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Modeling of static machining force in axial ultrasonic-vibration assisted milling considering acoustic softening

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ABSTRACT

Ultrasonic-vibration assisted milling (UAM) process is one of the most recent advancements in the area of milling. In axial UAM process, milling cutter is rotated and vibrated in axial direction simultaneously with high frequency and small amplitude. Experimental studies showed that superposition of axial ultrasonic vibrations in milling operation improved the process by reducing cutting forces and enhancing surface finish. This study is focused on analytical study of the UAM process with axial vibration of end milling tool. A process physics-based model was developed to evaluate the cutting forces in axial ultrasonic assisted milling process. The developed model included acoustic softening, intermittent cutting and end mill helix angle effects. For validation of the developed model an experimental setup was developed. Axial UAM of Al6063 alloy workpiece was carried out with a high speed steel end milling tool. The predicted values and trend were found in good agreement with experimental results.

1. Introduction

In the current manufacturing era, milling is one of the most commonly used machining process. Milling is mainly used to machine the components with freeform surface like dies and molds. However, milling of newly developed materials like high-strength aerospace alloys causes high cutting forces, poor surface roughness and fast wear of cutting edges [1]. Application of coolant is the most commonly used technique to address the aforesaid problems. However, the use of coolant makes machining costly and ecologically harmful [2,3]. Growing demand of machining of difficult to machine materials requires improved milling process.

A few techniques were developed to avoid the problems associated with the milling of hard material. Most commonly used technique among them is the high speed milling that enables reduction in cutting forces [4]. Nevertheless occurrence of chatter becomes very prominent in high speed milling [5]. Chatter leads to fast tool wear and low surface quality [1]. To avoid chatter, Liu et al. [6] analytically modeled it by considering system response and cutting forces. They plotted the chatter stability lobes to obtain the parameters for chatter free milling.

Minimum quantity lubrication (MQL) has been used with milling to minimize the associated problems while machining difficult to machine materials. In MQL, a small amount of lubrication is applied in the cutting zone that causes lowering of cutting force and improvement of surface finish. Researchers [7] also tried MQL with nano particles and found that cutting forces and surface roughness got further reduced. The experimental studies [8] showed that the formation of thin film in the secondary shear zone resulted in lowering of frictional coefficient.

Ultrasonic vibration assisted milling (UAM) is a newly developed process to enhance the performance of milling operation in an ecofriendly manner. In axial UAM, milling cutter is rotated and vibrated axially with high frequency and small amplitude [9]. However, most of the researchers applied ultrasonic vibration to the workpiece instead of cutting tool [10–13]. The effect of ultrasonic vibration on cutting was first analyzed in the late 1950s on traditional macro-scale turning operations. The ultrasonic assisted cutting of materials like steel, glass, and brittle ceramics resulted in better surface finish, longer tool life and lower cutting forces [9]. Reduction of cutting forces in UAM is due to intermittent cutting that occurs only in certain range of cutting parameters [10–12].

The effect of ultrasonic vibrations in milling operation has shown good promise in reducing cutting forces and improving surface finish [14,15]. Ultrasonic vibrations have been applied in different directions like axial, feed and cross-feed directions; in all the cases it resulted in reduced cutting forces. However, vibrations in axial and feed directions have produced better surface finish than cross-feed direction due to ironing effect [15]. Axial vibration is considered more advantageous as it provides flexibility to perform UAM in any direction resulting in uniform surface finish. Experimental studies [16–20] have showed that the

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Nomenclature

α, k	Specific heat and thermal conductivity of material
β	Helix angle of the tool
γ, i, ϑ	Rake angle, inclination angle and side cutting edge angle of milling tool
ε, $\dot{\varepsilon}$	Strain and strain rate at primary shear zone
$\dot{\varepsilon}_o$	Reference strain rate
η	Factor that accounts for plastic work transformed into heat
η_c	Chip flow angle
θ	Angle made by resultant force with the shear plane
λ	Friction angle
λ_s	Fraction of generated heat conducted into the workpiece
v	Velocity at specific material point
ρ	Density of the material
σ	Flow stress
$\sigma_{accoustic}$	Acoustic stress in material due to ultrasonic vibration
τ_b	Shear flow stress of material at primary shear zone
ϕ	Shear angle
ψ	Coefficient for thermal softening
$\emptyset$	Angular position of cutter tooth during milling
c	Velocity of sound in the medium
d, e	Constants for acoustic softening factor
f	Frequency of ultrasonic vibration
h, Δh	Axial depth of cut, width of each slice
n_t	Number of flutes on milling tool
q	Thickness of the shear zone
r_c	Contact ratio
t	Uncut chip thickness
t_c, t_s	Time of contact, time of separation of tool from cutting zone
w	Width of cut
x, y	Material constants that depends on its thermo-mechanical properties
D	Milling tool diameter
A, B, C, n, m	Johnson-Cook material constants
E_u	Ultrasonic energy intensity
$F_x(t)$, $F_y(t)F_z(t)$	Instantaneous forces in X, Y and Z direction during milling
F_c, F_T, F_R	Cutting, thrust and radial forces in oblique cutting
P_1, P_2, P_3	Resolved cutting forces in angular coordinate
R	Resultant force at the shear plane and tool–chip interface
R_t	Thermal constant which depends on workpiece material thermomechanical property
T_b	Temperature of primary shear zone
T_r, T_m	Reference temperature and Melting temperature
V_n, V_{ul}	Velocity of the cutting edge due to rotation of the tool and ultrasonic vibration
V_c	Total cutting velocity at the edge of the milling tooth

application of axial ultrasonic vibration reduces cutting forces, surface roughness, cutting temperature and tool wear. Important research work in the field of UAM is discussed briefly.

Maurotto and Wickramarachchi [21] analyzed the effect of frequency of vibration (axial vibration in ultrasonic assisted end-milling of AISI 316L with cemented carbide tool. Their experimental results revealed that with an increase in the frequency of vibration, surface roughness increases. The 40 kHz frequency was found to be unsuitable for the UAM from the point of view of tool wear and residual stresses. UAM at 20 kHz resulted in an enhanced tool life as compared to UAM at 40 kHz and 60 kHz frequencies.

Shen et al. [11] experimentally analyzed the effect of ultrasonic vibrations (in feed direction) in a slot milling operation. They compared the effect of ultrasonic vibration assistance in milling operation by measuring cutting forces, surface roughness, chip morphology and slot dimensional accuracy. They concluded that ultrasonic vibration aided the milling operation by performing intermittent cutting. Abootorabi Zarchi et al. [13] experimentally analyzed the effect of process parameters on cutting forces during ultrasonic assisted side milling. Their experimental results showed 42% reduction in cutting forces due to intermittent cutting. It was noted that as the cutting speed increased, the ultrasonic effect decreased and the machining behavior approached to conventional milling process.

Li and Wang [22] studied the effect of process parameter on tool wear and surface roughness in UAM of SKD61 Tool Steel. Their experimental results showed that the assistance of axial ultrasonic vibration improves the milling process by reducing tool wear, surface roughness and burr height. The results also show that effect of ultrasonic vibration decreases with increase in rotational speed.

Elhami et al. [23] studied the effect of machining parameters on cutting forces during ultrasonic assisted milling of hardened AISI 4140 along with heating of the workpiece with concentrated plasma heat source. They proposed an analytical model by considering the effect of vibration on instantaneous chip thickness. The model could also predict the temperature field in the workpiece and reduction in cutting forces due to thermal softening.

Abootorabi Zarchi et al. [12] proposed an analytical model to predict the cutting forces in ultrasonic assisted milling. They considered change in the un-deformed chip thickness that occurred due to ultrasonic vibrations provided to the workpiece. Developed model was validated by performing experiments on AISI 420 stainless steel. Shen et al. [24] developed an analytical model by considering the effect of vibration on instantaneous chip thickness. Their results were validated by performing slot milling with the assistance of ultrasonic vibration on aluminum (Al6061).

Ding et al. [25] developed a model to predict cutting forces in two-dimensional vibration-assisted micro milling (2-D VAMM). Instantaneous chip thickness was evaluated by considering the machine dynamics in cutting force model. The experimental results ascertained the importance of machine dynamics for the accurate prediction of cutting forces.

It is inferred from the literature that in most of the studies ultrasonic vibration was applied to the workpiece in feed direction. There is no analytical model to predict the cutting forces in UAM with axial vibrations. In this study, a physics based model is proposed for the axial UAM process. The developed model considers the effect of ultrasonic vibrations on cutting kinematics and the work material flow stress. A new approach of acoustic softening and intermittent cutting was considered in the developed model. The softening constants were evaluated by performing ultrasonic assisted tensile tests. The kinematics of milling tool with superimposed vibration was studied by performing simulation on ANSYS workbench software. In order to validate the proposed model an experimental setup was developed in which the tool executed axial vibrations during the milling operation. The UAM experiments were performed on Al6063 alloy and the cutting forces were measured with the help of dynamometer. The experimental results affirmed that the proposed model could be used to predict the cutting forces in UAM process.

2. Modeling of cutting forces

Modeling of milling process is generally based on conventional turning models by considering milling parameters as turning parameters [26,27]. Experimental and analytical studies suggest that in turning op-