FINITE ELEMENT SIMULATION OF CHIP FORMATION IN ORTHOGONAL CUTTING

A Thesis Submitted

In partial fulfillment for the award of the degree of

Master of technology

In

Production Engineering

SUBMITTED BY

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(2K19/PIE/14)

UNDER THE GUIDANCE OF

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CANDIDATE'S DECLARATION

I, Divyanshu Srivastav, hereby certify that the work which is being presented in this thesis entitled "FINITE ELEMENT SIMULATION OF CHIP FORMATION IN ORTHOGONAL CUTTING" being submitted by me is an authentic record of my own work carried out under the supervision of Prof. A. K. Madan and Dr. M.S. Niranjan , Department of Mechanical Engineering, Delhi Technological University, Delhi.

The matter presented in this thesis has not been submitted in any other University/Institute for the award of M.Tech Degree.

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29-08-2021

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CERTIFICATE

I, Divyanshu Srivastav, hereby certify that the work which is being presented in this thesis entitled “FINITE ELEMENT SIMULATION OF CHIP FORMATION IN ORTHOGONAL CUTTING” in the partial fulfillment of requirement for the award of degree of Masters of Technology in Production Engineering submitted in the Department of Mechanical Engineering, Delhi Technological University, Delhi is an authentic record of my own work carried out during a period from July 2020 to June 2021, under the supervision of Prof. A.K. Madan and Dr. M. S. Niranjan, Department of Mechanical Engineering, Delhi Technological University, Delhi.

The matter presented in this thesis has not been submitted in any other University/Institute for the award of M.Tech Degree.

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Finally, and most important, I would like to thank my family members for their help, encouragement and prayers through all these months. I dedicate my work to them.

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ABSTRACT

This research is part of the Department of Mechanical Engineering's continuing research. A basic orthogonal cutting process was simulated under a variety of cutting circumstances, including changing the tool shape and cutting speed. Fracture criteria were utilized

to model ductile material fracture. The work on predicting ductile fracture onset and propagation in orthogonal cutting procedures is summarized in this article. The FEM program's findings demonstrate the modified FEM software's ability to forecast cutting variables and serrated chip production.

Key words: Finite-element method; Cutting; Damage; Chip formation

CONTENTS

LIST OF FIGURES

1. INTRODUCTION

The use of the finite-element method (FEM) has proven to be an effective technique to investigate and optimize forming processes. Simulation of cutting processes will be effective for improving cutting tool design and selecting optimum working conditions, especially in advanced applications such as in the machining of dies and moulds. This technique will reduce time consumption and expensive experimental testing.

In plastic deformation processes, such as cutting, extrusion and shearing, the prediction and the control of fracture are a critical issue for producing defect-free parts. Prediction of damage and fracture is necessary to investigate the sur- face finish and the integrity of the parts produced.

A commercial, general purpose FE code, DEFORM 2D, has been modified to study the material damage and the fracture propagation in orthogonal cutting [1,2]. In the numerical model, material fracture is simulated by deleting the mesh elements that have been subjected to high deformation and stress. Fracture occurs when the critical damage value, calculated using a ductile fracture criterion, is satisfied. The definition of the proper damage value for the separation criterion is a crucial point because it is not easily measurable by experiment. This study is introductory and a more detailed study on the breakage mechanism and on the critical damage values is required.

2. ORTHOGONAL TURNING PROCESS

A cutting process is called orthogonal if the cutting edge of the tool is perpendicular to the direction of the cutting velocity.

In order to achieve the basic knowledge of the mechanics in metal removal, the orthogonal two-dimensional cutting is going to be explained in this section. The material is removed by the cutting tool edge precisely located perpendicular to the workpiece surface. Therefore, in this shaping process the tool's cutting edge is also perpendicular to the direction of the cutting velocity (Vc).

To understand the cutting process, some parameters have to be defined. As an introduction, width of cut (w) and depth of cut (Ap, or Uncut chip thickness represented by to in Fig.) are two properties that are going to describe the dimension of the metal chip removed.

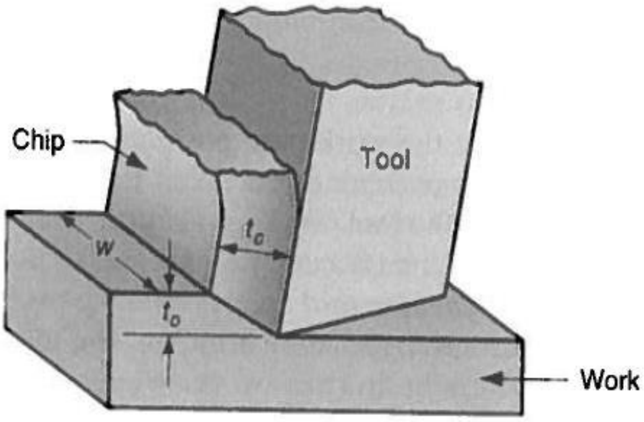


Figure 1 Three-dimensional orthogonal cutting representation

In cutting operations it is known that the chip formed flow off as series of parallel plates sliding relative to each other (Groover, 2011). As the chip is formed along the shear plane, the uncut chip thickness increases to the deformed chip thickness (tc), the relation between them is called the chip compression ratio(rc). Related as follows (Altintas, 2012).

3. CUTTING FORCES DURING TURNING

The cutting is assumed to be uniform and the cutting forces are going to be found in the directions of the velocity and the feed rate (f). These two forces are called Tangential Force (Ft) and Feed force (Ff). Only orthogonal two-dimensional cut is being explained by now, in oblique cutting a third force appears due to the inclination angle (i) of the cutting edge. This force acts in the radial direction, Radial Force (Fr).

In the figures below the deformation geometry caused by the removal operation and the forces generated in it are shown. In this simple explanation, it is assumed that the cutting edge is sharped and without nose radius, so the deformation produced in the shear zone is thin enough.

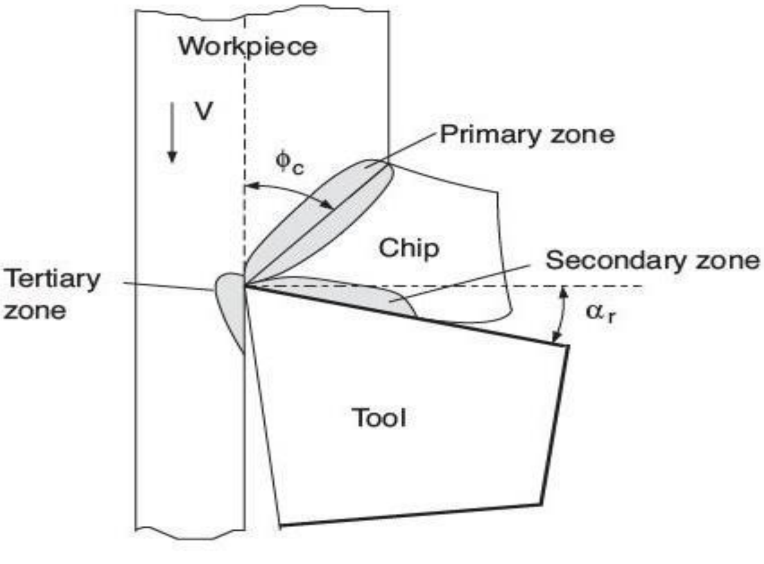


Figure 2 Orthogonal cutting zones

To describe in a better way the geometry, some parameters are explained. The shear angle φc is defined as the deviation between the share plane and the direction of the cutting speed. Also the rake angle (αr) of the tool is shown. It is also known that the normal stress (σs) and the shear stress (τs) are considered constant. (Altintas, 2012).

Force equilibrium is found as the relation between forces. The resultant cutting force is the formed from the tangential cutting force (Ft) and the Feed force (Ff), as presented by (Altintas, 2012).

$$F_c = \sqrt{F_t^2 + F_f^2}$$

Feed force (Ff) is found in the direction of the uncut chip thickness and Tangential force (Ft) on the direction of the Cutting Velocity (Vc). As the equilibrium theory proves, the tool receives the same forces in equal amplitude but opposite direction (Altintas, 2012).

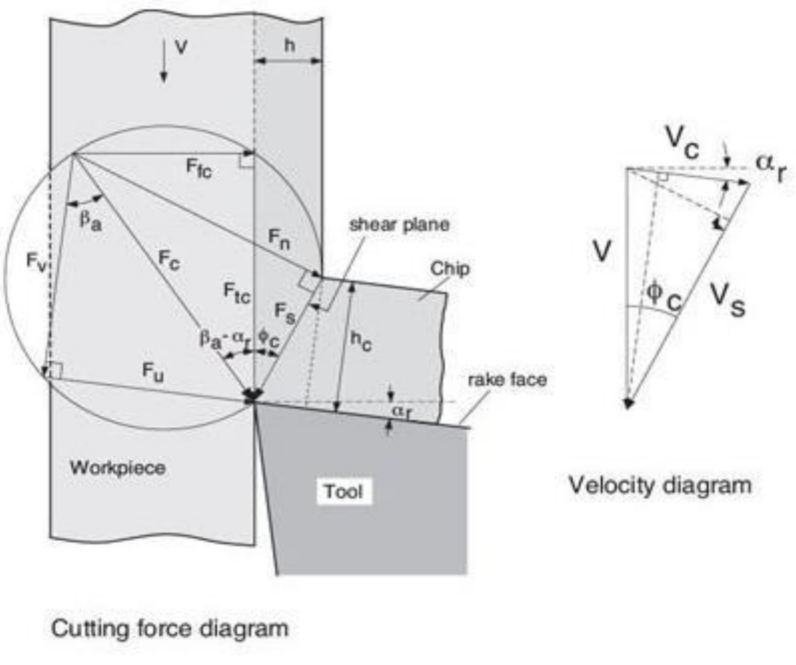


Figure 3 Mechanics of orthogonal cutting

The velocity diagram (see Fig.) also called shear strain triangle, is used to derive strain equation.

However, it has to be highlighted that not all forces can be measured directly. In fact, only the forces acting on the tool can be measured directly. Tangential cutting force (Ft) and Feed force (Ff)(also called Thrust force).

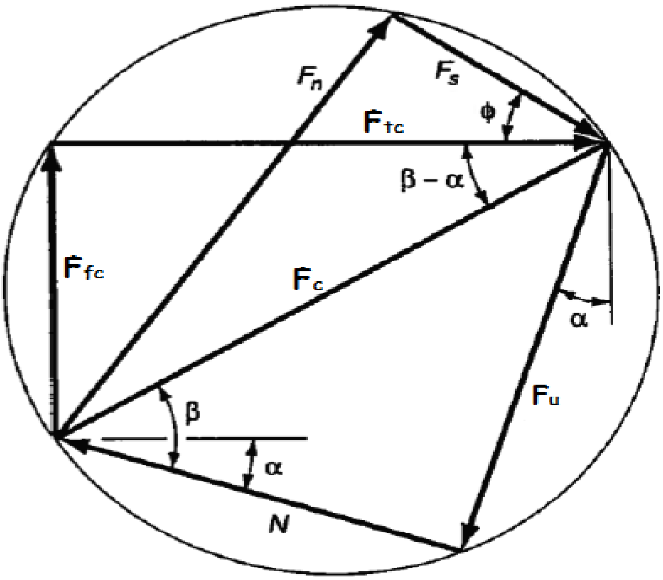


Figure 4 Mechanics of Merchant Circle

The rest of forces are the ones acting in the chip and for calculating them, the relationship between them must be known.

The Shear force (Fs) is the force acting in the shear plane and it can be calculated as (Altintas, 2012):

$$Fs=Fc\cos(\phi c+\beta-\alpha r)$$

Also, there is a Normal force (Fn) acting on the shear plane and it is similarly described by the equation (Altintas, 2012),

$$F_n = F_c \sin(\phi + \beta - \alpha)$$

Two components of the cutting force belonging to the secondary shear zone are acting directly on the rake face of the tool. The normal force (N) and the Friction force (Fu) on the rake face are presented as follows

$N = F_t \cos\alpha_r - F_f \sin\alpha_r$

$F_u = F_t \sin\alpha r - F_f \cos\alpha_r$

Shear stress (τs) is the component of stress that is coplanar with the shear plane surface. As it is

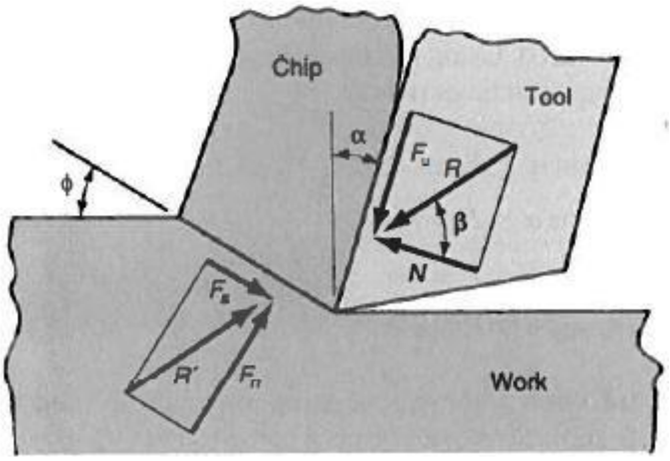


Figura 5 Forces acting in the chip

$\tau s = Fs/As$

Where As is the Area of the shear plane and it is determined by

$As = wh/\sin\phi$

Where w is the width of cut and h the uncut chip thickness (depth of cut in turning).

In the moment when the shear angle is needed the (rc) ratio must be calculated. The shear angle is found from the geometry as a function of the rake angle and the chip compression ratio as (Altintas, 2012),

$\phi=\tan-1(rc\cos\alpha/1-\sin\alpha)$

As it is known, orthogonal cutting cannot be directly applied to practical cutting calculations due to numerous facts such as tool geometry, workpiece material or chip breaking grooves. It is recommended to carry on some experiments to determine the constant parameters of the cutting operations. Moreover, oblique cutting mechanics and plasticity analysis are needed to establish the real behaviour of a particular cutting process.

3.1 Tool Geometry

In machining, tool geometry is an important aspect to consider due to its influence in cutting forces dimensions and chip formation behaviour. Moreover, these factors will directly affect to other issues such as tool deflection, vibration, etc.

The most important geometrical parameters are included in the figure below. These parameters are the side cutting edge angle, end cutting edge angle, cutting edge inclination and the nose radius.

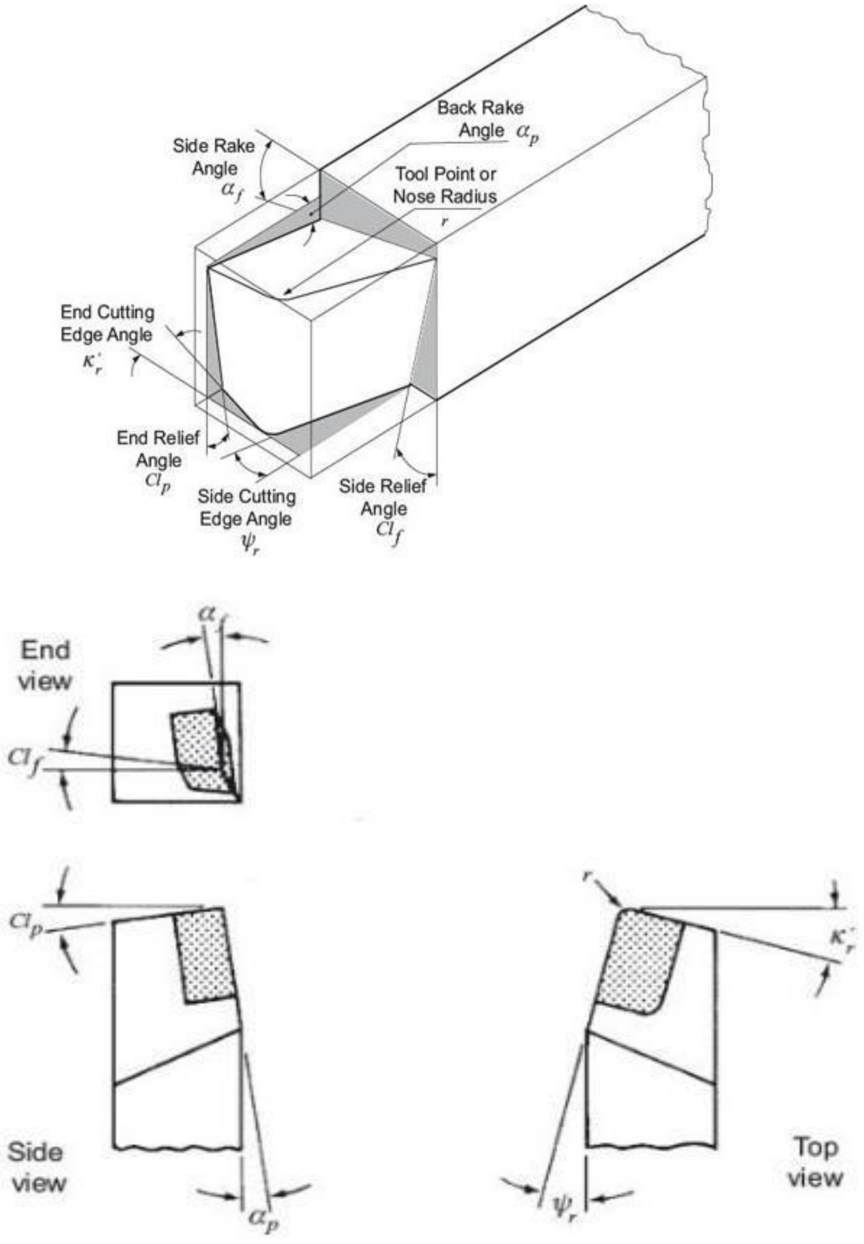


Figure 6 Geometry of a turning tool

3.1.1. Side cutting edge angle

Side cutting edge angle (ψ) is the angle between the side cutting edge and the axis of the tool. It is used to reduce impact load and is also useful for a better distribution of the forces along the cutting tool. Chip thickness, feed and radial forces can be controlled by the correction of this parameter.

Increasing the side cutting angle produce an enlargement of the chip contact length and decreases chip thickness. Therefore, cutting forces are dispersed acting in a longer cutting surface and in different directions. Depending on the direction of this angle, it can make reduce or increase the radial forces

Therefore, thin and slender tools/workpieces can suffer from bending problems. Modification of the side cutting angle is a useful measure to avoid undesired radial forces and prolong tool’s life. Thus, rigidity of the machine is also important when considering changing this angle. Side cutting angle producing big forces in radial direction is not recommended in low rigidity machines.

3.1.2. End cutting edge angle

End cutting edge angle (Ϗ) is the angle, the end cutting edge makes with the width of the tool. It is normally used to avoid interference between the machined surface, often with difficult and irregular shapes, and the tool. Usually the end cutting angle goes from 5° to 15°.

Decreasing the end cutting edge angle increases cutting edge strength but also increases forces in the back part of the tool, that can cause chattering and vibrations during the cutting operation. Edge temperature is also increased by decreasing this angle.

3.1.3. Cutting edge inclination (Rake iangle)

The rake angle indicates the inclination of the rake face, inclination towards the edge of the tool, which is perpendicular to the surface of the workpiece in turning.

The cutting edge receives a heavy impact at the beginning of each cut, this inclination protects the tool's cutting edge from receiving the whole impact and avoids fracturing.

Cutting edge inclination is also important for chip formation and the disengagement of it.

A large rake angle reduces the tool's cross section, area of the tool that absorbs the heat. This can make the tool become weak and reduce its life.

This angle is composed by two different angles:

- Back rake angle: is the slope given to the face or the surface of the tool. This slope is given from the nose along the length of the tool.
- Side rake angle: This slope is given from the nose along the width of the tool.

A negative cutting edge inclination makes the chip flow in the workpiece direction. Otherwise, a positive cutting edge inclination disposes the chips in the opposite direction, flowing out of the operation.

Positive rake angle geometry is suitable for machining soft, ductile materials (Ex: aluminum) and negative is for cutting hard materials, where the cutting forces are high (Hard material, high speed and feed). It can also affect in matters of chattering and vibrations as a result of the increment of back forces due to a negative cutting inclination. By the way, this property can also increase the cutting edge strength.

3.1.4. Nose radius

Nose radius is probably the most important characteristic about the tool geometry. It is the angle between the side cutting edge and the end cutting edge. The selection of it depends on the depth of cut (Ap) and the feed rate (f), and influences in the surface finish, the insert strength and the chip breaking. Nose radius also affects in the chip formation, at the same feed rate, a smaller nose radius generates a better chip breaking. A small nose radius is recommended for small depths of cut. The insert strength is reduced but also undesired radial forces that can produce vibrations are avoided. However, while a large corner radius and small federate create good surface, small corner radius and large feed rates leave more material behind causing a rougher finish.

In the other hand, a big nose radius can be useful if higher values of feed rate or depth of cut are required. This factor will increase the insert strength but also can lead to increased radial forces.

It is assumed that axial forces are preferred to radial forces. Radial forces can lead to bending, chattering or vibrations and therefore, poor surface finish. As higher the depth of cut, higher axial forces and lower radial.

Figure 7 Force relation with depth of cut

4. CHIP FORMATION IN TURNING PROCESS

The basic mechanics of forming a chip are the same regardless of the base material. As the cutting tool engages the workpiece, the material directly ahead of the tool is sheared and deformed under tremendous pressure. The deformed material then seeks to relieve its stressed condition by fracturing and flowing into the space above the tool in the form of a chip. The real difference is how the chip typically forms in various materials.

Regardless of the tool being used or the metal being cut, the chip forming process occurs by a mechanism called plastic deformation. This deformation can be visualized as shearing. That is when a metal is subjected to a load exceeding its elastic limit.

The crystals of the metal elongate through an action of slipping or shearing, which takes place within the crystals and between adjacent crystals.
Cast Iron, Hard Brass and other materials that produce a Powdery chip

“Discontinuous Chip - Discontinuous or segmented chips are produced when brittle metal such as cast iron and hard bronze are cut or when some ductile metals are cut under poor cutting conditions.

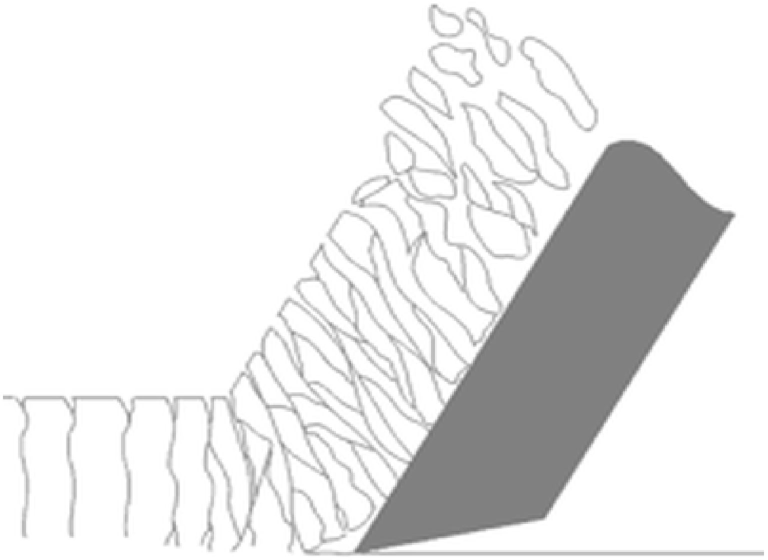


Figure 8 Discontinuous Chip

As the point of the cutting tool contacts the metal, some compression occurs, and the chip begins flowing along the chip-tool interface. As more stress is applied to brittle metal by the cutting action, the metal compresses until it reaches a point where rupture occurs and the chip separates from the unmachined portion.

This cycle is repeated indefinitely during the cutting operation, with the rupture of each segment occurring on the shear angle or plane. Generally, as a result of these successive ruptures, a poor surface is produced on the workpiece."

Notice how the chips deform and begin to break up at a considerable distance in front of the cutting edge. Chip control is usually not a problem when machining these materials. Harder, more heat and wear resistant Carbide Grades can be used in these applications. Edge strength becomes less of a factor vs. machining Steel or Stainless or other materials that make long chips. Medium to High carbon and alloy Steels – Long Chipping Materials

“Continuous Chip - Continuous chips are a continuous ribbon produced when the flow of metal next to the tool face is not greatly restricted by a built-up edge or friction at the chip tool interface. The continuous ribbon chip is considered ideal for efficient cutting action because it results in better finishes. Unlike the Type 1 chip, fractures or ruptures do not occur here, because of the ductile nature of the metal.”

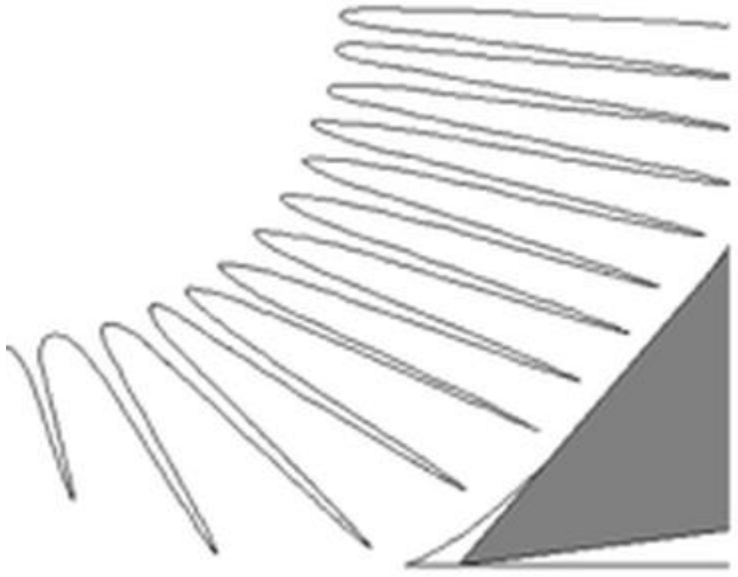


Figure 9 Continuous Chip

Carbon and Alloy Steels such as 1030, 1035, 1045, 1144, 4130, 4140, 4340 contain at least .3% carbon that allows them to be hardened by heating and quenching. They produce long continuous chips.

When machining these metals with Carbide Inserts the material in front of the cutting edge deforms resulting in high temperatures which softens the metal and consequently lowers it's strength and hardness making it easier to machine.

The chips weaken and begin to break in front the cutting edge; the tool acts much in the same way that a wedge does when splitting wood. In some cases, air, oil or coolant quenches the hot chips, hardening them and making them brittle and easier to break.

The chips produced when cutting these metals contact the face of the tool behind the cutting edge creating a zone of high heat that can result in cratering. Coatings usually eliminate this problem.

Type 2: Continuous chip materials are the other area where many of our competitors have focused their attention.
Low carbon Steels, Stainless Steels, Nickel Alloys, Titanium, Copper, Aluminum and other soft, “gummy’ Materials.

Sheared Chips or as some refer to it “Continuous Chip with a Built-up Edge (BUE). The metal ahead of the cutting tool is compressed and forms a chip which begins to flow along the chip-tool interface

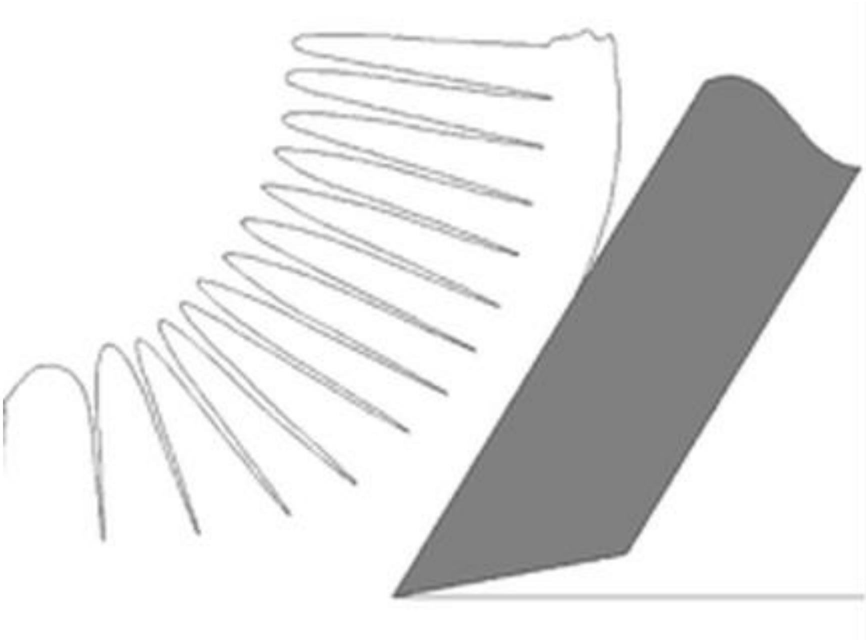


Figura 10 Sheared Chips

As a result of the high temperature, the high pressure, and the high frictional resistance against the flow of the chip along the chip-tool interface, small particles of metal begin adhering to the edge of the cutting tool while the chip shears away.

As the cutting process continues, more particles adhere to the cutting tool and a larger build-up results, which affects the cutting action. The built-up edge increases in size and becomes more unstable. Eventually a point is reached where fragments are torn off. Portions of these fragments break off and stick to both the chip and the workpiece.

The build-up and breakdown of the built-up edge occur rapidly during a cutting action and cover the machined surface with a multitude of built-up fragments. These fragments adhere to and score the machined surface, resulting in a poor surface finish.

These metals readily deform in front of the cutting edge and have to be "sheared" by the tool. What the above paragraph doesn’t tell you is that these materials require tools with sharper cutting edges than those used for machining cast Iron or higher carbon content Steels. The chips tend to compress onto the face of the tool which can result in built-up edge.

The chips formed when cutting these metals are thicker than those produced by Medium Carbon or Alloy Steels at the same Feed Rates and Depths of Cut. These thicker chips are stronger and harder to break. Destiny Tool, through a combination of rake face geometry, carbide substrate and concentricity tolerance is able to enable the chip to more readily "separate from itself" which not only improves MRR, but also reduced heat into the end mill and thereby extends tool life as the feed rate increases.

High strength metals such as Stainless Steel, Nickel Alloys and Titanium generate high heat and high cutting pressures in the area of the cutting edge. This results in reduced tool life compared to easier to machine materials.

5. EXPERIMENTAL PROCEDURE

5.1 The customized FEM model

To simulate orthogonal cutting with serrated chip formation, the FEM code DEFORM 2D has been used and customized. New sub-routines have been written and linked to the original code. This new modified version has the potential of simulating material breakage by deleting the mesh elements of the workpiece material when their damage is greater than a defined critical value. The modified code differs from the original code in the remeshing module, where new features are highlighted. of the workpiece is extracted and it is smoothed. This smoothing operation reduces the loss of volume in the workpiece determined by element deletion and helps in the convergence of the FEM solver. A new mesh is generated and the interpolation gives the new elements of the mesh the corrected properties.

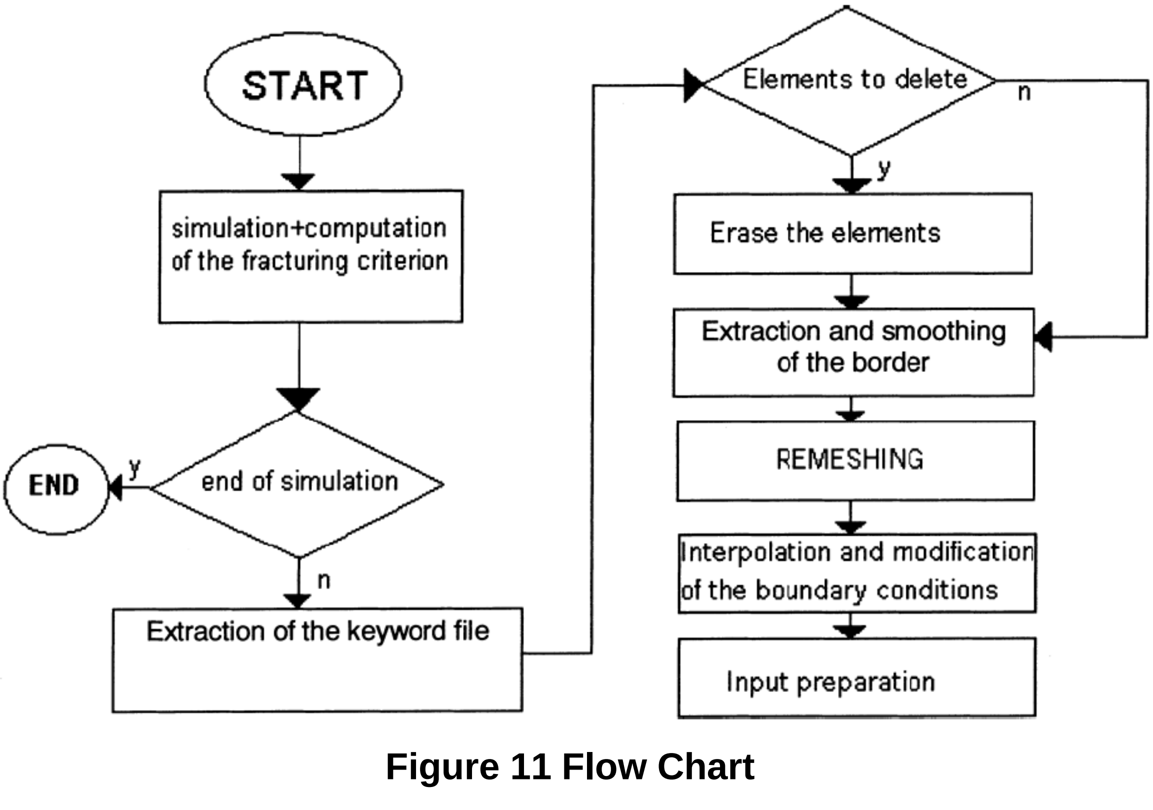


Figure 11 Flow Chart

5.2 Damage criteria

The Cockroft and Latham damage criterion has been used. The damage is evaluated according to the equation

Fig. shows the new remeshing module. The remeshing operation occurs when the elements of the mesh are too distorted or at a regular limiting range of steps defined by the user. The database of the simulations is opened and a keyword (ASCII) file is generated, saving all the data of the actual step. For each element of the workpiece mesh the damage is evaluated. When the damage criterion used is satisfied by an element, the code of the element is stored in a temporary file. A new sub-routine opens the temporary file and deletes all the coded (listed) elements. Then the border

$$C_i = \int_{0}^{o_f} \bar{a} \, \frac{a^{m}\Sigma}{a} \, d\bar{o},$$

where Ci is the critical damage value given by a uniaxial tensile test, of the strain at the breaking condition, o the effective strain, the effective stress and is the maximum stress.

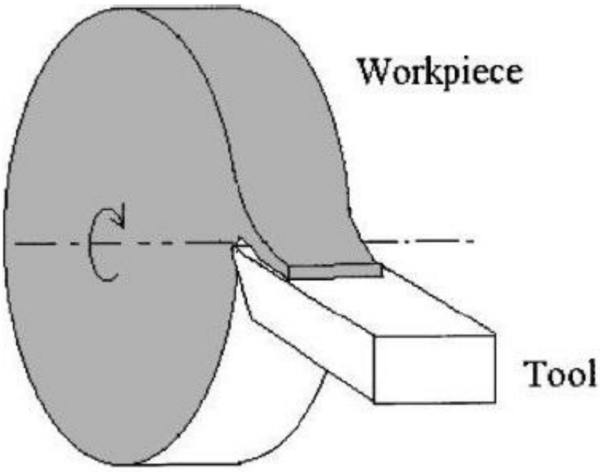
The criterion predicts the material damage when the critical value Ci is exceeded. To optimize the material fracture in cutting operations a combined criterion has been used. The Cockroft and Latham criterion has been combined with a criterion based on the effective stress.

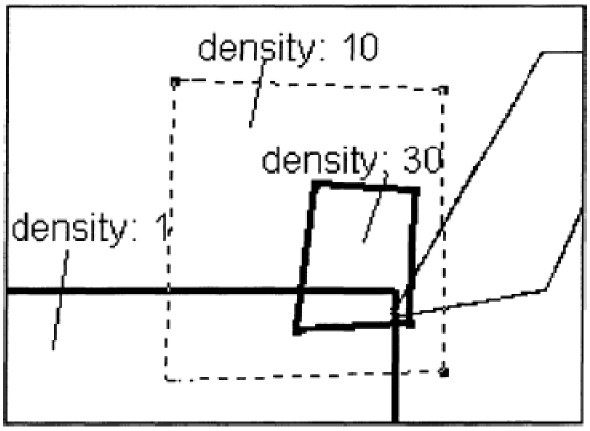
Two critical values have been defined, Ci and amax. The damage is evaluated for each element of the workpiece. The element deletion occurs when both the damage values are satisfied.

The theoretical assumption was that the critical damage value is a workpiece material constant and it does not depend on the working operation or on the tool material. The critical value is evaluated by a tensile test. During the simulative runs, to obtain results in agreement with the experimental observations, different critical values have been used, and their dependence on the type of process noted.

5.3 Orthogonal cutting simulation

The cutting operation shown in Fig. was simulated. When the diameter of the cylinder is large compared to the depth of cut, the plane-strain condition is satisfied. The orthogonal cutting operation is modelled as shown in Fig.





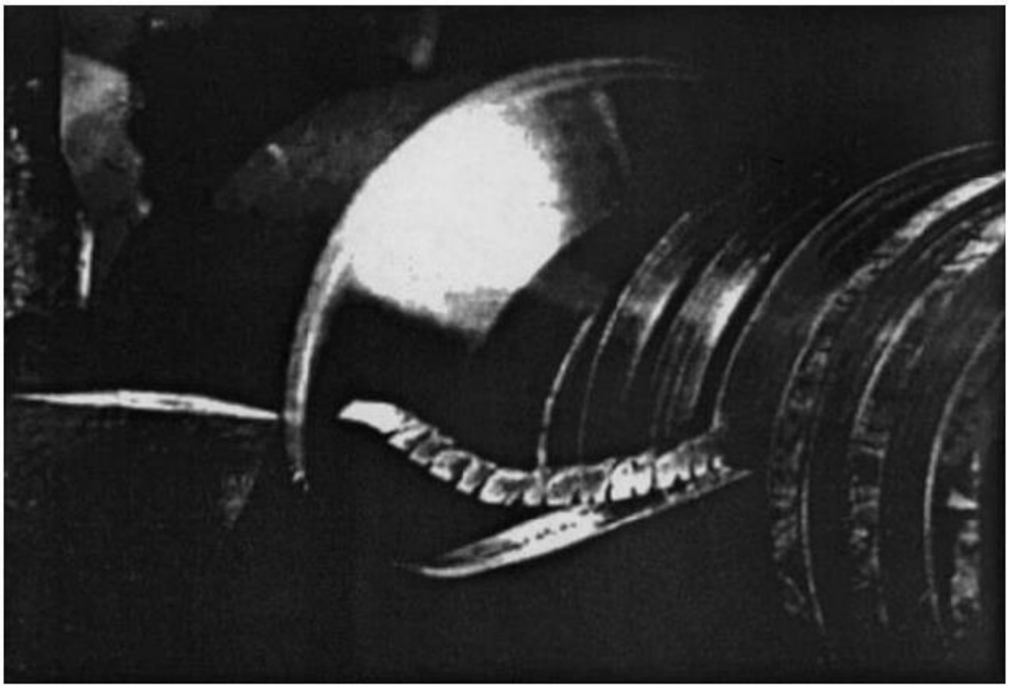


Figure 12 Machining process

The width of the cutting tool is larger than the engaged workpiece. The model of the simulation is plane-strain and non-isothermal. In the simulations the workpiece is assumed to be rigid–plastic and to have a rectangular shape, see Fig. The latter figure shows the regions with a different density for the elements of the mesh. The mesh density is increased in the area affected by the cutting process in order to reduce time consumption and storage space. The tool is assumed to be a rigid body.

Several data have to be provided to the pre-processor of the FEM program: the geometry of the tool and the work- piece, the material properties (flow stress as a function of strain, strain rate and temperature), the thermal properties, the boundary conditions and the interaction between the tool and the workpiece. The post-processor of the FEM code provides output such as: material flow (velocity, strain and strain rate fields), loads (stresses, forces and power), temperatures and damage.

5.4 Simulation set-up

The workpiece material is steel AISI 1043 and the cutting tool material is a high-speed steel (H11). Different cutting tools were used and different cutting speeds were selected. No lubricant is used at the tool–workpiece interface. The cutting conditions are shown in Table. Simulation set C refers to a chip breaker tool.

5.5 Simulation results: chip formation

5.5.1 Simulation ret A

In the following figures the chip formation is shown for different tool paths. The chip shapes obtained from the simulations with different cutting speeds are compared. Since no experimental data are available, only a qualitative comparison is possible.

For the same tool position, the different simulations show results in agreement with the general experimental observations in the literature [6]. For example,

(i) in- creasing the cutting speed results in modifying the chip flow from continuous to serrated or discontinuous, and

(ii) reducing the depth of cut or increasing the cutting speed has the same effect on the chip shape, i.e., the segmentation increases, although the length of the cuts in the chip becomes shorter.

Over a certain particular cutting speed limit, the chip shape turns again into con- tenuous. The critical values used for the damage criterion for this set of simulations are: amax 830 Mpa¡ Ci 0.3 (Cockroft and Latham).

The analysis of the chip formation shows that increasing the cutting speed increases the segmentation of the chip, but the cuts in the chip are shorter. The greater the cutting speed, the less curled are the chip. The chip shape is in agreement with experimental results obtained from the cutting of a mild steel, as shown in Fig. and with the experimental observations mentioned above. The break- age starts in the region close to the tool rake face. The same kind of behaviour is expected according to the Merchant prediction for discontinuous chip formation with positive rake angle.

6. DEFORM 2D

DEFORM-2D is a powerful process simulation system designed to analyse the two-dimensional (2D) flow of complex metal forming processes using an axisymmetric or plane strain assumption. Typical applications include:

closed die forging, open die forging machining, rolling, extrusion, heading, drawing, cogging, compaction, upsetting

DEFORM-2D is an ‘open system’ that provides incredible flexibility to designers and analysts working on a range of applications, development and research. DEFORM-2D supports user routines and user defined variables. Complex multiple deforming body capability with arbitrary contact allows users to simulate mechanical joining and coupled die stress analysis.

Based on the finite element method, DEFORM has proven to be accurate and robust in industrial application for more than two decades. The simulation engine is capable of predicting large deformation material flow and thermal behaviour with astonishing precision. DEFORM is the most widely used simulation program in the world by leading research institutes and manufacturers. See our product information for additional details.

7. FEM

The finite element method (FEM) is a numerical analysis technique for obtaining approximate solutions to a wide variety of engineering problems. A finite element model of a problem gives a piecewise approximation to the governing equations. The basic premise of the FEM is that a solution region can be analytically modeled or approximated by replacing it with an assemblage of discrete elements (discretization). Since these elements can be put together in a variety of ways, they can be used to represent exceedingly complex shapes.

Several approximate numerical analysis methods have evolved over the years. As an example of how a finite difference model and a finite element model might be used to represent a complex geometrical shape, consider the turbine blade cross section in Figure 1 and plate geometry in Figure 2. A uniform finite difference mesh would reasonably cover the blade (the solution region), but the boundaries must be approximated by a series of horizontal and vertical lines (or "stair steps"). On the other hand, the finite element model (using the simplest two-dimensional element-the triangle) gives a better approximation of the region. Also, a better approximation to the boundary shape results because the curved boundary is represented by straight lines of any inclination. This is not intended to suggest that finite element models are decidedly better than finite difference models for all problems. The only purpose of these examples is to demonstrate that the finite element method is particularly well suited for problems with complex geometries and numerical solutions to even very complicated stress problems can now be obtained routinely using finite element analysis (FEA)

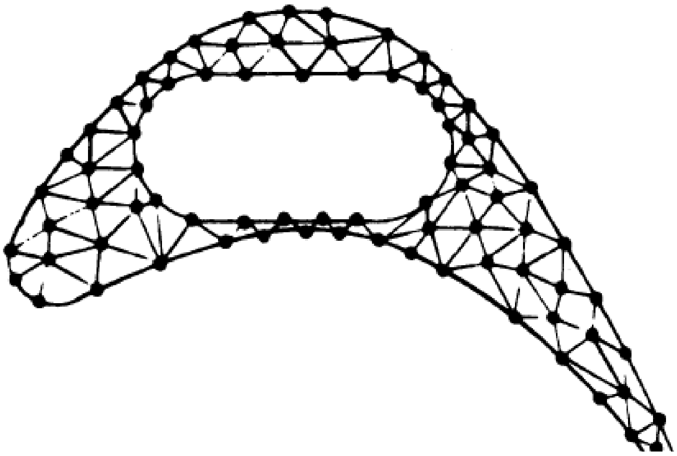


Figure 13 finite element discretization's of a turbine blade profile

The finite element discretization procedure reduces the problem by dividing a continuum to be a body of matter (solid, liquid, or gas) or simply a region of space into elements and by expressing the unknown field variable in terms of assumed approximating functions within each element. The approximating functions (sometimes called interpolation functions) are defined in terms of the values of the field variables at specified points called nodes or nodal points. Nodes usually lie on the element boundaries where adjacent elements are connected. In addition to boundary nodes, an element may also have a few interior nodes. The nodal values of the field variable and the interpolation functions for the elements completely define the behaviour of the field variable within the elements. For the finite element representation of a problem the nodal values of the field variable become the unknowns. Once these unknowns are found, the interpolation functions define the field variable throughout the assemblage of elements. Clearly, the nature of the solution and the degree of approximation depend not only on the size and number of the elements used but also on the interpolation functions selected. As one would expect, we cannot choose functions arbitrarily, because certain compatibility conditions should be satisfied. Often functions are chosen so that the field variable or its derivatives are continuous across adjoining element boundaries.

An important feature of the finite element method that sets it apart from other numerical methods is the ability to formulate solutions for individual elements before putting them together to represent the entire problem. This means if we are treating a problem in stress analysis, we find the force–displacement or stiffness characteristics of each individual element and then assemble the elements to find the stiffness of the whole structure. In essence, a complex problem reduces to a series of greatly simplified problems. Another advantage of the finite element method is the variety of ways in which one can formulate the properties of individual elements. There are basically three different approaches.

The first approach to obtaining element properties is called the direct approach because its origin is traceable to the direct stiffness method of structural analysis. Although the direct approach can be used only for relatively simple problems, it is the easiest to understand when meeting the finite element method for the first time. The direct approach suggests the need for matrix algebra in dealing with the finite element equations. Element properties obtained by the direct approach can also be determined by the variational approach. The variational approach relies on the calculus of variations. For problems in solid mechanics the functional turns out to be the potential energy, the complementary energy, or some variant of these, such as the Reissner variational principle. Knowledge of the variational approach is necessary to work beyond the introductory level and to extend the finite element method to a wide variety of engineering problems. Whereas the direct approach can be used to formulate element properties for only the simplest element shapes, the variational approach can be employed for both simple and sophisticated element shapes.

A third and even more versatile approach to deriving element properties has its basis in mathematics and is known as the weighted residuals approach. The weighted residuals approach begins with the governing equations of the problem and proceeds without relying on a variational statement. This approach is advantageous because it thereby becomes possible to extend the finite element method to problems where no functional is available. The method of weighted residuals is widely used to derive element properties for nonstructural applications such as heat transfer and fluid mechanics.

8. CONCLUSION

The results of this study demonstrate the effectiveness of the customized FEM model (for simulating serrated chip formation in orthogonal cutting) in:

(i) predicting chip shapes and the influence of cutting conditions, and

(ii) predicting cutting forces and process para- meters.

The definition of the critical values is crucial. According to Kim et al., it has been noted that the critical values depend on the operation simulated. For instance, the critical damage value in compression or traction tests is different. In the same way, the critical value for simulation with a positive or a negative rake angle is different. In fact, to obtain realistic results for simulations with a tool with a negative rake angle, a critical value 10 times smaller was used for the Cockroft and Latham criterion.

9. FUTURE REFERENCE

In order to predict fracture in cutting more accurately, it is necessary to determine the critical values under realistic deformation conditions (high strain rate and temperatures) and conduct additional studies to compare FEM-based results with the results of experiments.

Different experimental observations were found for orthogonal cutting operation with a tool with a positive rake angle, so that an accurate analysis of the damage critical values is required. Chip segmentation similar to that found for the negative rake angle tool could be simulated by reducing the Cockroft and Latham critical value. An experimental comparison should be made to estimate the breakage mechanism and position for the different cutting conditions (speed and rake angle) and for different steels also.

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