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Thermal modeling for white layer predictions in finish hard turning

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Abstract

Part thermal damage is a process limitation in finish hard turning and understanding process parameter effects, especially, tool wear, on cutting temperatures is fundamental for process modeling and optimization. This study develops an analytical model for cutting temperature predictions, in particular, at the machined-surfaces, in finish hard turning by either a new or worn tool.

A mechanistic model is employed to estimate the chip formation forces. Wear-land forces are modeled using an approach that assumes linear growth of plastic zone on the wear-land and quadratic decay of stresses in elastic contact. Machining forces and geometric characteristics, i.e. shear plane, chip–tool contact, and flank wear-land, approximate the heat intensity and dimensions of the shear plane, rake face, as well as wear-land heat sources. The three heat sources are further discretized into small segments, each treated as an individual rectangular heat source and subsequently used to calculate temperatures using modified moving or stationary heat-source approaches. Temperature rises due to all heat-source segments are superimposed, with proper coordinate transformation, to obtain the final temperature distributions due to the overall heat sources. All heat sources are simultaneously considered to determine heat partition coefficients, both at the rake face and wear-land, and evaluate the final temperature rises due to the combined heat-source effects.

Simulation results show that, in new tool cutting, maximum machined-surface temperatures are adversely affected by increasing feed rate and cutting speed, but favorably by increasing depth of cut. In worn tool cutting, flank wear has decisive effects on machined-surface temperatures; the maximum temperature increases 2–3 times from 0 to 0.2 mm wear-land width. White layers (phase-transformed structures) formed at the machined-surfaces have been used to experimentally validate the analytical model by investigating tool nose radius effects on the white layer depth. The experimental results show good agreement with the model predictions.

The established model forms a framework for analytical predictions of machined-surface temperatures in finish hard turning that are critical to part surface integrity and can be used to specify a tool life criterion.

Keywords: Hard turning; machined-surface temperature; phase transformation temperature; thermal modeling; tool flank-wear; white layer

1. Introduction

Tool life in finish hard turning is limited by part surface characteristics, e.g. microstructural alterations and surface finish, indirectly correlated to tool wear. Thermal damage due to temperature rises at the machined-surface is the primary source of surface degradation, e.g. side flow [1,2] or white layer [3]. Understanding the complex thermal phenomenon is fundamentally important to deploy efficient thermal management strategies for part damage minimization. In hard turning, due to high specific cutting energy, tool wear growth is rather fast, and, thus, wear-land effects are desirably concerned for process analysis. The presence of flank wear-land accompanies additional cutting forces as well as heat generation to the thermo-mechanical process. Tool wear is detrimental to part quality, in particular, to part surface integrity because of temperature rises at the machined-surface. It has been reported that tool wear is a primary factor to white layer formation, an undesirable by-product, in hard turning [3–5].

Cutting forces due to flank wear-land have been studied by several researchers. There seems to be two schools of thought. One reported chip formation to be independent on wear-land traction, which solely depends on wear-land geometry and cutting conditions [6–9]. One the other hand, Wang and Liu suggested that chip formation forces are affected by wear-land interactions [10,11]. According to Waldorf et al. [6], flank wear-land contact consists of both plastic flow region and elastic contact if the width of wear-

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Nomenclature

a	angle at lead cutting edge in wear-land geometry model (degree), Fig. 1(b)
A_c	uncut chip area (mm^2)
A_r	area of rake face heat source (mm^2)
A_s	area of shear plane heat source (mm^2)
A_w	area of wear-land heat source (mm^2)
b	angle at tail cutting edge in wear-land geometry model (degree), Fig. 1(b)
CL	contact length between cutting tool and work-piece along the cutting edge
d	depth of cut (mm)
f	feed rate (mm/rev)
F_a	axial cutting force in turning (N)
$F_{a,w}$	axial force component due to wear-land in worn tool cutting (N)
F_f	frictional cutting force at rake face (N)
F_n	normal cutting force at rake face (N)
F_{PW}	cutting force due to wear-land (N)
F_{QW}	thrust force due to wear-land (N)
F_r	radial cutting force in turning (N)
$F_{r,w}$	radial force component due to wear-land in worn tool cutting (N)
F_s	shear force on shear plane (N)
F_t	tangential cutting force in turning (N)
$F_{t,w}$	tangential force component due to wear-land in worn tool cutting (N)
h_θ	uncut chip thickness as a function of location across the cutting edge (mm)
k	thermal conductivity of workpiece (W/m K)
k_t	thermal conductivity of cutting tool (W/m K)
K_f	specific frictional pressure (N/mm^2)
K_n	specific normal pressure (N/mm^2)
l_r	tool chip contact length as a function of location across the cutting edge (mm)
l_s	shear plane length as a function of location across the cutting edge (mm)
q_r	heat flux of rake face heat source (W/m^2)
q_s	heat flux of shear plane heat source (W/m^2)
q_w	heat flux of wear-land heat source (W/m^2)
r	tool nose radius (mm)
ΔS_θ	discretized shear plane heat source
$\Delta S'_\theta$	image heat source of discretized shear plane heat source
t_θ	chip thickness as a function of location across the cutting edge (m)
T_0	initial tool and workpiece temperature (20 °C)
T_c	temperature in a chip (°C)
$T_{c,r}$	temperature rise in chip due to rake face heat source (°C)
$T_{c,s}$	temperature rise in chip due to shear plane heat source (°C)
T_t	temperature in a tool (°C)
$T_{t,r}$	temperature rise in tool due to rake face heat source (°C)
$T_{t,w}$	temperature rise in tool due to wear-land heat source (°C)
T_w	temperature in a workpiece (°C)
$T_{w,s}$	temperature rise in workpiece due to shear plane heat source (°C)
$T_{w,w}$	temperature rise in workpiece due to wear-land heat source (°C)
$\Delta T_{c,r}$	temperature rise in chip due to rake face heat source (°C)
$\Delta T_{c,s}$	temperature rise in chip due to shear plane heat source (°C)
$\Delta T_{t,r}$	temperature rise in cutting tool due to rake face heat source (°C)
$\Delta T_{w,s}$	temperature rise in workpiece due to shear plane heat source (°C)
V	cutting speed (m/s)
V_c	cutting chip speed (m/s)
V_s	shear plane speed (m/s)
VB	width of flank wear (mm)
VB_P	width of plastic flow region on flank wear (mm)
α	rake angle (rad)
α_0	nominal rake angle (rad)
β_r	heat partition coefficient of rake face heat source
β_w	heat partition of for wear-land heat source
χ	thermal diffusivity (m^2/s)
ϕ	shear angle (rad)
σ_0	normal stress at plastic flow region of flank wear-land (N/m^2)
σ_w	normal stress at elastic region of flank wear-land (N/m^2)
τ_0	shear stress at plastic flow region of flank wear-land (N/m^2)
τ_s	shear flow stress on shear plane (N/m^2)
τ_w	shear stress at elastic region of flank wear-land (N/m^2)
θ	a variable (angle) to define location across the cutting edge
θ_1	θ associated with tail cutting edge (rad)
θ_2	θ associated with lead cutting edge (rad)

land, VB, is greater than a certain level VB_{cr}. Smithey et al. [7,8] further proposed that the width of plastic flow region (VB_P) linearly increases with VB and the proportionality is independent of cutting conditions, but solely a function of the workpiece and cutting tool materials. Following the assumption of the linear growth of plastic zone, stresses are modeled to be constant in plastic flow region and quadratic distribution in elastic contact. Once normal and