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RESEARCH ARTICLE

COMPUTATIONAL MODELING IN MECHANICAL MICROMACHINING – A REVIEW

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ABSTRACT

The current efforts in mechanical micro-machining research and applications, especially for micro- turning operations, are surveyed and presented**.** Micromachining deals with creation of precise work pieces with dimensions in the range of a few nanometers to few millimeters by removing material using cutting tools with defined geometry. The motivation for micro-mechanical cutting comes from the translation of macro-machining domain knowledge to the micro-domain. There are lots of challenges and limitations to micro-machining and simple scaling cannot be used to model micro-machining operations. This review paper starts by reviewing the theory of micro machining, introduces the advantages associated with micro machining and elaborates some of the mathematical models available in the literature for prediction / optimization of various parameters in micromachining process. The available results that relate surface generation, cutting forces, tool wear and other issues in micro- machining are reviewed. Also the developments and future requirements in the field of micro manufacturing are considered.

INTRODUCTION

The current efforts in mechanical micro-machining research and applications, especially for micro- turning operations, are surveyed**.** Areas from macro-machining that should be examined and researched for application to the improvement of micro- machining processes are presented. The broader development of micromechanical cutting will be an enabling technology that can bridge the gap between the macro- and nano/micro-domain. Since the material costs for micro-components can be relatively small compared with the macro-processes, further studies are required to explore the differences in machining various work piece materials including engineering alloys, composites, plastics and ceramics. Computational models for optimization of process parameters and predicting the responses in micromachining process are reviewed in a detailed manner. The mathematical model developed, for predicting the real position of tool tip, cutting and feed forces of micro turning process is being reviewed and analyzed. Review of analytical micro-machining cutting force model for the calculation of chip thickness by considering the trajectory of the tool tip is presented. But it is being found that the authors had not considered the negative rake angle effect, elastic-plastic work piece, or the deflection of tool. Investigated the effect of static tool deflection by assuming the tool as a simple cantilever beam. Compensated for the deflection errors in micro-tools by predicting the cutting and thrust forces. Since at micro-scales, cutting force influences tool deflection and tool deflection influences the cutting force, cutting force models should include this coupling. Had developed neural networks to predict tool wear using cutting force and wear data, the neural networks estimated tool condition in the micro-machining of aluminum and steel, with slower tool wear rates for aluminum than in steel, Schaller et al. This phenomenon is in agreement with tool wear in the soft/hard work piece cutting observed. Areas from macro-machining that should be examined and researched for application to the improvement of micro-machining processes are presented.

Process Models

Armarego and Ostafiev (2001) had developed a methodology which incorporates various machining process models developed in the last two decades. Each of these models has undergone extensive validation experiments. The cutting forces are determined using the mechanistic model in which the cutting forces are proportional to the chip area. The constants of proportionality (i.e., specific energies) are functions of the cutting speed, chip thickness, and normal rake angle, and are determined by conducting a few calibration tests for a wide range of cutting conditions for a given tool/work piece combination. An analytical solution derived by Kuster *et al.,* 2001 is used to determine the chip area. Grooved tools are used in turning operations for better hip

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breakability, reduced forces, improved surface finish and reduced tool wear. The cutting force model for grooved tooling developed by Zhu *et al.* (1999) is incorporated in the turning process model. This model considers five groove parameters, and adds two parameters to the equations of flat-tool specific energies. During machining, the tool geometry changes as a result of tool wear, which may have undesired effects, such as increased cutting force and power consumption, and poor part accuracy. The worn-tool force model developed by Smithey *et al.,* (2001) calculates the additional forces arising due to pre-specified wear-land width. When the cutting forces are determined by the force models described above, the power consumption can be calculated based on the cutting force, cutting speed and user input machine tool efficiency (Kalpakjian, 1995). The surface finish is calculated using the surface finish formula for the turning operation based on the feed rate and nose radius of the tool. The classic Taylor tool life equation is used to calculate the tool life, which is a function of the cutting speed and two empirical coefficients for each work piece/tool material combination. A process model-based planning methodology has been developed to provide a process planner with advice on the selection of machining conditions to best meet pre-stated process performance requirements for complex contour turning operations.

Young *et al.* (1987) had presented a three-dimensional cutting force for nose radius tools with a chamfered main cutting edge incorporated with a tool-worn factor. The variations in shear plane areas occurring in the tool-worn situation are used. The results obtained from the proposed model shows good agreement with the experimental data on both chip formation as well as cutting forces. In the experimental work the throwaway tips are locked onto the pocket of the tool holder. Performed by Rao *et al.* 1999 the holders for special tools are designed first. Next, the tool holders are manufactured by using medium carbon-steel bars and the mounting tips are designed based on various specifications. Finally, the nose radius tips mounting in the tool holder are ground to a wear depth, and the worn tool dimensions are measured by using a profile projector. Takayama and Murata (1963) developed. A model capable of accurately estimating the cutting force for round nose tools with a chamfered main cutting edge, Analysis of the three-dimensional cutting forces when tool wear occurs has received extensive attention recently.

Colwell *et al.* (1971) have observed that virtually all the conventional tools used in the industry have a nose radius, as it not only improves surface finish but also offers a stronger corner than does a sharp-nose tool. Therefore, the development of a sufficiently accurate model for predicting the chip flow angle and cutting forces for machining operations with nose radius tools is of great importance**.** (Abdelmoneim and Scrutton 1973) had demonstrated that an ideal shape for a cutting edge may be considered as a portion of a cylindrical surface joining the rake and clearance faces of the tool, an edge may in fact wear rapidly to form a cylindrical surface with a larger radius and an adjoining flat wears land. Therefore, success of any attempts aimed at a better understanding of the action of a slightly worn cutting edge may be expected to lead to real economic gains. Sewailem and Mobarak (1981) had reported that wearing of a cutting tool is affected by several factors, e.g., materials, cutting conditions, geometry (rake angle, cutting edge angle and nose radius) and cutting forces.

Models in stability analysis of turning operations Budak and Altintas (1990) had a discussed the problem related to surface quality and low productivity. It was mentioned that Chatter can be avoided by applying stability diagrams which are generated using stability models. The stability analysis of turning has mostly been performed using single dimensional, so-called oriented transfer function approach whereas the actual turning processes usually involve multi-dimensional dynamics. (Lazoglu *et al.,* 2002) had performed**;** a comparative analysis between one dimensional (1D) and multi-dimensional stability models for turning operations**.** (Minis et al., 1993) The multi dimensional model includes the inclination and side edge cutting angles and insert nose radius in order to demonstrate their effect on absolute stable depth of cut predictions. Chatter experiments are conducted in order to compare with both model predictions. It is demonstrated that for higher inclination angles and insert nose radii 1D models result in significant errors and multi-dimensional solutions are required. (Minis *et al.,* 1993) The regeneration mechanism which is responsible for chatter vibrations was first discovered by Tlusty and Tobias (1963) and offered one-dimensional (1D) stability model based on oriented transfer functions for orthogonal cutting operations in order to predict stability limits. This stability model has become the most commonly used model for boring and turning operations, and was applied to milling stability as well. However, it was later shown by Minis and Yanushevsky (1993) that using constant directional coefficients and 1D model yield erroneous results. Similarly, for turning processes, 1D simplified stability models may result in inaccurate predictions as some important multi-dimensional aspects of the process such as tool angles and cutting tool nose radius are neglected. The effects of several factors such as tool geometry and part/tool dynamics on the stability limit prediction accuracies of 1D and multi-dimensional turning stability models are evaluated. The use of multi-dimensional stability models in turning has been very limited. For example, (Kuster *et al.,* 1960) developed a model for the dynamic chip thickness in boring analytically using cross-coupling terms in order to reflect the effect of deformation in one direction on the other. However, the solution was obtained using an oriented approach, i.e. one dimensional model. In another study, modeled the self-excited chatter and chatter marks left on the surface in turning by a two-dimensional (2D) model using a numerical solution where the results were mostly based on experimentation**.**

Mathematical model of micro turning process

Chandiramani and Pothala (2006) had mentioned that in recant year, significant advances in turning process have been achieved greatly due to the emergent technologies for precision machining. Turning operations are common in the automotive and aerospace industries where large metal work pieces are reduced to a fraction of their original weight when creating complex thin structures. These models are based on empirical constants, orthogonal cutting data and oblique cutting relations, and have been widely applied in modeling for predicting the instantaneous milling forces. In this study an approach based on the Kienzle model is used, since this seems to be simplest and is widely applied on the shop floor. The machining force relation for a particular tool element. and using Equation (1) as follows

$$F_c = k_{c1.1} b h^{1-m_c},$$

(Ozlu *et al.,* 2006) had sharked that the analysis of forces plays an important role in characterizing the cutting process, as the tool wear and surface texture, depends on the forces. In this paper, the objective is to show how the micro turning process can be utilized to predict turning behavior such as the real feed rate and the real cutting depth, as well as the cutting and feed forces. By this observation, the dynamic problem is reduced to a 2D model. Therefore, the Dynamic chip thickness resulting from the vibrations of the tool and the work piece can be expressed as follows (2)

$$h(t) = \Delta x \cos c \pm \Delta y \sin c$$

The developed two-degrees-of-freedom model includes the effects of the process kinematics and tool edge serration. In this model, the input feed is changing because of current forces during the turning process, and the feed rate will be reduced by elastic deflection of the work tool in the opposite direction to the feed. With this model, it is possible for a machine operator, using the aforementioned turning process parameters, to obtain a cutting model at very small depths of cut. The dynamic cutting forces on the tool in the base coordinate system can be expressed by a transformation and using Equation (3) as follows:

$$\begin{Bmatrix} F_x \\ F_y \end{Bmatrix} = b[A]\begin{Bmatrix} \Delta x \\ \Delta y \end{Bmatrix}$$

Ozlu and Budak (2009) proved that the developed mathematical model predicts the real position of the tool tip and the cutting and feed forces of the micro turning process accurately enough for design and implementation of a cutting strategy for a real task during turning.

Applications of Micromachining

Micromachining is key to provide proper tooling for micro-mass production technology such as micro molding, micro forming, and micro-die casting. (Schaller *et al.,* 1994) The quality of products and reliability of these processes is highly dependant on tooling manufactured primarily by micromachining. As in conventional molding, the precision of the mold is one of the most important factors in micro molding. Mold precision represents the quality of the molded products. As a result, diamond machining is an excellent candidate for hard ferrous materials that are generally preferred for the micro-mold fabrication. Mold life is another important factor in micro molding since that influences manufacturing costs and part quality by (Brinksmeier *et al.,* 2004). The affinity of diamond to ferrous material causes serious problems in machining the tool steels or mold. Hence, various efforts have been made to avoid such problems, these approaches have been partially successful in minimizing wear of the diamond tool but, with the exception of the ultrasonic vibration assisted cutting, the applicability to industry is questionable**.**

Kuster (1990) proposed the stability model for turning operations that includes the cutting geometry and transfer functions of the work piece and the cutting tool. The model is formulated in detail which excludes the effect of the nose radius and is acceptable for rough turning operations with inserts having relatively small radii. This basic modeling is also a basis for boring stability model. The turning stability model that includes the insert nose radius effect can be found in detail in that work done by Ozlu *et al.,* 2006. In order to determine the stable cutting conditions for turning operations, a relationship between the dynamic chip thickness and dynamic turning forces must be established as a starting point. Rao *et al.* (1999). The self excited chatter vibrations have been studied by many researchers in the last half a century. The early work focused on the “micro” aspects of dynamic cutting process more, such as force coefficients, process damping etc., whereas “macro” aspects, such as effect of machine tool dynamics, vibration modes etc., were considered in later works. The modeling of chatter stability started with analysis of orthogonal cutting where a very simple process model was considered in order to understand its fundamental mechanisms (Atabey *et al.,* 1985). The approach proposed by which is still used widely, reduces the multi-dimensional dynamic system in 1D by resolving and orientating the process dynamics in one direction using a simplified orthogonal cutting model and tool geometry. Reducing a 2D or multi-D cutting system, which can only be accurately represented as an exigent value problem, into a single algebraic equation would result in inaccurate stability predictions as presented in several works. Later, the stability of other processes such as turning, where the process geometry and the system dynamics are more complex, was also investigated

Cutting force model of the oblique turning process

Luo *et al.* (2002) had mentioned that in recant year it is extremely difficult to model the whole machining system by using an exact mathematical model, since there are not only linear factors but also non-linear factors in the process. The model was implemented with MATLAB SIMULINK programming. The non-linearity is built into the model by using different kinds of functions as specified. For instance, the sinusoidal function is used to denote the spindle imbalance which imposes additional force acting on the machining system; the assumption is consistence with the error analysis on ultra-precision diamond turning machines by Altintas (2000). The cutting force applied on the tool is decomposed into three components along their perpendicular directions as illustrated. The amplitude of the sinusoidal function equals to the spindle specification provided by the machine tool manufacturer, where its frequency is that of the spindle revolution. The internally repeated ramp function denoted for the variation of the tool rake angle duo to the generation and removal of the built-up edge during the machining process, and the a series of impulse values randomly generated at regular intervals to emulate the work piece hard spots and their effects on the work material’s characteristics, i.e. the changing of shear stress during the machining process. Cheng (2002) had sharked that, those non-linear factors can be switched on or off very easily and their effects on the surface generation can thus be interactively visualized and quantitatively investigated on the basis of an individual isolated event as specified. The proposed model can be used to predict the surface generated and to optimize the cutting conditions in the light of machining instability avoidance.

Simulation and experimental validations

Davies *et al.* (1996) the whole machining dynamics model is implemented in a MATLAB simulink environment. It includes the cutting force module and machining system response module. In the turning process, the frequency of the ramp function for simulating the effects of BUE is about 5.25 Hz. It is assume that the increasing of the shear stress is ten percent of the initial shear stress due to the existence of hard spots in the work piece materials. A delay function s used to represent the regenerative vibration effects on the variation of the depth of cut and the feed rate, its frequency is that f the spindle revolution. Machining trials are carried out on a lathe to validate the model and simulation. The simulated machined surface and the measured surfaces are shown in Fig. 1 the direction of the lay is evident in both the simulated surface and the experimentally generated.

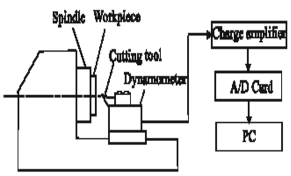

Fig. 1. Experimental configuration of the cutting trials

The dynamic cutting forces are measured by a Kistler dynamometer, 9257BA, on which the carbide tool insert is mounted. Burns *et al.* (1997) the machined surfaces are measured by the Zygotic New view 5000 optical microscope. The aluminum alloy and steel sample components are turned in the experiments. Evans (1991) the tendency that the radial cutting forces increases with the increment of the feed rate. When the feed rate 0.0397 mm/rev is applied, the simulated machined surface and the measured surfaces. The direction of the lay is evident in both the simulated surface and the experimentally generated.

Two-body and three-body abrasive wear models

Kramer and Suh (1980) had developed a model-based approach that brings out the physics behind tool wear allows the developed equation to be extended to different types of work materials, such as advanced alloys and composites, and many advanced coated-inserts, such as those with multi-layer and tertiary coatings. The use of such an approach can potentially reduce a large number of experimental investigations and associated costs. In this paper, we will propose a model-based approach to understanding the wear of coated tools, using experimental results that have partially motivated the approach and are used to illustrate its consistency by Brun *et al.* (1985) had developed a To implement this approach, the responsible mechanisms that dominate the wear process must be first identified. In addition, the quantitative models of each wear mechanism which describes the functionality of the various parameters must be obtained. A model-based approach to describe crater wear of coated carbide inserts quantitatively was first introduced by Kramer and Kwon (1895) Had mentioned that in recant year as the interfacial temperature increases, the dominating mechanism for crater wear has been identified to be an equilibrium process of dissolution. The smooth wear surface of the crater is a characteristic of such a mechanism. Abrasion by hard inclusions can also play a significant role at lower interfacial temperature. Consequently, the comprehensive model for crater wear is comprised of both dissolution and abrasion mechanisms. Crater wear is much more complicated and the debate between dissolution and diffusion mechanisms still continues. Kramer and Suh (1980) argued that diffusion mechanism does not describe the observed wear rate qualitatively. In addition dissolution is an interfacial phenomenon whereas diffusion is a volumetric or bulk phenomenon. Thus it is plausible to quantify tool wear based on dissolution. Both abrasive and dissolution mechanisms contribute to crater wear. Dissolution dominates at high cutting speeds while abrasion dominates at low cutting speeds. A previous dissolution model assumes that the tool material dissolves into the matrix of ferrite. Based on the experimental evidence of the phase transformation affecting flank wear, crater wear has been reformulated with the assumption of the tool dissolving into the austenite phase.

3D finite element analysis of tool wears in machining

Sewailem and Mobarak (1981) Had developed a Tool wear is of great significance in manufacturing because it affects the quality of the components, tool life and machining costs. For this reason a relevant number of papers on tool wear can be recognized in literature. While only few regard the simulation of tool wear Moreover, until now the attention was mainly focused on 2D simulation in orthogonal cutting conditions, since 3D models are very time consuming and are not reliable in terms of prediction accuracy. Nowadays, the increase of hardware and software efficiency makes 3D models effective to simulate actual machining processes. In particular, remising algorithms permit to manage complex geometries with a suitable accuracy despite of the still high calculation time**.** The present paper was developed according to the described strategy. In fact, the study aims to scale-up the knowledge acquired with 2D models to 3D ones in order to obtain results which are closer to the industrial needs. In particular, a simple turning process of an AISI 1045 specimen using an uncoated WC tool was investigated. Flank and crater wear evolution was predicted utilizing a diffusion wear model implemented into an Arbitrarian Lagrangian Eulerian (ALE) numerical formulation. Brun *et al.* (1985) had mentioned that in recant year the model was firstly calibrated through 2D simulations and orthogonal experimental tests; then a 3D analysis, provided with a new 3D updating procedure for the dynamic prediction of the tool wear was carried out. Finally, a series of three-dimensional experimental tests was carried out in order to validate the simulation strategy. 2. The proposed tool wear model According to the technical literature, several wear mechanisms can be denned, namely abrasion (related to thermo-mechanical action), adhesion (related to micro-welding and Built-Up Edge formation and removal), diffusion (chemical alteration due to atomic migration at high temperature), and fatigue.

Conclusions

In this paper, a novel modelling approach and the simulation system are presented with the case studies on turning and milling processes. The preliminary research findings include:

1. The modelling and simulation approach proposed is based on combining a numerical computing method, cutting mechanics, block diagrams and non-linear functions to simulate the complexity of the machining system as a whole. It therefore avoids the lengthy algebraic manipulations in deriving the outcome and thus improves the simulation accuracy and comprehensiveness.
2. A set of models are developed, which represents the dynamic characteristics of the machining system and also includes major non-linear factors within the machining process.
3. The modelling and simulation developed can be used to predict the onset of the machining instability, but also to observe the post-instability motion in the time domain.
4. The approach contributes to the comprehensive understanding of the machining system. The models and simulation will assist the machining operators to select optimal machining parameters.
5. The modelling and simulation will potentially lay down a foundation for researching on-line monitoring and control of the machining instability and its control algorithms.

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