A brief review of numerical simulation in process machining

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Abstract. Machining is a technological process that involves removing the material by generating chips, aiming to obtain flat, cylindrical, helical surfaces etc. This processing method is widespread in the industry and it is, therefore, necessary to define appropriate technical and economic solutions concerning the materials and geometry of the tools, the orientation and fixture of the devices, and the machine-tool used. It is also particularly important to use the most appropriate cutting parameters for modern industrial applications. Scientific research addresses these issues through analytical, semi-empirical, or numerical modeling. Numerical modeling and simulations can satisfy with very good precision the solutions of these aspects, with diverse methods and techniques used in the study of the cutting simulation. This paper presents an analysis of recent studies, briefly presenting the main approaches and techniques used in numerical modeling and simulation of machining. The input parameters, components, and output parameters of these numerical models are identified as well. Finally, the advantages and disadvantages of using these methods and techniques are summarized, as well as the problems to be developed in the area of numerical modeling and simulation of cutting processes.

1. Introduction
Cutting processes are still the main industrial process, applicable in all areas of manufacturing. Cutting procedures have a wide range of applications, the most common being turning, milling and drilling, figure 1. Understanding the mechanisms of chip formation continues to be a challenge, being also the main challenge for researchers as well as increasing the productivity of these types of processes and improving tool life.

(a) (b) (c)

Figure 1. The main cutting processes: (a) turning; (b) milling; (c) drilling.
The objective of using numerical simulations for cutting processes is to generate, in the design phase of the technology, valid results compared to those obtained in real applications, such as cutting force, process temperatures, stresses and strains in the workpiece etc. This makes it possible, on one hand, to understand the phenomena and mechanisms associated with the cutting process and, on the other hand, to establish optimal values for the geometric parameters of the tools and for the parameters of the cutting speed, leading to the achievement of certain goals, such as: maximum productivity, minimum cost, etc.

Modern cutting materials and processes, such as high hardness alloys, high cutting speed machining, processing accompanied by certain ultrasonic techniques or liquid nitrogen cooling etc., support the need to develop appropriate numerical models to reduce the cost of processing and increase the quality of the parts.

In this paper, an analysis of recent studies is presented, briefly outlining the main methods and techniques used in numerical modeling and simulation of machining.

2. Specific elements for numerical modeling and simulation of machining
A numerical model describing a cutting process must have the ability to generate a chip of at least the same shape as that obtained experimentally. Therefore, it is necessary to learn the mechanisms of chip removal, being described several types of chips, which are continuous, lamellar, segmented and discontinuous. For most numerical models, continuous chip shapes are considered, with the focus on topical research and their validation by experiments, respectively, being oriented more towards the study of forces and temperatures, the strains and stresses, in the areas of tool-workpiece contact.

These aspects are due to the fact that current research on the modelling of cutting processes is not yet sufficiently developed to define the morphology corresponding to the formation of the chip, and the correct implementation of the contact conditions.

The chip is formed when the cutting body penetrates the material to be removed, advancing in the cutting direction. In other words, we can say that the chip forming process has three stages: plastic deformation, cutting initiation and forming.

![Numerical Models Diagram](image)

**Figure 2.** Numerical inputs, formulations and results.
To study the chip morphology, forces and temperatures occurring in the cutting process, respectively stresses and strains using numerical models that reproduce the experimental results as closely as possible, it is necessary to implement initial conditions related to geometry, material behavior etc., respectively appropriate approaches and formulations. They are presented schematically in figure 2 and detailed in the following sub-chapters. The relevance of the results obtained with such models is reflected in the correct choice of these parameters. In other words, the model should be updated/ improved until it generates adequate results compared to those obtained experimentally.

2.1. Numerical input

This first stage consists in entering the data regarding the description of the geometries, the behavior of the material to be processed, the contact conditions, the failure criterion, the technological parameters etc.

Model geometry

For an orthogonal cutting model, the workpiece is described by: the thickness of the undeformed chip (h), the size of the failure area (h_f), where a model with such an area is used [1], as well as the dimensions of the part to be machined (l, L), and the cutting tool must be described by: the rake angle (α), the flow angle (γ), the radius at the tip of the tool (r_e), as shown in figure 3.

![Figure 3. Model geometry.](image)

Material behavior

The behavior of the alloy is defined by: density; thermal conductivity; elasticity: Young's modulus, Poisson's ratio; the fraction of transformation of mechanical deformation work into heat; thermal conductivity; specific heat; the model of plastic behavior.

The plastic model of material behavior is of the greatest interest for research in this field. Thus, paper [2] examines four models of the plastic behavior of the processed material: Johnson-Cook [3], Zerilli-Armstrong [4], Arrhenius [5] and Norton-Hoff [6], for different cutting speeds (150, 200 and 250 [m/min]). By comparing process force and temperature data obtained by numerical simulation with those obtained experimentally, it is concluded that Johnson-Cook and Zerilli-Armstrong plastic behavior models provide the best results compared to experimental ones.

The most commonly used model describing the plastic response of materials is the Johnson-Cook model [3], used in many studies [2, 7-22], presented in equation (1). It is a thermo-elasto-visco-plastic model, whose parameters are frequently identified by the shear compression specimen (SCS) [23], consisting of three types of tests: quasi-static at room temperature, quasi-static at various elevated temperatures and dynamic test at room temperature. Table 1 presents the values of the Johnson-Cook model for some materials identified in scientific literature.
\[
\sigma_{ec} = (A+B \cdot (\varepsilon^p)^n) \left(1+C \cdot \ln \left(\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_0} \right) \right) \left(1 - \left(\frac{T - T_1}{T_m - T_1}\right)^m\right) \tag{1}
\]

where:
- \( \sigma_{ec} \) is the equivalent stress Johnson-Cook;
- \( A \) is the yield strength of the material;
- \( B, C, n \) and \( m \) are the parameters of the material model;
- \( \varepsilon^p \) is the equivalent strain;
- \( \dot{\varepsilon}^p \) is the equivalent strain rate normalized to a reference speed \( \dot{\varepsilon}_0 \);
- \( T \) is the evolution of temperature;
- \( T_1 \) is the transition temperature;
- \( T_m \) is the melting temperature of the material.

**Table 1.** Johnson-Cook model parameters for some materials identified in the literature.

| No. | ISO Material | A [Mpa] | B [Mpa] | n | C | m | Source |
|-----|--------------|---------|---------|---|---|---|--------|
| 1.  | C45          | 50      | 176     | 0.517 | 0.105 | 0.56 | [24]   |
| 2.  | Ti6Al4V      | 875     | 793     | 0.386 | 0.033 | 0.71 | [8]    |
| 3.  | NiCr19Nb5Mo3 | 1262    | 1354    | 0.5   | 0.006 | 1.08 | [17]   |
| 4.  | X40CrMoV5-1  | 908.5   | 321.4   | 0.278 | 0.028 | 1.18 | [20]   |
| 5.  | 36CrNiMo4    | 792     | 510     | 0.26  | 0.014 | 1.03 | [3]    |
| 6.  | 50CrMoV13-15 | 1539    | 477     | 0.18  | 0.012 | 1    | [3]    |
| 7.  | 42CrMo4      | 595     | 580     | 0.133 | 0.023 | 1.03 | [25]   |
| 8.  | Cu-OFE       | 90      | 292     | 0.31  | 0.025 | 1.09 | [3]    |
| 9.  | CuZn28       | 112     | 505     | 0.42  | 0.009 | 1.68 | [3]    |
| 10. | AlCu4Mg1     | 265     | 426     | 0.34  | 0.015 | 1    | [3]    |
| 11. | AlZn4Mg3     | 337     | 343     | 0.41  | 0.01  | 1    | [3]    |
| 12. | AlZn5.5MgCu  | 527     | 575     | 0.72  | 0.017 | 1.61 | [26]   |
| 13. | AlZn6MgCu    | 546     | 678     | 0.71  | 0.024 | 1.56 | [26]   |
| 14. | AlMg4.5Mn    | 167     | 596     | 0.551 | 0.001 | 0.859| [27]   |

**Description of the element failure model**

Material removal and chip formation on the tool flow surface occurs due to shear forces, which lead to critical values in the plastic field of the curve describing the material behavior, eliminating the elements in the failure zone (\( h_f \)). In general, this failure of ductile materials can only be correctly interpreted in numerical models using FEM.

For the description of how the chip breaks, several models are presented in specialized studies, such as Cockroft-Latham [14, 21], modified Cockroft-Latham [12] and Johnson-Cook [7-9, 12, 13, 15-18, 20, 22] where the elimination of the elements occurs when the accumulated stresses in the failure zone reach a maximum value. Of these models, the most widely used is the Johnson-Cook model [3], from equation (2), which leads to the best results. Table 2 displays the parameters of the Johnson-Cook fracture model for some materials identified in scientific literature.

\[
\tilde{\varepsilon}^p = (D_1 + D_2 + D_3 \cdot \varepsilon^{D_4 \cdot n}) \left(1 + D_4 \cdot \ln \left(\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_0} \right) \right) \left(1 - \left(\frac{T - T_1}{T_m - T_1}\right)^m\right) \tag{2}
\]

where:
- \( D_1, D_2, D_3, D_4, D_5 \) material parameters.
Table 2. Fracture values for the Johnson-Cook model, for certain alloys identified in the literature.

| No. | ISO Material       | D_1 | D_2 | D_3  | D_4  | D_5  | Source |
|-----|-------------------|-----|-----|------|------|------|--------|
| 1.  | C45               | 0.04| 1.52| -6.9 | -0.023| 1.3  | [24]   |
| 2.  | Ti6Al4V           | -0.09| 0.25| -0.5 | 0.014| 3.87 | [8]    |
| 3.  | NiCr19Nb5Mo3      | 0.406| 0.75| 1.45 | 0.04 | 0.89 | [17]   |
| 4.  | X40CrMoV5-1       | -0.8| 2.1 | -0.5 | 0.0002| 0.61 | [20]   |
| 5.  | 36CrNiMo4         | 0.05| 3.44| -2.12| 0.002| 0.61 | [3]    |
| 6.  | 50CrMoV13-16      | 0   | 0.56| -1.5 | 0    | 0    | [28]   |
| 7.  | 42CrMo4           | 1.5 | 3.44| -2.12| 0.002| 0.1  | [25]   |
| 8.  | Cu-OFE            | 0.54| 4.89| 3.03 | 0.014| 1.12 | [3]    |
| 9.  | CuZn28            | 0   | 2.65| -0.62| 0.028| 0    | [28]   |
| 10. | AlCu4Mg1          | 0.13| 0.13| -1.5 | 0.011| 0    | [28]   |
| 11. | AlZn4Mg3          | 0.14| 0.14| -1.5 | 0.018| 0    | [28]   |
| 12. | AlZn5.5MgCu       | 0.11| 0.572| -3.446| 0.016| 1.099| [26]   |
| 13. | AlZn6MgCu         | -0.068| 0.451| -0.952| 0.036| 0.697| [26]   |
| 14. | AlMg4.5Mn         | 0.0261| 0.263| -0.349| 0.247| 16.8 | [27]   |

Modeling of contact conditions

To obtain a valid numerical model, it is also needed to define the contact conditions that accurately reflect the interaction between tool-chip and chip-workpiece, as shown in figure 4. Most of the studies presented in the literature take contact conditions into account in the definition of models and, in most cases, use Coulomb type friction conditions [2, 12, 16, 17, 20, 21], which consider the coefficient of friction to be constant, equation (3), which contradicts the actual contact behavior.

\[
\mu = \frac{F_n}{F_f}
\]  

(3)

where:
- \( \mu \) is the friction coefficient;
- \( F_n \) is the normal force;
- \( F_f \) is the friction force.

Figure 4. Contact conditions [22].

Figure 5. Cause-effect diagram for the interpretation of friction behavior [19].

In document [17], the coefficient of friction is considered to be temperature dependent and even an algorithm is proposed to optimize it. The results are favorable and the errors are less than 6%. In document [19], several models for contact conditions are compared and a new model is proposed, in
which the friction coefficient depends on relative speed, temperature and contact pressure. A cause
and effect diagram of figure 5 is proposed, in which a model interpreting the contact conditions has to
take into account all the parameters introduced in a cutting process: from the external and internal
mechanical stresses in the material being processed, to the types of material and the coolant lubricant
used.

2.2. Numerical formulation

Discretization of space

The most widely used method in the discretization of the numerical model is the finite element
method, which analyses the deformations and mechanisms of the solid. For this method, the
Lagrangian formulation [2, 10, 12-19, 21, 22, 29] is most often used from the mechanics of the
continuous mediums. This is the analysis of the discretization, following the evolution of each point in
time, or, in other words, the discretization follows the material. This type of formulation is used with
remeshing and adaptive mesh [2, 8, 10, 16, 17, 22, 29]. The Eulerian formulation [16], in which the
discretization remains fixed and the material evolves through it.

From these two classical types of formulations, other formulations have been developed. On one
hand, the CEL formulation is used, which assumes that the material is defined using the Eulerian
formulation, and the tool is featured with the Lagrangian formulation or vice versa. On the other hand,
the ALE formulation merges the advantages of Lagrangian and Eulerian formulations and has the
property that the discretization structure follows the evolution of the material, maintaining the same
connections of the elements. Unlike the Lagrangian formulation, ALE does not need to regenerate the
discrete structure, remaining the same structure in the contact area. This leads to much shorter
calculation times.

In paper [30], most numerical simulation models are analyzed, describing non-discretization
models and those based on particle-type methods, figure 6. These types of methods are extremely
useful for describing failure models and for calculating very large deformations.

Figure 6. Types of numerical models used in cutting processes [30].

Integration methods

Computation time in models that simulate cutting processes is relatively long, due to the fact that
they are complex dynamic problems. The implicit integration methods are mainly suitable for linear
problems. Explicit methods, which are the most used in technical literature [2, 7-22], solve nonlinear
and dynamic problems, as found in the cutting processes. Explicit methods are suitable for problems
involving complex contacts between the tool-chip and chip-workpiece. No comparison is made in the
literature between the two integration methods, in order to understand in which situations they are
more appropriate in simulating cutting processes, although there are software products that use only
one of the two methods.

3. Numerical results and models

Results generated by the numerical models used for validation

The process measurements that can be determined experimentally in cutting processes are rather
limited in their scope. Thus displacements, displacement rates and temperatures in the contact zones or
inside the tool can be measured by means of specialized devices [9, 12, 13, 18, 21, 22]. In order to determine other important parameters necessary for the understanding of cutting processes, such as tool and workpiece stresses, numerical models respond favorably to the interpretation of these variables, with the ability to generate relevant results, as opposed to conventional empirical tests.

One of the most important parameters in the validation of numerical models, but also the one most often used in the interpretation of the results, is the cutting force [2, 7-22]. Basically, a series of tests are performed on the basis of which the numerical models are calibrated, redefining the material and contact parameters, until they provide results compared to those obtained experimentally in relation to the cutting force. In papers, these calibrations are carried out until the models generate errors between a maximum of 5-10%.

The measured temperature [2, 7-9, 11, 14, 15, 17, 18, 22, 24] is another process value on the basis of which the numerical model is validated. This is measured experimentally using thermocouples inserted in tools [15, 20] or by means of thermal cameras [7, 8, 14]. Although in some cases [8], thermocouples may interfere with technological processing systems, they provide relevant information on the accuracy of temperature measurement. Instead, thermal cameras can record very high temperatures, which can occur in cutting processes.

Results of numerical simulations relevant to research and industry

Validated numerical models are then used in research and development studies of the cutting process, in order to improve/ optimize industrial applications, to process new materials or to process certain materials under particular conditions.

The multitude of studies in which the effect of the various geometrical parameters of the tools in machining is noted and thus leads to their geometrical optimization. These include:

- The influence of the flow angle [29] in the orthogonal cutting process on chip formation and interrupted chip generation is studied. The variation of the flow angle for different cutting thicknesses determines the points of stability and instability, figure 7, which leads to energy conservation in the cutting process;
- The effect of the flow angle [11] on the temperature and the chip is studied in the orthogonal cutting process. This study leads to the conclusion that with increasing the flow angle, temperature and the chip degree of segmentation decrease, for an undeformed chip thickness of 0.1 mm and a cutting velocity of 160 m/min, figure 8;
- The tool tip radius influence [15] in the orthogonal cutting process on the cutting force, temperature and thickness of the chip is studied. The thickness of the chip is insignificantly influenced by the tool tip radius, while the cutting force and temperature are significantly influenced by it. It is observed that the cutting force and temperature are influenced by the technological parameters, and less by the material of the workpiece or the tool;

![Figure 7. Stability equilibrium diagram [29].](image1)

![Figure 8. Evolution of temperature and chip segmentation degree for different flow angles [11].](image2)
The effect of different micro-milling on the inserts used in milling processes, figure 9 [7], and turning, figure 10 [21], on cutting force, temperature and chip formation is studied. These micro-milling operations improve cutting performance, conservation of cutting forces, reduction of workpiece and tool temperatures.

Another part of the studies is oriented towards the analysis of the shapes of the chips in the cutting processes. So:

- The optimal size of the chip thickness is studied [18], in the orthogonal cutting process, depending on the radius at the tip of the tool. It is found that the thickness of the chip must be at least a quarter of the size of the tool radius;
- The shape of the triangular [12, 15, 17], rectangular [8, 9, 16, 18, 19, 22] undeformed chip is studied in the orthogonal machining. The study of triangular chips, figure 11, is performed to imitate as accurately as possible the shape of the chips in the milling processes;
- The serrated chip formation is studied [8, 19], in orthogonal cutting processes, influenced by cutting speed and feed, figure 12. Following these analyzes, the morphology of the chips is studied by measuring the tips and depths of the serrated chips and comparison of these experimentally obtained dimensions with those generated by simulations.

At the same time, there are numerous studies based on the use of numerical simulation in which the influence of the different technological parameters is analyzed, on the dimensions of the processes (cutting forces, temperatures), the durability of the tool or the finished quality of surfaces (roughness, microdurability, residual stresses, etc.), the tool- workpiece contact length. These include:
- The effect of the cutting velocities of 160, 180 and 200 m/min is studied for different feed rates of 0.01, 0.055 and 0.1 mm/rev, in the turning process of high-hardness steel 42crmos4 [22], on the cutting force and contact length, figures 13 and 14. It is found that the simulation model provides results similar to those obtained experimentally, with errors of less than 10% in the case of the forces. The errors are greater for the tool-workpiece contact length, since the friction model is not the most suitable for this simulation.

Figure 13. Comparison of cutting forces obtained experimentally and from simulations for different technological parameters [22].

Figure 14. Comparison of tool-workpiece contact length obtained experimentally and from simulation for different technological parameters [22].

- The effect of the cutting velocities of 25 and 40 m/min, for feed rates of 0.008 and 0.005 mm/rev, with an undeformed chip thickness of 2 mm, in the milling process with the high hardness steel Ti6Al4V [8], on the cutting force and temperature, figures 15 and 16. It is found that the proposed simulation model has errors of up to 6%.

Figure 15. Comparison of cutting forces obtained experimentally and from simulations [8].
a. 25 m/min and 0.008 mm/rev
b. 40 m/min and 0.005 mm/rev

Figure 16. Comparison of temperatures measured experimentally and in simulations.
a. 25 m/min and 0.008 mm/rev
b. 40 m/min and 0.005 mm/rev
4. Conclusions and perspectives
In the study of cutting processes, the use of numerical methods has become the main topic, providing more appropriate results for optimizing the technological parameters and geometry of cutting tools, compared to conventional analytical or empirical methods. For the description of the behavior of ductile materials, Johnson-Cook model, Lagrangian formulation and Johnson-Cook failure model are most often used. The contacts between the tool-chip and chip-workpiece must also be very well described, so that most often the classic Coulomb model of the friction coefficient is used. After the simulations, the most important step is the validation of the model comparing the results with those obtained experimentally. Usually, the numerical model is continuously improved, until the errors generated are decrease below 10% compared to those determined experimentally.

The main numerical models used to simulate cutting processes are those using the finite element method, but in recent years a large number of new models have emerged, mainly inspired by fluid mechanics, based on particle models and without meshing, which tend to provide even more relevant results.

The main conclusions regarding the limitations of the current numerical models used for the simulation of cutting processes, derived from the analyzed literature, are summarized as follows:
- the database on the specific parameters of the material models that have proved to be suitable (plastic behavior of the material, the way the chip breaks) is limited to certain alloys;
- the mechanisms of chip formation are still incomplete, although recent numerical models provide relevant information about them. This is due to the fact that they are not yet very well defined to meet all the conditions imposed on cutting processes. Among these are the modeling of how to break the chips, as well as the tool-chip and chip-workpiece contact requirements;
- in real cutting processes, almost always, coolants are used to reduce temperatures during cutting and thus improve the durability of the tool and increase the finished quality of surfaces. Numerical models are limited to predict possible behaviors that may occur from the use of such liquids.

Based on the conclusions summarized above, it follows that the main research directions for modelling and simulation of cutting processes are aimed at overcoming the limitations identified. For example, there is a tendency to move from two-dimensional orthogonal cutting processing studies to more complex three-dimensional calculations for turning, milling, drilling, etc., in order to obtain results that are as relevant as possible to the industry. Another main direction of the study is the development of robust numerical models that could meet today's industrial requirements, which simulate cutting processes with a short calculation time and the simplest use, also at the lowest cost.

This study will continue, on one hand, by increasing the number of bibliographical sources studied and, on the other hand, by focusing on specific cutting processes, such as turning and milling at high cutting speeds or the machining of hard alloys. Subsequently, it is intended to develop numerical models capable of simulating as accurately and with a reasonable calculation time real cutting processes, specific to current industry trends.

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