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Analytical modeling of residual stress formation in workpiece material due to cutting

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ABSTRACT

Residual stress on surface layer of workpiece has significant effects on service life of parts, including fatigue strength and corrosion resistance. Metal cutting process is widely used on manufacturing parts, which will cause severe mechanical and thermal stress on the material and then result in the formation of residual stress on workpiece surface layer. A thorough analysis of residual stress formation due to cutting is essential to create parts with desired residual stress distribution. After analyzing stress field in workpiece based on previous work, the authors in this paper observe that stress of a point during cutting is time dependent, and then proposed that initial condition is mandatory in order to determine initial stress state in stress relaxation procedure. Then the authors propose a criterion to determine initial condition based on the calibration of surface residual stress. Using this criterion and calibration method, the residual stress in different depth of machined surface can be compute using the proposed analytical residual stress model, and the computed results are consistent with experiment results. Moreover, the computed results show that the residual stress component in cutting speed direction is higher than that in axial direction, which is consistent with the general conclusion in the existing literatures. The proposed concept of initial condition and its calibration method in stress relaxation promote the understanding of physical mechanism of residual stress formation in cutting, and can be extended to the situations where the evolution of flow stress in workpiece during cutting is similar with that of in orthogonal cutting.

1. Introduction

In order to obtained parts with desired geometries, metal cutting is widely used to remove redundant materials, which will cause severe stresses and strains on workpiece material and lead to residual stress formation on surface layer of the machined parts. In metal cutting, the induced stresses in material are the combing effects of thermal and mechanical stress, and distribute in shallow layer within approximate 0.2 mm below surface, which are different from that of ordinary structural deformation and needs to be studied using special methods. Moreover, the induced residual stress in metal cutting on surface layer of material has significant effects on corrosion fatigue strength of the parts. Thus, the study of the mechanism of residual stress formation on workpiece material due to cutting is essential to guarantee the quality of machined parts. The methods used in the study of residual stress include the experimental method, finite element model (FEM) and analytical model.

X-ray diffraction technique is prevalent in the experimental study of residual stress. This technique is capable to measure residual stress in the layer within approximate 15 μm below workpiece surface, which can be extended to measure those in different depths below the surface. Knowing that the cutting parameters (cutting speed, feed rate, depth of cut and so on) have significant effects on stress state, Capello [1] studied the effects of cutting parameters on residual stress in workpiece after cutting using X-ray diffraction technique, and concluded that depth of cut did not influence the level of residual stresses, and the cutting velocity and primary rake angle played a minor role, while the key parameters that control residual stresses were the feed rate and nose radius. In his further research [2], the effects of machined materials on residual stress were studied. It shows that the mechanical properties of the machined material deeply influence the level of residual stresses, but did not influence the increment in residual stresses due to an increment in process parameters. El-Axir [3] investigated the residual stress distribution as a function of depth

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Nomenclature

B	fraction of shear plane heat conducted into workpiece
$B_{rubbing}$	fraction of tool flank workpiece rubbing heat conducted into workpiece
α	rake angle, (deg)
q_{shear}	heat liberation intensity of shear plane, (W/mm^2)
$q_{rubbing}$	heat liberation intensity of 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}	frictional force between tool flank and workpiece machined surface, (N)
L	width of shear plane heat source, (mm)
VB	width of tool flank workpiece contact zone, (mm)
t_c	depth of cut or undeformed chip thickness, (mm)
ϕ	shear angle, (deg)
w	width of cut, (mm)
V	velocity of 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	modified Bessel function of second kind of order zero
K_ω	dimensionless coefficient of modification of K_0
K_ω^{shear}	dimensionless coefficient of modification of K_0, corresponding to shear plane heat source
$K_\omega^{rubbing}$	dimensionless coefficient of modification 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 workpiece
R_t	tool edge radius, (mm)
R_w	radius of workpiece, (mm)
E_R	resultant elastic modulus of tool and workpiece, (Mpa)
E_t	elastic modulus of tool, (Mpa)
E	elastic modulus of workpiece, (Mpa)
P	resultant force in Z direction due to shear band, (N)
f_f	maximum force of the distributed load in Z direction due to shear band, (N)
f_v	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	shear flow stress, (Mpa)
ρ	prow angle of the workpiece directly in front of tool, (deg)
η_p	slip-line field angle for friction on stable build-up, (deg)
m_p	friction factor at the cutting edge of tool
m_w	slip-line field angle for friction on tool flank-workpiece contact region, (deg)
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	second invariant of deviatoric stress
σ_s	yield stress, (Mpa)
h	plastic modulus, (Mpa)
$\int \overline{d\varepsilon^p}$	accumulated plastic strain
k	hardening coefficient
$f_k(z)$	function of the depth of the point of interest $M(x, z)$
f	yield function of material
G	Green's function

in workpiece. By peeling the surface layer of the workpiece step by step using electrochemical etching technique, the author was able to measure the residual stress in different depths below workpiece surface. His study show that the residual stress profile can be fitted by a polynomial function of the depth, and the coefficients of this polynomial are functions of cutting parameters. However, the experimental methods have been proved to be high economic cost. Moreover, the empirical formula obtained from experimental measurement fails to reveal the physical mechanism of residual stress formation involved in cutting.

As a theoretical method, FEM could be used to compute the residual stress in material due to cutting at a lower economic cost compared with experimental method. Salio et al. [4] studied the residual stress distribution in turbine disks after turning process using FEM software MSC. Marc, and obtained the residual stress profile as a function of depth below the workpiece machined surface. Mohammadpour et al. [5] studied the effect of machining parameters on residual stress in orthogonal cutting also using FEM, and concluded that with increasing cutting speed and feed rate the maximum value of tensile residual stresses were increased. However, even though FEM is low economic cost, it is time-consuming because fine meshes are mandatory in order to obtain results with satisfactory accuracy. Moreover, FEM fails to provide an explicit description of physical mechanism of residual stress formation involved in cutting process.

Compared with experimental method and FEM, analytical model provides explicit description of the physical mechanism involved in cutting, which is useful to the users to identify the physical factors that affect the formation of residual stress in material, also also is both low economic cost and time-saving. Jiang and Sehitoglu [6] proposed an analytical model of residual stress in the object after rolling contact based on the work of Johnson and Merwin [7] on the study of plastic deformation in rolling. Their model is capable to calculate the residual stress profile as a function of depth in object, which has been extended to model the residual stress in machined surface layer because the interaction between tool and workpiece in cutting can be considered as rolling contact. For example, Ulutan et al. [8] proposed an analytical model of residual stress in machined surface layer based on the residual stress model of rolling contact in the work of [6]. In their model, the combing effects of mechanical stress and thermal stress are considered, which is different from those in rolling contact. Similarly, based on Jiang and Sehitoglu's model, Liang and Su [9] analyzed the residual stress in workpiece due to orthogonal cutting; Su et al. [10] proposed a predictive model of machining residual stresses in workpiece material considering effects of tool edge; Yan et al. [11] study the residual stress in workpiece machined surface layer in orthogonal cutting considering the effects of tool flank wear. In their work, the thermal model was based on the model of Komanduri and Hou [12], which