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Thermal Modelling of Heat Flux and Tool-chip Interfacial Temperature Distribution in Orthogonal Machining

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Abstract

Modeling of the heat flux generated during machining is of significant importance in order to understand its effect on the cutting tools and tribology of machining. An important criterion influencing the life of cutting tools is the tool-chip interfacial temperature, which affects the ability of the cutting tool to function properly without suffering unwanted damage or thermal degradation. This paper presents the estimates of transient heat flux and temperature distribution in the cutting tool based on temperatures measured below the cutting tool insert with an embedded thermocouple, during orthogonal machining of a plain carbon steel under dry cutting. The results indicate that the heat flux in machining, which is traditionally considered constant during machining, may have a time dependent variation.

Keywords: Dry Machining, Modelling of Machining, Tool Temperature

1. Introduction

Machining is a key manufacturing process for many critical components required for a wide range of applications. It has direct influence on the surface integrity and thus life of the parts being machined. Machining process involves plastic deformation of the material being cut, and according to estimates, almost all the energy supplied for machining gets converted into heat[1] .The areas where significant heat generation takes place, are shown in Figure 1.

The primary heat zone consists of shear plane, where the material is plastically deformed in a narrow shear band, and this energy is converted to heat. The secondary heat zone exists at the tool rake face near the cutting edge, where the chip slides, before leaving the tool and the frictional energy is converted into heat. The tertiary heat zone is formed due the rubbing of the cut workpiece material against the worn tool flank.

Traditionally, cutting fluids are employed in flooding mode to remove the heat generated in machining. Cutting fluids, however, are a major cause of operator health hazards and environment damage. Additionally, they require periodic disposal, which adds to the operational costs and poses serious ecological concerns.

Considerable research has taken place to eliminate or reduce the use of cutting fluids. Dry machining has been attempted by employing advanced tool materials and coatings which can withstand the high temperatures, hybrid machining with laser heating of the workpiece being cut, modulation assisted machining, cryogenic machining with liquid nitrogen and Minimum Quantity Lubrication (MQL) machining in which a compressed air jet containing very small amount of lubricant/cutting fluid (~10-100 ml/hr) in the atomized form, is directed at the cutting zone. In MQL process, the lubricant is consumed in the cutting process itself eliminating the need of disposal and environmental concerns.

Since dry/near dry machining generates considerable amount of heat, it is necessary to know its effect on workpiece and tool temperatures. Thermal degradation of the tool beyond certain temperature will affect the effectiveness of the cutting action. Thus the knowledge of

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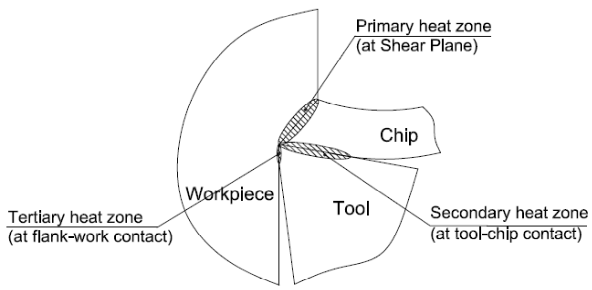

Figure 1. Zones of heat generation in machining.

temperature distribution on the tool-chip interface and the heat flux produced in machining assumes significant importance. Estimation of heat generation in metal cutting is an extremely arduous task due the complexity and non-linearity inherent in the process. Machining involves high strain and strain rate, coupled with high temperature, which significantly alters the material properties. Many different models have been proposed by researchers to estimate heat generation and its distribution in machining. The analytical approach relies mainly on heat partition model given by Blok[2] and friction slider model proposed in[3]. Analytical models for estimation of cutting tool temperatures was first proposed in [4–9] proposed a volumetric heat source at the tool-chip interface, as opposed to planar heat source considered by other researchers. Many refinements in these analytical models have since taken place. However the underlying assumptions of these models of a uniform source and steady-state condition are questionable due to the inherent transient nature of the metal working process. The numerical models employed for estimation of cutting temperatures generally fall in two categories: The finite element methods (FEM), and finite difference (FD) approach. The finite element approach was first presented in[10] and subsequently used by many researchers including[11–14] to name a few. The finite difference model for heat and temperature prediction has been used in[15–19] many other researchers.

In this paper, we have used a two-dimensional finite difference model for estimating heat influx and transient temperature distribution in the cutting tool based on temperatures measured below the cutting tool insert with an embedded thermocouple, during orthogonal machining of a plain carbon steel under dry cutting conditions.

2. Methodology

The finite difference model uses genetic algorithm to estimate the temperature at a given location inside the tool, which is compared with the measured temperature provided by an embedded thermocouple at that location. The square of difference in estimated and measured temperatures is summed up at different time steps to arrive at an error value. The genetic algorithm aims at minimizing the error value to provide a good matching of the predicted and measured temperatures.

The values of material properties have been taken from materials handbook. The value of heat flux entering the tool-chip contact zone was left as unknown, to be solved by the inverse transient heat conduction problem. The temperatures were calculated at the thermocouple location node and compared with the measured temperatures at different time intervals to compute the error. An evolutionary genetic algorithm was used to reduce the error and arrive at the near-optimum solution.

The finite difference discretization of the cutting tool insert and supporting shim is shown in Figure 2. An area of 10mm x 10mm has been considered for analysis and lower as well as right boundaries are taken at room temperature.

3. Experimental Setup

The orthogonal turning operation were performed on a CNC Turning Center. For cutting temperature measurements, a fine wire K-type thermocouple of 0.25mm diameter was embedded in the shim supporting the cutting tool insert. The workpiece material chosen was AISI 1045 steel. 3 mm thick disc shaped flanges were machined

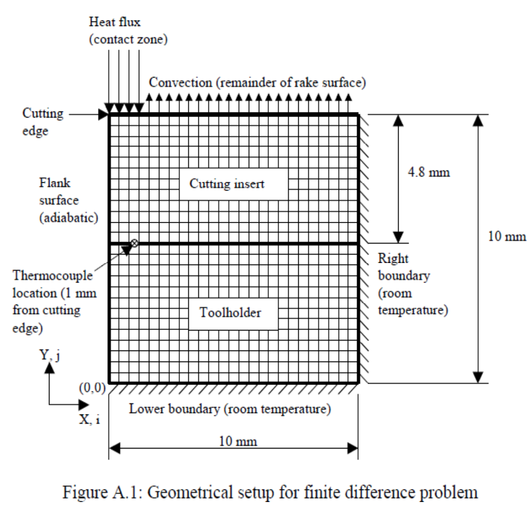

Figure 2. Finite difference discretization of the cutting tool insert and supporting shim.

on a CNC lathe with a straight-edged tool by performing face turning operation. The detailed experimental plan is listed in Table 1.

4. Results and Discussion

During the iterations of the genetic algorithm, the values of specific heat capacities, thermal conductivities and densities of the tool insert and tool holder were kept as constant. The coefficient of convection was also kept constant. The amount of heat entering through the tool-chip contact zone was the only variable left to be solved through the inverse transient heat conduction method.

Table 1. Experiment plan for orthogonal turning experiments

Parameter	Value
Machining operation	Orthogonal turning
Machine	CNC Turning Center
Work piece material	Steel AISI 1045
Cutting Tool	Flat faced tool type TNMA
Cutting insert	Uncoated tungsten carbide insert
Cutting speed	150 m/min
Feed / tooth	0.3 mm
Depth of cut	0.8 mm

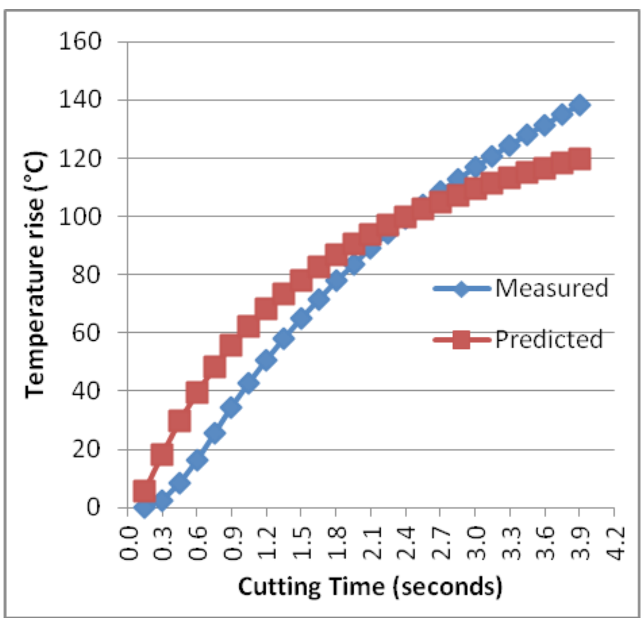

Figure 3. Estimated and actual measured temperatures for constant heat influx.

Figure 3 show the plots of estimated as well as actual measured temperatures as the cutting progresses when the value of heat flux was considered constant during the machining.

The value of heat input rate was kept as an unknown, and invariant with time in Figure 3. As can be seen from the figures, the estimated as well as actual values match reasonably well, however some error remains and the solution does not converge beyond a certain limit. In actual cutting, the heat input rate at the tool chip contact zone varies with time. The friction, and consequently the heat influx, at the tool-chip interface steadily increases as the cutting progresses. The simulations were run again with variable heat input rate and the results obtained for estimated temperatures at the thermocouple location are plotted in Figure 4.

It can be readily inferred from Figure 4 that variable heat input rate provides a much closer estimation of the cutting tool temperature distribution. The measured and estimated temperatures almost overlap each other.

The temperature distribution on the tool rake face with variable heat flux after 3.6 seconds of machining is shown in Figure 5.

From Figure 5, it can be seen that the maximum temperature occurs at a small distance from the cutting edge which is in synch with the experimental results obtained by various researchers.

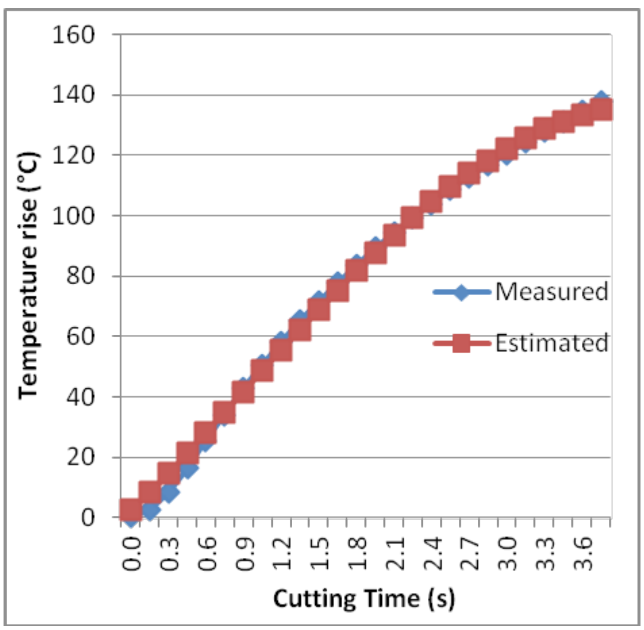

Figure 4. Estimated and actual measured temperatures for variable heat influx.

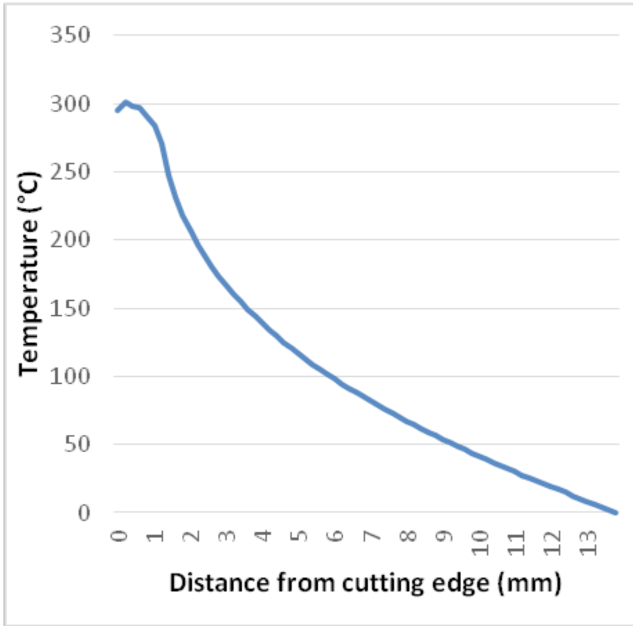

Figure 5. Temperature distribution on the tool rake face.

5. Conclusions

It can, thus be seen that a two-dimensional finite difference model utilizing inverse transient heat conduction estimation along with genetic algorithm can be successfully employed to calculate the temperature distribution in the cutting tool. Further, variable input flux in the tool-chip contact zone provides a much better estimation of temperatures, as compared to fixed value of heat flux, which is the usual convention. The estimation of distribution of tool temperature can be helpful in designing advanced tools and coatings suitable for dry machining.

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7. References

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