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On the separation criteria in the simulation of orthogonal metal cutting using the finite element method

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Abstract

This paper aims to gain an understanding of the reliability of the existing separation criteria for orthogonal metal cutting. To focus on their physical inherence, a simple finite element model under plane-strain deformation was used to investigate the mechanics of cutting from the incipient stage. The workpiece materials studied were elastic–perfectly plastic and elastic–plastic with work hardening. The chip separation criterion of failure stress was used as a default and based on this the thresholds and reliability of different criteria were examined. The study showed that none of the existing criteria is universal. A more comprehensive criterion needs to be established to provide consistent and reliable FEM simulation.

Keywords: Separation criteria; Metal cutting; Finite element simulation

1. Introduction

Metal cutting is a common process of manufacturing for producing parts of desired dimensions and shapes. To understand the mechanisms and mechanics of material removal during cutting, much attention has been paid to develop simplified models. Studies by Piispanen [1], Merchant [2] and Oxley [3] are the earlier representatives that explored the relationships amongst shear angle, tool rake angle and tool–work friction. Lee and Shaffer [4] used the slip-line field theory to understand the cutting of rigid–perfectly plastic materials. Pamler and Oxley [5] developed a new theory to include the effect of work hardening. These studies provided insight into the mechanics of cutting processes. However, to take into account more sophisticated cutting variables, such as friction variation at the chip-tool interface, temperature generation in the cutting zone, the influence of strain rate and the effect of edge build-up, large-scale numerical analyses become necessary.

Over the last two decades, the finite element method has been used extensively in the investigation of orthogonal metal cutting processes. For example, Klamecki [6] simulated the cutting process from the incipient state using three-dimensional FEM modelling. Usui and Shirakashi [7] investigated chip formulation under steady-state cutting conditions. Strenkowski and Carroll [8] introduced a chip separation criterion based on the effective plastic strain, simulated the chip formation from incipient state and discussed the effect of the criterion on the result of simulation. They found that varying the threshold of the effective plastic strain over the range of 0.2–1.0 had only a slight effect on the chip geometry and tool forces. However, the variation would alter significantly the residual stresses in the machined surface of the workpiece. In general, an increase of the threshold led to larger surface residual stresses. Komvopoulos and Erpenbeck [9] investigated the effect of edge build-up using a plane-strain steady state cutting model and applied the so-called distance separation criterion, where they assumed that when the distance between the tool-tip and the nearest finite element node on the cutting path reached to certain value, the node be separated from the workpiece material. Their study indicated that the critical distance, i.e. the threshold in their distance criterion, must be chosen carefully to simulate the cutting reasonably and to avoid numerical instability. In their study, the determi-

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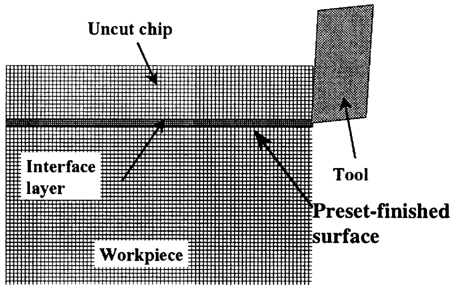


Fig. 1. The schematic of the plane-strain finite element model of cutting.

nation of a proper distance threshold was based on a series of trial-and-error simulations with various finite element meshes. Lin and Lin [10] introduced a chip separation criterion using the argument of strain energy, and investigated the chip geometry, the residual stresses in the machined surface, the temperature distributions in the chip and the tool and the cutting forces. They found that the calculated cutting forces agreed well with their experimental results and that the threshold of strain energy density at chip separation was independent of the uncut chip thickness. Watanable and Umezu [11] simulated the 3-dimensional continuous chip formation processes using LS-DYNA3D. The normal failure stress was used as the separation criterion and a good correlation was obtained between experimental and finite element simulation in terms of cutting forces and chip deformation. However, the rationale of the criterion was not examined.

To make a reliable FEM simulation, an appropriate separation criterion is necessary. A good criterion must reflect the mechanics and the physical mechanism of the material subjected to machining and produce reasonable results, such as the chip geometry, cutting forces, temperature distribution and residual stresses. Moreover, the threshold of separation of a sound criterion should not vary with the cutting conditions when the workpiece material is given. The criteria discussed above are based on the argument of effective plastic strain, strain energy density, failure stress or distance tolerance, and have various problems. For instance, the critical values of the strain energy density, tool-node distance and effective plastic strain were determined without a sound rule. Furthermore, the distance tolerance threshold has less physical intention and it is only known by experience that it must be sufficiently small to ensure continuous chip formation and numerical convergence. Similarly, the critical failure stresses must be chosen based on a trial-and-error process for a given material. Since the finite-element models using these criteria are all different, one is unable to assess their merits, disadvantages and relationships.

The present study aims to obtain a clearer figure about the reliability of the above separation criteria for orthogonal metal cutting. To focus on the physical inherence of the criteria, a simple finite element model under plane-strain deformation will be used to investigate the mechanics of cutting from the incipient stage.

2. The finite element modelling

The plane-strain finite element model for orthogonal metal cutting using LS-DYNA3D is shown in Fig. 1. The model consists of four parts: an uncut chip, a preset-finished workpiece, an interface layer and a cutting tool. The interface layer is arranged between the uncut chip and the preset-finished surface of the workpiece to realise chip separation when the failure stress criterion, which is the default criterion in this study, is satisfied. The left and bottom edges of the workpiece are fixed and the cutting tool is constrained to move horizontally with a given depth of cut. The control volume of the FEM model contains 1706 eight-node brick elements, which is great enough to eliminate the boundary effect according to a series of trial tests. The workpiece material used is copper having the material properties listed in Table 1. To understand the effect of work hardening, two constitutive models of the workpiece, i.e. elastic–perfectly plastic and elastic–plastic with work hardening, are examined in the simulations.

The failure stress criterion used in the simulation can be expressed as

$$\left(\frac{|\sigma_n|}{\tau_n}\right)^2+\left(\frac{|\sigma_s|}{\tau_s}\right)^2\geq 1 \quad (1)$$

where σ_n is the normal stress in an interface element in the model, as shown in Fig. 1, σ_s is the shear stress in such an element, τ_n is the threshold of such normal stress and τ_s is the threshold of the above shear stress. To use only the normal stress in the separation criterion, which can be called as a normal failure stress criterion therefore, τ_s must be set to a very large value such as 10 000 MPa. Based on a series of preliminary simulations with various normal failure stresses, the yield stress, Y, is found to be an appropriate threshold

Table 1
The mechanical properties of the workpiece material

Elastic modulus (Gpa)	Hardening modulus (Mpa)	Yield stress (Mpa)	Density (kg m^{-3})
128	292	90	8.960

Table 2
Cutting conditions and material constitutive models

Case	Material model	Rake angle (°)	Depth of cut (μm)	Cutting speed (m s^{-1})
1	EPP	0	2	2.3
2	EPP	5	2	2.3
3	EPP	10	2	2.3
4	EPP	0	1	2.3
5	EPP	0	2	4.6
6	EPW	0	2	2.3

of the criterion for elastic–perfectly plastic material model, under which the FEM prediction of the cutting force (4.0 N mm^{-1}) is in good agreement with the corresponding experimental measurement (4.7 N mm^{-1}) under identical nominal cutting condition (rake angle $\alpha = 0°$, cutting speed $v = 2.3$ m s^{-1} and depth of cut $d = 2$ μm). For the model of elastic–plastic material with work hardening, to obtain a stable result using LS-DYNA3D the threshold of the normal failure stress must vary from a lower value to Y in the first few separation steps. In the present study, such variation takes place linearly in the first five elements in the interface layer, as shown in Fig. 1.

In order to carry out a general comparison of results from different separation criteria, a series of simulations with different cutting conditions and material models, as listed in Table 2, are conducted. In the table, EPP indicates the elastic–perfectly plastic model and EPW stands for the model of elastic–plastic material with work hardening.

3. Results and discussion

3.1. Distance criterion

In all of the simulations, it was found that the distance between the tool tip and the node at separation in the interface layer was always zero. This demonstrated that if the distance separation criterion is used, the critical distance must be as small as possible to achieve the best results as long as numerical instability can be avoided. In other words, in the simulations with the cutting conditions and material models listed in Table 2, the distance criterion is inappropriate because one must use a finite distance to avoid numerical instability, whilst the the actual distance at separation is zero.

3.2. Effective plastic strain criterion

Fig. 2 shows the variation of effective plastic strain in the elements within the interface layer with the advancement of the cutting tool when separation occurs. The element numbers illustrated in the figure are those of interface elements, with 1638 being the first element on the separation path, followed by elements 1637, 1636, etc., when the cutting tool proceeds from the right to the left of the control volume. The results showed that in the transient stage, material separation is unstable, thus the values of the effective strain at the instant of separation vary significantly. However, when the cutting tool advances further, a stable cutting is reached, which is demonstrated by a constant values of the effective plastic strain. This means that the effective

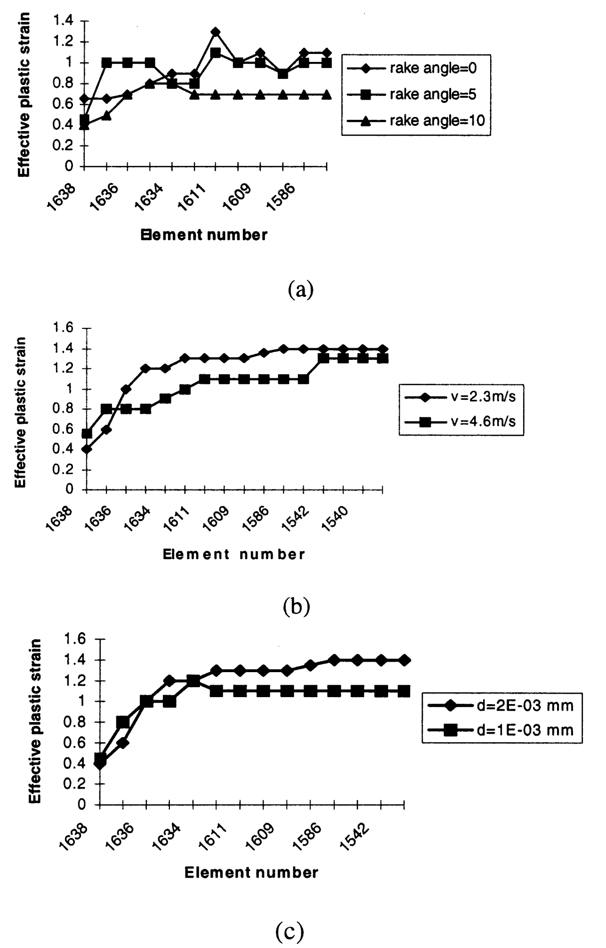


Fig. 2. Variation of effective plastic strain at separation with different cutting conditions: (a) effect of rake angle of the cutting tool ($d = 2$ μm, $v = 2.3$m/s); (b) effect of cutting speed ($d = 2$ μm, $\alpha = 0°$); (c) effect of depth of cut ($\alpha = 0°$, $v = 2.3$ m/s).

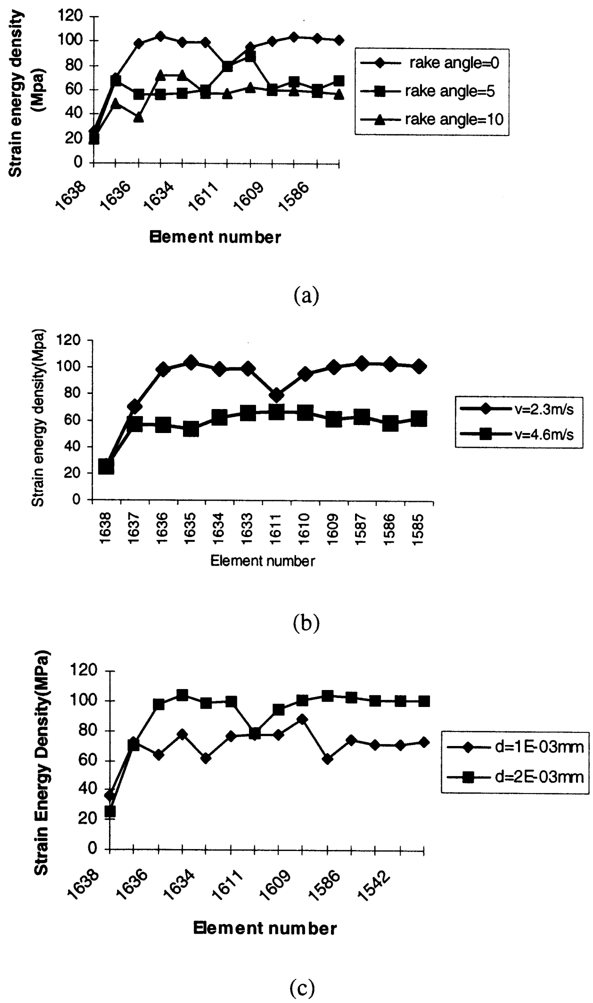


Fig. 3. Variation of the strain energy density at separation with different cutting conditions: (a) effect of rake angle of the cutting tool ($d = 2$ μm, $v = 2.3$ m/s); (b) effect of cutting speed ($d = 2$ μm, $\alpha = 0°$); (c) effect of depth of cut ($\alpha = 0°$, $v = 2.3$ m/s).

plastic strain is a mechanics quantity that reflects certain physical inherence of the material deformation at separation.

However, an effective plastic strain criterion cannot be reliable in a practical application if a single threshold is used, since, as demonstrated clearly by Fig. 2, the value of effective plastic strain varies significantly when the cutting conditions change even during stable cutting with a given material model. It decreases when the rake angle of the cutting tool increases (Fig. 2(a)), the cutting speed, v, increases (Fig. 2(b)), or the depth of cut, d, decreases (Fig. 2(c)). According to the mechanics of metal cutting, it is not difficult to understand that the change of cutting speed, rake angle, or depth of cut will change the strain rate locally in the cutting zone. Thus the above observation on the variation of the effective plastic strain at separation suggests that to generate a reliable separation criterion for all of the cutting conditions the effective plastic strain must be coupled, as a variable, with some other mechanics quantities, for example, with the strain rate during cutting.

3.3. Strain energy density criterion

The strain energy density in an element can be expressed as:

$$\frac{\mathrm{d}W}{\mathrm{d}V} = \int_0^{\varepsilon_{ij}} \sigma_{ij}\mathrm{d}\varepsilon_{ij}, \tag{2}$$

where σ_{ij} and ε_{ij} are the stress and strain components respectively, W is the total work stored in the element, consisting of elastic deformation energy and plastic flow work, and V is the vol. of the element. Under the conditions of plane-strain deformation, (Eq. (2)) becomes:

$$\frac{\mathrm{d}W}{\mathrm{d}V} = \int_0^{\varepsilon_{xx}} \sigma_{xx}\mathrm{d}\varepsilon_{yy} + \int_0^{\varepsilon_{yy}} \sigma_{yy}\mathrm{d}\varepsilon_{yy} \int_0^{\varepsilon_{xy}} \sigma_{xy}\mathrm{d}\varepsilon_{xy} \tag{3}$$

Fig. 3 demonstrates the variation of the threshold of the above defined strain energy density with the cutting conditions along the interface layer at the moment of separation of each element. Once again, element 1638 is the first element along the cutting path.

Similar to the behaviour of the effective plastic strain, the value of strain energy density at separation also reaches a constant during stable cutting under a specific cutting condition. The threshold of strain energy density decreases with the increment of the rake angle of the cutting tool (Fig. 3(a)) and cutting speed (Fig. 3(b)), but increases with increasing the depth of cut (Fig. 3(c)). Such tendencies are exactly the same as those of the effective plastic strain threshold when the corresponding conditions vary, see Fig. 2. Thus in this sense, the effective plastic strain criterion and the strain energy density criterion are equivalent but none of them are universal. If they are used in an FEM simulation, their threshold must be determined individually for individual cutting conditions with a given workpiece material. However, in the trasient stage of cutting, the variation of the effective plastic strain threshold is generally smoother. It is interesting to note that the present result shows a clear dependency of the strain energy density on the depth of cut, which is different from the conclusion of Ref. [10].

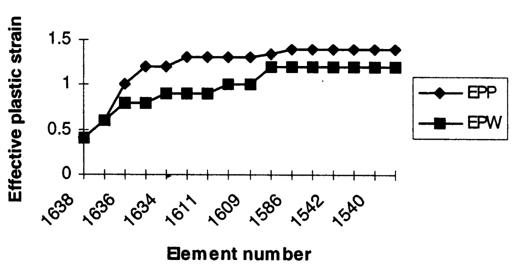
3.4. Effect of material properties

The above discussion has been based on a given workpiece material, and the calculations in Fig. 2 and Fig. 3 are with the elastic–perfectly plastic model. When the material properties change, the thresholds of the above criteria will all change.

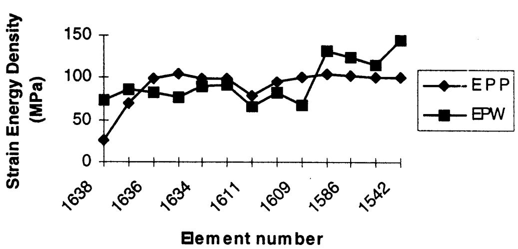
Fig. 4 shows the variations of the thresholds of both the effective plastic strain and the strain energy density with change of the mechanical properties of the workpiece materials, ie, the elastic–perfectly plastic (EPP) and elastic–plastic with work hardening (EPW). With the effective plastic strain criterion, material separation thresholds approach smoothly to their stable values when the cutting becomes stable (Fig. 4(a)). A workpiece material with EPW needs a less effective plastic strain for separation. However, with the strain energy density criterion, the stable cutting condition cannot be correctly reflected when with EPW. Thus once again, the strain energy density criterion is less applicable.

3.5. Normal failure stress criterion

The normal failure stress criterion has been used as a default in determining the material separation and, based on this, the corresponding thresholds of effective plastic strain, strain energy density and the distance between the element node and cutting tool tip, are obtained. The above comparison shows that all of the other thresholds vary when that of the normal failure stress is fixed. This immediately indicates that if one of the other separation criteria is used as the default to examine the behaviour of the normal failure stress criterion, its threshold will also vary correspondingly. This also means that the normal failure stress criterion cannot be universal.



(a)



(b)

Fig. 4. The effect of material properties on the variation of separation thresholds ($\alpha = 0^{\circ}$, $d = 2$ μm and $v = 2.3$ m/s). (a) effective plastic strain criterion; (b) strain energy density criterion.

4. Conclusions

Through the above investigation, the following conclusions can be drawn:

1. None of the single quantities, i.e. the effective plastic strain, strain energy density, the normal failure stress and the distance between the separation element node and tool tip, can be used reliably as a complete separation criterion in the FEM simulation of orthogonal metal cutting. If any of them is used, one always needs to determine the corresponding threshold whenever individual cutting conditions change. In other words, when a reliable prediction is concerned, one cannot rely on the threshold determined by comparing simulation results with only one or two experimental measurements. There does not exist a single threshold of separation for different cutting conditions even when the workpiece material is given.
2. Threshold variation of different criteria follows a common tendency when cutting conditions change. Thus a more feasible and reliable separation criterion may established by coupling an existing criterion with other key factors, i.e. by using a coupled variable group including effective plastic strain, strain energy density, failure stress, or the like. According to the present study, it seems that the variation of strain rate in the local deformation zone with chip separation has a considerable effect.
3. When using the normal failure stress as the default, the study shows that the effective plastic strain offers more reliable results.

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References

[1] V. Piispanen, Theory of formation of metal chips, J. Appl. Phys. 19 (1948) 876.
[2] M.E. Merchant, Mechanics of the metal cutting process, J. Appl. Phys. 18 (1945) 267.
[3] P.L.B. Oxley, Shear angle solutions in orthogonal machining, Int. J. Machine. Tool Des. Res. 2 (1965) 219.
[4] E.H. Lee, B.W. Shaffer, The theory of plasticity applied to a problem of machining, ASME J. Appl. Mech. 18 (1951) 405.
[5] W.B. Palmer, P.L.B. Oxley, Mechanics of orthogonal machining, Proc. Inst. Mech. Engrs. 173 (1959) 623.
[6] B.E. Klamecki. Incipient Chip Formation in Metal Cutting—A Three Dimension Finite Analysis, Ph.D. Thesis, Univeristy of Illinois at Urbana-Champaign, Urbana, IL. (1973).

[7] E. Usui, T. Shirakashi. Mechanics of Machining-From Descriptive to Predictive Theory on the Art of Cutting Metals-75 Years later, ASME PED-7 (1982) 13.
[8] J.S. Strenkowski, J.T. Carroll, A finite element model of orthogonal metal cutting, J. Eng. Ind. 107 (1985) 349.
[9] K. Komvopoulos, A.S. Erpenbeck, Finite element modeling of orthogonal metal cutting, ASME J. Eng. Ind. 113 (1991) 253.
[10] Z.C. Lin, S.Y. Lin, A coupled finite element model of thermo–elastic–plastic large deformation for orthogonal cutting, Trans. ASME, J. Eng. Mater. Tech. 114 (1992) 218.
[11] K. Watanabe, Y. Umezu. Cutting Simulation Using LS-DYNA3D, Third International LS-DYNA3D Conference, Kyoto Research Park, Kyoto, Japan (1995).