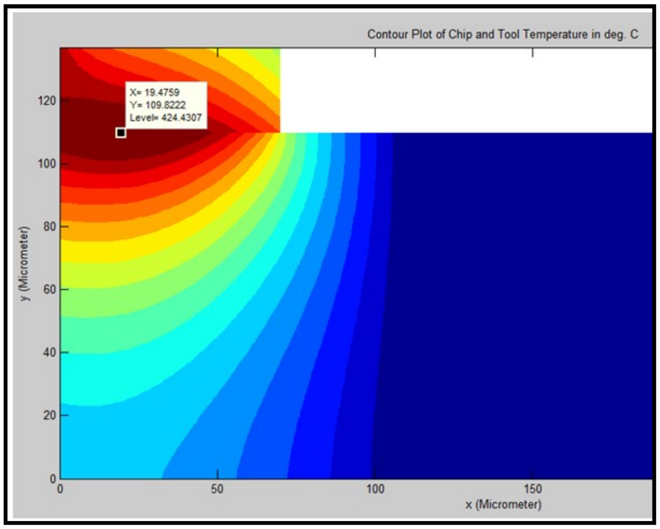

Fig. 4. Temperature distribution in chip and tool domains during machining simulation with 5 μm undeformed chip thickness

During the simulation, the proportion of frictional heat flowing into chip and tool were calculated through iterations, the iterations were run until the temperature at the tool-chip interface becomes equal. From Fig3 and Fig 4 it can clearly be seen that the temperature at the tool-chip interface is almost equal for corresponding nodes. Also, it can be inferred that the maximum temperature is at tool-chip interface points and the reason for this is the frictional heat generation due to relative motion between tool and chip interface points. Also as undeformed chip thickness increases, maximum temperature generated at the tool-chip interface also increases, this is due to direct relation of undeformed chip thickness with shear energy and frictional energy both. In turn, shear energy and frictional energy increase primary and secondary deformation zone temperatures respectively. The maximum temperature foundat a distance from the shear plane on the interface of tool and chip.

The results compared with the results of some published literature, as shown in Table 1 and are found to follow the same trends for both undeformed chip thicknesses.

Table 1
Result validation for different UCT values

Undeformed chip thickness (μm)	Simulated Maximum Temperature (°C)	Max. temperature from ABAQUS simulation (°C) [15]	Max. temperature reported in literature (°C)
4	405	384.4	240 [16]
5	424	392.7	454 [6]

7 CONCLUSIONS

In this study, a Finite Difference Method is used for prediction of temperature distribution while machining Ti-6Al-4V alloy with uncoated WC tool. The energy equations are solved for various nodes and temperature contours and maximum temperature are found by running code in MATLAB software for different undeformed chip thicknesses. The findings of this work are compared with previously published literature. The various findings of this work are.

(1) Finite difference method has been used for the prediction of temperature distribution in tool and chip domains under steady state conditions. The predicted temperature profiles have been compared with that of previously published literature [6], [15] and [16].
(2) Maximum temperature was obtained at some distance from the shear zone on the tool-chip interface.

(3) It was found that the temperature at the tool-chip interface has a direct relation with undeformed chip thickness. Increase in UCT results in more shear energy and causes increase in temperature at primary deformation zone. This is evident from the results shown in Table 1.

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