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Modeling of temperature distribution in drilling of titanium

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ABSTRACT

Understanding the temperature distribution in drilling tool and workpiece is crucial for enhancing the drill performance and the process efficiency. However, a complete analysis of the same is extremely challenging, particularly for difficult-to-machine materials such as titanium. The existing analytical and finite element analysis techniques normally assume a sharp drill point, which is not true as the drill may wear during the process. The main objective of the present study is to develop a comprehensive finite element model for evaluating temperature distribution in the process considering a variable heat partition model and ploughing forces, by incorporating a cutting edge radius of the tool. The cutting edge of the drill is divided into a series of independent elementary cutting tools (ECT). The model presented efficiently calculates forces encountered during drilling and then evaluates temperature distribution in the drill by considering the heat partition factors adopted. An experimental procedure is developed to measure the temperature in work piece with the help of an IR camera and observed results are successfully validated. The simulation results obtained are in agreement with the prior studies on tool temperature distribution, and the experimentally measured work piece temperatures.

1. Introduction

Titanium and its alloys are indispensable for a wide range of aerospace and medical applications due to their high strength-to-weight ratio, biocompatibility and excellent corrosion resistance. However, during machining operations, their poor thermal conductivity often leads to concentration of heat around cutting edge of tool causing its subsequent deterioration [1]. This is more severe in case of a drilling process which involves the use of two cutting edges in a confined circular region. Thus, the heat generation and consequent temperature distribution due to work tool interaction becomes very complex and needs a detailed consideration during drilling. Several experimental and numerical methods have been employed in the past to address heat generation and dissipation in drilling of Ti alloys, and for the selection of appropriate processing conditions.

A common experimental technique for temperature measurement includes embedding an insulating wire in the work piece to form a thermocouple [2]. Bono et al. [3] improved over the previous methods by using embedded foil tool-work thermocouple to measure tool temperature across the cutting edge. Perez et al. [4] used thermocouples and an IR camera for comparative analysis in measuring temperature during drilling of carbon fiber reinforced plastic. Coz et al. [5] proposed a method for temperature measurement of a tool during drilling and milling with the thermocouples integrated in a tool. A wireless transmitter unit and data conditioning system were incorporated in the tool holder unlike common thermocouple wires. Mills et al. [6] studied drill temperature by investigating microstructural changes using scanning electron microscopy. Agapiou and DeVries [7] obtained a steady-state temperature distribution in a twist drill using Jaeger's technique for moving heat source, while transient solution has been proposed for a constant heat flux. Agapiou and Stephenson [8] studied drill temperature analytically for arbitrary tool geometry assuming drill as semi-infinite body where, heat source characteristics were modeled using an empirical force equation from end turning test.

In order to evaluate the three-dimensional temperature field, several researchers have attempted continuum simulations. Bono and Ni [9] applied finite element method for predicting location of maximum temperature on the cutting edges of a drill based on variable heat partition factors, which determines the amount of heat flowing into tool, chip and work piece from the total heat generated during the process. Li and Shih [10] applied inverse heat transfer method to study temperature distribution in drilling of titanium. Kuo et al. [11] estimated temperature distribution for a tool during milling by incorporating the effect of worn tool. Bono and Ni [12] developed a model for calculating flow of heat into the work piece during drilling by using advection heat partition model. Tai et al. [13] proposed an inverse heat transfer model for estimating temperature during deep-hole drilling of ductile iron.

However, the estimation of heat partition factors during a drilling process remains a challenge. Due to the complex drill geometry and the resulting variation in cutting velocity along the cutting edge of the

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Nomenclature

a	half contact
b	chip width
C_t	specific heat of tool material
C_w	specific heat of work material
E	Young's modulus
F_c	cutting force
F_s	shear force along the shear plane
F_f	friction force on rake face
F_{cw}	component of force in the cutting direction on flank surface
J	mechanical equivalent of heat
k	Shear yield strength of material
k_s	shear flow stress of material
K_t	thermal conductivity of tool
K_w	thermal conductivity of work piece
l	chip contact length
m	friction factor
R_e	cutting edge radius
T_0	room temperature
t_1	uncut chip thickness
t_2	chip thickness
t_c	cutting time
V	cutting velocity
V_c	chip flow velocity
V_s	shear flow velocity
V_b	Flank wear width
δ	depth of ploughing region
ρ_w	density of work material
α_t	thermal diffusivity of tool material
α_w	thermal diffusivity of work material
ρ_t	density of tool material
w	angular velocity of drill

drill, the heat generated varies and hence the resulting heat partition factors. Moreover, material specific empirical relations for heat partition factors cannot be used due to lack of availability of relevant data on machining of titanium. Therefore, it is required to accurately predict the heat partition considering (a) the geometry of the drill, (b) thermo-mechanical properties of tool and work piece, and (c) processing parameters. Also, analytical and finite element analysis techniques normally assume a sharp drill point, which is not true as the drill wears during the process. There is a strong need to understand the behavior of ploughing forces arising due to a blunt cutting edge and their influence on the heat generation. Therefore, the main objective of the work is to develop a comprehensive finite element model for evaluating temperature distribution in both the drill and the work piece, considering the variable heat partitioning and the ploughing forces as a function of the cutting edge radius. It is envisaged that such a simulation tool can then be used for extensive parametric investigation and the drilling process optimization.

In the present study, we propose two separate models for predicting the temperature distributions in the tool and the workpiece respectively, which are then combined to understand the overall thermal behavior. For the validation of the tool temperature model, simulation results are compared with the experimental data from the literature, while the predictions of the workpiece temperatures are compared with the measurements performed in this work. The paper is organized as follows. Firstly, formulation of the model with its approach and assumptions is explained and calculation of forces around cutting edge of a drill and heat partitioning based on the generalized machining theories is presented. Subsequently, the paper discusses—(i) the experimental procedure for measuring temperature in work piece, and (ii) finite element model for thermal analysis for both tool and work piece. The predictions are validated with the experimental data from the present study for the workpiece and the available literature for the tool. Finally, the temperature distribution in the tool for various processing conditions is investigated.

2. Model approach and formulation

2.1. Model description

The heat generated during machining is attributed to frictional work in the following three zones: (a) the primary region due to plastic deformation of the material at the shear plane, (b) the secondary zone due to tool-chip friction on the rake face of the tool, and (c) the tertiary zone due to the friction between flank face and the machined surface to a considerably lesser extent [14].

Drilling is a complex process to analyze, primarily due to the variation in cutting velocity along its cutting lips as a result of varying radius. This leads to variable cutting forces and variations in the heat generation at points along the cutting lips of the drill. Therefore, analyzing heat generation and evolving temperature distribution becomes very difficult. To simplify the problem, cutting lip of a drill can be divided into elementary cutting tools (ECT) [10]. The metal cutting theory can be deployed for the calculation of cutting forces along the ECTs. With the knowledge of the forces around each ECT, the heat generation and the associated heat partitioning for an individual ECT can be calculated. This information is further used in the finite element model for predicting temperature distribution around the drilling lips and work piece.

The chisel edge and cutting lip of a drill are divided into a series of independent elementary cutting tools as shown in the Fig. 1. It is assumed that, each ECT performs a simple machining operation. Therefore, generalized machining theory can be applied to analyze the heat transfer across an individual ECT. The chisel edge can be considered to be in a plane normal to the axis of a drill, so the orthogonal metal cutting theory is considered for its mechanics. However, oblique cutting theory seems to be a fair assumption for each ECT on cutting lips. The calculated heat flux loads are applied over the individual ECTs to solve the model for temperature distribution.

The following assumptions (Refs. [8,22]) have been made for simplifying steps in the model development:

- The tool considered has a significant cutting edge radius (up to 50 μm). Therefore, three distinct regions of heat generation, such as primary, secondary and tertiary zones can be accounted for during the analysis.
- For each ECT, heat energy distribution in all the three distinct zones of heat generation is assumed to be uniform over their respective contact areas.
- Steady flow of heat into the deformation zones is assumed.
- The thermo-mechanical properties of the work and tool material are considered at fixed temperature for the simplicity in the modeling.
- Friction at the contact between the tool-chip and tool-work piece is assumed to be constant and not varying with the temperature.
- Work hardening of titanium work piece is ignored during the analysis.

2.2. Evaluation of forces around drill cutting edge

During drilling, material is being cut by chisel edge and cutting lip. The forces generated around these parts play an important role in the heat flow and consequently the temperature distribution. The accurate prediction of cutting forces in the regions is very important for better understanding of the process behavior.

2.2.1. Forces on chisel edge

The tangential velocity of points on the chisel edge is very low as compared to those on the cutting lips and the uncut chip thickness is