Finite Element Method Applied on Metal Cutting: from Chip Formation to Coating Delamination by Tribo-Energetic Approach

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Abstract
Research on finite element methods applied on metal cutting is reviewed. From manufacturing point of view, the implementation of finite element methods for modeling and simulating the process of metal cutting can potentially reduce the number of iterations and result in a substantial cost savings. A general view of machining process evolution from simple analytic models to sophisticated finite element models is depicted. The gist of current research as well as its strategy and the special feature in modeling the metal cutting process are outlined and the future research needs is discussed. In conclusion, the use of finite element methods on metal cutting is limited to modeling the orthogonal cutting, chip formation, distribution of stress, strain, strain-rate, temperature and residual stress with majority assumption that cutting tool is a rigid body.

Keywords: simple analytic models, sophisticated finite element models, orthogonal cutting, chip formation, cutting tool is a rigid body.

Introduction
The process of metal cutting is a series of stages in manufacturing to shape the new work surface by removing the excess stock of material, termed as chip. Although as the excess stock and to be removed; however, knowledge of the process of chip formation is required for understanding the condition of the new work surface [1]. Shortly, chip is the main agent in metal cutting process and its formation mechanism is the essential part that to be considered in studying the mechanics of machining process.

The mechanism of metal cutting process had been studied since the early of 1940s and several models with various degrees of complexity were proposed. Ernst and Merchant [2] and Merchant [3,4] develop a model that well known as orthogonal cutting and termed as a straight-edged cutting tool moving relative to the workpiece in a direction perpendicular to its cutting edge. They develop the model that relating the so-called shear-plane angle (φ) to the tool rake angle (α) and the coefficient of friction between the chip and the tool (μ), shown in Fig.1. Afterwards, Lee and Schaffer [5] develop a model by introducing plasticity of the workpiece material into the solution. A slip-line theory was used and the material assumed to be rigid-perfectly plastic but thermal and inertial effects were ignored.
To account the variation in the flow stress during machining, Palmer and Oxley [6] extend the ideal theory of plasticity by including the effect of work hardening.

Useful contributions in mechanism of metal cutting process have been provided by the former investigations. However, those models are developed based on the over-simplified assumption and some noteworthy features in metal cutting process, such as the frictional interactions at the tool-chip interface, strain hardening, strain rate sensitivity, and thermal are not yet considered. Recently, with the development of numerical analysis that is the finite element methods and the aid of the computer to provide reliable predictions, the models of metal cutting process have evolved from the simple analytic models to the sophisticated finite element models. The evolution, from manufacturing point of view, has a good impact in production since it can potentially reduce the number of iterations and result in a substantial cost savings.

The purpose of this effort is to review the models of metal cutting process, mainly with the aim of reviewing the model that is developed by utilizing the finite element methods. The current researches as well as the finite element model on metal cutting process are outlined and the future research needs is discussed.

**Current Research**

It was recorded that the finite element methods had been applied to modeling the machining process since 1970s [7]. In the paper of Okushima and Kakino [7], they make a theoretical analysis on the residual stress in metal cutting based on the mechanical effect of the ploughing force, which exists at the tool edge and the thermal effect of the temperature distribution produced in metal cutting process. They also compare the result of finite element computation with the result of measurement using X-ray diffraction technique and those show a good agreement.

From the recent review on machining process modeling authored by Ehmann et al. [8], generally, the gist of current research in modeling the mechanism of machining process are emphasized on chip formation investigation, distribution of stress, strain, strain-rate, temperature, and residual stress with majority assumption that cutting tool is a rigid body.

Chip formation, as the main agent in machining process, is in the first rank of the phenomena that to be considered. Based on its geometry, chip can be classified as continuous, discontinuous, built-up edge (BUE) and serrated (segmented or non-homogenous) types [1, 9, 10]. The chip formation of continuous chip type has been modeled by many authors but the other types, such as discontinuous [11-
In metal cutting, a plastically deformed layer is generated on and beneath the machined surface of the work material. Permanent deformations and residual stresses remain in this subsurface layer after machining. The residual stresses have a significant influence on the mechanical behaviours of the cut components. By these reasons, residual stresses become the important thing to be considered besides the investigations of stress, strain and strain rate distributions in the process of metal cutting. As mention previously, Okushima and Kakino [7] were the pioneers in studying this phenomenon by using the finite element methods. Afterwards, in the 1985, Strenkowski and Carroll [17] were studying this subject, followed extensively by Shih et al. [18], Yang et al. [19], Shih [20], and Obikawa et al. [13]. In the extensive study performed by Shih and his associates [18-20], they compared the result that computed by the finite element methods with the result of experiment measured by the X-ray diffraction. The results of comparison between models and experiment show that the distribution of residual stresses shows a good agreement in trend and a certain level of agreement in magnitudes.

In 1983, Stevenson et al. [21] conducted pioneering work in the thermal finite element analysis of metal cutting and followed by the other authors [11, 12, 16, 18-20, 22, 23]. Stevenson et al. [21] compare the direct metallurgical result with the finite element model for the identical tool and workpiece materials and close to the identical cutting condition in calculating temperature distribution in the chip and tool. In fact, the effect of thermal in metal cutting has been taken into consideration by almost of the authors who developing the model of metal cutting process except Zhang and Bagchi [24] but not all of them investigate the temperature distribution of machining in their work.

In metal cutting process, it is well known that tool material much harder than the work material to be machined. Therefore, in developing the machining process model, the tool usually is assumed as a rigid body and sharp as its ground condition. The assumption is also supported by the mechanical behaviour of materials that the deformation of the tool material in elastic range is much smaller than the deformation in the work material and chip.

To achieve a new invention and to enrich the model of metal cutting process, some authors develop the models with the cutting tool in worn condition. In 1991, Komvopoulos and Erpenbeck [14] claimed that they were the pioneers in studying and developing the effect of the wear cutting tool and built-up edge formation on the model of metal cutting process. In their research, however, the cutting tool was still modeled as a perfectly rigid body. The built-up edge on the tip of cutting tool was assumed as a stationery deposit of a highly work-hardening material and, for simplicity, it was considered as an integral part of the tool. They were also modeling the crater wear on the rake face and it was accomplished by modifying the geometry of the tool according to optical measurement of the crater's dimensions obtained from worn ceramic tools with a zero rake angle. At a later time, Yang and his associates [19] were also modeled the worn tool in their research. In addition, Strenkowski and Athavale [23] develop their model, which can be used to modeling the effect of groove as a chip breaker. They equip their model to simulate metal cutting process by using flat, obstruction and groove cutting tools.

Finite Element Model on Metal Cutting

In the attempt to accomplish the objective of research in developing the model of metal cutting process, some strategies have been established by the researchers. Moreover, in order to enhance the strategy in obtaining the accuracy of the results and to improve the model in achieving the most acceptable condition, some special features have been formulated and implemented. In this section, the strategies of the authors in developing their researches based on the formulation of finite element methods and material behaviors are reviewed as well as the special features in the chip formation process, the strategy to overcome mesh distortion problem, and the model of the chip-tool interaction.
There are two types of finite element formulations that have been utilized by researchers to model the metal cutting process: namely, Lagrangian and Eulerian formulations. The updated Lagrangian, which develops based on the Lagrangian formulation, is more widely used in modeling of metal cutting. This formulation requires a parting line mechanism and material failure criterion to allow the chip to separate from the workpiece. In a Lagrangian formulation, the finite element mesh is attached to the work material, whereas in an Eulerian formulation, the work material is assumed to flow through a meshed control volume. The Lagrangian formulation is well suited to simulate the entry and exit phases of chip formation as well as intermittent and discontinuous chip formation but those cannot be realized by Eulerian formulation. However, Eulerian formulation eliminates the need for a chip parting criteria or node splitting, avoids mesh distortion, and less expensive in computation by which those occur as the disadvantages of Lagrangian formulation. Lagrangian formulation was used by most of the researchers, except Strenkowski and Moon [22] and Strenkowski and Athavale [23] that prefer to use the Eulerian formulation.

Various chip separation criteria that formulated by parting line mechanism or material failure criterion have been proposed for the finite element methods simulation of metal cutting. In general, these criteria can be divided into two categories: geometrical and physical. Table 1 lists some chip separation criteria, which have been developed in modeling the metal cutting process.

**TABLE 1:** Chip separation criteria

<table>
<thead>
<tr>
<th>Type of Chip Separation Criteria</th>
<th>Researcher(s)</th>
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<tbody>
<tr>
<td>Geometrical</td>
<td>Obikawa et al. [13], Komvopoulos and Erpenbeck [14], Obikawa and Usui [16], Shih et al. [18], Yang et al. [19], Shih [20], Zhang and Bagchi [24]</td>
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<tr>
<td>Distance</td>
<td>Obikawa and Usui [16], Shih et al. [18], Yang et al. [19], Shih [20], Zhang and Bagchi [24]</td>
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<tr>
<td>Stress</td>
<td>Iwata et al. [25]</td>
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<tr>
<td>Effctive Plastic Strain</td>
<td>Strenkowski and Caroll [17]</td>
</tr>
<tr>
<td></td>
<td>Strenkowski and Moon [22]</td>
</tr>
<tr>
<td>Crack Propagation</td>
<td>Marusich and Ortiz [11,12], Obikawa et al. [13], Obikawa and Usui [16], Lei et al. [26]</td>
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</table>
Instead of using the parting line where the line unzipped when the tool tip is sufficiently close, or when a certain level of plastic strain is attained, Marusich and Ortiz [11,12] and Lei et al. [26] are establishing a new strategy in chip formation process that is fracture model. This model allows the arbitrary crack initiation and propagation in the regime of shear localized chips. The model correctly exhibits the observed transition from continuous to segmented chips with increasing the cutting speed. In the similar objective in modeling the segmented or discontinuous chip, Obikawa et al. [13] and Obikawa and Usui [16] are developed node separation technique. There are two kinds of node separations have been considered to produce discontinuous chips in this technique. One is a node separation at the tool tip because of tool advance and the other is due to crack nucleation and growth during the segmentation of discontinuous chips.

Besides assuming the cutting tool as a perfectly rigid body, the behaviours of workpiece material have been modeled by the researchers as an elastic-plastic model [13, 14, 16-19], a viscoplastic model [22, 23], an elastic-viscoplastic model [19, 20], and a rigid-plastic model [25, 27]. Komvopoulos and Erpenbeck [14] were adding the isotropic strain hardening and strain sensitivity to their model and Marusich and Ortiz [11, 12] were using a standard formulation of finite deformation plasticity based on multiplicative kinematics, while the true stress-strain curves for 0-3 strain range was chosen by Zhang and Bagchi [24]. In the recent study of modeling the orthogonal machining process, Lei et al. [26] treat the workpiece material as elastic-viscoplastic with isotropic strain hardening, and the numerical solution accounts for coupling between plastic deformation and the temperature field, including treatment of temperature-dependent material properties.

Temperature effect has also been considered in some of the models with the development of the thermo-mechanically coupled algorithm [17-20, 26], such as adopting a staggered procedure where temperature during mechanical step and heat generation during thermal step are assumed constant [11, 12].

The attempts to overcome mesh distortion problems in machining process model have been solved, such as by the implementation of mesh rezone technique [18-20, 26], which was developed to model the steady-state chip formation and to control the total number of elements within a computationally acceptable level. Another effort in this subject is the
continuous remeshing, which has been established by Marusich and Ortiz [11, 12].

Based on the experimental observations, the frictional behaviour along the tool-chip interface leads to the development of sticking and sliding regions [1]. This result has been implemented by some authors [13, 16, 18, 20, 24] in developing the model of metal cutting process with some modifications, such as in the length of sticking and sliding regions, and the selection of friction coefficient whether constant or various.

Future Needs

Many aspects in modeling metal cutting process have been touched. For example, tool has been modeled as a perfectly rigid body whether sharp as its ground condition or worn on its flank face and or rake face. However, it looks like the investigations just in one way direction that is down stream to the central issue in metal cutting process that is chip formation. In contrast, research to the opposite direction, up stream to modeling the tool condition by utilizing the finite element methods, e.g. prediction of tool life during machining process, is still untouched.

Most of the authors use the parting line technique in separating chip from the machined surface. In this case, Zhang and Bagchi [24] are noted as the developer of the latest parting line technique. Unlike that technique, Marusich and Ortiz [11,12], Obikawa et al. [13], Obikawa and Usui [16], and Lei et al. [26] develop the other techniques based on the fracture criterion in both separating chip from the machined surface and the modeling of the segmentation of discontinuous chip. This technique is still a new invention and since 1995, only few researchers [11-13,16,26] utilizing it in modeling the metal cutting process. Due to these facts, only two main techniques have been developed since the first implementation of the finite element methods on metal cutting in 1970. Thus, new techniques are needed to overcome the leak of both techniques and to achieve the higher acceptable level of simulation results.

From the workpiece material to be cut point of view, Obikawa and Usui [16] develop the model of difficult-to-machine material process that is titanium alloy (Ti-6Al-4V). This work is much different to the other works that usually devote to modeling of machining steel. This work is promising since the machining of titanium alloy is still a problem [28]. By developing the model of cutting this material, the production cost as well as the wide phenomena in titanium machining can be solved. Moreover, this technique can be extended to modeling the other difficult-to-machine materials, such as nickel-based alloy, stainless steel, and graphite.

To be more in modeling of machining titanium alloy, the recent publications of Ginting and Nouari [29], Nouari and Ginting [30], Calamaz et al. [31,32] and Nouari et al. [33] show some new results on the implementation of finite element model on metal cutting. In their paper, they show not only the serrated chip formation of titanium alloys Ti-6242S and Ti-64 but also some calculations regarding to strain rate (high strain rate as a unique case in metal cutting), cutting force and tribology parameters such as cutting pressure, friction, and cutting temperature. Besides, they also utilize the finite element method to compare behavior of uncoated and multilayer coated carbide tools when used in dry cutting both titanium alloys mentioned in above. Note here that they are also taking the latest issue in metal cutting that is dry machining. Among many figures published by Ginting and his research partners, two figures are presented in this paper. The serrated chip formation is presented in Fig. 3, while the result of cutting temperature calculation is in Fig. 4.
FIGURE 3: The simulation of serrated chip formation for titanium alloy Ti-6242S produced under dry end milling using coated carbide tool [29]

FIGURE 4: Temperature distribution on tool’s rake face [36]
Research on machining titanium alloy, especially utilizing finite element method to support the research, which is done by Ginting and partners [29-33] in LAMEFIP ENSAM Bordeaux, France is developed into the study on coating delamination. In this study, finite element is utilized in order to simulate the tribo-energetic properties of coated carbide cutting tool when used in dry cutting titanium alloy Ti-64. Shown in Fig. 5 is the result of finite element calculation on conductivity value at the tool nose where coating delamination takes place. Note that in this research, study is no longer focused on chip formation (mostly done by previous researchers) but upstream to the condition of cutting tool (tool wear either on rake and flank faces). The tribo-energetic is a novel method to describe tool wear phenomena in metal cutting. This method is still improved more and more by research collaboration among Ginting in University of Sumatera Utara, Nouari in ENSAM Bordeaux, El-Mansori in ENSAM Chalons-en-Champagne and Hisham in University of Wisconsin (34-35).

Continuous chip is a significant problem in high-speed automated machinery and in untended machining cells operations using computer numerically controlled machines. This type of chip tends to become entangled and interfere with cutting operations and can become a safety hazard. For this purpose, the cutting tool industry has developed a large variety of cutting insert geometry as well as chip breakers in order to control the chip formation in such a fashion that they can break easily. In this field of study, the attempts have been made to model the groove type chip breaker tools using numerical methods [23,37]; however, the investigation is still limited and further consideration on it is needed.

FIGURE 5: The continuous chip formation (after Marusich and Ortiz [12]).
Finally, the high speed machining should be taken into account. From those papers reviewed, only one paper that is authored by Marusich and Ortiz [12] covers this subject. They develop a model based on the finite element methods to simulate the machining of AISI 4340 steel at velocity of 30 m/s and feed rate of 250μm/rev, with a cutting tool material of tungsten carbide (Fig.3). The fundamental research issues, such as chip formation, cutting temperature, and so on that related to mechanics of machining at high cutting speeds create tremendous challenges to researchers in modeling the metal cutting process.

Conclusion

The following conclusions could be arranged with regard to the review of researches on finite element methods applied on metal cutting.

1. Machining process models have evolved from the traditional simple analytic models to sophisticated finite element models.
2. Updated Lagrangian and Eulerian formulations are usually used in developing the model to simulate the metal cutting process.
3. The advantages of finite element methods to study machining process can be seen from the following aspects: (a) material properties can be handled as functions of strain, strain rate and temperature; (b) the interaction between chip and tool can be modeled as sticking and sliding; (c) nonlinear geometric boundaries such as the free surface of the chip can be represented and used; (d) the global variables such as cutting force, feed force, chip geometry, the local stress and temperature distributions can also be obtained.
4. The implementation of finite element method in modeling the process of metal cutting is limited to orthogonal cutting, chip formation, distribution of stress, strain, strain-rate, temperature and residual stress with majority assumption that cutting tool is a rigid body.
5. Workpiece material generally is treated as elastic-plastic, viscoplastic, elasticviscoplastic, and rigid-plastic finite element model.
6. Parting line for element separation and crack propagation approaches have been established to simulate the chip formation whether for continuous, discontinuous, built-up edge, and serrated chip types.
7. To account the effect of temperature during machining process, a certain procedure called thermo-mechanically coupled algorithm has been developed.
8. The attempts to overcome mesh distortion problems in machining process model have been done, such as by the implementation of mesh rezoning technique and continuous remeshing.
9. The frictional behaviour along the tool-chip interface leads to the development of sticking and sliding regions with some modifications, such as in the length of sticking and sliding regions, and the selection of friction coefficient whether constant or various.
10. There are five main recommendations counted for future study: (a) utilizing the finite element methods to establish the model for predicting of tool life during metal cutting process; (b) developing the other techniques of chip-workpiece separation besides parting line and crack propagation; (c) developing machining process model for difficult-to-machine materials; (d) modeling of chip breaker as well as insert with groove to overcome a safety hazard in untended machining cells operations using computer numerically controlled machines; (e) developing model of high-speed machining.

References


