Orthogonal Metal Cutting Processes: A Review

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Abstract- *The Lagrangian and the Eulerian are the two different finite-element formulations that have been used extensively in the modeling of the orthogonal metal cutting process. The disadvantages of these formulations make modeling of cutting process inefficient. In this paper, it is shown that a more general formulation, the arbitrary Lagrangian Eulerian (ALE) method may be used to combine the advantages and avoid the shortcomings of both of the previous methods. It is also shown that due to the characteristics of the cutting process, this formulation offers the most efficient modeling approach.*

Keywords: Orthogonal metal cutting process; ALE; Finite-element method..

I. INTRODUCTION

Metal cutting is one of the most common manufacturing operations, and a great deal of research has been devoted in understanding the mechanics of this process, with the objective of gaining more effective cutting tools and more efficient manufacturing process plans. Traditionally, these objectives have been achieved by experimentation and prototyping.

In modern years, however, with the surge in computational power and ability, the focus has turned to numerical synthetic of the process with the objective of replacing costly testing and prototyping with numerical simulation. Many such simulations have appeared in the literature. In spite of the many simulation attempts reported in the literature, it is perhaps fair to say that cutting simulation has not become a common tool in industry, perhaps due to doubts about the consistency of such results and lack of sufficient verification. Much of this is related to the inherent difficulty of the process, which probably makes it one of the most challenging processes from the numerical point of view. Although the actual machining process is shortened to the most basic 2D plane-strain problem, orthogonal cutting, there are still many issues to deal with in such a numerical simulation.[1]

Arbitrary Lagrangian-Eulerian formulation

It can be seen that both the Lagrangian and the Eulerian methods are ineffective in modeling some of the features of the cutting process. The Lagrangian performs well in modeling unimpeded formation of chip boundaries and contact length, whereas the Eulerian is the method of choice as far as the material flow around the tip of the tool is disturbed. Therefore, it would be supreme if these two methods could be combined in a single analysis and each of them used where they perform the best. A more general approach, the ALE method provides this opportunity. In an ALE analysis, the FE mesh is neither attached to the material nor fixed in space. The mesh, in general, has a motion that is autonomous of the material. This general approach can be reduced to Eulerian or reorganized Lagrangian analyses as twospecial cases. In the following sections a scheme for the ALE method and its presentation in cutting analysis are reported.

ALE procedure

Starting from the principle of virtual work, an ALE formulation is derived in terms of two sets of velocities, those of the material point's v and those of the grid point's u. These velocities are in general independent of each other, but there exists a one-to-one mapping between the material and the computational (grid) domains, provided that the Jacobian of the mapping function is non-zero. To satisfy this, the boundaries of the two domains should coincide, requiring that:

$$(v - u) * n = 0 \qquad \ldots(1)$$

where n is the normal vector at any point on the boundary. The physical interpretation of Eq. (1) is that no normal convective velocity occurs across the boundary if the surface particles remain on the surface. To establish the mapping between the two domains, the time derivatives of a function f (x) in the computational reference system is expressed in terms of its material time derivative in the material reference system (x):

$$q = f + (v - u) * \frac{df}{dx} \qquad \ldots..(2)$$

where q and f are the computational and material time derivatives, respectively. Eq. (2) is important in the incremental analysis since it gives the relationship between the material-associated quantities and the grid-point-associated quantities, and thus makes it possible to track the material deformation history when ALE is used. Using the above equation in the expression for virtual work and after linearization of the equation, final incremental ALE formulation can be found.

Finite element modeling details

Because of the complex nature of metal cutting processes, a complete finite element simulation procedure for metal cutting simulation involves many component parts. In this light, it is noted that while a user-developed custom finite element code enables the user to modify the code according to personal needs, its development often requires advanced technical know-how in many areas, not to mention several years of intensive programming and debugging. On the other hand, many general-purpose commercial codes offer advanced modeling and pre- and post-processing options not available in custom finite element codes. Even though commercial codes are not specialized for metal cutting simulations, a careful integration of modeling options in the codes and custom user subroutines will facilitate metal cutting simulations using these codes. To this end, the purpose of this section is to discuss a set of custom modeling options in the commercial code ABAQUS that have been successfully integrated by the authors to simulate the orthogonal metal cutting process [1].

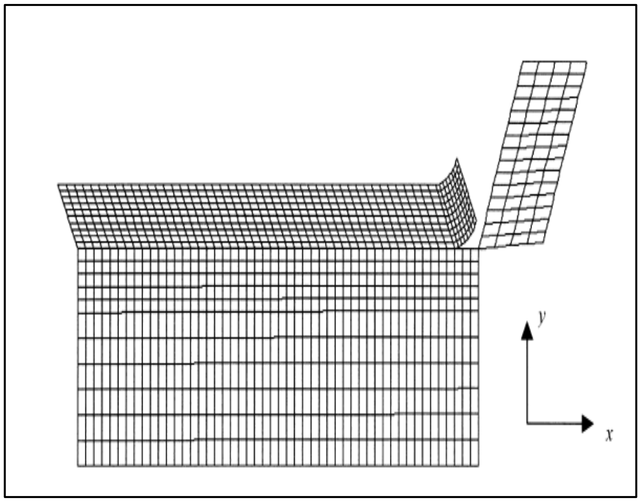

Fig 1: The finite element mesh used in the orthogonal metal cutting simulations

Chip-separation criterion

To investigate the chip formation and its separation from the workpiece, a chip- or element-separation criterion has been executed into the MARC finite element code. Cutting is imaginary to take place at the line representing the unreformed chip thickness, therefore, parting is assumed to occur only at the nodes lying along this line. The standard for the separation of nodes in front of the tool tip is based on a geometrical consideration. When the tool tip approaches a node within a small serious distance, that node separates from the work piece and becomes part of the chip (see Fig.3). When the distance D, between the tool tip and the node B, becomes equal or less than the pre-defined critical value Dc, a rezoning step is showed. The connectivity of the element E2 changes and a new node B0 replaces the node B in that element. Concurrently, the coordinates of the nodes B and B0 are altered, so that the node B moves upwards along BC by small distance, whereas node B0 moves downwards by a small distance along B0F. The algorithm applied into the MARC code for the application of the above mentioned procedure, is shown in Fig. Note that the rezoning feature, which has been used widely in metal forming problems to define a new mesh when the previous one is distorted due to additional plastic deformation, constitutes a very useful tool for amending the initial finite element mesh, in order to model the chip formation using a commercial finite element code. In the case of metal cutting with a continuous chip, experimental observations reveal that chip formation takes place without a crack extension in front of the cutting tool tip. Furthermore, chip-separation is a continuous process just ahead of the tool edge and, therefore, a geometrical separation criterion based on distance is a realistic assumption.

Note that comparison of the geometrical separation criterion in modeling the cutting process to other chip separation criteria, based on the values of effective plastic strain and strain energy density, is made in [3].

The value of the critical distance, which in the present work is equal to 3 mm and represents 5% of the element length, is taken as small enough to ensure continuous chip formation without causing numerical instability. Note that estimation of a proper value for the critical distance and its effect on the accuracy of the results involves difficulties and, therefore, it can be only validated experimentally.

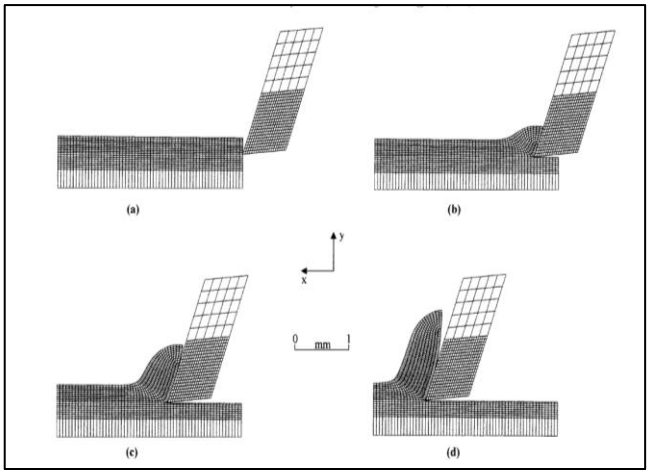

Fig 2: Chip formation in simulated orthogonal metal cutting: (a) initial undeformed state; (b) shape of the deformed chip after a tool path of 0.48 mm; (c) shape of the deformed chip

after a tool path of 1.44 mm; (d) shape of the deformed chip after a tool path of 2.58 mm.

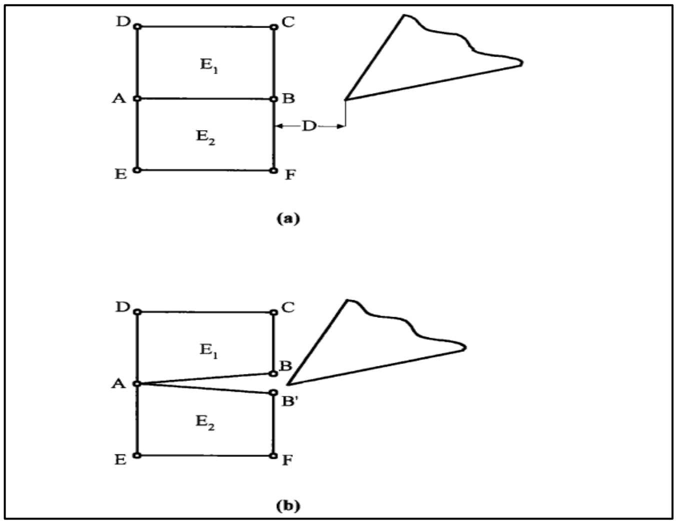

Fig 3: Schematic diagram of the geometrical separation criterion: (a) before element separation, D >Dc; (b) after element separation, D <Dc.

II.ORTHOGONAL CUTTING AND THE TYPE 2 CHIP

The analysis presented in this paper is in theory limited to the case of orthogonal cutting with a tool having a plane face and a single straight cutting edge. The term "orthogonal cutting" has been coined1 to cover the case where the cutting tool generates a plane surface parallel to an original plane surface of the material being cut and is set with its cutting edge perpendicular to the direction of relative motion of tool apd workpiece. This is to distinguish it from the more general cases where the cutting edge is oblique to the direction of rf'\ativp motion, termed oblique cutting, or where the surface generated is not a plane, to be discussed later in this series. If in practice the above conditions are fulfilled to a good degree of approximation, then the present analysis also holds to a good degree of approximation. For instance, in a conventional turning operation with a single point tool there are at least two cutting edges; the first removes the major amount of material while the second produces the final surface. In addition the surfaces generated are not plane but cylindrical.

Further, the cutting edge is often slightly oblique to the direction of relative motion of tool and work. However, if the depth of cut is quite large compared to the value of the feed per revolution, and if the tool has no appreciable nose radius, then the condition requiring a single straight cutting edge is well approximated. If the radius of the cylindrical surface generated is large compared to the thickness of the chip removed, then the approximation to a plane surface is good. If the primary cutting edge is not oblique by more than a few degrees, then the approximation to orthogonality is good. if not all, of these factors will be treated in a quantitative manner later in this series.

As for the geometry of chip formation, it has been pointed out by Ernst2 that there are three basic types of chips found in the cutting of metal, as illustrated in his classic examples given in Fig. 1. Type 1 is discontinuous, while types 2 and 3 arc continuous. Type 3, however, has a so called "built-up edge" interposed between chip and tool in the vicinity of the cutting edge. Strictly speaking, the analysis presented in this paper applies only to the type 2 chip. However, it has been found by experiment that it generally offers a good approximation in the case of the type 3 chip also. When machinery steel with the sintered carbide type of tool materials, at recommended speeds, a type 2 chip is practically always produced, so that the present analysis is particularly apt for application to such operations[4].

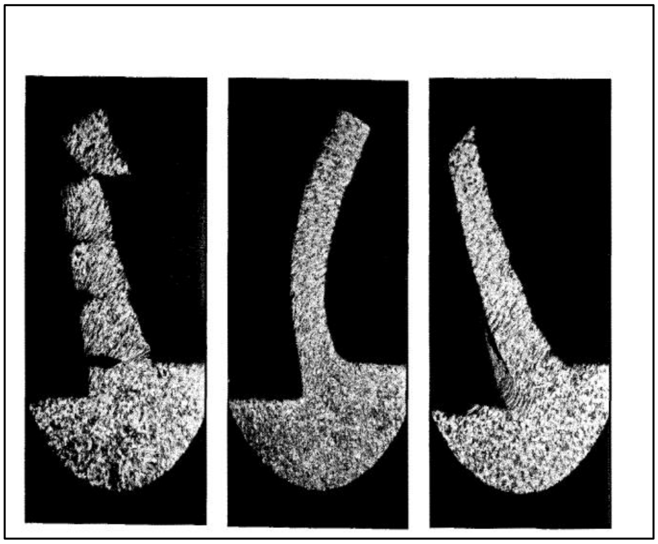

Fig 4: The three basic chip types according to Ernst: Type 1, Discontinuous or segmental chip, Type 2, Continuous chip without built-up edge, and Type 3, Continuous chip with built-up edge.

Heat generation in metal cutting

In theoretical analyses of cutting temperatures it was assumed that the work material was sheared at a plane (termed the shear plane) and that the heat source due to this shearing was a plane heat source of unvarying strength. It was also supposed that the heat source due to friction between the chip and tool was a plane heat source of uniform strength. The resulting perfect model of the cutting process, shown in Fig. *5*, may not, however, be representative of actual conditions. Palmer and Oxley (I), using cine-photography to observe the cutting process, found that, when mild steel was machined at low speeds, the primary distortion zone had the form shown in Fig. 6.By photographing the cutting action Nakayama showed that this wide deformation zone had constant magnitudes for cutting speeds of upto 500 fii min. Thus the statement that the heat source due to shearing of the work material is a plane heat source of uniform strength would appear to be invalid under these conditions.

Nakayama, using a technique for rapidly stopping the cutting action, produced measurable suggestion of a secondary zone of deformation within the chip due *to* the friction between the chip and tool. The distortion of lines previously etched on the copper sample showed that the material head-to-head to the rake face was being deformed as it stimulated up the face, and he was able to calculate the variation of strain rate within the chip. A typical result is shown in Fig. *7,* where it can be seen that the secondary distortion zone is roughly triangular with maximum rate of strain at the tool point. Clearly the assumption that the frictional heat source is confined to the chip-tool interface and is of uniform strength (as under gliding frictional conditions) is invalid under the conditions examined by Nakayama.

The effect of these circulated heat sources on the temperatures produced during cutting is considered in the present analysis[5].

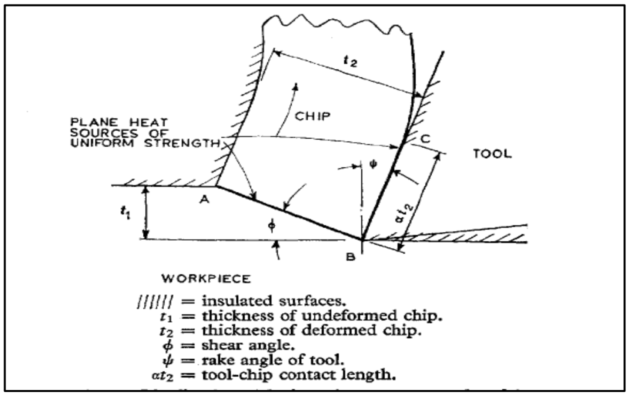

Fig 5: Idealized model of cutting process employed in previous theories

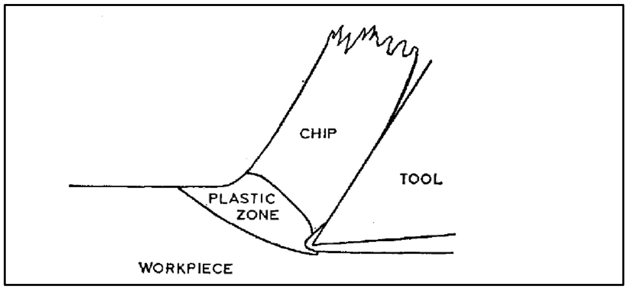

Fig 6: Model of orthogonal cutting process suggested by Palmer and Oxley showing wide primary deformation zune.

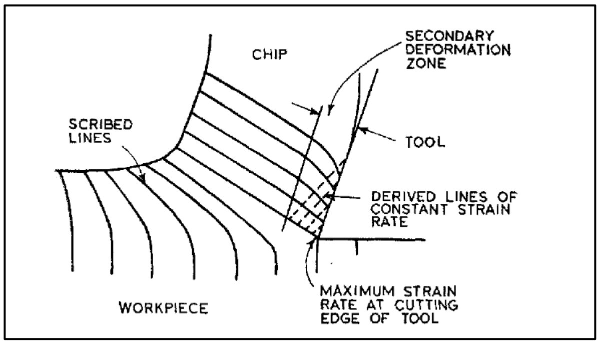

Fig 7:Distortion of lines on a suddenly stopped specimen showing derived distribution of strain rate with the secmtdaly deformation zone (after Nakayama).

III. CONCLUSION

An ALE finite-element formulation is defined and then engaged to model the metal cutting process. It is shown that both the Lagrangian and Eulerian studies suffer from inadequacies in modeling this process, and that the strong point of both methods can be combined to accomplish a more efficient cutting simulation. The features of an ALE analysis of cutting process are as follows:

1. No node-separation criterion is necessary, and no change in mesh topology is needed.
2. The density of the mesh around the tool tip need not be very high, and thus the process is computationally resourceful.
3. The chip formation occurs by continuous plastic flow of the material around the tool.
4. The shape and the thickness of the chip are developed mechanically in the process and there is no need for iterative alteration of the limitations[1].

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