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Analytical Modeling and Simulation of Metal Cutting Forces for Engineering Alloys

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ABSTRACT

In the current research, an analytical chip formation model and the methodology to determine material flow data have been developed. The efforts have been made to address work hardening and thermal softening effects and allow the material to flow continuously through an opened-up deformation zone. Oxley's analysis of machining is extended to the application of various engineering materials. The basic model is extended to the simulation of end milling process and validated by comparing the predictions with experimental data for AISI1045 steel and three other materials (AL-6061, AL7075 and Ti-6Al-4V) from open literatures.

INTRODUCTION

Background

Machining operations are widely employed in different industries to produce a variety of products. Chip formation is a fundamental feature of all traditional machining processes, such as turning, milling, drilling, broaching, etc. Excessive cutting forces are generated during the chip formation process. Cutting forces determine the machine tool power requirements and bearing loads, and cause deflections of the workpiece, cutting tool, fixture, and even the machine tool structure. As a result, an understanding of what is happening during the metal removal process is necessary for the study of machining mechanics as well as for the tool design and the machine tool building.

Research objectives

The objectives of this work are to perform a fundamental study towards the better understanding the chip formation process and develop a predictive model for the orthogonal machining process of conventional engineering alloys; based on the developed model, inverse analysis will be applied with optimization techniques to identify the material mechanical properties by minimizing a particular norm of the difference between the calculated and experimental machining data, in an attempt to reach the extreme conditions (large strain, large strain rate and high temperature) encountered in metal chip formation process.

LITERATURE REVIEW

Intensive efforts have been made by many researchers towards the development of the predictive machining models. In this chapter, the geometric definition of orthogonal and oblique cutting will firstly be introduced and the classic works of the orthogonal machining theory will be introduced.

Orthogonal and oblique cutting process

Metal cutting is the process of removing a layer of metal in the form of chips from a blank to give the desired shapes and dimensions with specified quality of surface finish. In metal cutting, as shown in Figure 2-1, the chip is formed by a shear process mainly confined to a narrow plastic deformation zone that extends from the cutting edge to the work surface. This narrow zone is referred to as the primary shear zone since the chip is basically formed in the zone. Besides, two other deformation zones exist during metal cutting: the secondary shear zone along the chip-tool interface due to the high normal stress on the tool rake face; the tertiary shear zone along the work-tool interface due to the high pressure at the tool tip.

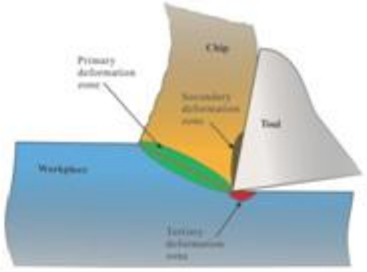


Figure 2-1 Plastic deformation zones in metal cutting

EXTENSION OF OXLEY'S MACHINING THEORY FOR VARIOUS MATERIALS

Introduction

The predictive machining theory developed by Oxley and coworkers, in which the machining characteristic factors are predicted from input data of workpiece material properties, tool geometry and cutting conditions, is an enlightening example of how to analyze the metal cutting and provides us the possibility of expressing the machining process physically and mathematically. However, there is still some challenging work to prepare for the prediction. It is essential to conduct high speed compression tests for preparing proper material property data such as flow stress versus velocity modified temperature and strain-hardening index versus velocity modified temperature. A curve fitting method is also needed to express the flow stress and strain-hardening index in the universal formulae for different kinds of cutting conditions of the experimental workpiece material. This fact makes the availability of whole class of solutions restricted to a relatively narrow range of materials. . In order to apply Oxley‟s machining theory to a wider range of materials, Johnson-Cook constitutive material model [12], in which the constants are available for most commonly machined materials, is adopted in this work to represent the material flow stress or flow behavior under cutting conditions.

END MILLING SIMULATION

Introduction

Milling operations are one of the most common machining operations in industry. Milling, as a versatile material removal process, can be used for face finishing, edge finishing, material removal, etc. Most complicated shapes can be machined with close tolerances by using milling operations.

Most of the current models for analysis of 3D milling processes are empirically based semi-analytical models with the primary aim of predicting cutting forces without getting involved in the physics of the process and root cause of different phenomena occurring in machining. These models require experimentation to find a few calibration constants that establish a close relationship between the model predictions and measured values for different cutting parameters. These techniques (mechanistic methods) are reliable, however, the coefficients that govern the force models are often restricted to a particular operation and the condition tested.

Results and verification

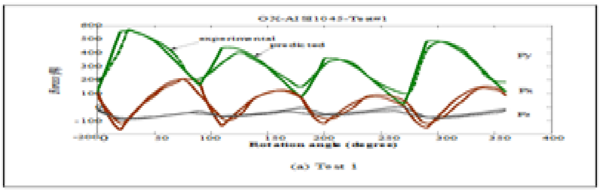
In order to verify the predictive milling force model, a set of experiments has been carried out on AISI 1045 with CNC milling machine under 4 combinations of different cutting conditions.

A HSS flat-end mill with four flutes, 12.7mm diameter, 5^o normal rake angle and 30^o helix angle was used in the experiment. A list of specific cutting conditions for the tests is shown in Table 4-1.The material used in the experiments is AISI 1045 prepared in a block shape. Six holes are drilled into the block in order to be attached to the dynamometer. The chemical composition of AISI 1045 is listed in Table 4-2.

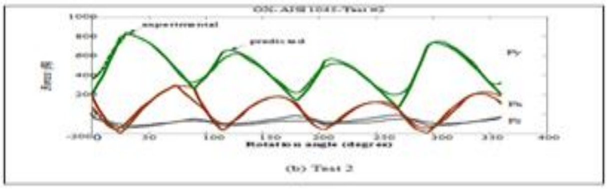
The comparisons of predicted cutting force profiles based both on the original Oxley‟s machining theory and the one modified with Johnson-Cook material model, with data from milling test on AISI 1045 are shown in Figure 4-14 and Figure 4-15. The modified model is further verified by comparing the simulated results with published data for AL-6061-T6 [34], Ti-6Al-4V [26] and AL-7075-T6 [27]. The cutting conditions are listed in Table 4-3, Table 4-4 and Table 4-5. The comparisons are shown in Figure 4-16, Figure 4-17 and Figure 4-18 respectively. F_x , F_y and F_z represent forces in the feed, normal to the feed and the axial directions. Each plot pictures the cutting force profiles for one revolution of the milling cutter.

Table 4-1 Cutting conditions for end milling of AISI1045

Material: AISI1045									
Exp.No	Feed	Feed rate	Cutting speed	Spindle speed	Axial cutting depth	Type of milling	Radial depth	Runout	Runout angle
	(mm/min)	(mm/tooth)	(m/min)	(RPM)	(mm)		(mm)	(mm)	(degree)
1	76.2	0.0381	19.95	500	3.81	down	6.35	0.007	41
2	88.9	0.0445	19.95	500	5.08	down	6.35	0.007	41
3	76.2	0.0381	23.94	600	3.81	down	6.35	0.007	41
4	88.9	0.0381	23.94	600	3.81	down	6.35	0.007	41



(a) Test 1



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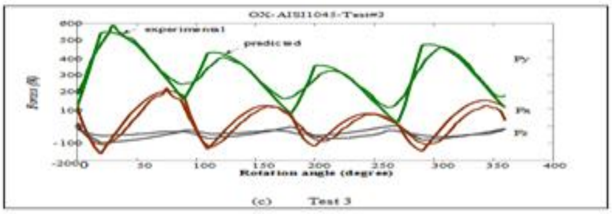

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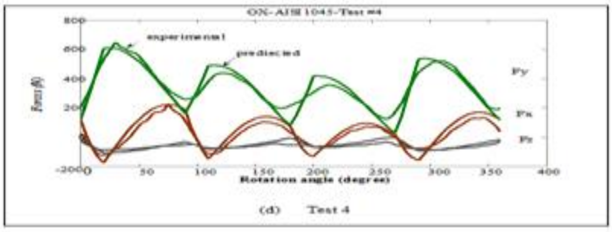
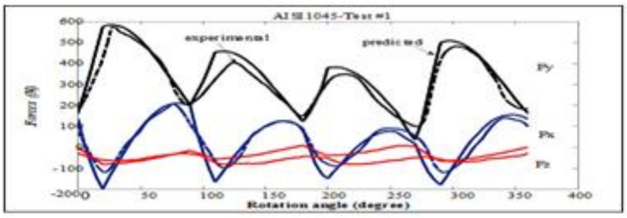
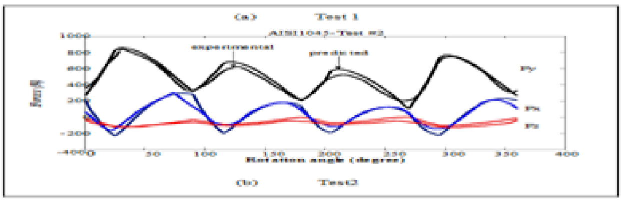


(d) Test 4

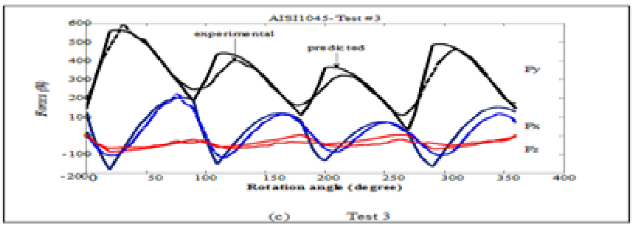
Figure 4-14 Comparison of predicted cutting forces based on Oxley’s original model with measured data for AISI 1045



(a) Test 1



(b) Test2



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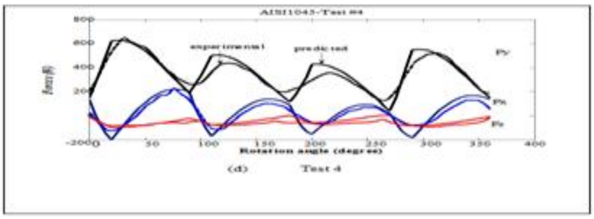


(d) Test 4

Figure 4-15 Comparison of predicted cutting forces based on modified Oxley’s model with measured data for AISI 1045

Table 4-3 Cutting conditions for end milling of Al6061-T6

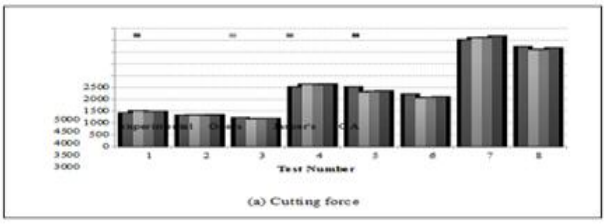
Material: AL6061-T6									
Exp.No	Rake angle	Feed rate	Cutting speed	Helix angle	Axial cutting depth	Type of milling	Radial depth	Runout	Runout angle
	(degree)	(mm/tooth)	(degree)	(RPM)	(mm)		(mm)	(mm)	(degree)
1	5	0.0381	30	500	6.350	down	6.35	0.01	221.2
2	5	0.0508	30	500	6.350	down	6.35	0.01	221.2
3	5	0.0381	30	500	3.175	down	6.35	0.01	221.2
4	5	0.0508	30	375	6.350	down	6.35	0.01	221.2

Table 4-4 Cutting conditions for end milling of Ti-6Al- 4V

Material: Ti-6A1-4V									
Exp.No	Rake angle	Feed rate	Cutting speed	Helix angle	Axial cutting depth	Type of milling	Radial depth	Runout	Runout angle
	(degree)	(mm/tooth)	(degree)	(RPM)	(mm)		(mm)	(mm)	(degree)
1	12	0.051	30	30	5.080	up	9.525	0	N/A
2	12	0.025	30	30	5.080	up	9.525	0	N/A

Table 4-5 Cutting conditions for end milling of Al-T7075

Material: T7075 Aluminum alloy									
Exp.No	Rake angle	Feed rate	Helix angle	Spindle speed	Axial cutting depth	Type of milling	Radial depth	Runout	Runout angle
	(degree)	(mm/tooth)	(degree)	(RPM)	(mm)		(mm)	(mm)	(degree)
1	5	0.052	30	1167	8.900	up	10.16	0	N/A
2	5	0.076	30	1167	8.900	up	10.16	0	N/A



(a) Cutting force

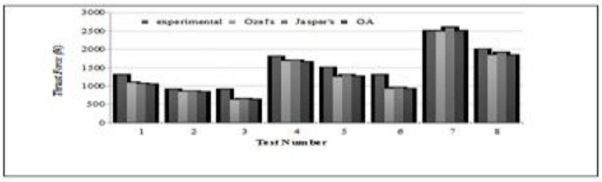
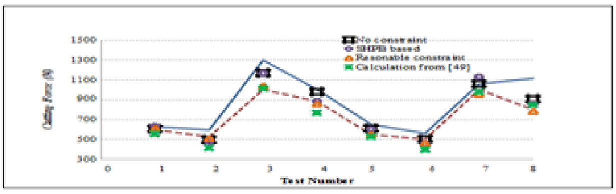


Figure 6-6 Comparison of cutting forces with data used for system Identification



(a) Cutting force

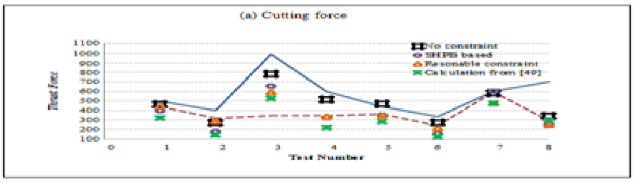


Figure 6-7 Comparison of the cutting forces using GA determined JC parameters with the experimental data from[39]

TRIBOLOGICAL ANALYSIS AT THE CHIP-TOOL INTERFACE

Chip-tool interface friction is a critical factor in determining the quality of machining operations. It is influenced by many factors such as the stresses exerting on the cutting tool rake face, mechanical and thermal properties of work piece and cutting tool, tribological conditions at the chip-tool interface etc. In turn, the frictional behavior influences the geometry of the cutting process. Early thin shear plane chip formation models [1, 3, 5] did not take any of these factors into consideration. Instead, the tribological behavior was represented by Coulomb coefficient of friction $_a$ that experimentally determined from the measured cutting forces, as shown in Equation (7.1).

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$$\frac{F_T\,F_C \quad \tan}{a \quad F_T \quad F_C \quad \tan} \qquad (7.1)$$

In Oxley's analysis, the tribology at the chip-tool interface was assumed to be fully represented by the shearing in the secondary shear zone. However, experimental observations of the chip-tool interface [6, 50] suggest that the contact condition consists of two tribological regions along the total contact length (l_c). The first region is the sticking zone near the cutting edge in which there is no relative motion between chip and tool due to the high normal pressure. The contact nature in this region is governed by the pure shear and the shear flow stress is uniformly distributed. Right after the sticking zone, the second region is the sliding zone from the end of SSZ to the boundary of the contact, in which the elastic friction dominates due to the decreased normal pressure. The normal and shear stress distributions were suggested being the pattern shown in Figure 7-1.

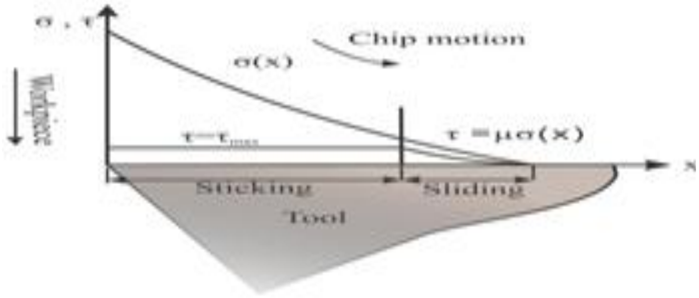

Figure 7-1 Distribution of normal and shear stress at chip-tool interface

Many researchers have carried out experimental investigations to explain the tribology at the tool-chip interface. However, most of the achievements are still qualitative. The quantitative or the analytical studies are few. In particular, the work done by Karpat and Ozel [51] and by Ozlu et al. [52] represents the state of the art in the analytical analysis of the machining tribology. However, in [51], the coefficient of friction was calculated based on the analysis in the secondary deformation zone, so that the reaction of the work-tool couples was not considered at all. In [52], a more realistic method was used to obtain the coefficient of friction for different work-tool combinations using cutting and non-cutting tests. However, the Merchant's simple shear angle equation which is derived for perfectly plastic material was used for the primary shear zone analysis. Moreover, the secondary shear zone was not analyzed. In this chapter, the stress distribution in the dual zone chip-tool interface is analyzed and incorporated in the developed chip formation model.

Conclusion

In this chapter, frictional behavior at the chip-tool interface is analyzed based on the dual friction zone hypothesis. A triangular secondary shear zone is assumed. According to Von Mise's flow rule, 0.577 is chosen as the critical coefficient of friction to define the boundary of sticking and sliding zones.. With the input of sliding coefficient of friction, a new methodology is proposed to carry out the cutting force simulation. In comparison of previous models, the new model is closer to the physics of metal cutting and able to provide more information, such as stress distributions on the tool rake face, the length of sticking and sliding zone, etc. The accurate determination of sliding friction coefficient under the conditions of metal cutting would lead to the improved model and profound analysis in the effect of cutting conditions on these processing parameters.

Future work

The velocity field in the secondary deformation zone can be further analyzed, so that the variation of the chip flow velocity on the tool rake face, shear strain and strain rate along and across the secondary shear zone can be investigated.

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