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An investigation of workpiece temperature variation in end milling considering flank rubbing effect

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ABSTRACT

Better prediction about the magnitude and distribution of workpiece temperatures has a great significance for improving performance of metal cutting process, especially in the aviation industry. A thermal model is presented to describe the cyclic temperature variation in the workpiece for end milling. Owing to rapid tool wear in the machining of aeronautical components, flank rubbing effect is considered. In the proposed heat source method for milling, both the cutting edge and time history of process are discretized into elements to tackle geometrical and kinematical complexities. Based on this concept, a technique to calculate the workpiece temperature in stable state, which supposes the tool makes reverse movement, is developed. And a practicable solution is provided by constructing a periodic temperature rise function series. This investigation indicates theoretically and experimentally the impact of different machining conditions, flank wear widths and cutter locations on the variation of workpiece temperature. The model results have been compared with the experimental data obtained by machining 300M steel under different flank wear widths and cutting conditions. The comparison indicates a good agreement both in trends and values. With the alternative method, an accurate simulation of workpiece temperature variation can be achieved and computational time of the algorithm is obviously shorter than that of finite element method. This work can be further employed to optimize cutting conditions for controlling the machined surface integrity.

1. Introduction

The heat generated in cutting process is one of the most important issues in the metalworking industry. High temperature in metal cutting degrades the tool life, surface integrity, size accuracy and machining efficiency dramatically. In the aviation industry, currently more and more difficult-to-machine materials find their applications. The special properties of these materials, such as superior strength, high hardness and low thermal conductivity, can result in both pretty high cutting force and workpiece temperature in metal removal processes. The coupled thermo-mechanical behavior has a great influence on the tool wear and residual stress in machined surface. With the rapid development of aviation industry, the demands for high-quality aeronautical parts are growing due to their service occasions [1]. Machined surface integrity is an important indicator in assessing the qualities of aeronautical parts. The studies of cutting forces and temperatures, particularly for workpiece, are indispensable to guarantee excellent machined surface integrity. A big amount of heat is conducted into the work material and becomes a critical problem in production. It is likely to degrade the surface integrity of products and even causes surface defects that may lead to irreversible failure in aeronautical parts.

In early years, a great deal of work has been carried out to establish analytical models of the cutting temperature distribution. Most of this work has focused on thermal modelling of grinding and orthogonal cutting. In the light of complexity of part geometry and increasing requirement of machining efficiency, very large volumes of materials are machined away by milling. Once surface burning phenomenon which changes metallographic structure occurs in milling process, subsequent processes hardly continue and the whole workpiece is likely to be destroyed. To date, however, very meager efforts have been dedicated to thermal modelling in milling especially for workpiece.

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Nomenclature

a_n	General term of a series used in proof of convergence
a_p	Axial depth of cut (m)
$A, B, C, C_1, C_2, C_3, C_4, C_5, C_6, D$	Constants used in proof of convergence
A_γ	Tool rake face
$\overline{A}, f_0, \overline{f_0}, \overline{f_f}, \overline{f_s}, L_0, u, W_0, X_0, Y_0$	Intermediate variables for calculating average temperature rise of heat source
$B_f(\tau,z)$	Fraction of the flank wear-land heat conducted into the workpiece
$B_{s,j}(\tau,z), B_{s,j}^{rev}(t,z)$	Fractions of the shear plane heat conducted into the workpiece in direct integration calculation and reverse integration calculation, respectively
c	Specific heat capacity (J/kg °C)
c_w	Specific heat capacity of work material (J/kg °C)
$dF_{ac,j}(\tau,z), dF_{rc,j}(\tau,z), dF_{tc,j}(\tau,z)$	Elemental axial, radial and tangential force components due to chip removal, respectively (N)
$dF_{c,j}(\tau,z)$	Elemental resultant force due to chip removal (N)
$d\boldsymbol{F_{c,j}}, d\boldsymbol{F_{c,j}}'$	Elemental resultant cutting force vectors acting on cutting tool and workpiece due to chip removal, respectively
$d\boldsymbol{F_{fc,j}}, d\boldsymbol{F_{nc,j}}$	Components of $d\boldsymbol{F_{c,j}}$
$d\boldsymbol{F_{s,j}}, d\boldsymbol{F_{ns,j}}$	Components of $d\boldsymbol{F_{c,j}}'$
$dF_{xn}, dF_{yn}, dF_{zn}$	Force components of $dF_{c,j}(\tau,z)$ in $\boldsymbol{X_n}$, $\boldsymbol{Y_n}$ and $\boldsymbol{Z_n}$ directions, respectively(N)
$dF_{rf,j}(\tau,z), dF_{tf,j}(\tau,z)$	Elemental radial and tangential force components due to tool flank wear, respectively (N)
$dt, d\tau$	Lengths of tiny time interval in reverse integration calculation and direct integration calculation, respectively (s)
dz	Elementary axial length (m)
$d\theta_{f,j}(\tau,z)$	Workpiece temperature rise induced by instantaneous elemental flank wear-land heat source (°C)
$d\theta_{s,j}(\tau,z)$	Workpiece temperature rise induced by instantaneous elemental shear plane heat source (°C)
$d\theta_{si,j}(\tau,z)$	Workpiece temperature rise induced by instantaneous elemental image shear plane heat source (°C)
$f_{s,j,\varphi_0}(t,z)$	Workpiece temperature rise induced by instantaneous elemental shear plane heat source in reverse integration calculation (°C)
$h_j(\tau,z), h_j^{rev}(t,z)$	Instantaneous uncut chip thicknesses in direct integration calculation and reverse integration calculation, respectively (m)
K_{ac}, K_{rc}, K_{tc}	Cutting force coefficients due to chip removal (N/m^2)
K_{nf}, K_{tf}	Cutting force coefficients due to tool flank wear (N/m^2)
K_r	Determination coefficient to check whether stable state is reached or not
L, W	Length and width of rectangular heat source, respectively (m)
$\boldsymbol{M}$	A point in workpiece
N	Number of cutter teeth
$\boldsymbol{OXYZ}$	Global stationary coordinate system
$\boldsymbol{O_hX_hY_hZ_h}$	Coordinate system of heat source
$\boldsymbol{O_fX_fY_fZ_f}$	Coordinate system of elemental flank wear-land heat source
$\boldsymbol{O_{fi}X_{fi}Y_{fi}Z_{fi}}$	Coordinate system of elemental image flank wear-land heat source
$\boldsymbol{O_nX_nY_nZ_n}$	Coordinate system of elemental cutting edge
$\boldsymbol{O_sX_sY_sZ_s}$	Coordinate system of elemental shear plane heat source
$\boldsymbol{O_{si}X_{si}Y_{si}Z_{si}}$	Coordinate system of elemental image shear plane heat source
P	An element of cutting edge
$P_n, P_o, P_r, P_s, P_{sh}$	Normal plane, orthogonal plane, reference plane, cutting plane and shear plane, respectively
${}^f\boldsymbol{p}, {}^s\boldsymbol{p}, {}^{si}\boldsymbol{p}, {}^w\boldsymbol{p}$	Position vectors of point $\boldsymbol{M}$ in coordinate systems $\boldsymbol{O_fX_fY_fZ_f}$, $\boldsymbol{O_sX_sY_sZ_s}$, $\boldsymbol{O_{si}X_{si}Y_{si}Z_{si}}$ and $\boldsymbol{OXYZ}$, respectively
${}^f_{rev}\boldsymbol{p}, {}^s_{rev}\boldsymbol{p}, {}^{si}_{rev}\boldsymbol{p}, {}^w_{rev}\boldsymbol{p}$	Position vectors of point $\boldsymbol{M}$ in coordinate systems $\boldsymbol{O_fX_fY_fZ_f}$, $\boldsymbol{O_sX_sY_sZ_s}$, $\boldsymbol{O_{si}X_{si}Y_{si}Z_{si}}$ and $\boldsymbol{OXYZ}$ in imaginary reverse milling process, respectively
q	Heat flux of rectangular heat source (W/m^2)
$q_{f,j}(\tau,z)$	Heat flux of instantaneous elemental flank wear-land heat source (W/m^2)
$q_{s,j}(\tau,z), q_{s,j}^{rev}(t,z)$	Heat fluxes of instantaneous elemental shear plane heat source in direct integration calculation and reverse integration calculation, respectively (W/m^2)
Q	Specific energy of instantaneous rectangular heat source (J/m^2)
t, τ	Time in imaginary reverse milling process and actual milling process, respectively (s)
t_i^n	Time of the ith tiny time interval in T_n (s)
t^n	Time defined in time range of T_n (s)
t_s	Time which is studied on (s)
T	Rotating period of tool (s)
T_n	The nth period
${}^f_wT, {}^s_wT, {}^{si}_wT$	Transformation matrices from $\boldsymbol{OXYZ}$ to $\boldsymbol{O_fX_fY_fZ_f}$, $\boldsymbol{O_sX_sY_sZ_s}$ and $\boldsymbol{O_{si}X_{si}Y_{si}Z_{si}}$ in actual milling process, respectively
${}^f_wT_{rev}, {}^s_wT_{rev}, {}^{si}_wT_{rev}$	Transformation matrices from $\boldsymbol{OXYZ}$ to $\boldsymbol{O_fX_fY_fZ_f}$, $\boldsymbol{O_sX_sY_sZ_s}$ and $\boldsymbol{O_{si}X_{si}Y_{si}Z_{si}}$ in reverse milling process, respectively
V	Cutting velocity (m/s)
$\boldsymbol{V}$	Cutting velocity vector
V_0	Velocity of rectangular heat source moving obliquely on semi-infinite conducting medium (m/s)
$\boldsymbol{V_c}$	Chip velocity vector
V_s	Shear velocity (m/s)
$\boldsymbol{V_s}$	Shear velocity vector
VB	Tool flank wear width (m)
x_f, y_f, z_f	Coordinates of point $\boldsymbol{M}$ in coordinate system $\boldsymbol{O_fX_fY_fZ_f}$ (m)
x_{fi}, y_{fi}, z_{fi}	Coordinates of point $\boldsymbol{M}$ in coordinate system $\boldsymbol{O_{fi}X_{fi}Y_{fi}Z_{fi}}$ (m)
x_h, y_h, z_h	Coordinates of point $\boldsymbol{M}$ in coordinate system $\boldsymbol{O_hX_hY_hZ_h}$ (m)
x_s, y_s, z_s	Coordinates of point $\boldsymbol{M}$ in coordinate system $\boldsymbol{O_sX_sY_sZ_s}$ (m)
z	Axial position of elemental cutting edge (m)
α	Thermal diffusivity (m^2/s)
α_n	Tool normal rake angle (°)
α_w	Thermal diffusivity of work material (m^2/s)
β	Tool helix angle (°)
β_a	Friction angle (°)
$\Gamma_j(\tau,z)$	Engagement recognition factor
η_c	Chip flow angle (°)
θ	Temperature rise (°C)
$\overline{\theta}$	Average temperature rise on rectangular heat source (°C)
$\theta_{f,\varphi_0}, \theta_{s,\varphi_0}, \theta_{si,\varphi_0}$	Workpiece temperature rises in stable state induced by flank wear-land heat source, shear plane