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Determination of tool friction in presence of flank wear and stress distribution based validation using finite element simulations in machining of titanium and nickel based alloys

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ABSTRACT

Tool friction plays a very important role in machining titanium and nickel-based alloys and is an important parameter in Finite Element based machining simulations. It is the source for the high amount of heat generation, and as a result, the excessive flank wear during machining these materials. The worn tool is known to create poor surface qualities with high tensile surface residual stresses, machining induced surface hardening, and undesirable surface roughness. It is essential to develop a methodology to determine how and to what extent the friction is built up on the tool. This study facilitates a determination methodology to estimate the stress distributions on the rake and flank surfaces of the tool and resultant friction coefficients between the tool and the chip on tool rake face, and the tool and the workpiece on tool flank face. The methodology is applied to various tool edge radii and also utilized in solving stagnation point location on the tool edge. Predicted friction results are further validated with comparison of predicted stress distributions from FE simulations for machining of titanium alloy Ti-6Al-4V and the nickel-based alloy IN-100. It was found that tool stresses and friction are mainly influenced by tool rake angle, edge radius, and tool flank wear and are slightly affected by the cutting conditions in the ranges that were considered in this study.

1. Introduction

Machining difficult-to-process materials such as titanium and nickel-based alloys has been a major hurdle for manufacturing industry in terms of productivity for a significant amount of time, and there are a number of issues that are yet to be resolved. The effect of friction is an important issue, yet its understanding in machining titanium and nickel-based alloys is not complete. Let alone 3D machining processes, the work on friction in 2D orthogonal machining processes still lacks entirety. It is known that with increasing friction, heat build-up and tool wear increases especially in the case of titanium and nickel-based alloys due to their low thermal conductivity and chemical affinity with tool materials at elevated temperatures. Consequently, there are surface integrity problems at the end product that will reduce product effectiveness, quality and reliability.

While it is extremely important to understand the role of friction, attempts at measuring in situ detailed frictional properties during machining have been a far cry from success. Hence, attempting to get the optimum approximation by modeling friction still remains a tangible approach to this problem. Childs (2006a) reviewed friction laws and models existed in metal cutting and claimed that different friction models should be considered in low, intermediate, and high speed cutting regimes. He also pointed out the limitations of using traditional metal forming based friction models available in Finite Element Modeling software and suggested an improved friction model based on a constant friction coefficient being replaced by one which increases with plastic strain rate. Finite Element-based models comprise the most important part of the modeling work, and it is known that FE-based models are practically used to find optimal cutting conditions and tool geometry parameters. In addition, flow stress characteristics of work material at specified cutting parameters and friction characteristics at tool/chip interface are two important factors that affect FE-based simulation capability and predictability. Özel (2006) investigated several friction models applicable to FE-based simulations of metal cutting and claimed a friction coefficient varying with normal stress provides better predictions of cutting forces and tool stress distributions. Arrazola et al. (2008) showed that a friction coefficient alone is inadequate and does not represent the friction between chip–tool interfaces in metal cutting. They also suggested a variable friction coefficient that is empirically obtained from cutting tests. Arrazola and Özel (2010) investigated the influence of limiting shear stress on the tool–chip contact friction and

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concluded that friction models that limit the increasing shear stress are more effective in predicting physical variables in metal cutting. Childs (2006b) focused on FE-based simulation and the role of friction models in plastic and elastic–plastic workpiece assumptions to explore the physical limitations of the friction. He claimed that friction stress proportional to normal stress is a tolerable friction law in the FE-based simulations but acknowledged that it is unrealistic in plastically flowing conditions. Meanwhile, other friction models for analytical and semi-empirical machining modeling have been proposed. Özlü et al. (2009) used a friction model that considers both apparent and real contacts exist on tool rake face. They also proposed an experimental method to identify the parameters of such a friction model. Thus, continued attention has been given to friction modeling in literature.

In parallel to those studies, present Finite Element based simulation models for machining nowadays take tool friction at rake and flank faces as an input to the model. In addition, shear friction and sliding friction can be represented together in a “hybrid friction model” at the tool–chip contact for a cutting tool with an edge radius ($r_\beta > 0$). In this model, coexisting friction regions are defined; a shear friction region ($m = \tau/k$, where τ is material shear stress and k is shear flow stress in the shearing zone) around of the tool edge radius curvature and a sliding region along the rest of the rake face represented with a friction coefficient ($\mu = \tau_f/\sigma_n$, where τ_f is the friction stress and σ_n is the normal stress on the tool face). Similarly friction at the tool–workpiece contact can be represented while the extent of sticking region and friction coefficient in sliding region remaining as major unknowns in metal cutting conditions.

This study will introduce a comprehensive friction determination methodology beginning with measured cutting forces at various cutting conditions, tool geometry, and tool flank wear for machining titanium and nickel-based alloys. Tool contact friction on rake and flank faces will be determined by using an analytical modeling approach and an iterative solution methodology to identify stress distributions and related friction coefficients at those faces for each cutting condition. FE-based simulation modeling working in an iterative algorithm together with the analytical and empirical models will be utilized to validate predicted tool friction coefficients and stress distributions. Particularly, the developed friction models with and without tool wear will be introduced, and their validation with force measurements for force components as well as FE-based model for stress distributions will be shown. The paper will be finalized by suggestions on how to utilize the information and findings of this study for future research.

1.1. Friction determination methods

There have been many attempts to determine the friction coefficient during machining, and one should know the strength and weaknesses of all of these methods to propose a new method. Despite being similar to each other in many ways, there are nuances that separate these methods, and it is important to understand these differences.

In the pin-on-the-disk method, a tribometer with a stationary pin is contacted with the rotating disk, measuring the forces. The ratio of the force components gives the coefficient of friction, but the machining temperature and pressure cannot be maintained for the measurement. According to Bonnet et al. (2008), this leads to inaccurate measurements, since the coefficient of friction is considered to be dependent on these factors. In order to achieve machining temperature, Olsson et al. (1989) and later Hedenqvist and Olsson (1991) proposed methods where the pin follows the cutting tool, so the workpiece is still at cutting temperature. They used an improved method that also imitates the cutting pressure and measured forces very similar to machining forces. In their method, Bonnet et al. (2008) coated the pin with the tool material, which

Nomenclature

a-h_{1-2}	coefficients of the non-linear relationships
A,B,C,D	FE material model coefficients
m,n,p,r,s	FE material model coefficients
b	depth of cut
c_p	specific heat capacity
h	heat conduction coefficient
l_c	chip–tool contact length along the tool rake face
l_p	plastic contact length along the tool rake face
E	Young’s Modulus
F_c	total cutting force
F_f	total feed force
F_{c_o}	cutting force for the 3rd zone—ploughing or edge components
F_{f_o}	feed force for the 3rd zone—ploughing or edge components
$F_{n_{1-3}}$	normal force components
$F_{t_{1-3}}$	tangential force components
$F_{n_{1-3c}}$	cutting force components due to normal stresses
$F_{n_{1-3c}}$	cutting force components due to tangential stresses
$F_{n_{1-3f}}$	feed force components due to normal stresses
$F_{n_{1-3f}}$	feed force components due to tangential stresses
m	exponential coefficient for Region III
n	exponential coefficient for Region I
r_β	cutting edge radius
T	temperature
T_0	ambient temperature
T_m	melting temperature
t_u	uncut chip thickness
VB	tool flank wear length
v_c	cutting speed
x_{1-2}	distance along the rake and flank faces from edge face
α	angle measured from cutting speed direction for Region II
α_0	starting angle for Region II
α_f	final angle for Region II
α_t	thermal expansion constant
γ_1	rake angle
γ_2	clearance angle
γ_s	stagnation point angle
ε	true strain
$\dot{\varepsilon}_0$	reference true strain rate
$\dot{\varepsilon}$	true strain rate
θ	tool flank wear angle
λ	thermal conduction coefficient
μ	mean friction coefficient
μ_{ap}	apparent friction coefficient
μ_{sl}	sliding friction coefficient
μ_1	friction coefficient along the rake face
μ_2	friction coefficient along the flank face
σ	flow stress
σ_{1-3}	normal stress at the rake, edge, and flank faces
$\sigma_{1\max}$	maximum normal stress at the rake face
$\tilde{\sigma}_2$	normal stress at the stagnation point in Region II for the worn tool
$\sigma_{3\max}$	maximum normal stress at the flank face
τ_{1-3}	shear stress at the rake, edge, and flank faces
$\tau_{1\max}$	maximum shear stress along the tool rake face
$\tilde{\tau}_2$	frictional shear stress at the stagnation point in Region II for the worn tool
$\tau_{3\max}$	maximum shear stress along the tool flank face