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Abstract

This thesis proposes a new three-dimensional cutting process model. The basic features and improvements over previously developed models include: (1) cutting force calculations based on the concept of equivalent orthogonal cutting process (EOC), which converts the modeling of three dimensional cutting process into the modeling of orthogonal cutting processes. In the model , both cutting force coefficient and chip load are considered as functions of cutting conditions, tool geometry, and machine-tool structural vibrations. (2) microstructure hardness variation of workpiece material has been taken into consideration. (3) the regenerative mechanism and mode coupling effect in machining are included. The structural dynamics equations, which include five vibration modes, are in the form of a set of simultaneous differential equations. The forth-order Runge-Kutta method is applied to solve these equations numerically.

Based on the proposed model, systematic simulation of turning processes has been conducted. The simulation results show the relation

between the cutting force and surface finish (output of the process) and the feed, spindle speed, depth of cut, nose radius, rake and lead angles (the input parameters of the process).

The simulation results of surface finish and cutting force are verified experimentally. The simulated surface finish and cutting force are in agreement with the experimental results.

نمذجة عملية الخراطة

أعداد : وفاء محمود فالح بطاينة

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المشرف المشارك : د. محمد الهياجنة

الملخص

هذه الأطروحة تعرض نموذج طريقة القطع ثلاثية الأبعاد. المميزات الرئيسية والتطويرات لهـــــذا النموذج المطور تشمل: (١) حسابات قوى القطع بالاعتماد على مبدأ عملية القطع المكافئ العموديـــــة، حيث يتم تحويل النموذج ثلاثي الأبعاد إلى نموذج ثنائي الأبعاد. في هذا النموذج كلا ثابتي قوى القطــع و حمل الشظية يعتمدان على ظروف القطع و شكل الأداة و اهتزاز آلة القطع. (٢) أخذ التغير في قســـاوة السطح للعينة بعين الاعتبار.

المعادلات الديناميكية للهيكل والتي تضم خمس حالات اهتزازية على شكل مجموعة معـــادلات تفاضلية حيث اعتمد نظام (رنج كتا) الرباعي لحل هذه المعادلات عدديا.

بالاعتماد على هذا النموذج ، تم عمل نموذج رياضي للخراطة و نتائج هذا النموذج تبين العلاقة بين قوى القطع و الإنماء السطحي(مخرجات العملية) و التغذية, سرعة الدوران, عمق القطع, نصف قطـر طرف أداة القطع, و زاوية الجرف(مدخلات النموذج).

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b	cutting width
C	cutting force ratio
C_s	Three dimensional cutting process lead angle
C_{se}	effective lead angle
C_{sor}	equivalent orthogonal cutting lead angle
CEL	cutting edge length
d_o	nominal depth of cut
ECT	equivalent chip thickness
f_o	nominal feed rate
F_x, F_y, F_z	cutting force in x,y,z direction
F_{xt}, F_{yt}, F_{zt}	cutting force without considering ploughing force and microhardness
F_{xp}, F_{yp}, F_{zp}	cutting force considering ploughing force
F_p, F_q	cutting force in orthogonal plane
F_d, F_{dx}, F_{dz}	ploughing force
h	time interval
i	inclination angle

K	specific cutting force
K_α	damping factor in the cutting process
m	Meyer exponent
m_1, c_{1i}, k_{1i}	tool dynamic characteristics (i=1,2,3)
m_2, c_{2i}, k_{2i}	workpiece dynamic characteristics (i=1,2)
r	chip thickness ratio
R	tool nose radius
R_a	arithmetic average surface roughness
R_a'	R_a considering minimum undeformed chio thickness
R_{th}	peak to valley surface roughness
R_{th}'	R_{th} considering minimum undeformed chip thickness
N	workpiece rotation speed
S	undeformed chip thickness
t_m	minimum undeformed chip thickness
t'	time lag between two end points of the shear plane
v	cutting velocity
W(r)	geometrical shape function
X,y,z	tool-workpiece relative vibration
X,Y,Z	global coordinates
x_1, y_1, z_1	tool vibration
x_2, y_2, z_2	workpiece vibration
x_n	vibration in the direction normal to cutting edge

τ_s shear stress

β friction angle on tool face

α rake angle

α_o nominal rake angle

α_e effective rake angle

α_{eo} effective rake angle without vibration

α_y nominal rake angle considering vibration in y-direction

α_{ey} effective rake angle considering vibration in y-direction

$\delta\alpha_e$ effective rake angle change due to vibration in x-z plane direction

γ_e effective relief angle

γ_{eo} effective relief angle without vibration

γ_y nominal relief angle considering vibration in y-direction

γ_{ey} effective relief angle considering vibration in y-direction

$\delta\gamma_e$ effective relief angle change due to vibration in x-z plane

Φ shear angle

Φ_e effective shear angle change

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MODELING OF TURNING PROCESS

at

Jordan University of Science & Technology

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MODELING OF TURNING PROCESS

BY

Wafa' Mahmoud Batayneh

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at

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Signature of Author: ______________ **May, 2000**

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To my Father, Mother, Sisters and Brothers...

Wafa'

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CHAPTER 1

INTRODUCTION

The study of turning process has lasted more than a century, but it still attracts a large amount of research effort. This is because turning is not only the most frequently used machining operation in the modern manufacturing industry, but also because it is a typical single-point machining operation. Other machining operations, such as milling, drilling and boring are multiple–point machining operations that can be investigated based on the contributions of single–point machining operations. Thus the study of turning can contribute greatly to the knowledge of metal cutting principles and machining practice.

However, turning is a complex process, it involves friction, plastic flow and fracture of materials under more extreme conditions than those normally found in other manufacturing processes, such as stamping and drawing. As a result, high temperature and high strain rate are characteristics of turning process.

It is important to understand how the process " inputs" such as cutting conditions (depth of cut, feed, cutting speed), tool geometry (nose radius, rake angle, relief angle, lead angle, etc.) affect the process behavior " output", such as cutting stability, tool wear, surface finish, cutting force, and cutting power. The understanding will enable engineers to optimize cutting operations, which is the motivation in developing models to describe the input-output relationship of cutting process.

Due to great advances in computers, simulation has become a powerful tool in studying machining process. Simulation has a number of advantages over analytical and traditional experimental methods: it can run without expensive experimental setup, requires much less cutting tests, and more importantly it can reveal detailed information and mechanisms in metal cutting processes, such as the basic non-linearity in chatter vibration [Tlusty and Ismail, 1981].

In this thesis, modeling of cutting forces is first investigated. It is known that dimensional accuracy, surface finish, and productivity are the three major requirements in turning, especially in finish turning. They are all affected by vibration, which is a function of system dynamic characteristics and cutting forces. Poor dynamic characteristics and large cutting forces can induce excessive vibration or chatter, which would result in poor surface finish, early cutting failure, and noise. Vibration in cutting process involves very complex mechanisms and is difficult to control. Vibration during turning can be classified into two categories: forced vibration and self-excited vibration. One kind of forced vibration may be caused by excitation forces outside the cutting zone, such as from a vibrating base, or from the unbalanced workpiece. Another kind of forced vibration may be initiated by the cutting process, such as the interrupted cutting. The characteristic of forced vibration is that the predominant vibration frequency component coincides with the excitation force.

Self-excited vibration in turning may take two forms. The first form is regenerative effect [Hahn, 1954]. This is due to the fact that vibration in previous revolution leaves behind an undulation of workpiece surface. This undulation causes the changes of cutting conditions, which brings about the variation of cutting force. The variation of cutting force keeps the vibration maintained or amplified, which in turn leaves behind surface undulation for cutting in the subsequent revolution, and so forth. The second form is the effect of mode coupling [Tlusty and Polacek, 1963], whereby the variation of cutting condition in one direction may induce cutting force change as well as vibration in the perpendicular direction.

Generally speaking, turning is a three-dimensional cutting process, i.e. the cutting edge involved in cutting is not a straight edge, instead, the tool nose radius takes a substantial part of cutting load. This is particularly true in finish turning, where both feed and depth of cut are small. There are two problems with the current three dimensional cutting process models. These problems are

(a) The assumption that cutting force coefficient is a constant, which results in two shortcomings:

(1) The number of cutting tests required to calibrate a model is enormous, due to the combinations of cutting conditions.

(2) The omission of cutting force variation caused by the variation of cutting force coefficient.

(b) Chip load is oversimplified as the product of depth of cut and feed, which neglects the effect of tool nose radius. In order to overcome the above mentioned shortcomings, the proposed model has made the following improvements:

(1) The cutting force coefficient is calculated based on the principles of cutting mechanics, which can include different cutting conditions and effect of machine-tool vibration in cutting processes. This is done with the aid of the concept of Equivalent Orthogonal Cutting process (EOC) which converts a three dimensional cutting process into its equivalent orthogonal cutting process.

(2) Chip load is accurately calculated, which accommodates the effect of tool nose radius and machine – tool vibration.

(3) Workpiece microstructure hardness is taken into consideration. The effect of microstructure hardness variation in the light cutting conditions can be severe.

Another major concern of the thesis is the generation mechanisms of surface finish. It is known that there are four effects that can contribute to surface finish [Shaw, 1984]. The first one is the feed mark of tool tip, which reproduces tool tip on the machined surface as a series of arcs equally spaced with the center points all in the same level. The second is the effect of minimum undeformed chip thickness, which causes a small portion of workpiece material left behind, which should be removed by cutting. The third is the effect of vibration. The fourth is the effect of side flow, which is basically a workpiece material property. The effect of side flow tends to make surface roughness larger. All the effects listed above are considered in this thesis, except the effect of side flow. This is due to the fact that the effect of side flow is small compared to other effects under normal cutting conditions.

The main objectives of the research include:

(1) The development of new comprehensive computer simulation model, that is capable of simulating cutting force, vibration, and surface finish with a higher accuracy and less cutting tests calibration.

(2) Through computer simulation, study of the surface finish generation process under different cutting conditions and tool geometry.

(3) Investigation of the relationship of cutting force and surface finish with cutting conditions and tool geometry.

The thesis is organized into six chapters. Chapter 2 reviews the models of metal cutting processes and discusses the mechanisms of machined surface finish. Chapter 3 describes the proposed simulation model in detail. Chapter 4 presents the simulation results, and experimental verification. Chapter 5 presents a discussion for the results. Chapter 6 summarizes the proposed model and the simulation results, and discusses future work.

CHAPTER 2

LITERATURE REVIEW

For years, researchers in the area of metal cutting have attempted to develop models of cutting processes that describe the mechanisms involved and predict the important behaviors in the process without requiring a large amount of cutting tests. Various models have been developed for this purpose. In this chapter, previous publications relating to the theoretical models are reviewed. The reviewed topics are organized as follows:

(1) Static cutting force models

(2) Dynamic cutting process models

(3) Surface finish mechanisms

(4) Computer simulation of surface generation.

2.1 STATIC CUTTING FORCE MODELS:

Static cutting force models deal with situations where machine–tool vibration can be omitted. They can be divided into three groups: three dimensional cutting force models, oblique cutting force models, and orthogonal cutting force models. Three-dimensional cutting process is the general form of cutting process, where the cutting edge is a curved edge with cutting velocity inclined to it. Oblique cutting is the case when cutting edge is a straight line with cutting velocity inclined to it. Orthogonal cutting is the case when cutting edge is a straight line with cutting velocity perpendicular to it [Shaw, 1984]. In this section, orthogonal cutting and three dimensional cutting force models will be discussed.

2.1.1 Orthogonal Cutting Force Models

Orthogonal cutting process modeling forms the foundation of all metal cutting modeling. Although it has taken an inordinate amount of research effort, models that can accurately predict cutting behaviors, like cutting force, temperature, vibration, etc, have not yet been developed. Below some representative works will be briefly reviewed.

2.1.1.1 Merchant's Model

An early and still the most frequently used work in orthogonal cutting force modeling is that of Merchant [1945]. In this model, the relationships among