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Modelling Requirements for Computer Simulation of Metal Machining

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Abstract

Machining modelling efforts are summarised and some important shortcomings of these are presented. The reasons for these shortcomings have been investigated. The investigations are based on machining simulation research and accompanying experimental studies. The reasons are found to be mainly in the approaches taken towards modelling the mesh and boundary conditions, the flow stress of the workpiece material and the frictional properties at the interface between the chip and the cutting tool. The handlings of the extremely high temperature increases and the mechanism taking place during separation of the chip from the workpiece by the tool are also among the significant reasons. The aim of this paper is to present some solutions towards modelling these aspects of machining.

Key Words: Machining, simulation, friction characteristics, flow characteristics, chip separation.

Metal Kesmenin Bilgisayarla Simülasyonunda Modelleme Şartları

Özet

Metal kesme işlemini modelleme çalışmaları özetlenmekte ve bazı önemli eksiklikleri sunulmaktadır. Bu eksikliklerin nedenleri araştırılmıştır. Araştırmalar, bir metal kesme simülasyonu çalışmasına ve bunun için yapılan deneylere dayandırılmıştır. Sonlu elemanlar ağ yapısının ve sınır şartlarının, iş parçasının mekanik özelliklerinin ve kesme takımı ve talaş arayüzeyi arasındaki sürtünmenin modellenmesi sırasında takip edilen yaklaşımların eksikliklerin ana nedenleri olduğu belirlenmiştir. Kesme sırasında ortaya çıkan aşırı yüksek sıcaklıkların ve talaşın iş parçasından ayrılmasının ele alınış biçimi diğer önemli nedenler arasında yer almaktadır. Bu makalenin amacı metal kesmenin bu yönlerinin modellenmesi ile ilgili bir takım çözümler getirmektir.

Anahtar Sözcükler: Metal kesme, simülasyon, sürtünme özellikleri, malzeme özellikleri, talaş ayrılması.

Introduction and Problem Presentation

Machining is a removal process for shaping materials to required forms. It is one of the most frequently carried out manufacturing processes. An understanding of machining provides insight into achieving a better control over the dimensions and surface characteristics of the product. A fundamental theory that could describe the phenomena that are effective during a machining operation would be more economical compared to workshop experience. Consequently, one of the main objectives of machining research has been to provide such a theory.

The achievement of this objective has depended on a solution to the following problem: Under specified cutting conditions and appropriate work and tool material properties, what are the shape and the properties of chip formation together with the associated stresses, strains, strain rates and temperatures? While working towards the solution, researchers have proposed many analytical and numerical machining models over the years. The usual approach in analytical studies has been to propose a model of chip formation from experimental observations and then to develop an approximate machining theory based on this. The best known model of this kind is the shear plane model (Ernst and Merchant, 1941). The model, as shown in Figure 1, was of the following form:

$$2\phi + \beta - \alpha = 90^\circ \tag{1}$$

where α and ϕ are the rake and shear angles, respectively, and β is the friction angle. However, the comparison of this model with experimental results proved unsuccessful. In a later attempt by Merchant (1945), the effect of compressive (or hydrostatic) stress on the shear stress of the metal cut was considered and a second model, represented in Eq. (2), was suggested.

$$2\phi + \beta - \alpha = c \tag{2}$$

Here c is a constant which takes different values for different workpiece materials. This model appeared to offer a degree of approximation to the experimental results obtained in the case of SAE 4340 steel. However, this result was only brought into agreement with theoretical relations by assuming that the value of the yield stress was some function of the hydrostatic stress on the shear plane. This is a hypothesis true for rupture, but generally regarded as inadmissible at ordinary metal working levels (Bridgeman, 1952 and Finnie, 1963).

Lee and Shaffer (1951), following the work done by Ernst and Merchant, have taken a further step and analysed the machining process by applying slip-line field analysis. The model (see Figure 2) is given as

$$\phi + \beta - \alpha = 45^\circ \tag{3}$$

On the other hand, for certain reasonable values of friction and rake angles (for example, $\alpha = 0^\circ$ and $\beta = 50^\circ$), the model in Eq. (3) produces a negative value for the shear angle ϕ, whereas ϕ is greater than zero in practice. Consequently, this solution is inapplicable.

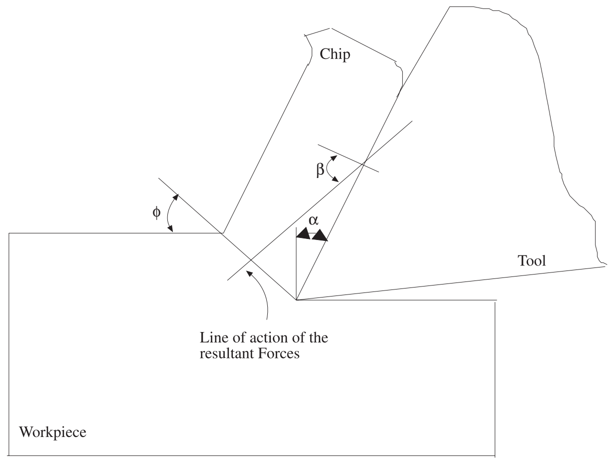

Figure 1. Two-Dimensional (2-D) Ernst and Merchant Model.

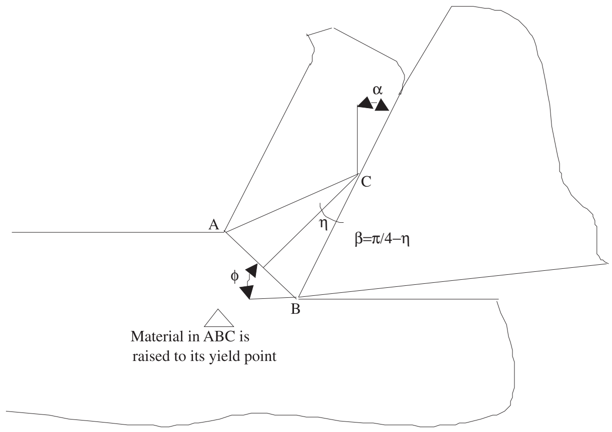

Figure 2. Lee and Shaffer solution

Among other models, those that should be considered in the course of analytical machining model developments include that of Kobayashi and Thomsen (1962), who used the limit-load theorem; that of Kudo (1965), who proposed several new slip-line field solutions; that of Childs (1980), who incorporated the elastic effects in slip line field modelling; and that of Oxley (1989), who based his theory on a shear zone model.

The limitations of the analytical theories, either in their assumptions of constant flow stress deformation with no work hardening and simple friction characteristics or afterwards by the restrictions of the analytical tools employed (such as limit load and slip-line field) have rendered them inadequate in predicting accurate chip flow. As a result, a more recent approach in the studies of metal machining has been the use of numerical tools such as the finite element (FE) method (Clough, 1960). The advantages of using the FE method in machining studies can be seen in the following aspects:

Material properties can be handled as functions of strain, strain-rate, and temperature.

Friction boundary conditions between chip and tool can be modelled more appropriately.

Nonlinear geometric boundaries such as the free surface of the chip can be represented.

In addition to the global variables such as cutting forces and chip geometry, the local stress and temperature distributions can also be obtained.

One of the first FE models of machining was by Klamecki (1973). This was an updated-Lagrangian, elastic-plastic, three-dimensional model. However, it was limited to only the initial stages of chip formation. The first two-dimensional (or orthogonal) FE machining simulation was by Shirakashi and Usui (1974,1982). They used the elastic-plastic material model and assumed the chip shape and the material stream lines. They developed a special method of computation, called the 'Iterative Convergence Method (ICM)', in order to obtain solutions for a steady state of cutting and for quickening the convergence of computations in comparison with the real transient process. The main limitation of this model is the treatment of chip separation by a small crack at the cutting edge that contradicts the plastic deformation nature of the machining process at steady-state conditions. Iwata et al. (1984) have developed a method of numerical modelling for plane strain orthogonal cutting in steady state on the basis of the rigid-plastic material model. Here, the temperature effects were neglected. Carroll and Strenkowski (1985,1988) described computer models dealing with orthogonal metal cutting using the FE method. The models were based on a specially modified version of a large deformation updated Lagrangian code called NIKE2D, which employed either elastic-plastic or visco-elastic material models and either simple Coulomb's Law or friction elements for simulating friction between the chip and the cutting tool. The NIKE2D code was modified to allow the separation of the chip from the workpiece, at a preselected node. Chip separation was allowed to occur when the effective plastic strain at a node adjacent to the cutting edge reached a critical value. The temperatures in the deforming zone were determined with this model. Childs and Maekawa (1990) reported their study on the development of an elastic-plastic and thermal FE analysis of chip flow and stresses, tool temperatures and wear in metal cutting. The computer model was based on a simplified version of a supercomputer program (Usui et al., 1981). The flank and crater wear rates of the steel-cutting carbide tool were determined by use of an empirical relation which depended on temperature and contact stress. Additionally, empirical relations provided the flow stress and friction characteristics. FE analysis gives good predictions of tool cutting forces but is in error with respect to thrust forces and temperatures under the imposed friction and wear characteristics. Lin and Lin (1992) developed a thermo elastic-plastic cutting model. The finite difference method was adapted to determine the temperature distribution within the chip and the tool. In this model, a chip separation criterion based on the strain energy density was introduced. It was stated that this criterion was a material constant and therefore independent of cutting conditions involved. The constant friction coefficient has been used to describe chip/tool interface friction. Shih and Yang (1993) have developed a finite element simulation method for metal cutting which was based on the updated-Lagrangian formulation and which included the effects of elasticity, viscoplasticity, temperature, strain-rate and large strain on the stress-strain relationship as well as the effect of frictional force on the tool-chip interface. An element separation criterion based on the distance between the tool tip and the nodal point connecting the four elements ahead of the cutting tool was assumed. A friction model which assumed a constant friction coefficient in the sticking region and a linearly decaying (to zero) friction coefficient in the sliding region were proposed. Wu et al. (1992) developed a thermo visco-plastic finite element cutting model. In this model, the chip-tool friction conditions are characterised by a temperature-dependent friction model. The temperature effect was incorporated into this model by assuming that the friction stress was directly related to the local value of the effective stress that had already been considered to vary with temperature during calculations. Zhang and Bagchi (1994) reported a new chip separation criterion based on two-dimensional, conditional link elements that are placed between the chip and the workpiece along a predefined separation path. Childs et al. (1999) confirmed through an experimental and a theoretical study that not only the experimentation but also the selection of an appropriate constitutive model affected the predicted machining parameters. A study (van Luttervelt et al., 1998) which compares several machining simulation studies from different institutions presents the current situation in the modelling of machining.

From the above studies, it can be said that finite element simulation of metal machining has not been as successful as would have been expected. However, the models presented above demonstrate the flexibility of using the finite element method in machining research. The common shortcomings of the above models can be overcome through stressing the aspects that are stated in the following sections.

Modelling Requirements for Metal Machining

Mesh, Method of Simulation, and Boundary Conditions

The design of the initial finite element mesh is critical to the accuracy, efficiency, and convergence of numerical simulations. However, there is generally no single way of modelling an actual continuum with finite elements because usually such elements are basically mathematical regions of the continuum rather than discrete physical parts. In almost all circumstances, the derived element relationships and the structural relationships assembled from them are approximate. Therefore, the accuracy of the analysis will depend on the accuracy of the individual element relationships and on the number, type and arrangement of the elements in the mesh (Rowe G.W. et al., 1991). The accuracy of a finite element analysis generally improves as the number of elements is increased. However, this number is limited by the computing time. Beyond a certain limit, the computing cost of constructing a very fine mesh rises rapidly without a corresponding gain in accuracy. In order to save time and effort, it is usual to combine large-element meshes in regions of secondary interest with finer meshes in critical regions. Besides these general principles, finite element analyses, which employ iterative procedures, such as rigid or elastic-plastic models, require the discrimination of the states the elements experience. In such cases, it is important and sometimes imperative to use finer meshes and convenient mesh patterns in order to appropriately analyse the state of the regions the elements occupy. With special reference to machining simulations, it may be said that the rather steep temperature, strain, and strain rate gradients in the deformation regions (Figure 3) cannot be expected to be handled properly by coarse meshes. The reverse may result in considerable fluctuations in predictions from successive iterations and in poor simulations at the end. An example of a workpiece and tool mesh models with their appropriate numbering and transformations is given in Figure 4.

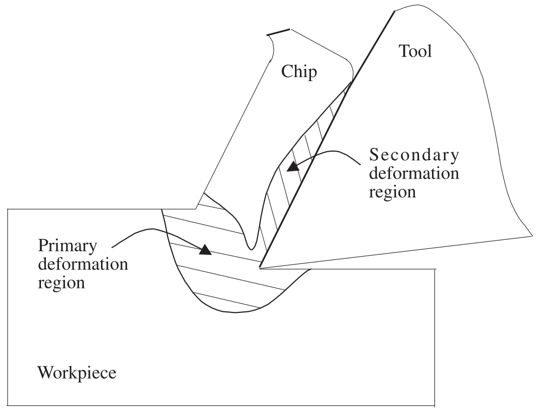

Figure 3. Deformation regions in machining (Figure 3)

As mentioned in the previous sections, simulation of machining requires an analysis, which mutually depends on high temperatures, high strain rates, and large deformations. Such an analysis requires a thermal and, due to the importance of the elastic effects (Childs 1980), an elastic-plastic analysis. The thermal analysis makes it possible to identify the changes due to temperature in parameters affecting the nature of deformation, and the temperature distribution itself along the deformation zones in machining. The elastic-plastic response is governed by the classical incremental theory of plasticity based on the Prandtl-Reuss equations. This analysis requires a yield function such as the von Mises criterion, which gives the yield condition that specifies the state of multiaxial stress corresponding to the start of plastic flow. Additionally, a hardening rule such as that to be mentioned in the next section is necessary to specify how the yield function is modified during plastic flow.

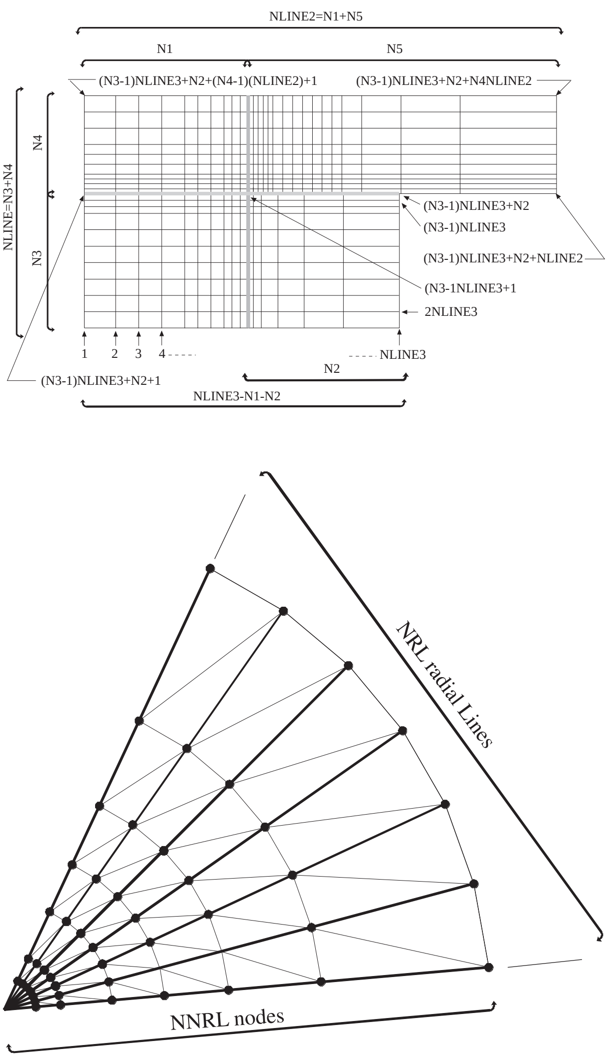

Figure 4. An example of a workpiece and tool mesh models with their appropriate numbering and transformations.

A flow rule such as the Prandtl-Reuss relation, which relates the plastic strain increments to the current stresses and stress increments, is also essential. The finite element formulations required for these analyses are detailed by Bathe (1996). The associated thermal and elastic-plastic boundary conditions in machining and a methodology for the simulation can be given as in Figures 5a and b and 6, respectively.

Material Property Requirements

One of the most important, but in many cases less considered, aspects of machining is the flow property of the workpiece material and an appropriate relation for its incorporation into the finite element method. It has been reported (Childs, 1973) that average values of strain and temperature ranging from 1 to 2 and 150 to 250°C, respectively, in the primary shear zone, and from 3 to much higher values and 800 to 1200°C, respectively, in the secondary shear zone, with a strain rate of up to $10^5\ s^{-1}$ are usually encountered in machining processes.

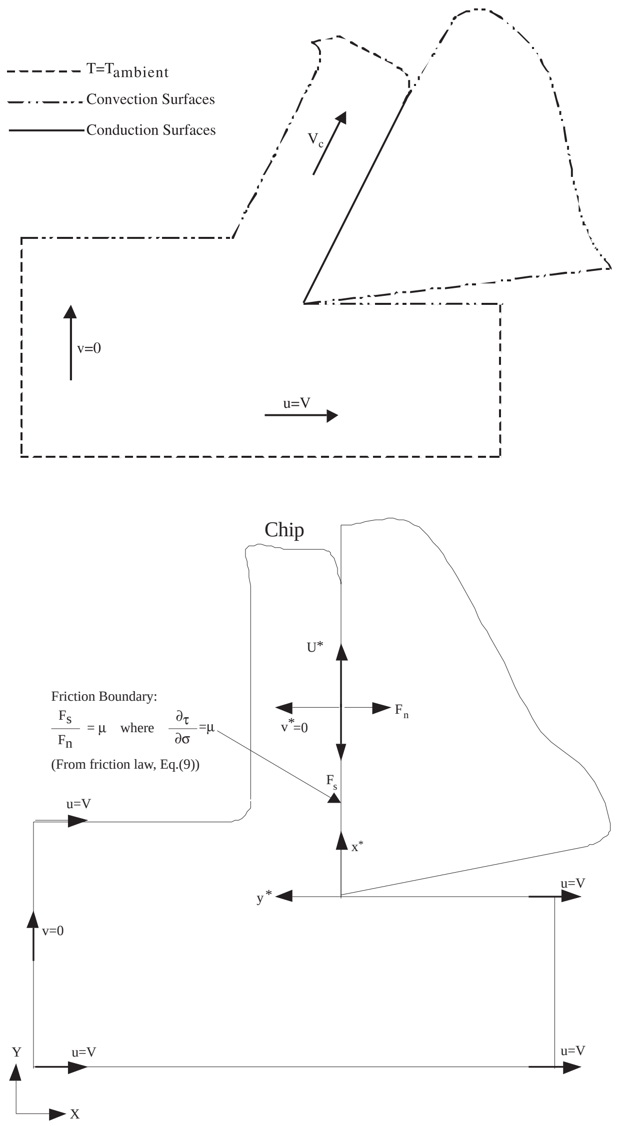

Figure 5. a, b. The thermal and elastic-plastic boundary conditions in machining.

In most of the machining researches such as those presented above, however, probably due to the unavailability of an appropriate experimental setup, simple material flow properties have been used. Despite this, a number of constitutive relations have been proposed to establish the plastic flow characteristics under these severe strain, strain-rate, and temperature conditions. Among these, the relations by Usui et al., (1981, 1982) and Oxley (1989) are worthy of mention.

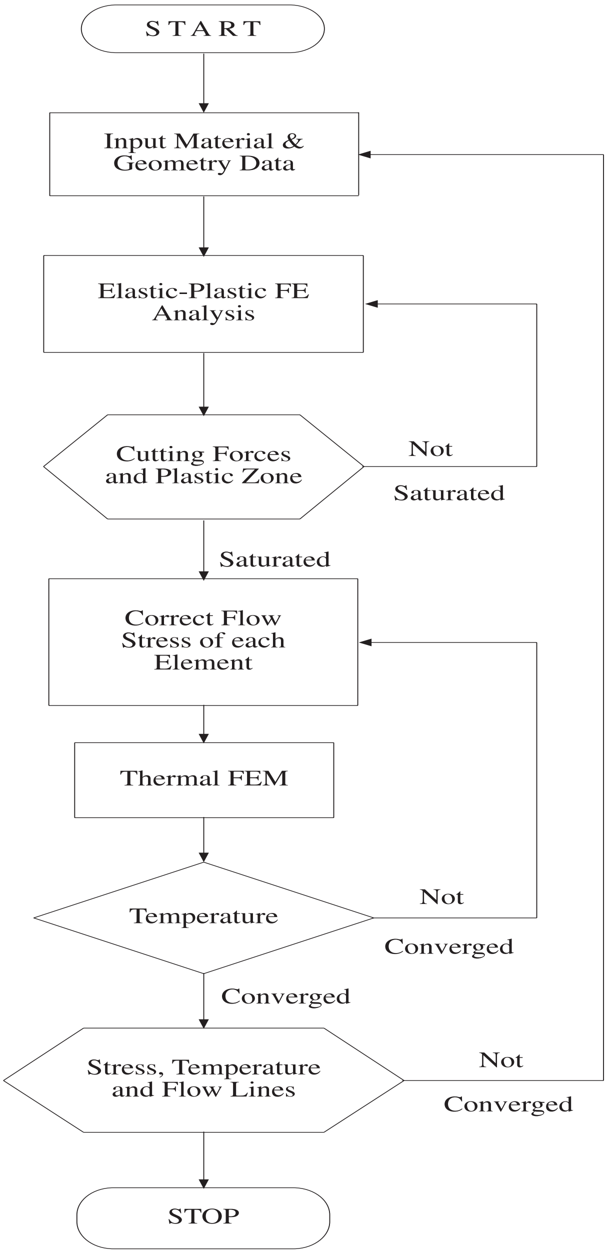

Figure 6. A methodology for computer simulation of machining

Usui and his coworkers used a split Hopkinson bar apparatus to obtain the deformation characteristics of different types of steel samples for simulating the same characteristics in machining. The samples were deformed under high-speed compression tests by the use of the apparatus, and as a result, strains of up to 2.0 and strain rates of up to 2000 s^{-1} were obtained. At the same time, an induction coil was used for rapid heating of the test samples and temperatures of up to 700°C were reached. The strain, strain-rate, and temperature values reached are considered satisfactory for light to medium cutting conditions of most commercial free cutting steels. For steels other than these or for heavier cutting conditions, which may correspond to the extreme values mentioned at the beginning of this section, simply no convenient experimental setup exists. Therefore, the method of extrapolation was used for covering the remaining range. The relation by Usui is of the following form:

$$\bar{\sigma} = B \left[\frac{\dot{\bar{\varepsilon}}}{1000}\right]^M e^{-kT} \left[\frac{\dot{\bar{\varepsilon}}}{1000}\right]^m \left\{ \int_{path} e^{kT/N} \left[\frac{\dot{\bar{\varepsilon}}}{1000}\right]^{-m/N} d\bar{\varepsilon} \right\}^N \tag{4}$$

where $\bar{\sigma}$ is the flow stress, and $\bar{\varepsilon}$ and $\dot{\bar{\varepsilon}}$ are the equivalent strain and strain rate, respectively. The coefficients B, M, and N are called the strength factor, the strain-rate sensitivity, and strain hardening index, respectively, and are functions of temperature, T. k and m are constants. The integral part accounts for the history and path effects. In the absence of these effects, as was suggested by Childs et al. (1994, 1997), Eq. (4) reduces to the following form:

$$\bar{\sigma} = B \left[\frac{\dot{\bar{\varepsilon}}}{1000}\right]^M \bar{\varepsilon}^N \tag{5}$$

Examples of flow stress relations for a low carbon leaded free cutting steel (PbLCFCS) and a medium carbon free cutting steel (SAE 1144, see compositions in Table 1), respectively, are given as follows (see also Figure 7):

From Eq. (5), (Dirikolu, 1997), for PbLCFCS steel;

$$\begin{aligned} B = {} & 960 \exp(-0.0012T) + 210 \exp \\ & \left(-0.00005(T-290)^2\right) + 100 \exp \\ & \left(-0.00005(T-590)^2\right) \\ N = {} & 0.15 \exp(-0.0012T) + 0.1 \exp \\ & \left(-0.00003(T-330)^2\right) \end{aligned}$$

$$M = 0.0000177T + 0.023 \quad k = 0.00025 \quad m = -0.0021$$

and for SAE 1144 steel;

$$B = 1300\exp(-0.0016T) + 210\exp\left(-0.00012(T-250)^2\right) + 260\exp\left(-0.00001(T-400)^2\right)$$
$$N = 0.11\exp(-0.0016T) + 0.09\exp\left(-0.000035(T-475)^2\right)$$
$$M = 0.000018T + 0.019 \quad k = 0.000094 \quad m = -0.0026$$

Table 1. Compositions of the steel specimens by percentage weight

Steel Sp.	C	Si	Mn	P	S	Cr	Ni	N	Pb	O
PbLCFCS	.08	.04	1.49	.073	.42	.02	.02	.043	.27	.014
SAE 1144	.44	.13	1.45	.013	.30	.15	.022	.008	-	-

The units of B and T are MPa and °C, respectively. The complexity of B copes with the *blue-brittleness* effect which is inherent in the machining of steels and is considered to be a result of dynamic strain ageing, a phenomenon used to denote ageing processes taking place simultaneously with plastic strains (Baird, 1963). This model has been used in machining simulations and has been found to provide excellent comparisons with measurements under light to medium cutting conditions (Childs et al. 1997b).

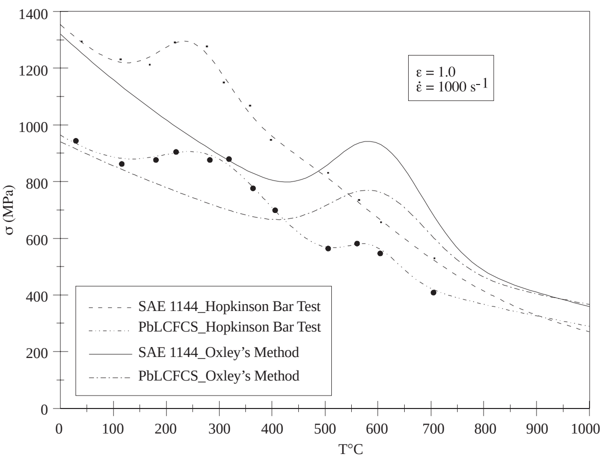

Figure 7. Flow stress results as obtained from split-Hopkison bar measurements and Oxley's method for a low carbon leaded free cutting steel (PbLCFCS) and a medium carbon free cutting steel (SAE 1144).

Oxley (1989) has suggested a Holloman type material flow property model. The flow stress properties, however, have been obtained from a combination of hot compression and machining tests. He used a velocity-modified temperature, $T_{mod}(T_{mod} = T(1 - 0.09Log(\dot{\varepsilon}))$to account for the combined effects of temperature and strain-rate. The relation is

$$\bar{\sigma} = \sigma_1 \bar{\varepsilon}^n \tag{6}$$

where $\bar{\sigma}$ is the flow stress, σ_1 and n are functions of temperature and strain-rate. Flow stress relations for the PbLCFCS and SAE 1144 steels, respectively, are given as follows and in graphic form in Figure 7 (Dirikolu, 1997):

For PbLCFCS steel

$\bar{\sigma} = 890\varepsilon^{0.25}$ MPa, from room temperature plain strain compression tests. Modification of this stress as suggested by Oxley to higher strains, strain rates, and temperatures and transformation to Eq. (5) type, yielded

$$B = 940\exp(-0.00094T) + 230\exp\left(-0.00006\,(T-600)^2\right)$$
$$N = 0.25 \; M = 0.03.$$

For SAE 1144 steel,

$\bar{\sigma} = 1233\varepsilon^{0.18}$, and modification of this resulted in,

$$B = 1320\exp(-0.0013T) + 330\exp\left(-0.00007\,(T-600)^2\right),$$
$$N = 0.18 \; M = 0.03.$$

Figure 7 shows that both methods give flow stress results that agree well with each other. The only exception is the difference in their dynamic strain ageing peaks, which was found to have a negligible effect on simulations. It is here claimed that materials and experimentation researchers should concentrate on extending the capabilities of these material models to heavier cutting conditions in order to widen this bottleneck for machining researchers.

Friction Properties

Of at least equal importance to the flow stress characterisation of the work-material is the characterisation of the friction mechanism taking place at the interface between the chip and the tool. In many of the previously presented machining analyses, this has been treated as a classical friction situation, in which frictional forces tend to restrain movement across the tool surface. The forces have been considered in terms of a constant coefficient of friction, μ, at the interface, based on the friction model by Coulomb. As a result, the relation between the friction (τ_f) and normal (σ_n) stresses has simply been stated as

$$\tau_f = \mu \sigma_n \tag{7}$$

While this rule represents good approximations under usual low load conditions for bodies in sliding contact, it may fail partially or sometimes completely under sufficiently abnormal high-load conditions as in machining operations where extremely high contact stresses are observed (Childs, 1990). Additionally, from analysis of tool forces, it has been verified that two different contact regions, namely, the sticking and sliding regions at the tool rake face, exist when machining under dry, unlubricated conditions. Given these aspects of friction in machining, more appropriate models should be employed when analysing this process. Several models have been proposed for representing the normal and frictional stress distributions on the tool rake face. Bailey (1975) gives an extensive review of these models. The best known model among these is the one presented by Zorev (1963). This model, as shown in Figure 8, states that where the contact between the chip and the tool ends, the friction and normal stresses are equal to zero and as the distance 'x' from this point increases towards the tool cutting edge, the normal stress increases exponentially. In the sliding region, the friction stress increases according to Coulomb's law as stated in Eq. (7). In the sticking region, however, the friction stress becomes equal to the shear strength, k, of the softer material (i.e., chip).

Based on Zorev's model, Usui et al. (1981, 1982) proposed the following friction model:

$$\tau_f = k\left[1 - \exp\left(-\mu\sigma_n/k\right)\right] \tag{8}$$

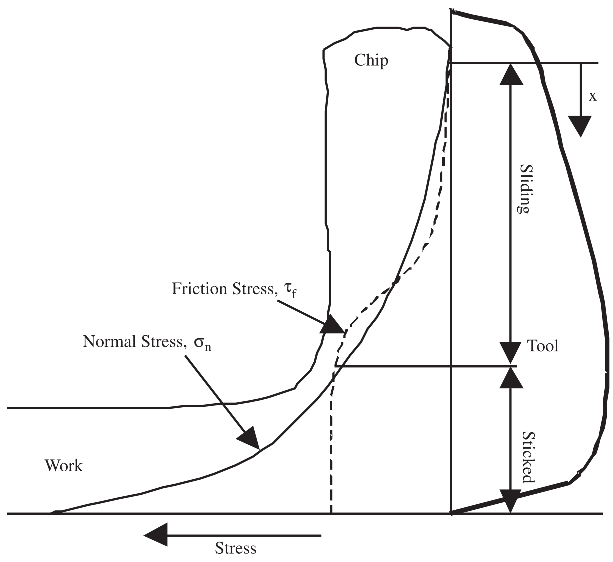

Figure 8. Zorev's model for tool rake face stress distribution.

Regarding the above relation together with Zorev's model, however, it was also shown that the mean friction stress on the tool rake face might differ substantially from the friction stress in the sticking region. Due to this, Childs (1990) proposed a friction model. The model is a modification of Eq. (8) in order to let the high friction stresses in the sticking region be other than the shear strength, k. The following empirical equation was obtained regardless of steel specimens:

$$\tau_f = mk\left[1 - \exp\left(-\left(\mu\sigma_n/mk\right)^n\right)\right]^{1/n} \tag{9}$$

where 'm' and 'n' are correction factors. m ensures that at high normal stresses, the friction stress does not exceed the shear flow stress of the material, namely that if $\sigma_n \to \infty$, then $\tau_f \to mk$, and n controls the transition from the sticking to the sliding region. Eq. (9) also satisfies the frictional conditions in the sliding region. Differentiation of this equation with respect to σ_n leads to:

$$\frac{d\tau_f}{d\sigma_n} = mk\sigma^{n-1}\left(\frac{\mu}{mk}\right)^n \exp\left(\frac{\mu\sigma_n}{mk}\right)^n \left[1 - \exp\left(\frac{\mu\sigma_n}{mk}\right)^n\right]^{(1/n^{-1})} \tag{10}$$

and later a Taylor series expansion of Eq.(10) reduces to

$$\frac{d\tau_f}{d\sigma_n} = \mu\left[1 - \left(\frac{\mu\sigma_n}{mk}\right)^n\right] \tag{11}$$

Then as $\sigma_n \to 0$, $\frac{d\tau_f}{d\sigma_n} \to \mu =$ constant, meaning that Eq. (7) holds.

The coefficients m and n above can be obtained from split-tool dynamometer tests. The test method (see Figure 9) has been explained in detail by Gordon (1967) and Kato et al. (1972), but basically it requires the use of a composite tool divided into two parts parallel to a cutting edge for measuring separately the forces acting on one section of the tool (Tool 1). The forces acting on each part during a test are measured by strain gauges on the separate supports. The measurement of the forces on the second half, namely Tool 2 in Figure 9, is required in order to ascertain that the cutting force is unchanged with the variation of the split position. Examples of split tool test results for the PbLCFCS and SAE 1144 steels mentioned in the previous section are given in Figure 10.

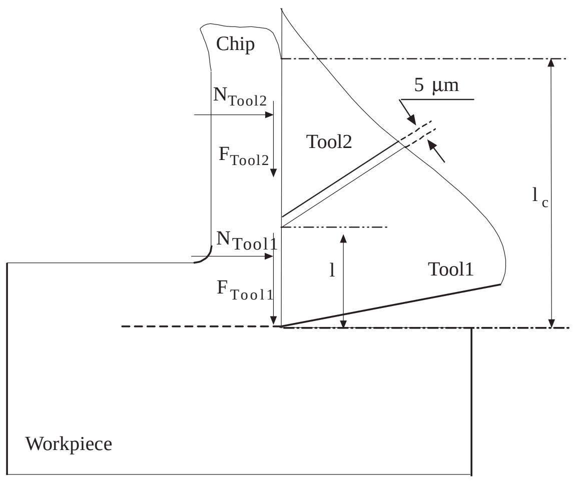

Figure 9. Principle of split-tool dynamometry.

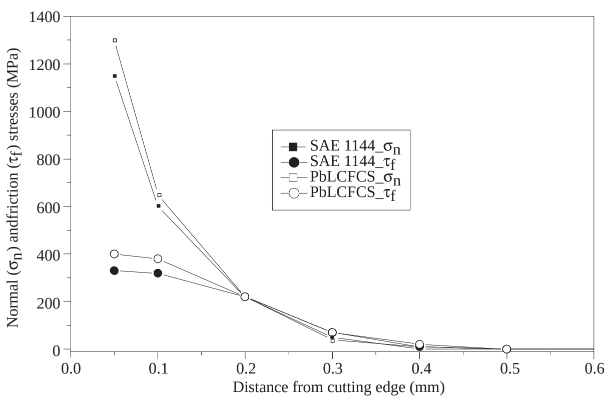

Figure 10. Split tool test results for PbLCFCS and SAE 1144 steels.

These are for a cutting speed of 250 m/min, 1mm depth of cut, and 0.1 mm/rev feed rate and a 0°-rake angle, with a P20 cemented carbide cutting tool. The incorporation of this type of friction model in machining simulations has only been satisfactory for light- to medium-range cutting, however. The model has been observed to underpredict the friction stress obtained from split tool tests at heavy cutting conditions, for instance at cutting speeds higher than 200 m/min. Further research has been carried out for improving this model (Childs et al., 1997). For example, the factor m was varied with changing local temperatures on the rake face. Although the improved model was reported to provide better predictions for certain conditions, generalisations for different workpiece-tool material combinations have not been successful. Therefore, further research is needed to find a better friction model based on split-tool dynamometry, possibly by incorporating the local pressure distribution values.

Temperature Considerations

As mentioned in Section 2.1, the temperature somewhere at the interface between the tool and the chip may reach up to 1200°C in a matter of milliseconds depending on the severity of the cutting conditions. It is also known that these high temperatures considerably affect tool and work properties, and tool wear and as a result the economy of metal cutting operations. Therefore the calculation of the temperature distribution should be given special attention in machining simulations.

A quantitative description of the temperature distribution in machining was given by Boothroyd (1963) and Tay et al. (1974). Since then, various analysis techniques which depended on different assumptions of boundary conditions and heat sources have been developed and quite successful results, especially by the use of the finite element technique, have been reported. Tay (1993) has recently given a review of these studies. The outcome of these temperature researches should be incorporated into the ongoing machining simulation researches in order to obtain realistic results. Another point of great importance is to use thermal properties varying with temperature. One cannot expect the thermal conductivity and the specific heat values to be constant for a temperature range of 25 to 1200°C, as shown in Figure 11 for various steel types (ASM, 1979). A comparative study by Childs et al. (1997) reflects the importance of using variable thermal properties for work material. The same study also points out that variable properties for tool materials do not have a considerable effect on the temperature distributions.

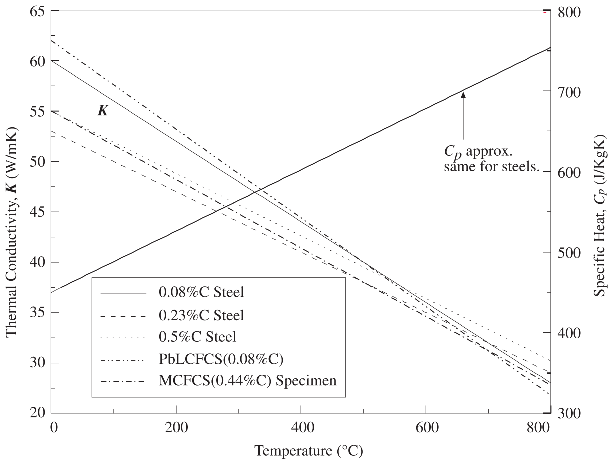

Figure 11. Variation of thermal conductivity and specific heat with temperature for various steels (ASM, 1979).

Chip Separation Criterion

With respect to the methods used for chip separation at the cutting edge, it can be said that no effective criterion has yet been reported (Zhang and Baghci, 1994). However, such a criterion is quite important in determining the chip tool interactions at the cutting edge. Huang and Black (1996) have reviewed up-to-date developments in this aspect of machining. Machining researchers have employed several different criteria for simulating chip separation. One way has been to assume a small gap at the cutting, as shown in Figure 12a. A node reaching the cutting edge of the tool is bifurcated both on the rake face and on the side of the machined surface. This criterion is equivalent to assuming a predetermined critical distance at which nodes start to separate into two. However, different critical distances have been found to result in different plastic strain distributions (Lin and Lin, 1992). Another method has been the use of a singular FE element to allow the chip to separate from the work. The element allows twin nodes to split round the cutting edge, as shown in Figure 12b. This criterion is more suitable than the previous one in that the workpiece material approaching the cutting edge is not in any way externally forced to split, but is purely dependent on the cutting conditions and the flow properties of the material being cut. However, this criterion introduces a velocity discontinuity at the cutting edge, which causes a certain amount of force imbalance between the workpiece and the tool. This criterion is suggested, but it is believed that more research needs to be done to provide better separation criteria for machining simulations.

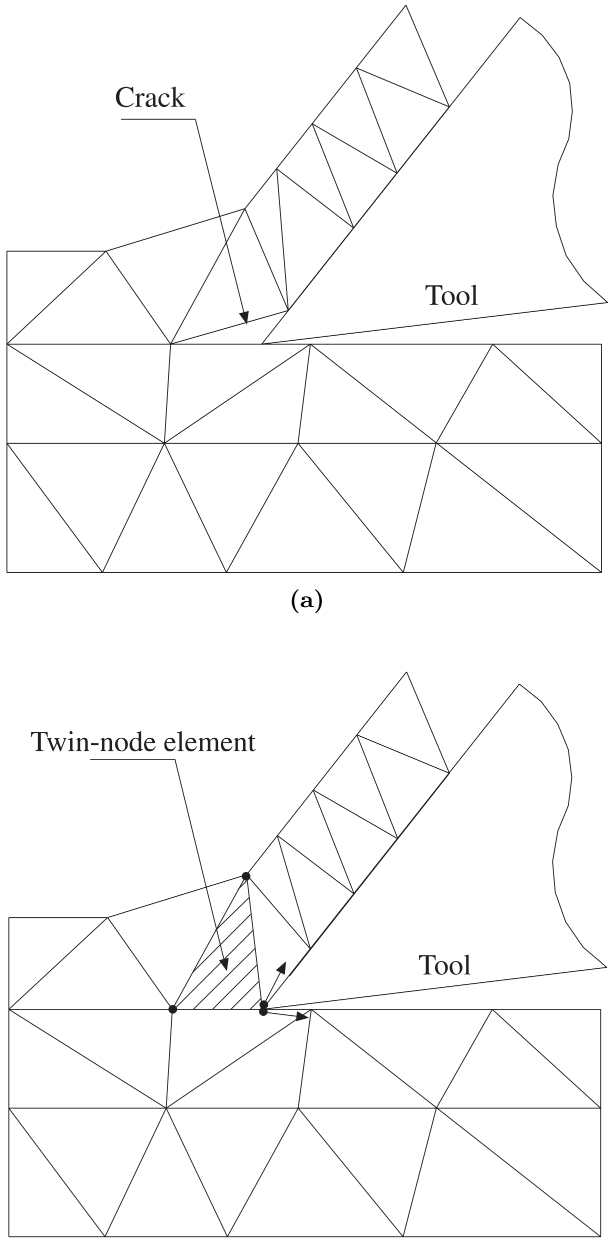

Figure 12. Chip separation criteria; (a) crack at the cutting edge, (b) twin-node element

Conclusions

In this paper, analytical and the numerical machining modelling efforts have been summarised and some important guidelines for overcoming the shortcomings have been presented. An important yet a very complicated process, machining requires special attention during a modelling procedure. As stated, elsewhere in this paper, the selection of an initial mesh comparatively dense in the critical regions, an appropriate method of simulation which accounts for the mutual dependence of plastic flow and heat generation is the first step. The material property model and an appropriate reference frame (i.e., Lagrangian or Eulerian) for formulation is a second step. Thirdly, a flow stress relation and a convenient experimental setup for determining the relevant material parameters should be decided on and then designed. Extreme frictional behaviours have been observed during machining operations. Therefore, the fourth step should be the handling of the frictional properties between the chip and the cutting tool. Together with these requirements, the machining researcher should take the thermal effects into account during material property input. This is because of the fact that temperatures in metal machining for example may reach up to 1200C which may result in the bad surface integrity of the product and also increased costs due to accelerated wear of the cutting tool used. One very important finding from this research has been that the work material thermal conductivity and the specific heat should be taken to vary with temperature. A peculiarity of modelling this process is the separation of the chip from the workpiece by the tool. The methods that have been mentioned in this paper can be considered as a guide, or a better approach should be developed to tackle this fifth aspect of modelling machining.

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List of Symbols

α	Rake angle of the cutting tool
ϕ	Shear angle
β	Friction angle
μ	Coefficient of friction
τ_f	Friction stress
σ_n	Normal stress
$\bar{\sigma}$	Flow stress
$\bar{\varepsilon}$	Equivalent strain
$\dot{\bar{\varepsilon}}$	Equivalent strain rate
k	Shear strength
B, σ_1	Strength factor
M	Strain-rate sensitivity index
N, n	Strain hardening index
T	Temperature
k	Constant in Eq. (4)
m	Constant in Eq. (4)
m, n	Correction factors in Eq. (9)

References

ASM Metals Handbook *9th* ed., 1979.

Bailey, J. A., "Friction in Metal Machining-Mechanical Aspects", Wear, 31, 243-275, 1975.

Baird, J. D., "Strain Aging of Steel-A Critical Review", Iron and Steel, 36, 450-457, 1963.

Bathe, K-J., Finite Element Procedures, Prentice Hall, 1996.

Boothroyd, G., "Temperatures in Orthogonal Metal Cutting", Proc. I.Mech.E, 177, No.29, p.789, 1963.

Bridgman, P. W., Studies in Large Plastic Flow and Fracture with Special Emphasis on the Effects of Hydrostatic Pressure, McGraw-Hill, New York, 1952.

Carroll, J. T. and Strenkowski, S. J., "Finite Element Models of Orthogonal Cutting with Application to Single Point Diamond Turning", Int. J. Mech. Sci., 30, 899-920, 1988.

Childs, T. H. C. and Maekawa, K., "Computer Aided Simulation and Experimental Studies of Chip Flow and Tool Wear in the Turning of Low Alloy Steels by Cemented Carbide Tools", Wear , 139 , pp235-250, 1990.

Childs, T. H. C. and Rowe, G. W., Physics of Metal Cutting, Rep. Prog. Phys., 36, p.223, 1973.

Childs, T. H. C., "Contact Stresses in Metal Cutting", IOP Short Meetings, Ser. 25, 49-62, 1990.

Childs, T. H. C., Dirikolu, M. H., and Maekawa, K., "Modelling of Friction in the Simulation of Metal Machining", 24th Leeds-Lyon Symposium on Tribology, Tribology for Energy Conservation, Part of World Tribology Conference, London- England, 4-6 September, 1997a.

Childs, T. H. C., Dirikolu, M. H., Sammons, M. D. S., Maekawa, K., and Kitagawa, T., "Experiments on and Finite Element Modelling of Turning Free-Cutting Steels at Cutting Speeds up to 250 m/min.", Proc. 1st French and German Conf. on High Speed Machining (HSM), Metz-France, 17-18 June, 1997b.

Childs, T. H. C., "Elastic Effects in Metal Cutting Chip Formation", Int. J. Mech. Sci., 22, 457-466, 1980.

Childs, T. H. C., Otieno, A. M. W., and Maekawa, K., "The Influence of Material Flow Properties on the Machining of Steels", Proc. Third Int. Conf. on The Behaviour of Materials in Machining, (Institute of Materials), Warwick, 104-119, 15-17 Nov. 1994.

Childs, T. H. C., Bezas, K. and Dirikolu, M. H., The Sensitivity of Finite Element Predicted Machining Parameters to Small Variations in Flow Stress Behaviour, 2nd CIRP International Workshop on Machining, Nantes, France, Jan 24, 1999.

Clough, R. W., "The Finite Element in Plane Stress Analysis", Proc. 2nd ASCE Conf. on Electronic Computation, Pitsburg, PA, 1960.

Dirikolu, M. H., Computer Aided Simulation and Experimental Studies on Machining, Ph.D. Thesis, University of Leeds, Leeds, 1997.

Ernst, H. and Merchant, M. E., "Chip Formation, Friction and High Quality Machined Surfaces", Surface Treatment of Metals (ASM), 299-378, 1941.

Finnie, E., A "Comparison of Stress-Strain Behaviour in Cutting with That in Other Materials", Int. Res. Prod. Eng., ASME, N.Y., p.76, 1963.

Gordon, M. B., "The Applicability of the Binomial Law to the Process of Friction in the Cutting of Metals", Wear, 10, 274-290, 1967.

Huang, J. M. and Black, J. T., "An Evaluation of Chip Separation Criteria for the FEM Simulation of Machining", J. Manuf. Sci. Engg., 118, p.545, November 1996.

Iwata, K., Osakada, K., and Terasaka, Y., "Process Modelling of Orthogonal Cutting by Rigid-Plastic Finite Element Method", J. Eng. Ind., ASME., 106 ,p.32, 1984.

Kato, S., Yamaguchi, K., and Yamada, M., "Stress Distribution at the Interface Between Tool and Chip in Machining", J. Eng. Ind., Trans. ASME, p.683, May-1972.

Klamecki, B. E., Incipient Chip Formation in Metal Cutting - A 3-D Finite Element Analysis, Ph.D. Dissertation,Univ. of Illinois at Urbana Champaign, 1973.

Kobayashi, S. and Thomsen, E. G., "Metal Cutting Analysis-I: Re-evaluation and New Method of Presentation of Theories", J. Eng. Ind., 63-80, 1962.

Kudo, H., "Some New Slip-Line Solutions for Two-Dimensional Steady-State Machining", Int. J. Mech. Sci., 7, 43-55, 1965.

Lee, E. H. and Shaffer, B.W., "The Theory of Plasticity Applied to a Problem of Machining", J. Appl. Mech., 73 , p.405, 1951.

Lin, Z. C. and Lin, S. Y., "A coupled Finite Element Model of Thermo-Elastic-Plastic Large Deformation for Orthogonal Cutting", J. Eng. Matrl. Tech., Trans. ASME, 114, p.218, April 1992.

Merchant, M. E., "Mechanics of the Cutting Process", J. A Phys., 16, 267-275, 1945.

Oxley, P. L. B., Mechanics of Machining: An Analytical Approach to Assessing Machinability, Ellis Harwood, 1st Ed., 1989.

Rowe, G. W. et al., "Finite Element Plasticity and Metalforming Analysis", Cambridge University Press, 1991.

Shih, A. J. and Yang, H. T. Y., "Experimental and Finite Element Predictions of residual stresses due to Orthogonal Metal Cutting", Int. J. Num. Methods Eng., 36, 1487-1507, 1993.

Shirakashi, T. and Usui, E., "Simulation Analysis of Orthogonal Metal Cutting Mechanism", Proc. Int. Conf. on Prod. Eng., Tokyo , 535-540, 1974.

Strenkowski, J. S. and Carroll, J. T., "A Finite Element Model of Orthogonal Metal Cutting", J. Eng. Ind., ASME, 107, 2, 349-354, 1985.

Tay, A. A. O., "A Review of Methods of Calculating Machining Temperature", J. Matrl. Proc. Tech., 36, 225-257, 1993.

Tay, A. A. O., Stevenson, M.G., and de Vahl Davis, G., "Using Finite Element Method to Determine Temperature Distributions in Orthogonal Machining", Proc. I.Mech.E., 188, 627-638, 1974.

Usui, E. and Shirakashi, T., "Mechanics of Machining - From "Descriptive" to "Predictive" Theory", ASME Publ. PED Vol-7, 13-35, 1982.

Usui, E., Maekawa, K., and Shirakashi, T., "Simulation Analysis of Built-up Edge Formation in Machining of Low Carbon Steels", Bull. Jpn. Soc. Prec. Eng., 15, 237-242, 1981.

van Luttervelt, C. A., Childs, T. H. C., Jawahir, I.S., Klocke, F. and Venuvinod, P.K., Present Situation and Future Trends in Modelling of Machining Operations, CIRP Annals, vol 47, Part 2, 587-626, 1998.

Wu, J., Dillon, O.W.Jr., and Lu, W., “Thermo-Viscoplastic Modelling of Machining Process using a Mixed Finite Element Method”, J. Eng. Matrl. Tech., Trans. ASME, 118, p.470, Nov. 1992.

Zhang, B. and Bagchi, A., “Finite Element Simulation of Chip Formation and Comparison with Machining Experiment”, J. Eng. Ind., 116, p.289, Aug. 1994.

Zorev, N.N., “Interrelationship Between Shear Processes Occurring Along Tool Face and on Shear Plane in Metal Cutting”, Proc. Conf. Int. Res. in Prod. Eng., 42-49, ASME, New York, 1963.