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Analytical model of stress field in workpiece machined surface layer in orthogonal cutting

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ABSTRACT

Residual stress and strain in workpiece machined surface layer have significant effects on the quality of machined parts, including machining distortion and corrosion fatigue strength. It has been known that the flow stress in workpiece induced by cutting force and cutting temperature during cutting is essential to the generation of residual stress and strain. In this paper, an analytical model of stress field in workpiece machined surface layer in orthogonal cutting is proposed to calculate the stress in workpiece during cutting. In this model, the heating time at a point of interest in workpiece is introduced to improve the original model to investigate its effects on stress distribution. The contours of deviatoric stress components S_{11}, S_{22}, S_{33} and S_{12} computed by the original model and the improved model were compared with that of the commercially available finite element model software ABAQUS. The computed results of the improved model show that the stress field in workpiece was in a limited area, which indicates that the stress values on a point of interest would experience increasing and decreasing procedure as the tool moves closer to the point and then travels far away. The results are consistent with that of ABAQUS. Furthermore, the contours of principal shear stress computed by the two models were compared with that of the photoelastic experiment in literature. The computed results of the improved model show the trends that the principal shear stress distribute radially around two radiology centers that locate in the vicinity of the tool tip; the contours of the radially distributed stress around these two centers can be separated by their common tangent; the stress values and gradients closer to the centers are larger, while further are smaller. These trends are consistent with that of photoelastic experiment. However, the computed results of the original model show that the stress field was not in a limited area, indicating that the stress values on a point of interest in workpiece would keep increasing as the tool moves closer to the point and then travels far away, which is not consistent with those of ABAQUS and photoelastic experiment. The improved analytical model of stress field provides a new insight into the stress distribution in workpiece during cutting, and is of great significance to study the residual stress and strain in workpiece machined surface layer.

1. Introduction

It is well kwon that residual stress and strain in workpiece machined surface layer have significant effects on fatigue life, corrosion resistance, and machining distortion of machined parts. One of the origins of residual stress and strain is the stress during machining which is induced by the combining effects of cutting force and cutting temperature. Thus, the study of stress field in workpiece during machining is the preparation to research residual stress and strain in machined surface layer. For a long time, the approaches to study the stress field in cutting process have been the experimental method based on photomechanics, and the theoretical method based on finite element model (FEM).

One of the experimental method based on photomechanics is photoelastic experiment that prevailed before 1970 s when FEM technique was not widely used due to the limitation of computer technology. This method relies on the birefringence property of some specific materials such as epoxy resin which will present different interference patterns in exposure to polarized lights in different stress condition. The patterns can be observed visually using special apparatus. For example, Chandrasekaran and Kapoor [1] studied the variation of the stress-state condition at the tool tip for variations in the tool rake angle using photoelastic method, and successfully obtained the isochromatic stress patterns in the tool made of photoelastic material. Later, Ramalingam and Lehn

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Nomenclature

B	fraction of the shear plane heat conducted into the workpiece
$B_{rubbing}$	fraction of the tool flank-workpiece rubbing heat conducted into the workpiece
α	rake angle (°)
q_{shear}	heat liberation intensity of the shear plane (W/mm^2)
$q_{rubbing}$	heat liberation intensity of the tool flank-workpiece rubbing zone (W/mm^2)
F_c	cutting force (N)
λ	thermal conductivity (W/(mm °C))
F_t	feed force (N)
F_{cw}	friction force between tool flank and workpiece machined surface (N)
L	width of the shear plane heat source (mm)
VB	width of the tool flank-workpiece contact zone (mm)
t_c	depth of cut, or undeformed chip thickness (mm)
φ	shear angle (°)
w	width of cut (mm)
V	velocity of a moving plane heat source, or cutting speed (mm/s)
ρ_0	density (kg/mm^3)
c	specific heat capacity (J/(kg °C))
a	thermal diffusivity ($=\lambda/(\rho_0{}^*c)$ mm^2/s)
μ	friction coefficient between tool flank and workpiece machined surface
N_{th}	thermal number ($=t_cV/a$)
K_0	the modified Bessel function of the second kind of order zero
K_ϖ	dimensionless coefficient of the modification of K_0
K_ω^{shear}	dimensionless coefficient of the modification of K_0, corresponding to shear plane heat source
$K_\omega^{rubbing}$	dimensionless coefficient of the modification form of K_0, corresponding to tool flank-workpiece rubbing heat source
t	heating time (s)
t_{shear}	heating time of point $M(x,z)$ due to shear plane heat source (s)
$t_{rubbing}$	heating time of point $M(x,z)$ due to tool flank-workpiece rubbing heat source (s)
R	resultant radius of the workpiece
R_t	tool edge radius (mm)
R_w	radius of the workpiece (mm)
E_R	resultant elastic modulus of the tool and workpiece (Mpa)
E_t	elastic modulus of the tool (Mpa)
E	elastic modulus of the workpiece (Mpa)
P	resultant force in the Z direction due to shear band (N)
f_f	the maximum force of the distributed load in Z direction due to shear band (N)
f_v	the maximum force of the distributed load in X direction due to shear band (N)
VB^*	thresh hold of plastic deformation of VB (mm)
k_f	the shear flow stress (Mpa)
ρ	the prow angle of the workpiece directly in front of the tool (°)
η_p	the slip-line field angle for friction on stable build-up (°)
m_p	the friction factor at the cutting edge of the tool
m_w	the slip-line field angle for friction on the tool flank-workpiece contact region (°)
υ	Poisson's ratio
α_0	coefficient of linear expansion for per °C
σ_{ij}	stress tensor
S_{ij}	deviatoric stress tensor
ε_{ij}	strain tensor
ε_{ij}^p	plastic rain tensor
J_2	the second invariant of the deviatoric stress
σ_s	yield stress (Mpa)
h	plastic modulus (Mpa)
$\int \overline{d\varepsilon^p}$	the accumulated plastic strain
k	the hardening coefficient
$f_k(z)$	the function of the depth of the interested point $M(x, z)$, z
f	yield function of the material
G	Green's function
τ_{max}	principal shear stress
σ_i	principal stress ($i=1,2,3$)
l_t	the displacement of the tool tip along x direction (mm)

[2] studied the stress field in workpiece in orthogonal cutting using birefringent plastic workpiece, and found that the state of stress in the workpiece during orthogonal cutting is equivalent to that in a semi-infinite plate when a line load is applied to the edge of the plate. The photoelastic experiment provides an access to observe the geometries of the contours of stress field in workpiece intuitively which can be extended to estimate those in the material without birefringent.

FEM provides a theoretical access to compute the stress field in object. Because of its advantages of wide adaptability and low cost, it prevails gradually as the development of computer technology since 1980s. Shet and Deng [3] studied orthogonal cutting using FEM software in plane strain hypothesis, and obtained the fields of temperature, stress, strain, and strain rate in workpiece and chip for a range of tool rake angle and friction coefficient values. However, even with the increasing computing power available nowadays, FEM simulations are time-consuming, especially when fine meshes are adopted in order to obtain more accurate results. For example, in the study of machined surface integrity using FEM, in order to investigate the field of temperature, strain, and stress in a small zone approximate 0.2 mm below the workpiece surface, the users have to use fine meshes to obtain better solution, which results in significant increase of the consumptions of CPU time and memory space of the computer. Moreover, the physical phenomenon involved in cutting presented by FEM is not as explicit as that of the analytical method, which makes it difficult for the users to study the mechanism of machining.

The background of the development of analytical modeling of cutting process is the growing interests in less calculation time and memory space of computer, and more explicit description of the physical mechanism involved in cutting. Komanduri and Hou [4] proposed an analytical model of cutting temperature based on previous work. The model has become the basics of many researches on analytical modeling of cutting temperature and residual stress. Based on Komanduri and Hou's thermal model, Liang and Su [5] modeled the residual stress in workpiece in orthogonal cutting; Su et al. [6] proposed a predictive model of machining residual stresses in workpiece considering tool edge