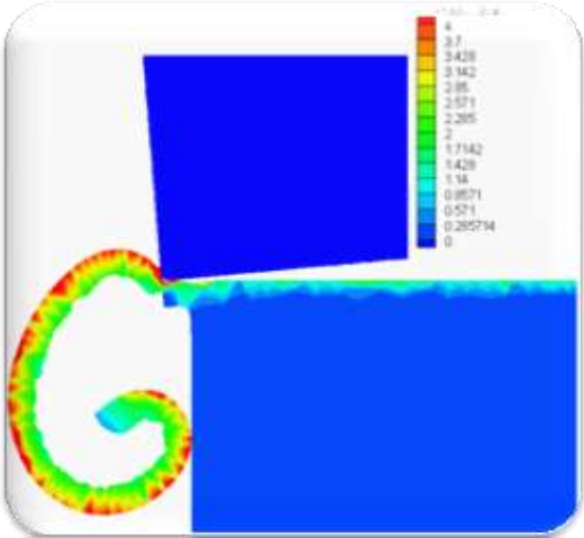


Application of FEM in Precision Machining

Dr-Ing Angelos Markopoulos, Lecturer
National Technical University of Athens
Greece

Rzeszow, Poland
16 September 2015

Machining

- By the term **machining**, processes that shape parts by removing unwanted material, are described. Unwanted material is carried away from the workpiece usually in the form of a chip; evaporation or ablation may take place in some machining operations.
- The more narrow term cutting is used to describe the formation of a chip via the interaction of a tool in the form of a wedge with the surface of the workpiece, given that there is a relative movement between them.

Machining economics

- Surveys indicate that 15 % of all mechanical components value, manufactured in the world, comes from machining operations and that annual expenditure on machine tools and cutting tools are several billion € for industrially developed countries.
- If labor, machinery, tools and materials costs, social impact from employment in machining related jobs and technological developments becoming available from machining advances are considered, then the importance of machining and its impact on today's industry and society is quite obvious.

Machining trends

- Trends in manufacturing technology are driven by two very important factors, which are closely interconnected, namely ***better quality*** and ***reduced cost***.
- Modern industry strives for products with dimensional and form accuracy and low surface roughness at acceptable cost; an extreme paradigm being micromachining of miniaturized components.
- From an economic point of view, machining cost reduction achieved through the increase of material removal rate and tool life without compromising surface integrity even for hard-to-machine materials is highly desirable, e.g. precision turning of hardened steels by CBN tools at increased speeds or as it is usually referred in the literature High Speed Hard Turning.
- Understanding chip formation mechanisms and predicting cutting forces are of the greatest importance on realizing both the above goals and one way to achieve this, probably the most used one, is modeling.

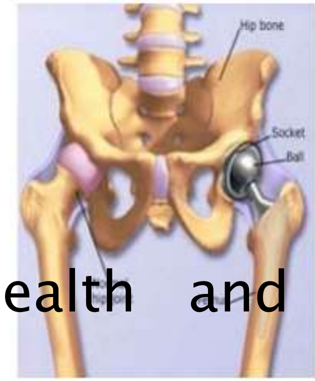
Machining modeling

- Machining of metals, although is one of the oldest and very important manufacturing process, has been subjected to systematic study for a little more than a century. Almost for the second half of this time period, studying of metal machining is accompanied by modeling methods.
- The initial objective of studying and modeling metal machining was to provide a theory which, without any experimental work, would enable researchers to predict cutting performance and thus solve practical problems confronted in industry.
- The first analytical models set the basis for more advanced methods developed later in the course of time and when the tools for realistic computational cost and analysis time became available with computer advances.

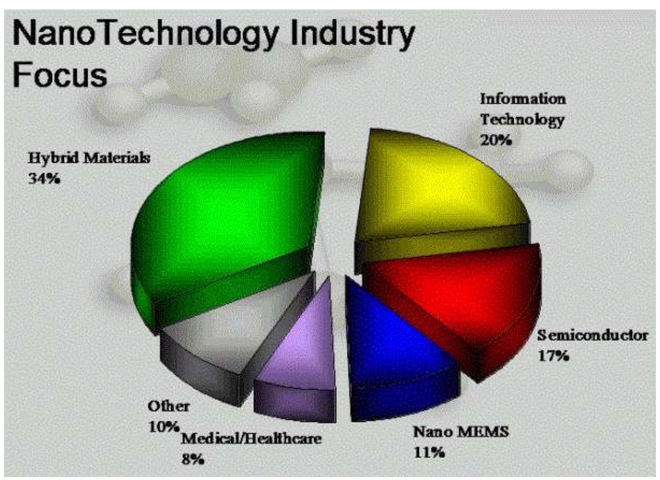
FEM in machining

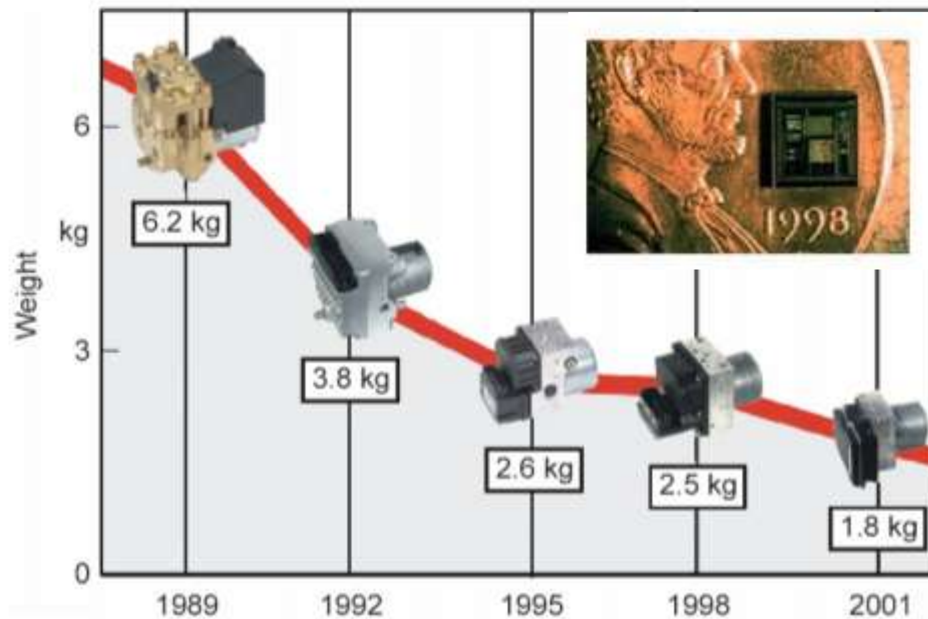
- In the early 1970s some pioneering works on machining modeling with the Finite Element Method (FEM) begun to find their way in scientific journals.
- Over the years and with the increase of computer power as well as the existence of commercial FEM software, this method has proved to be the favorite modeling tool for researchers of the field.
- Finite element models are used today for gaining knowledge on fundamental aspect of material removing mechanisms but more importantly for their ability to predict important parameters such as cutting forces, temperatures, stresses etc. essential for the prediction of the process outcome, the quality of the final product and in a timely and inexpensive way.

Applications…

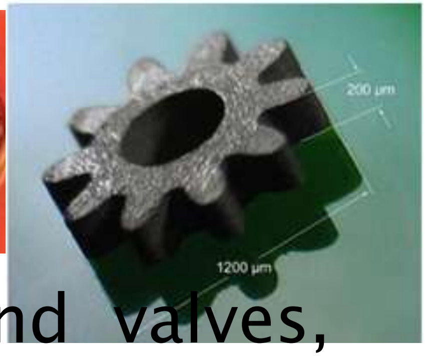


- in sectors such as automotive industry, health and biomedicine and telecommunications.
- At the same time, the integration of microsystems in more applications of the aforementioned areas of interest has given a boost to micro and nanomanufacturing and thus has intensified the research pertaining to MEMS and NEMS, advanced technology, increased performance and decreased cost.

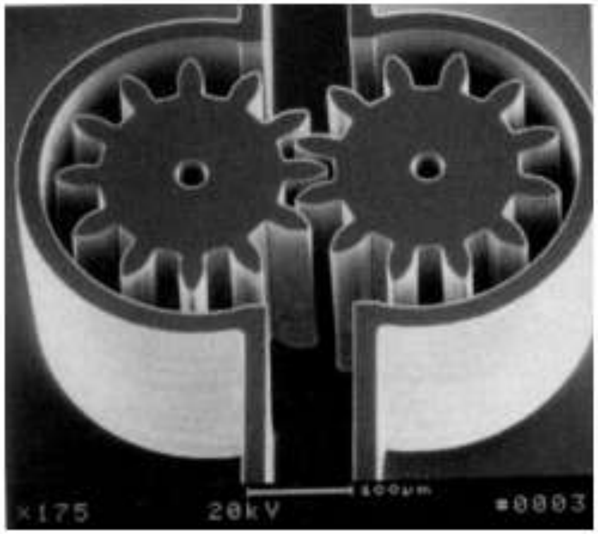


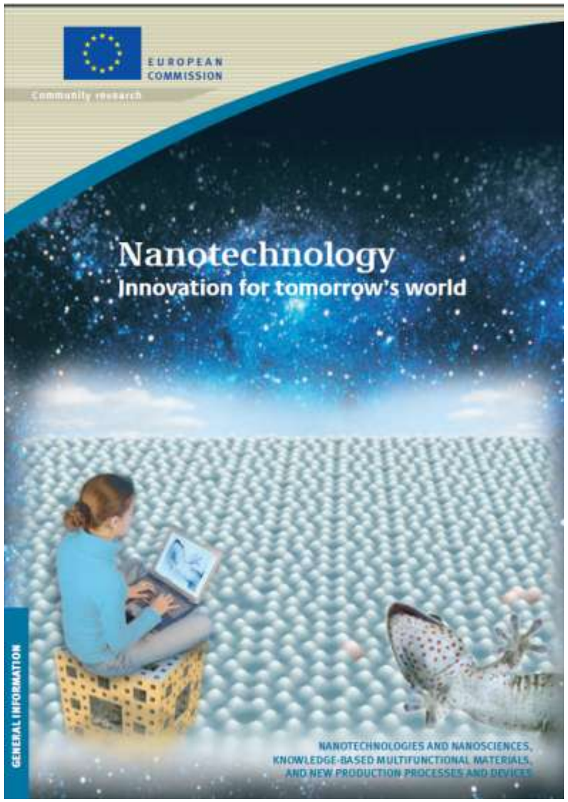


More applications…



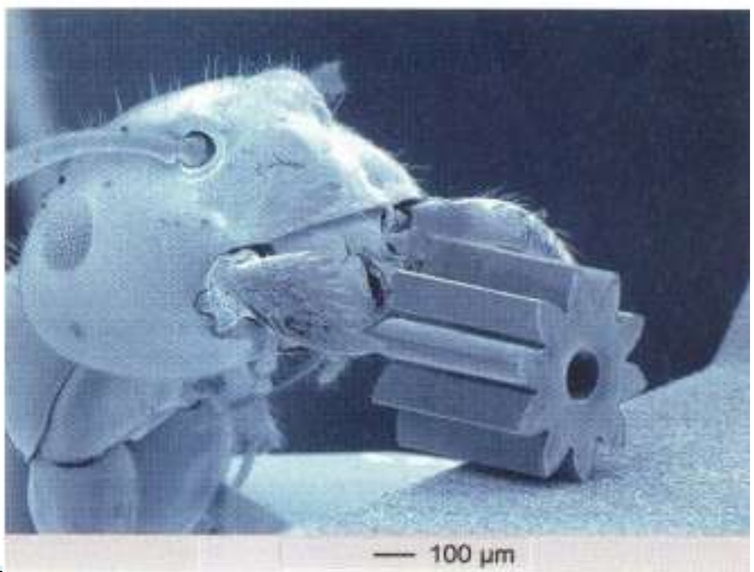
- … pertain to microfluidics, pumps and valves, micronozzles, optical components, micromolds and microholes on various materials just to name some.



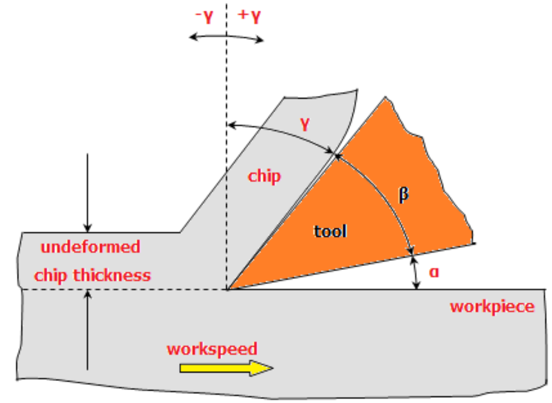


Accurate processing

- It is worth noting that **precision manufacturing** may refer to micromachining and the construction of miniaturized parts but may also refer to precision and ultraprecision process performed on large scale components with some features (size accuracy, tight tolerances, high surface quality etc.) similar to those encountered in miniaturized parts.



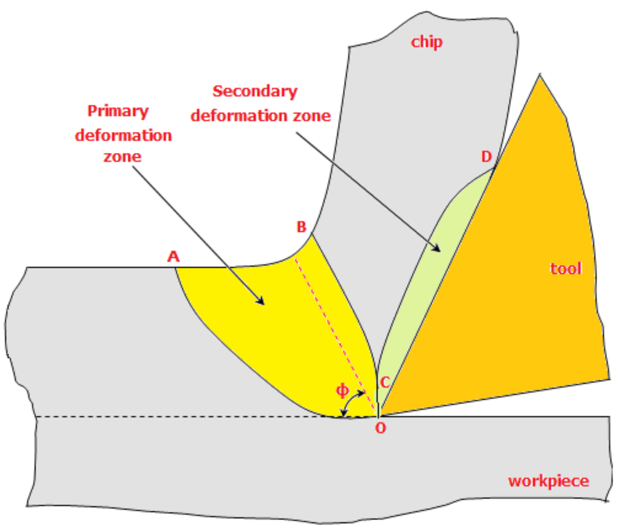
Orthogonal cutting



- Orthogonal cutting represents a two-dimensional mechanical problem with no side curling of the chip considered.
- It represents only a small fragment of machining processes, i.e. planning or end turning of a thin-walled tube.
- However, it is widely used in theoretical and experimental work due to its simplicity. Because of its 2D nature many independent variables are eliminated, e.g. two cutting forces are only identified to orthogonal cutting problems.

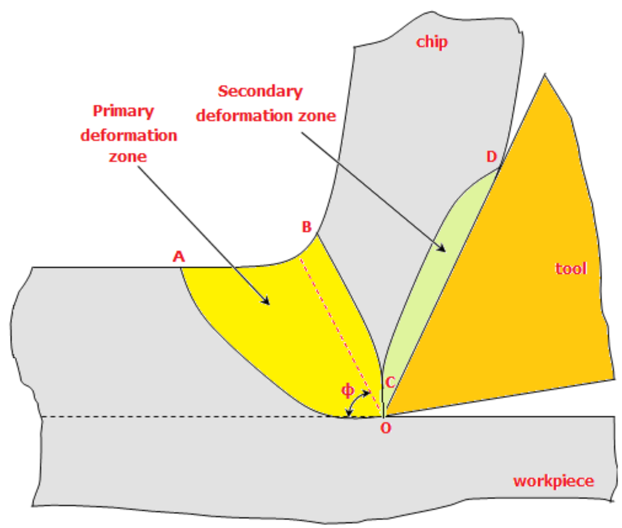
Primary deformation zone

- There are two deformation areas distinguished in machining, namely the primary and the secondary deformation zones.
- In the primary deformation zone, the workpiece material crossing the OA border undergoes large deformation at high strain rates and exits the zone at OB border, work hardened.
- It is determined by microscopic examination and experiments that chips are produced by shear within this region. Most of the experimental studies conclude that this zone is of average thickness of about one tenth of chip thickness.



Secondary deformation zone

- In the secondary deformation zone, in the contact length between the rake face of the tool and the chip, the material is deformed due to intensive interfacial friction.
- The secondary deformation zone is characterized by two regions, the sticking region, closer to the cutting tool tip and the sliding region, above the previous one.
- In the sticking region, material adheres to the tool and as a result shear within the chip is observed.



Single shear plane model

- Both deformation zones are characterized by temperature rise due to severe plastic deformation in the primary and due to friction in the secondary deformation zone.
- Furthermore, high cutting speeds do not allow for heat conduction to take place and heat is concentrated at a small area around the cutting tool edge.
- <u>Strain hardening</u> due to deformation and <u>softening</u> due to temperature alter the chip formation characteristics in every step of its formation.
- The friction coefficient is very hard to be measured in the secondary deformation zone and several theories have been proposed for the calculation of friction.
- A simplified approach proposes that shearing in the primary deformation zone takes place along a shear plane, characterized by shear angle ϕ, between the shear plane and the workpiece surface.
- Although this single shear plane model is criticized, it is usually referred in machining handbooks due to its simplicity and it is the basis for calculating several process parameters, e.g cutting forces, through numerical modeling.

Cutting mechanics

Model	Formula	Year
Ernst–Merchant	$\phi = \frac{\pi}{4} - \frac{1}{2}(\rho - \gamma)$	1941
Merchant	$\phi = \frac{C}{2} - \frac{1}{2}(\rho - \gamma)$	1945
Stabler	$\phi = \frac{\pi}{4} - \rho + \frac{\gamma}{2}$	1951
Lee–Shaffer	$\phi = \frac{\pi}{4} - (\rho - \gamma)$	1951
Hucks	$\phi = \frac{\pi}{4} - \frac{a\tan(2\mu)}{2} + \gamma$	1951
Shaw et al.	$\phi = \frac{\pi}{4} - (\rho - \gamma) \pm \eta$	1953
Sata	$\phi = \frac{\pi}{4} - \gamma \pm \frac{\gamma - 15^\circ}{2}$	1954
Weisz	$\phi = 54.7^\circ - (\rho - \gamma)$	1957
Kronenberg	$\phi = a\cot\left[\frac{e^{\mu\left(\frac{\pi}{2}-\gamma\right)} - \sin\gamma}{\cos\gamma}\right]$	1957
Colding	$\phi = a\tan\left[-\frac{2\left(\frac{F}{H}+2\right)}{\left(\frac{F}{H}+1\right)}\cot(2\Omega) - (\rho - \gamma)\right]$	1958
Oxley	$\phi = a\tan\left[1 + \frac{\pi}{2} - 2\phi + \frac{\cos 2(\phi-\gamma)}{\tan\rho} - \sin 2(\phi - \gamma)\right] - (\rho - \gamma)$	1961
Sata–Yoshikawa	$\phi = a\cot\left\lfloor\cot\theta + \frac{\cos\theta}{\sin(\theta+\gamma)}kL\right\rfloor$	1963
Das–Tobias	$D = \frac{\cos(\rho-\gamma)}{\cos(\rho-\gamma+\phi)}$	1964

Zorev's simplified model

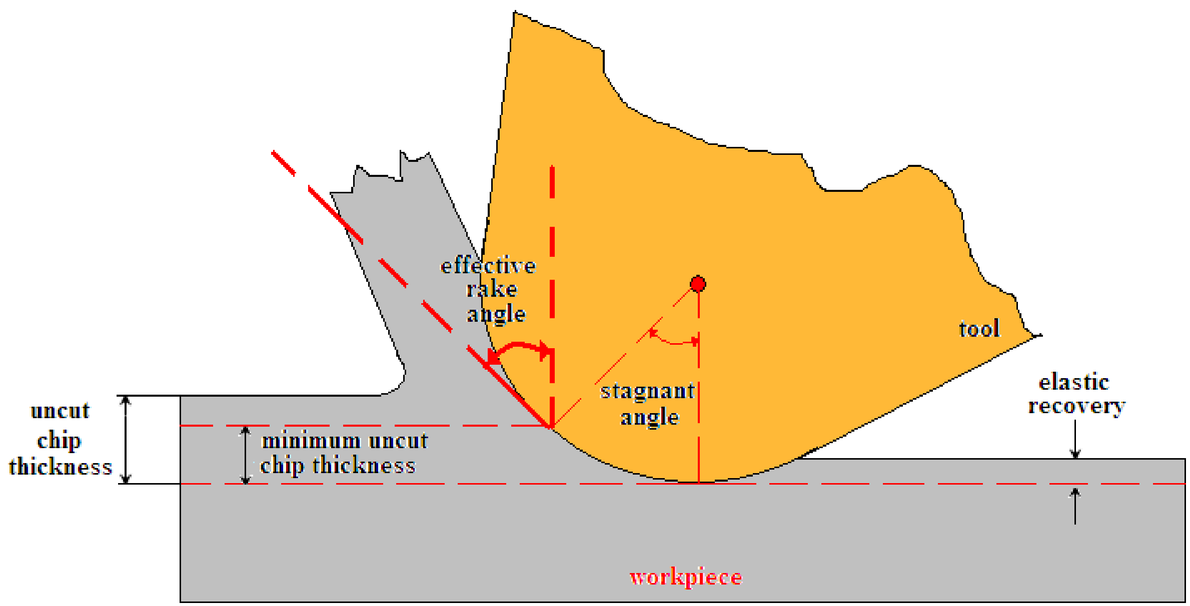
Oxley's shear zone theory

Machining mechanics downscaling

- There are features of machining and phenomena that are considerably different in precision machining and do not allow for a simple “downscaling” of a theory.
- In precision machining and micromachining operations the depth of cut may be below 10 µm and the anticipated surface roughness only a few nm.
- The cutting edge can no longer be considered sharp; the cutting edge radius is comparable in size to the uncut chip thickness.
- At this level, Merchant’s model seems unrealistic.

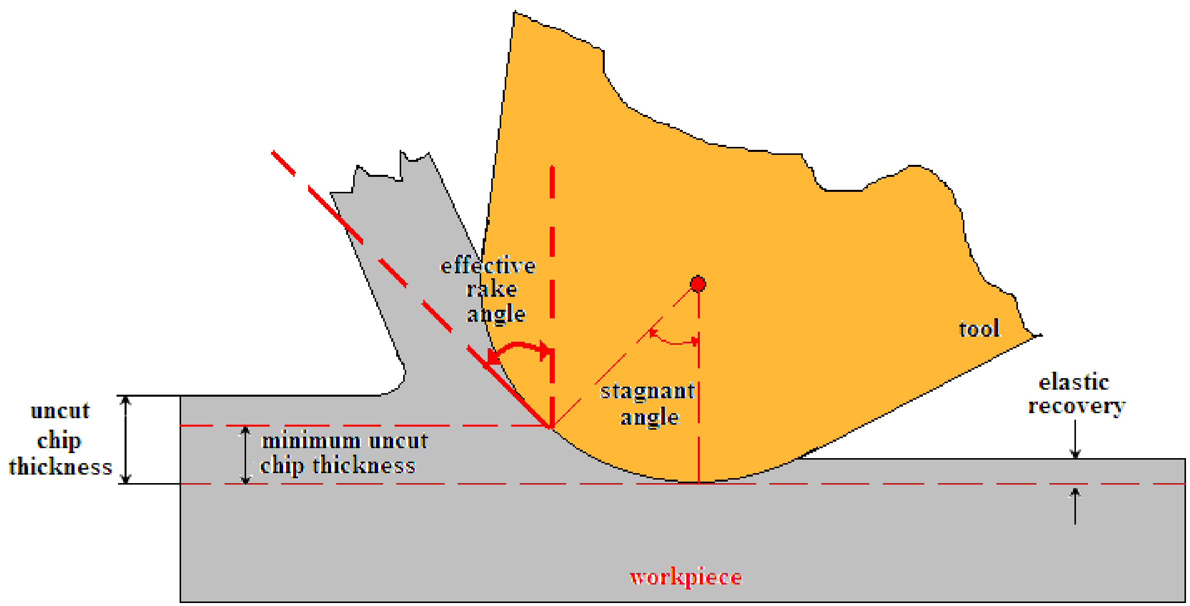
Effective rake angle

- The rake angle of the tool is probably not the actual rake angle participating in the processes.
- There may be an effective rake angle.
- In this case, the elastic-plastic deformation of the workpiece material and the ploughing need to be taken into account, as well as the elastic recovery at the clearance face.



Stagnation point

- From the above, the existence of a <u>minimum chip thickness</u> that can be removed from the workpiece surface in a mechanical micromachining operation can be deducted.
- A stagnation point above which a chip is formed and below only elastic-plastic deformation takes place is assumed.

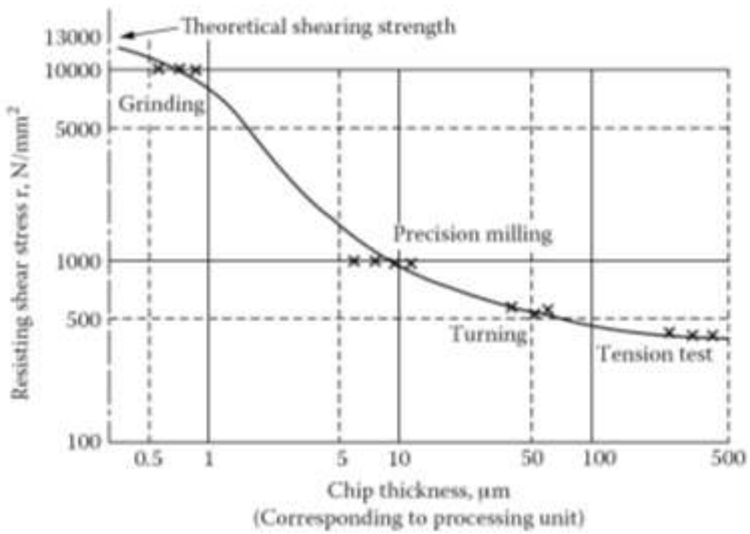


Minimum chip thickness

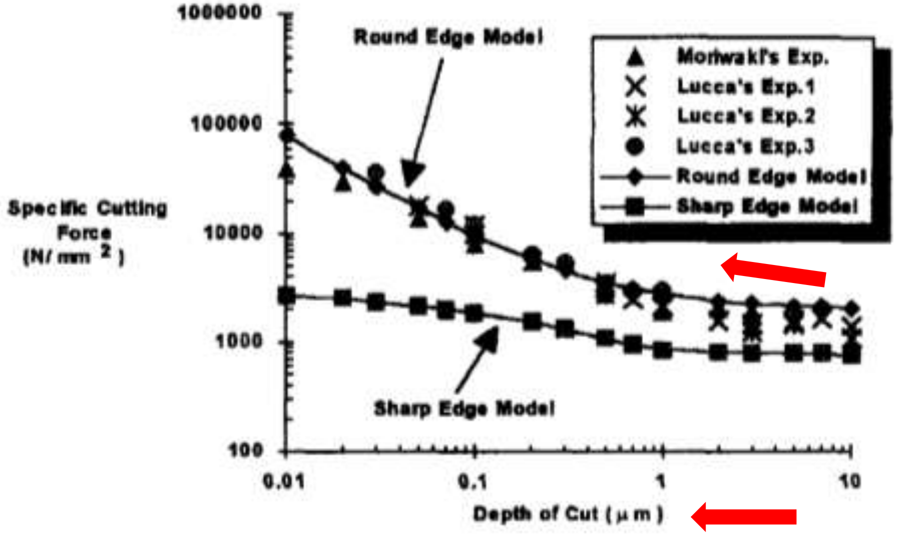
- The existence of minimum chip thickness has been experimentally verified and theoretically studied.
- The minimum chip thickness determines whether a chip is formed or not because if the depth of cut for a microcutting operation is set below this minimum, then the cutting edge is expected to just plastically deform the workpiece material without producing a chip.
- This is the **ploughing** mechanism which except the obvious effect on the surface integrity and the quality of the finished workpiece alters significantly the cutting forces and thus the process stability in precision machining and makes the force prediction methods described hereafter ineffective.

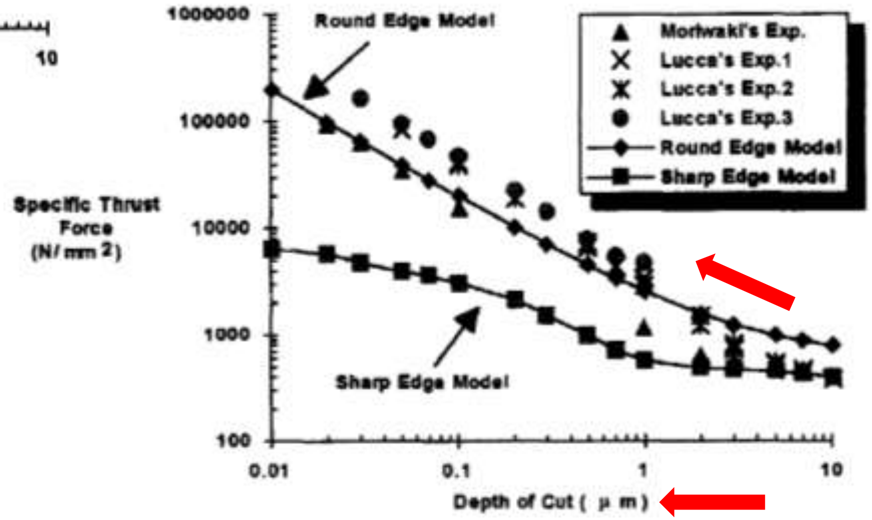
Size effect

- Although ploughing may exist in traditional macroscale machining, its effect on the overall process may be neglected.
- However, this effect caused by cutting edge radius is important in precision machining.
- Many researchers consider this mechanism to be the main reason for the so-called **size effect**.
- Size effect is the non-linear increase in the specific energy and thus in the specific cutting force with decreasing depth of cut, which is observed in precision cutting and micromachining.



Micromachining experiments





Size effect is attributed to …

- the significantly reduced amount of imperfections, namely crystallographic defects such as grain boundaries, missing and impurity atoms and inhomogeneities present in all commercial metals, encountered when deformation takes place in a small volume. With smaller uncut chip thickness the material strength is expected to reach its theoretical value of strength.
- material strengthening due to an increase in the strain rate in the primary shear zone.
- the decrease of temperature in the tool-chip interface with decreased chip thickness.
- the energy required for new surface creation via ductile fracture.
- micro-nano-indentation and its extension to machining. The increased hardness of a material with reduced indentation depth is a result of the dependence of material flow stress on the strain gradient in the deformation zone; strain gradient plasticity can be the reason of size effect in machining because of the intense strain gradients observed.

Predominant theory

- Although size effect is present in metal cutting, like minimum chip thickness, it is of special importance when it pertains to precision machining and micromachining.
- From the literature review it is evident that many reasons for the size effect in machining and micromachining have been reported.
- It is not clear which of the above mechanisms is dominant or whether there could be more than one mechanism acting at the same time.
- Even in the case of multiple mechanisms acting together, there may be factors that alter the contribution of each factor in each case.

Machining modeling challenges

- The <u>strain rates</u> observed are very high; this holds true for even low cutting speeds.
- <u>Plastic deformation</u> takes place in small regions, the primary and secondary deformation zones, around the cutting edge, making difficult the selection of the appropriate boundary conditions.
- The <u>ploughing-shearing</u> mechanism of micromachining further complicates the matter.
- <u>Strain hardening</u> of the workpiece material is usually neglected, although it plays a significant role, as is concluded from experimental results.
- <u>Temperature rise</u> in the region due to plastic deformation and friction induce material softening and alter the workpiece material properties in relation to strain rates and temperatures.
- <u>Data for the workpiece material</u> for varying temperature and strain rate at the levels which occur in metal machining are not easily found in the literature (non-linear analysis).
- Temperature rise needs to be taken into account to the various calculations performed, which means that besides the mechanical problem, <u>a heat transfer problem</u> must be dealt with simultaneously.
- <u>The grain size</u> of the workpiece material, which is comparable to depth of cut, needs to be addressed.

The problem and the solution

- Finite elements appear to be the most suitable method for modeling precision machining problems.
- Due to its inherent characteristics it can solve non-linear problems and with advances in computers and the use of commercial software it can readily perform coupled thermo-mechanical analysis.
- Still, chip formation is difficult to be modeled. Except the physical phenomena already explained two more challenges need to be addressed.

1. The first one is to provide accurate data to the model; this is common sense however it can be problematic.
2. The second is to actually choose a finite elements method. There are different approaches or strategies proposed for metal machining modeling with FEM pertaining to formulation, treatment of friction, material behavior, iteration scheme etc. used for approximating a solution.

For beginners…

- In FEM the basic principle is the replacement of a continuum by finite elements forming a mesh; this procedure is called discretization.
- Each finite element is simpler in geometry and therefore easier to analyze that the actual structure.
- Every finite element possesses nodes where the problem initial and boundary conditions are applied and the degrees of freedom are calculated; the finite elements are connected to one another in nodes.
- Between the nodes, problem variables are derived by interpolation.
- The problem variables as well as properties applied on the nodes of each element are assembled and global relations are formatted.
- Usually, the analysis involves a great number of algebraic equations to determine nodal degrees of freedom and that is why a personal computer is employed for processing.

Time integration

- There are two different time integration strategies in order to face non-linear and dynamic models, namely implicit and explicit schemes.
- The **explicit** approach determines the solution of the set of finite element equations by using a central difference rule to integrate the equations of motion through time.
- The **implicit** method is realized by solving the set of finite element equations, performing iterations until a convergence criterion is satisfied for each increment. The length of the time step is imposed by accuracy requirements.

Numerical formulation

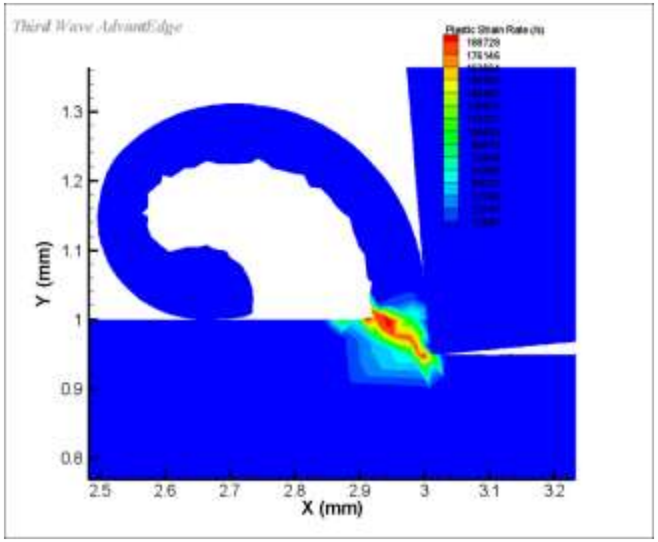
- The ones used in metal cutting FEM models are so far of three types, namely Eulerian, Lagrangian and the newer Arbitrary Lagrangian-Eulerian (ALE) analysis.
- In the Eulerian approach the finite element mesh is spatially fixed and covers a control volume. The material flows through it in order to simulate the chip formation. This implies that the shape of the chip, shear angle and the contact conditions must be a priori known, derived from experiments, or assumed.
- In the Lagrangian approach the elements are attached to the material. The material is deformed due to the action of the cutting tool and so is the mesh. This way there is formation of the chip due to deformation from the tool. Unconstrained material flow in Lagrangian formulation allows for simulations from incipient chip formation to steady-state conditions and modeling of segmented chips besides the continuous one.

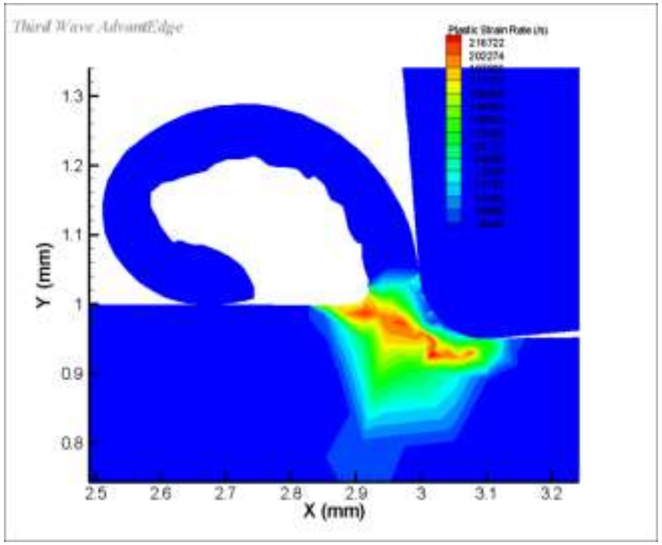
Lagrange formulation

- A disadvantage of the Lagrange formulation is connected to the large mesh deformation observed during the simulation.
- Due to the attachment of the mesh on the workpiece material, the mesh is distorted because of the plastic deformation in the cutting zone. Such severe distortions of the mesh may result in the failure of the model as they cannot be handled by the elements applied in the mesh.
- Furthermore, for the formation of the chip, a chip separation criterion in front of the tool edge is applied. This procedure can be quite thorny; it has been the topic of several papers and no generally accepted criterion is adopted.
- The latest development in the Lagrangian formulation, an updated Lagrangian analysis, has overcome the disadvantage of a chip separation criterion by applying continuous re-meshing and adaptive meshing, dealing at the same time with the mesh distortion.

Model geometry

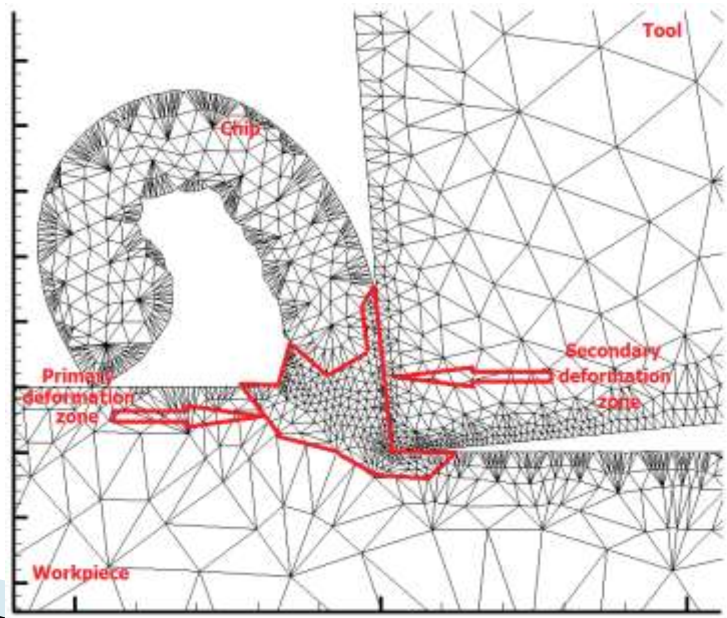
- For precision machining, the geometrical characteristics of the tool and the workpiece greatly influence the outcome of the process.
- More specifically, the tool edge radius is connected to size effect, minimum chip thickness, effective rake angle, stagnation point and ploughing mechanism.
- A significant number of papers is dedicated to the investigation of the influence of the tool edge radius on the size effect.



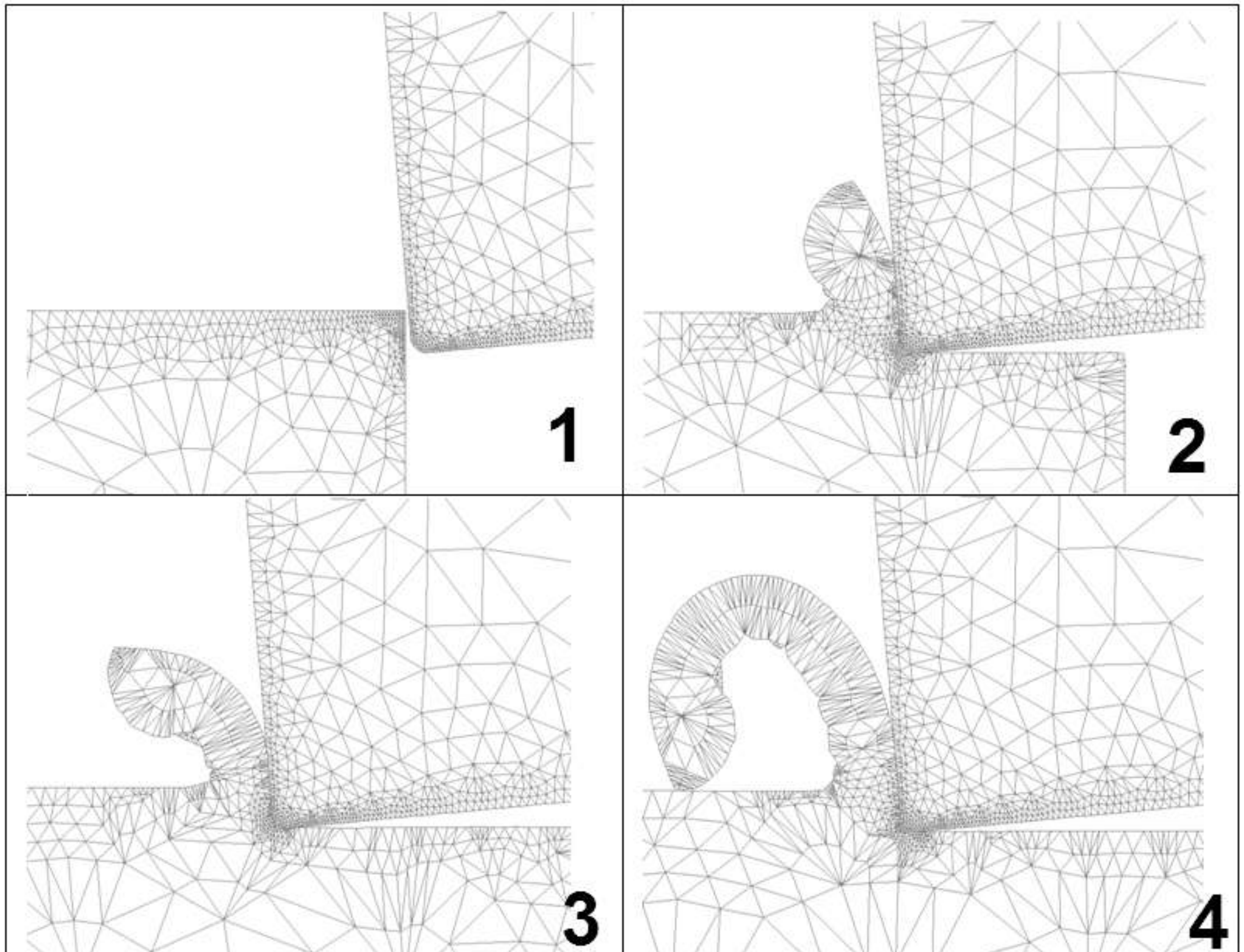


Meshing

- The initial mesh of the workpiece is significant for the results the model will provide. The convergence of the numerical procedure and the accuracy of the predicted variables depend on it. The obvious is that the mesh must be able to represent accurately the workpiece geometry and be able to handle the analysis to be performed.
- The <u>size</u>, <u>number</u> and <u>type</u> of the elements used in the mesh play a significant role on the simulation outcome as well.
- In machining the action takes place in the primary and secondary deformation zones; the mesh in these parts of the workpiece is expected to be denser in order to obtain better geometry of the chip and also be able to cope with the strains, strain rates and temperature gradients expected there.

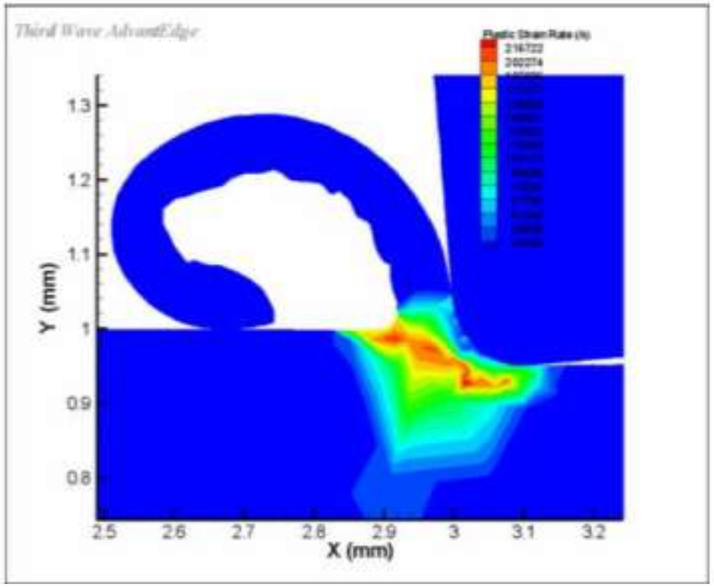


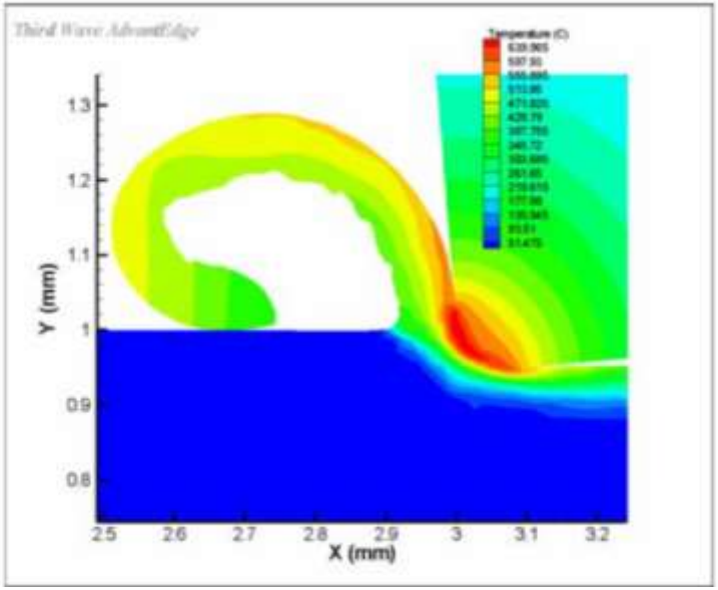
Adaptive meshing example



Thermo-mechanical coupling

- Of interest is the way thermo-mechanical coupling is considered.
- In cutting processes heat generation originates from the two deformation zones, i.e. the primary and the secondary, due to inelastic and frictional work.
- The heat is conducted into the tool and chip and transferred away from the chip to the environment or the cutting fluid by convection.
- The above are either modeled by heat sources at the heat generation regions or usually with material and tribological models that are functions of mechanical and thermal behavior with strain, strain-rate and temperature.
- The associated strain hardening and thermal softening is interpreted to non-linear analysis.





Material modeling

- Material modeling in machining in general and in precision machining in particular is of great importance.
- Especially the flow properties of the workpiece material and the corresponding equations that are included into FEM have been extensively studied.
- These constitutive equations describe the flow stress or instantaneous yield strength at which work material starts to plastically deform or flow; the elastic strains are much lower than plastic strains in metal cutting and so workpiece material flows plastically into the cutting zone.
- The constitutive models presented in the literature are mainly elasto-plastic, elasto-viscoplastic, rigid-plastic and rigid-viscoplastic.
- Machining conditions subject workpiece material to high levels of strain, strain rate and heat which greatly influence flow stress. In the primary zone strain and temperature ranges from 1-2 and 150°C-250°C respectively and in the secondary deformation zone from 3 to much higher and 800°-1200°C, while strain rates reach values of up to $2x10^4$ s^{-1} and 10^5 s^{-1} in the to zones.

Material data

- One problem of material modeling is the lack of data for high stresses, strain rates and temperatures as the ones encountered in machining.
- In many cases the constitutive data are taken from standard tension tests that are not sufficient for machining processes. Dynamic experimental material tests such as Split Hopkinson Pressure Bar (SHPB) impact testing is employed. Samples are deformed under high speed compression with strain rates of up 10^5 s^{-1} and temperatures of up to 700ºC.
- However, the obtained results are often criticized:
  - they are not sufficient for the deformation behavior of metals, especially in high speed machining; values beyond test results are calculated by interpolation.
  - the available data are not from specialized laboratories; generally speaking SHPB requires special equipment.
  - high temperatures in metal cutting are localized; metal cutting is a cold working process, although the chip only is of high temperature.
  - it not clear how to correlate uniaxial impact testing results of SHPB with materials that are triaxially stressed, as in metal cutting.

Constitutive models

Model	Constitutive equation
Usui et al.	$\sigma = B\left[\frac{\dot{\varepsilon}}{1000}\right]^{M} e^{-kT}\left[\frac{\dot{\varepsilon}}{1000}\right]^{m}\left\{\int_{Path} e^{kT/N}\left[\frac{\dot{\varepsilon}}{1000}\right]^{-m/N} d\varepsilon\right\}^{N}$
Oxley	$\sigma = \sigma_1 \varepsilon^{n}$
Johnson-Cook	$\sigma = (A + B\varepsilon^{n})\left[1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_o}\right)\right]\left[1 - \left(\frac{T - T_a}{T_m - T_a}\right)^{m}\right]$
Zerilli-Armstrong	$\sigma = C_o + C_1\exp[-C_3T + C_4T\ln(\dot{\varepsilon})] + C_5\varepsilon^{n}$ $\sigma = C_o + C_2\varepsilon^{n}\exp[-C_3T + C_4T\ln(\dot{\varepsilon})]$

Johnson–Cook model

- Among the most used material models is the Johnson–Cook model. It is a thermo–elasto–visco–plastic material constitutive model, described as:

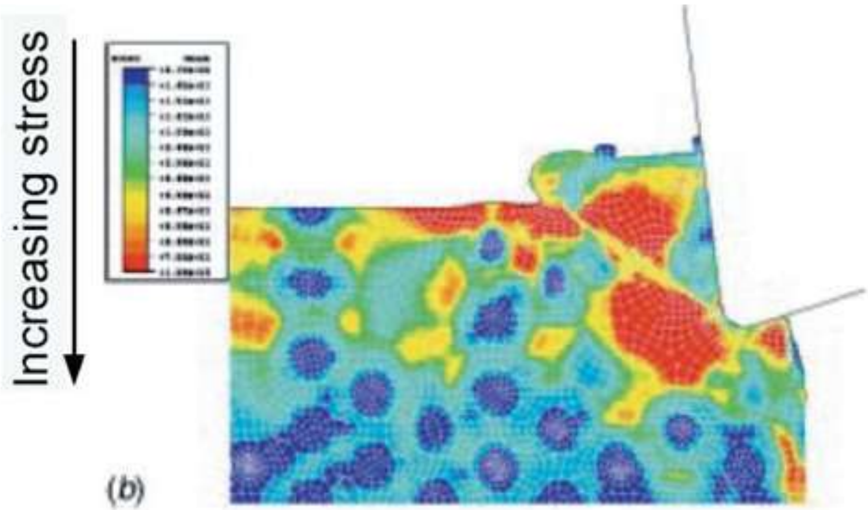
$$\sigma = \left(A + B\varepsilon^n\right)\left[1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_o}\right)\right]\left[1 - \left(\frac{T - T_a}{T_m - T_a}\right)^m\right]$$

- The equation consists of three terms the first one being the elasto–plastic term to represent strain hardening, the second is viscosity, which demonstrates that material flow stress increases for high strain rates and the temperature softening term.
- T_α is the ambient temperature, T_m the melting temperature and A, B, C, n and m are constants that depend on the material and are determined by material tests.

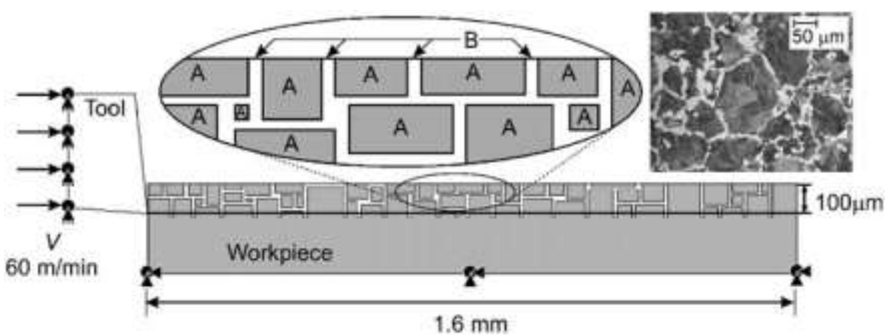
Multi phase materials

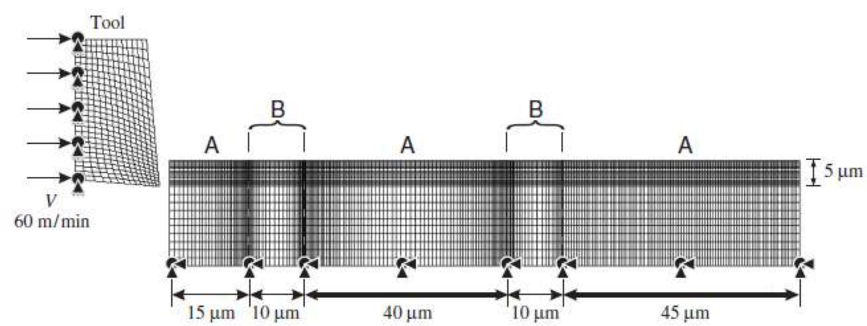
- In mechanical micromachining the cutting tool radius is comparable to the size of the grains of the material being processed.
- Furthermore, in materials with surface defects or multi phase materials, such as cast iron, the microcutting mechanism is quite different in comparison to non-heterogeneous materials due to the encounter of the cutting tip with these features of the material during the course of the process.
- For example, ductile iron and two of its constituents, namely pearlite and ferrite, were modeled in the same continuum, taking into account the microstructural composition, the grain size and the distribution of each material.
- In another example, 1045 steel, considering its microstructure, is represented by bands or sections of a pearlite-like behavior material and a ferrite-like behavior material.

Modeling multi phase materials



Ductile iron representation taking into account the microstructural composition, the grain size and the distribution of material phases





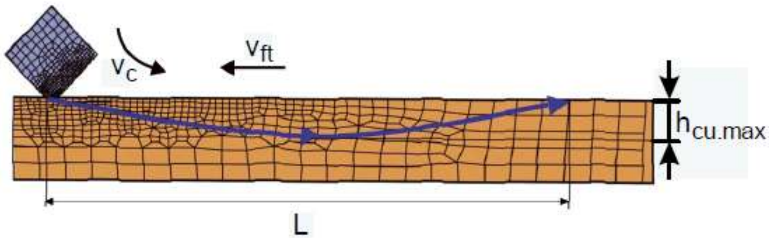
Representation of the microstructure of 1045 steel with (a) bands and (b) sections (material A: pearlite, material B: ferrite)

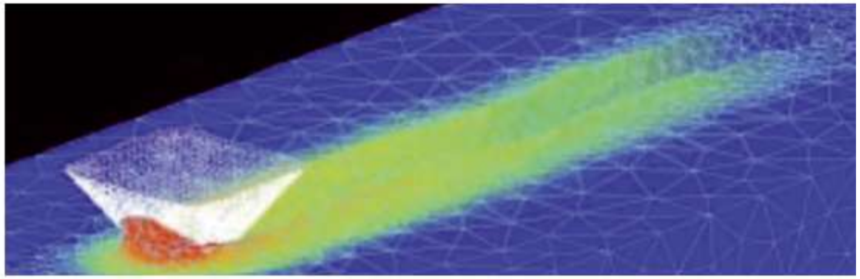
Two special cases

- It is worth noticing that two cases from macro machining are closely related to material modeling in the micro regime.

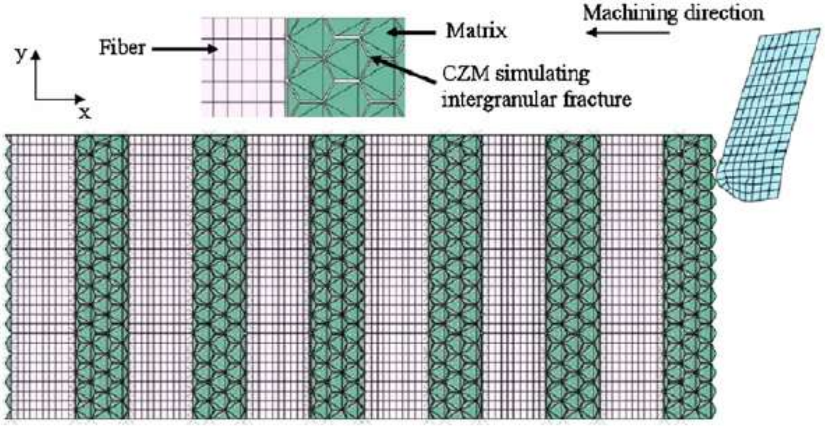
1. The first pertains to grinding, a precision finishing process. Although this process can be modeled in macro scale, it can also be modeled in micro scale. In the latter case the material removal mechanism of a grain of the grinding wheel is considered.
2. The second case pertains to the machining of metal matrix composite materials. The nature of these materials, a matrix material reinforced with fibers or particles of small size, is similar to the case of multiphase materials. It is clear that failure mechanisms of the composites materials in turning are different from monolithic materials; cracking of the reinforcement, debonding at the reinforcement-matrix interface, growth and coalescence of voids play an important role in the machining of composite materials.

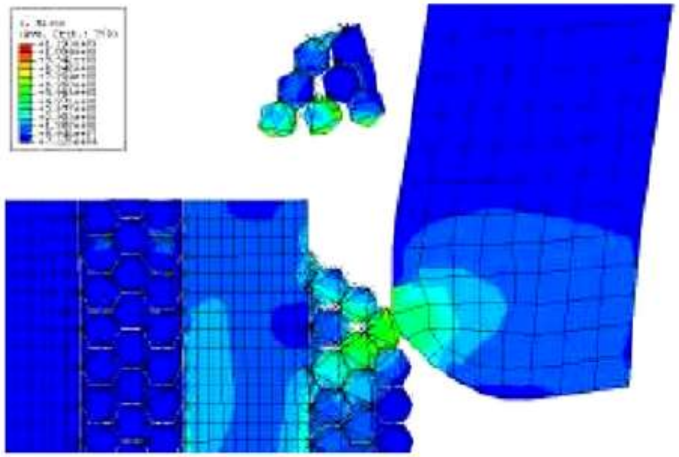
Grinding – composite materials





Grinding





Composite material turning

Friction modeling

- Friction modeling in the secondary deformation zone, at the interface of the chip and the rake face of the tool is of equal importance to the workpiece material modeling.
- It is important in order to determine cutting forces but also tool wear and surface quality.
- The detailed and accurate modeling is rather complicated. Many finite element models of machining assume that it is a case of classical friction situation following Coulomb's law.
- However, as the normal stresses increase and surpass a critical value, this equation fails to give accurate predictions.
- From experimental analysis it has been verified that two contact regions may be distinguished in dry machining, namely the sticking and the sliding region. Zorev's stick-slip temperature independent friction model is commonly used.
- In Zorev's model there is a transitional zone with distance ℓ_c from the tool tip that signifies the transition from sticking to sliding region.

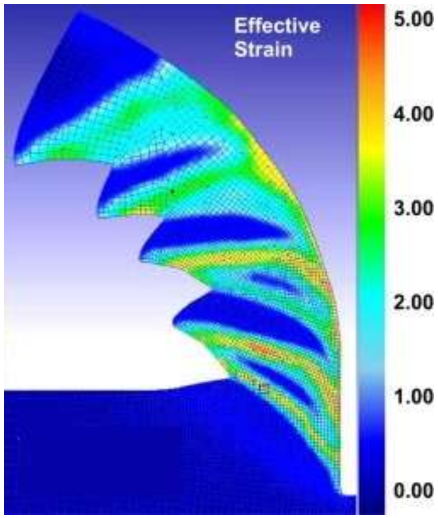
Friction models overview

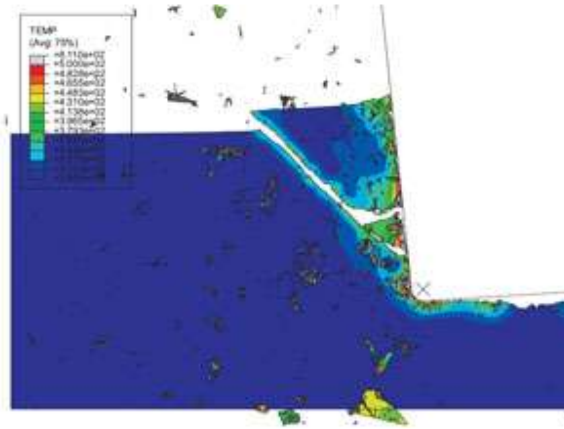
Model	Equation
Coulomb	$\tau = \mu\sigma$
Zorev	$\tau = \begin{cases} k, 0 \le \ell \le \ell_c \\ \mu\sigma, \ell > \ell_c \end{cases}$
Usui	$\tau = k\left[1 - \exp\left(-\frac{\mu\sigma}{k}\right)\right]$
Childs	$\tau = mk\left[1 - \exp\left(-\frac{\mu\sigma}{mk}\right)^n\right]^{1/n}$
Iwata et al.	$\tau = \frac{H_V}{0.07}\tanh\left(\frac{\mu\sigma}{H_V/0.07}\right)$
Sekhon and Chenot	$\tau = -\alpha K\left\|\upsilon_f\right\|^{p-1}\upsilon_f$
Yang and Liu	$\tau = \sum_{k=0}^{4}\mu_k\sigma^k$

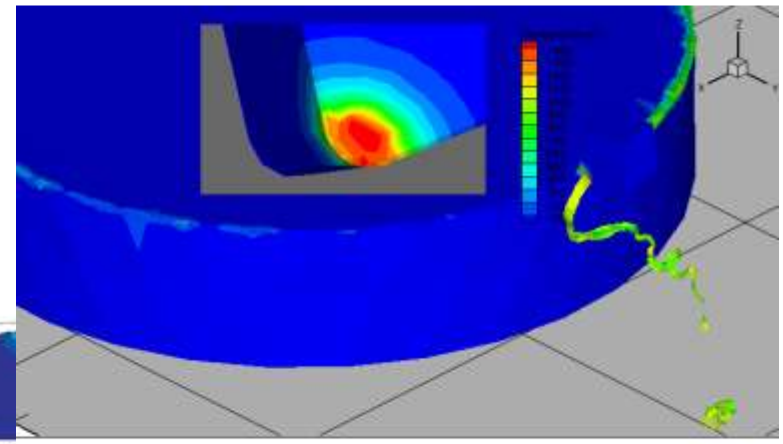
FEM software

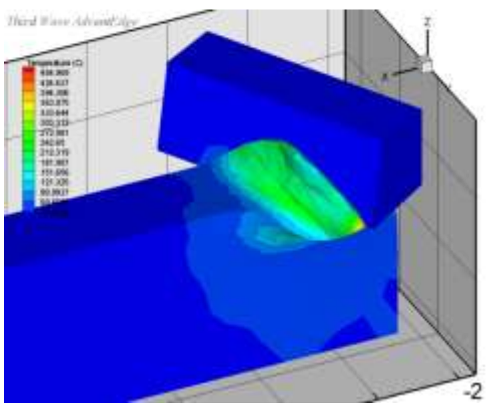
- It is true that modeling with FEM is not at all trivial.
- Use of a commercial FEM program, however, may simplify the procedure.
- For the past twenty years a wide range of commercial FEM packages became available. These programs have been widely accepted by researcher since they can simplify the overall procedure of model building.
- Commercial FEM add to the quality and accuracy of the produced models. These programs are made by specialists who have tested them and have implemented features and procedures to accelerate the slow process of model building. Most of the software have mesh generation programs, easy to use menus for applying boundary conditions, contact algorithms, automatic remeshing, material databases etc.
- Some researchers, however, remain skeptical due to limitations a model can impose, e.g. a model may only be able to solve a problem implicitly or explicitly.
- Regarding precision machining, researchers use either in-house FEM codes, commercial packages, e.g. MSC.Marc, Ansys, Abaqus etc. or commercial packages with specific menus machining, e.g. AvantEdge.

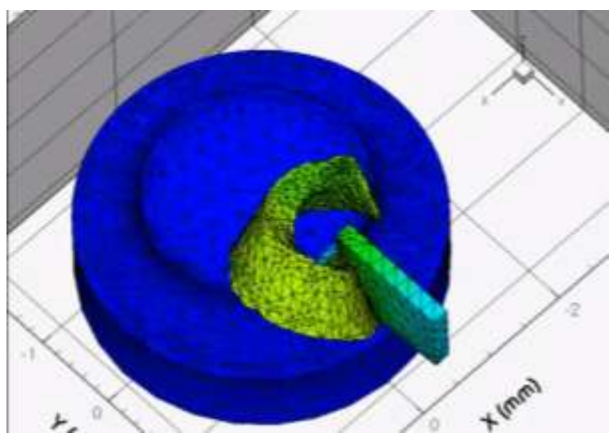
Hot topics

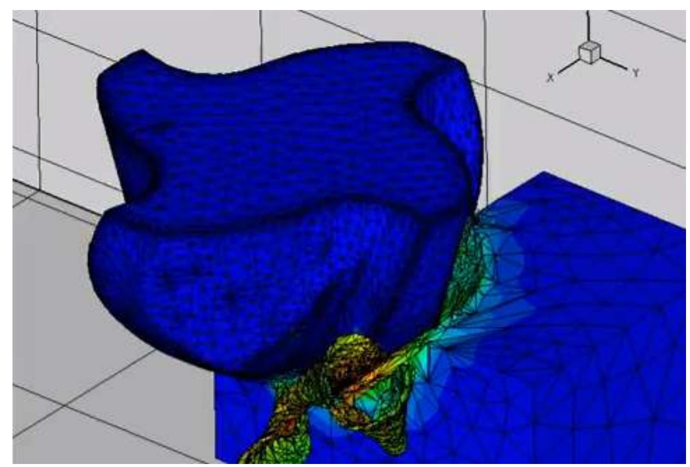












Case study 1: Hard turning

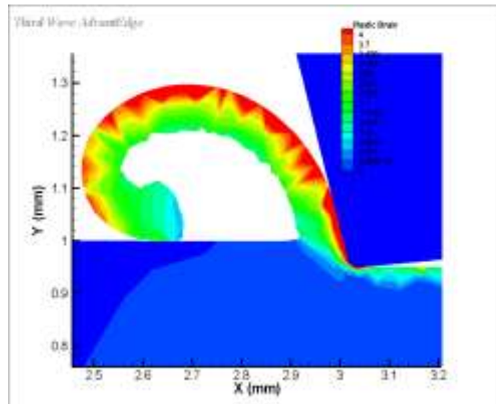
- Hard turning, a machining operation used for the processing of hard materials such as hardened steels, has been brought into the forefront of modern metal cutting operations with the increasing demand for manufacturing high quality components, e.g., gears, shafts, bearings, dies and tools.
- Cutting tools employed in hard turning are made of specialized tool materials, such as cubic boron nitrite (CBN), that are able to overcome the problems experienced during the process; they possess exquisite properties, even at elevated temperatures, allowing for their application at high cutting speeds, with minimum use of cutting fluids.
- In addition the combination of <u>hard turning</u> and <u>high speed machining</u> is proved to be very advantageous since a great reduction in processing time can be achieved.
- Hard turning is very advantageous for a wide spectrum of applications and is also considered as an alternative for a variety of processes, since the single-step superfinish hard turning can replace the abrasive processes, traditionally used as finishing operations, or non-traditional processes, such as electrical discharge machining (EDM), in machining hard parts, offering accuracy equal to or better than that provided so far, flexibility and considerable machining time and cost reduction.

AdvantEdge

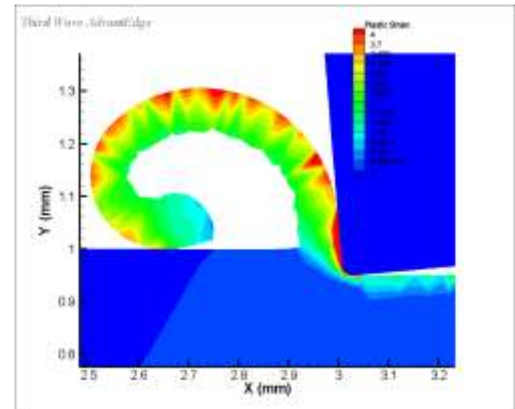
- The models described are developed employing the Third Wave AdvantEdge software, which integrates special features appropriate for machining simulation. The program menus are designed in such a way that they allow the user to minimize the model preparation time.
- Furthermore, the software includes a wide database of workpiece and tool materials commonly used in cutting operations, offering all the required data for effective material modeling.
- AdvantEdge code is a Lagrangian, explicit, dynamic code, which can perform coupled thermo-mechanical transient analysis. The program applies adaptive meshing and continuous remeshing for chip and workpiece, allowing for accurate results.

Rake angle vs chip plastic strain

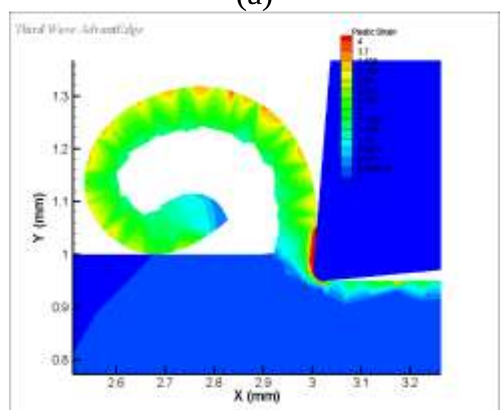
- Plastic strain for rake angle (a) –15º, (b)–5º, (c) 5º and (d) 15º
- Cutting speed and feed are 300 m/min and 0.05 mm/rev respectively, clearance angle is equal to 5º and tool and workpiece material are CBN and AISI H-13 (55 HRC) tool steel, respectively.



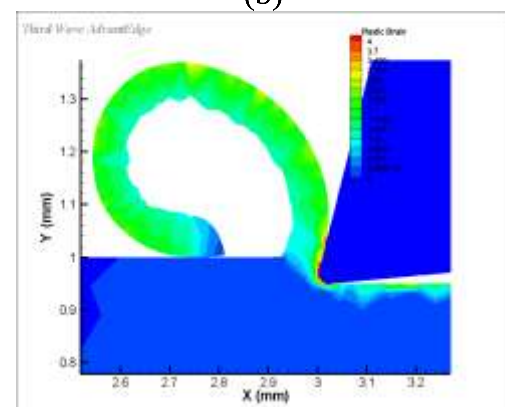
(a)



(b)

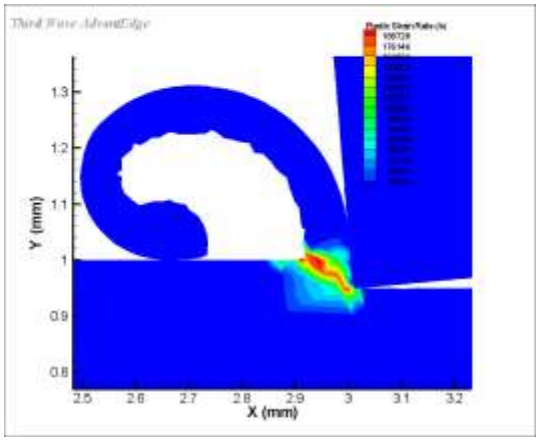


(c)

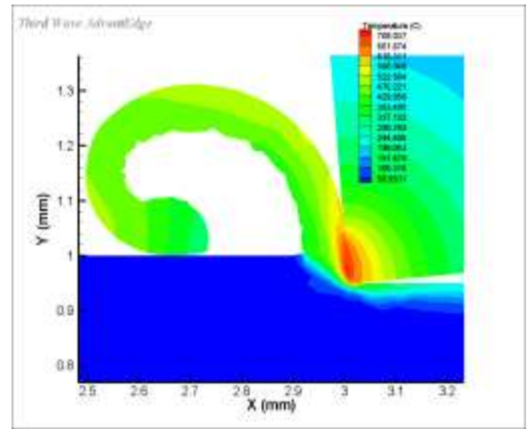


(d)

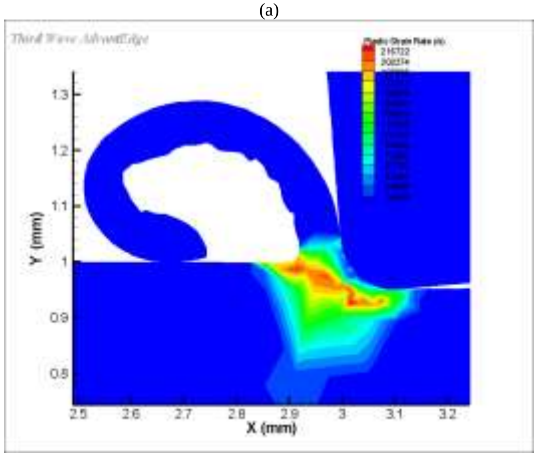
Cutting edge radius effect



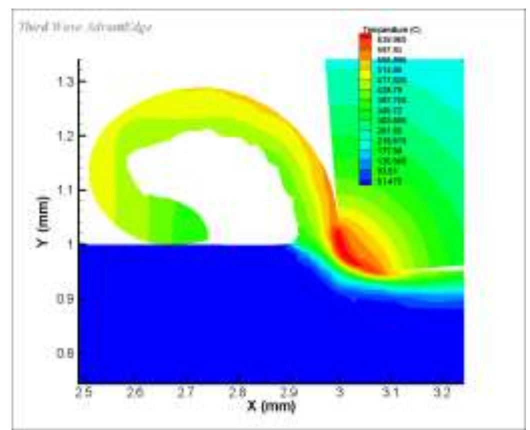
(a)



(a)



(b)



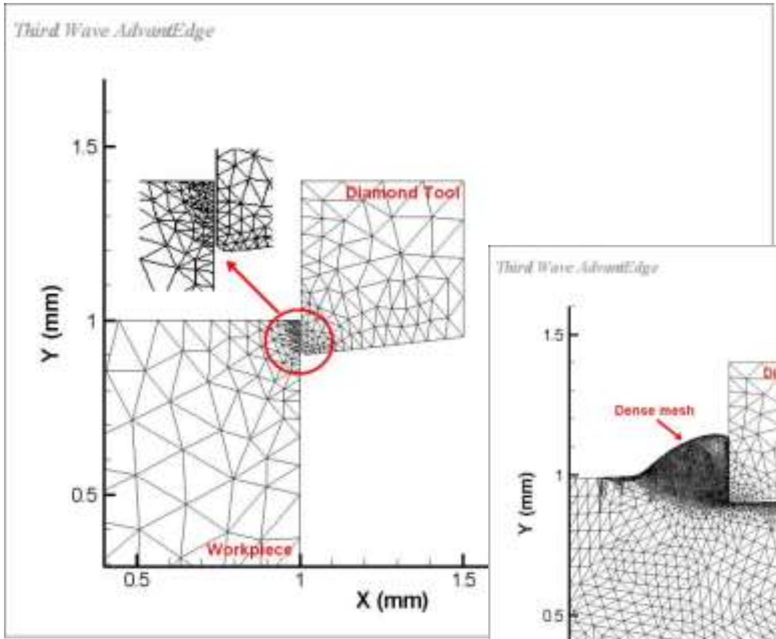
(b)

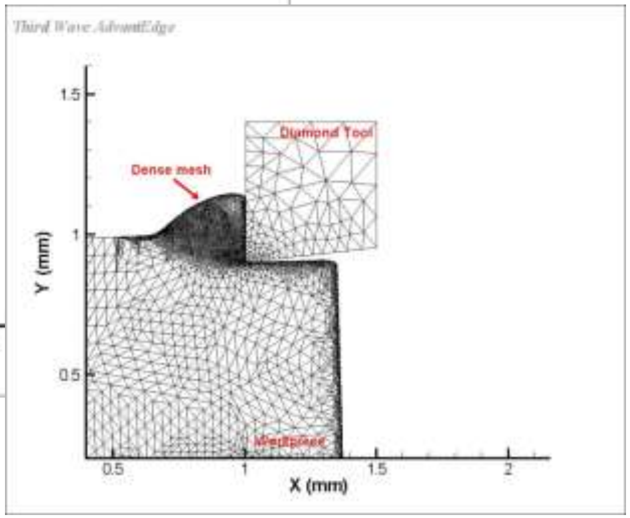
Plastic strain rate and temperature for cutting edge radius (a) 0.01 mm and (b) 0.1 mm

Case study 2: micromachining

- The present case study pertains to the construction of a 2D orthogonal cutting, round tool edge model that can predict micromachining cutting forces as well as workpiece and tool temperatures when copper is machined with diamond tools.

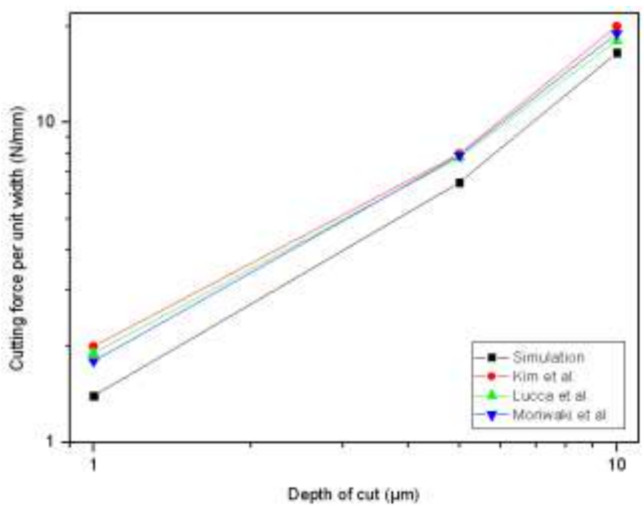
Workpiece	
Dimensions (length x height)	1 mm x 1mm
Material	Copper CDA110
Cutting tool	
Rake angle	0°
Rake length	0.5 mm
Clearance angle	6°
Clearance length	0.5 mm
Cutting edge radius	0.001 mm
Tool material	Diamond
Process	
Depth of cut	1, 5, 10 μm
Length of cut	0.5 mm
Feed	0.1 mm/rev
Cutting speed	94.2 m/min
Friction coefficient	0.3

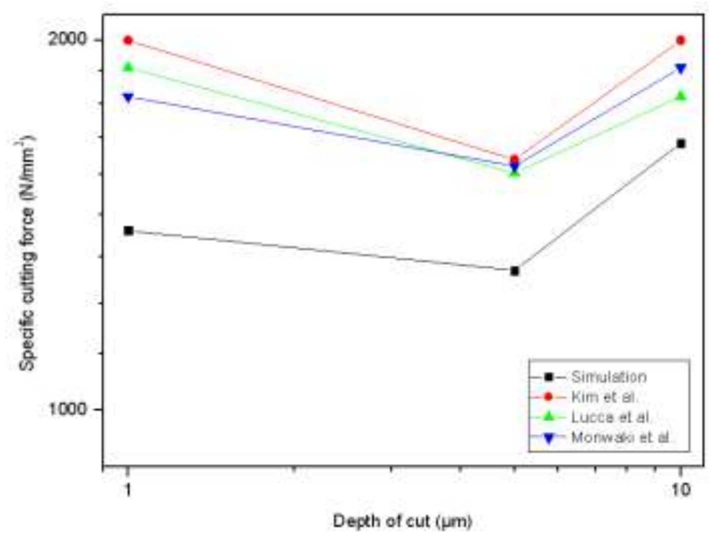




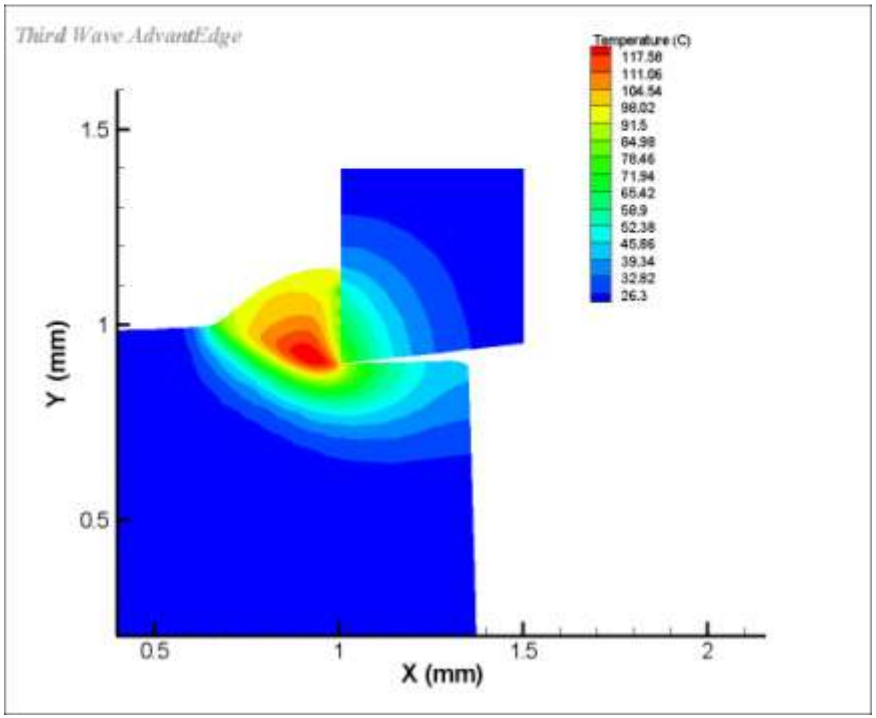
Size effect prediction

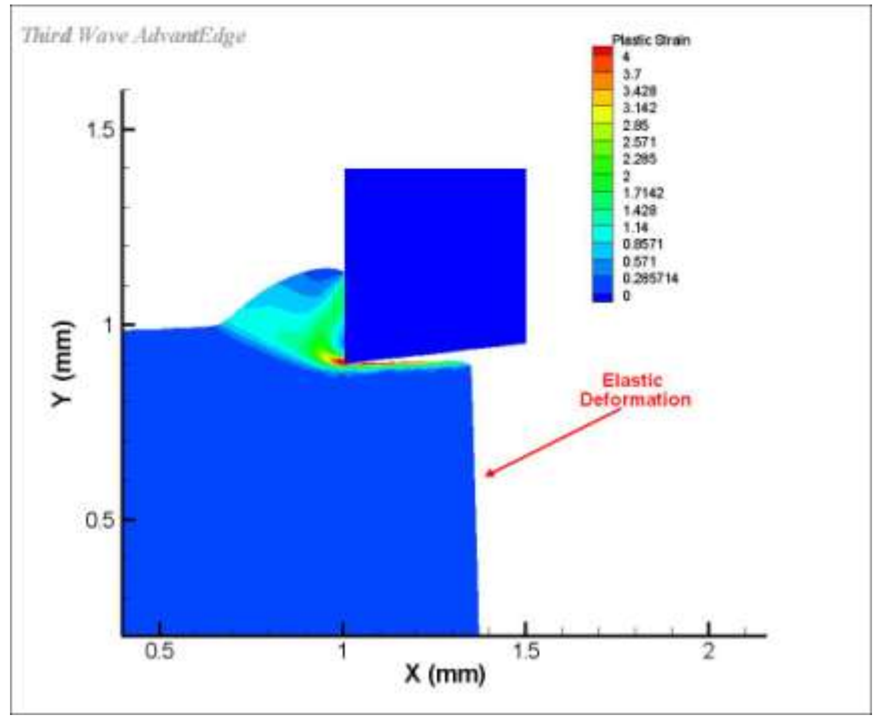
- The validation of the model is performed through comparison with results from papers with similar micromachining conditions.
- In order to determine the size effect in micromachining the specific cutting force is an appropriate characteristic. In the figures the specific cutting force for the three different depths of cut is depicted.
- For the specific cutting forces and for depth of cut lower that 10 μm the size effect can be observed.





Other results



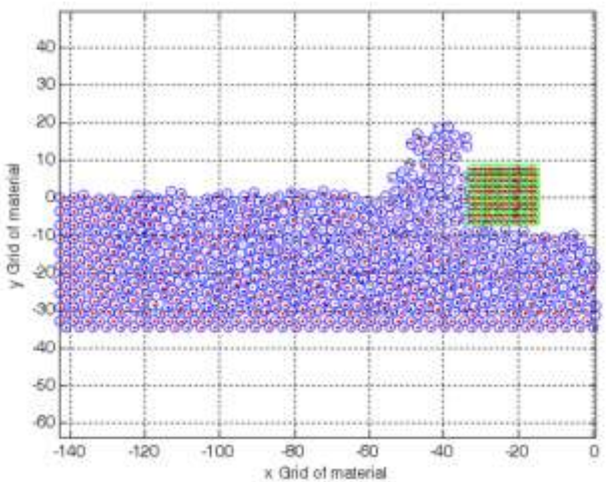


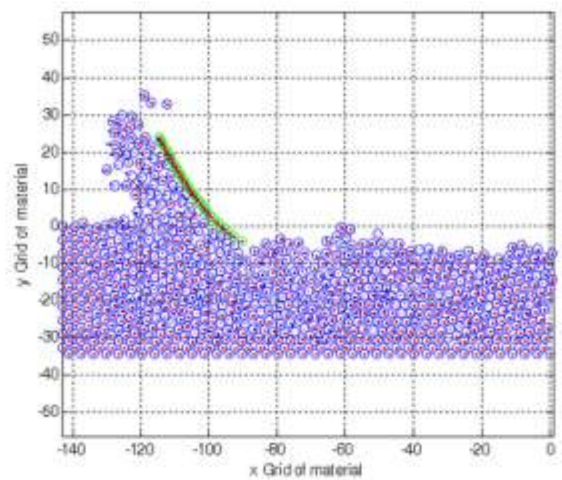
Other processes and modeling methods

- It should be noted that other precision machining processes, e.g. Electro-Discharge Machining (EDM), Water Jet Machining (WJM), Laser Machining (LM), Electro-Chemical Machining (ECM) etc., can be modelled with FEM.
- For every process, a different modeling strategy needs to be followed. Finite element method can treat all physical problems and with the right formulation, models for these processes can be constructed.
- Although this presentation is dedicated to finite elements, it would not be complete without reference to some other modeling techniques that are also used in precision machining.
- These include other numerical methods, e.g. the finite difference method (FDM), meshless methods, e.g. the element-free Galerkin (EFG) method and the smoothed particle hydrodynamics (SPH) method, soft computing modeling, e.g. Artificial Neural Networks (ANN) and a specialized method used for nanometric cutting, namely Molecular Dynamics.

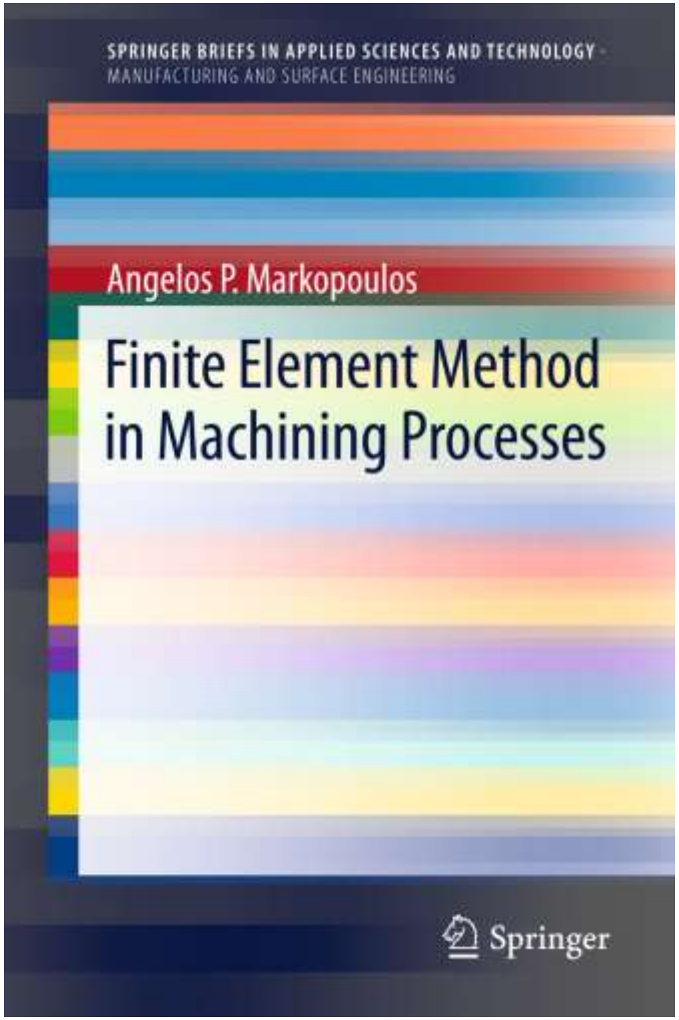
Molecular Dynamics

- MD is a modeling method in which atoms and molecules are interacting for a period of time, by means of a computer simulation.
- In order to simulate molecular systems, a very big number of particles is involved and a vast number of equations is produced to describe the properties of these systems; as a multidisciplinary method, laws and theories from mathematics, physics and chemistry consist the backbone of the method.
- In order to deal with these problems, numerical methods, rather than analytical ones, are used and algorithms from computer science and information theory are employed.





References



http://users.ntua.gr/amark/