Journal of Materials Processing Technology 180 (2006) 271–278

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

FEM optimization of tool geometry based on the machined near surface's residual stresses generated in diamond turning

W.J. Zong [a,*], T. Sun [a], D. Li [a], K. Cheng [a,b], Y.C. Liang [a]

[a] *Center for Precision Engineering, P.O. Box 413, Harbin Institute of Technology, Harbin 150001, PR China*
[b] *School of Engineering and Design, Brunel University, Uxbridge, Middlesex UB8 3PH, UK*

Received 19 February 2006; received in revised form 8 June 2006; accepted 8 July 2006

Abstract

In this work, based on the updated Lagrangian formulation and the commercial available software, Marc2001, a coupled thermo-mechanical plane-strain large deformation orthogonal cutting FE model is presented to simulate the diamond turning process and predict the residual stresses on the machined surface of workpiece. In order to consider the interactive influences of cutting edge radius, cutting velocity, rake angle and clearance angle on residual stresses, all simulations are programmed by an orthogonal design method, i.e. the combination design of general rotary method. As expected, two regression equations of tensile and compressive residual stresses are deduced according to the simulated results. The measured results in diamond turning show that the predicted results have a good consistency with the experimental ones. Therefore, some related analyses are carried out for the influencing factors based on the regression equations. Finally, the optimal analyses indicate that a rake angle of 15° and a clearance angle of 10° are the optimum geometry of a diamond tool in turning of ductile materials when this tool has a cutting edge radius of 100–300 nm.

Keywords: Finite element method; Diamond turning; Residual stresses; Regression analysis

1. Introduction

Diamond turning is an important technique in precision and ultraprecision machining of aerospace, automobile, computer, and optics components, etc. [1]. With the development of advanced science and technology and their increasing requirements in machining accuracy, the optimization for cutting parameters and prediction for machined surface quality are being required before actual diamond turning of these components. For example, to optimize processing factors and tool's geometry and to predict the near surface's residual stresses, cutting temperature and thermal deformation all can improve the machining accuracy and machined surface integrity. In these researching focuses, the most popular approach is by using of finite element methods (FEM) [2].

FEM was firstly used by Carroll to study the diamond turning process in late 1980s [3]. At the present time, the related studies in this field with FEM include cutting temperature, cutting force, stress, strain and residual stresses [4–7]. However, in Moriwaki's FE model, cutting temperature was ignored [4]. In Kim's model, only the thermal conduction was calculated [5]. And in Lin and Lo's models, the cutting edge radius was assumed to be very sharp and its effect was certainly neglected [6,7]. Especially for the researching of residual stresses, only the independent influence of single cutting factor was analyzed in the previous works, and their interactive influences of several independent factors have not been investigated by now.

Therefore, a FE model integrating the effect of cutting edge radius is proposed in this work. At the same time the thermal conduction and convection in the whole machining process can also be calculated in this newly developed model. Above all, the independent influencing factors are programmed with an orthogonal design method in order to take account of their interactive effects on the residual stresses.

2. Finite element model

2.1. Initial meshes and boundary conditions

As is well known, the width of cut is at least five times greater than depth of cut in diamond orthogonal cutting. So the realistic 3D cutting process can be simplified into 2D cutting model.

* Corresponding author. Tel.: +86 451 86412534; fax: +86 451 86415244.
E-mail address: zongwenjun@hit.edu.cn (W.J. Zong).

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doi:10.1016/j.jmatprotec.2006.07.004

Nomenclature

C	specific heat
E	Young's modulus
f_c	assignment operator of contact heat
f_p	percentage of plastic work converting into heat
F_f	contact frictional force
h_c	convection coefficient
M	mechanical equivalent of heat
q_c	heat flux consumed by convection on tool or workpiece surfaces
q_f	heat flux converting from friction
$\dot{q}_p$	rate of specific volumetric heat flux converting from plastic work
$\dot{Q}$	general rate of specific volumetric heat flux
R_n	cutting edge radius
S_c	contact area
t	time
T_{melt}	molten temperature of OFHC copper
T_{room}	ambient temperature
T_t	transient temperature in cutting region
V_r	cutting velocity
$\dot{W}_p$	rate of specific volumetric plastic work

Greek letters

α_0	clearance angle
γ_0	rake angle
$\bar{\varepsilon}$	equivalent total strain
$\dot{\bar{\varepsilon}}$	equivalent total strain rate
$\dot{\varepsilon}_0$	initial strain rate
κ	thermal conductivity
λ	thermal expansion coefficient
ν	Poisson's ratio
ρ	material density
$\bar{\sigma}$	flow stress
$\hat{\sigma}_x$	tensile residual stress
$\hat{\sigma}_y$	compressive residual stress

According to this assumption, a plane-strain FE cutting model is presented, which is based on the updated Lagrangian approach by using of a commercial available software, Marc2001. The initial finite elements mesh is shown in Fig. 1. V_r designates cutting velocity and R_n denotes cutting edge radius. The workpiece consists of four-node isoparametric quadrilateral plane strain coupled elements. Like a chucking system, the vertical and horizontal freedoms of the nodes at the bottom of workpiece are set as zero, and the same do the horizontal displacements of the nodes on the left side of workpiece. The dimensions of workpiece are 40 μm × 12 μm and their lengths are assumed large enough in directions x and y. Then the boundary conditions can be considered having no influences on the whole cutting process in simulation.

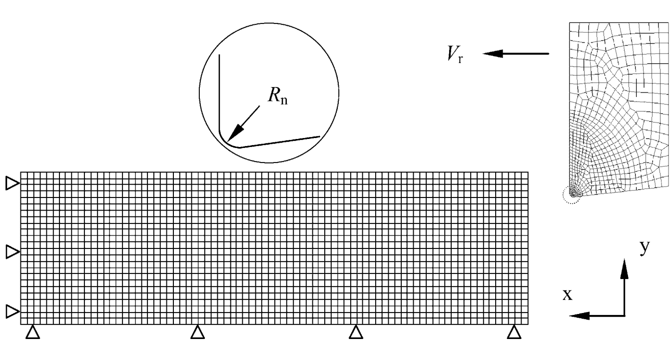

Fig. 1. Initial finite elements mesh.

The four-node heat transfer planar quadrilateral elements make up of diamond tool. And diamond tool is assumed to be a rigid and only heat transfer analysis is carried out for it. Furthermore, the tool keeps a horizontal velocity V_r along the predefined cutting path and has no displacements in direction y. The details in the vicinity of cutting edge radius are magnified at the top of Fig. 1.

2.2. Modeling on the workpiece material

Modeling the material is very important for the whole FE simulation. The material model must represent the actual changes of material physical properties during machining [8]. In present work, OFHC copper is employed as the workpiece material, and it is sensitive to strain, strain rate and temperature. Therefore, the ideas for stress calculation in Oxley's cutting model are introduced, i.e. that the flow stress is a function of strain, strain rate and temperature, and this function can be expressed as the form of Johnson–Cook's constitutive equation [9]:

$$\bar{\sigma} = (a + b\bar{\varepsilon}^n)\left(1 + c\ln\frac{\dot{\bar{\varepsilon}}}{\dot{\varepsilon}_0}\right)(1 - \overline{T}^m) \quad (1)$$

where $\bar{\sigma}$ is the flow stress, $\bar{\varepsilon}$ the equivalent total strain, $\dot{\bar{\varepsilon}}$ the equivalent total strain rate, $\dot{\varepsilon}_0$ the initial strain rate, $\dot{\varepsilon}_0 = 1$, and a, b, c, n, and m the constant factors, a = 90 MPa, b = 292.8 MPa, c = 0.025, n = 0.31, m = 1.09. $\overline{T}$ the normalized factor and $\overline{T} = (T_t - T_{room})/(T_{melt} - T_{room})$, where T_t is the transient temperature and T_{melt} = 1083 °C, the molten temperature of OFHC copper; T_{room} = 20 °C, the ambient temperature. The other physical properties, such as Young's modulus E, Poisson's ratio ν, specific heat C, material density ρ, thermal conductivity κ and thermal expansion coefficient λ of OFHC copper and diamond tool, are listed in Table 1.

2.3. Chip separation criterion

In this work, chip formation takes place by using of remeshing chip separation criterion. During the simulation process, if elements suffer excessive geometrical deformation, then the meshes are regenerated and the state variables are transferred from old elements to new elements. In this cutting model, the criteria considered to estimate element's distortion are internal angle's changing of workpiece elements and contact penetration between tool elements and workpiece elements.

In the first stage of calculation, each internal angle of workpiece elements is checked at the end iteration of previous incre-