Proceedings in MANUFACTURING SYSTEMS

Proceedings in Manufacturing Systems, Volume 6 , Issue 1, 2011 ISSN 2067-9238

REVISION OF ACTUAL STAGE IN MODELING OF CUTTING PROCESSES

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Abstract: *This paper makes a revision of the actual stage in modelling of cutting processes with bibliographic examples starting from analytical to orthogonal and ending with dynamic and genetic models. The authors make also a brief description of the history of the finite element analysis, a description of the finite element model formulations and give examples of 2D and 3D FEM simulation of machining processes.*

Key words: *cutting process, milling, cutting model, FEM, orthogonal, 3D model.*

1. INTRODUCTION

The modelling development of metal cutting processes, particularly the milling processes, to predict physical behaviour during cutting, the determination of stable cutting conditions and the design of more efficient machines have been a major concern in the field of production technology.

Effective methods to predict stable processes have been developed in recent decades Altintas et al. [1], Faassen [2]. An essential part of these methods is the development of a model, i.e. an ordinary differential equation. This model will be adjusted and will reproduce local characteristics of the actual cutting system, i.e. the dynamics at the tip of the cutter. In combination with a process model it allows to identify efficiently stable machining parameters by means of bifurcation analysis Faassen [3], Insperger [4], Szalai [5]. However, these methods provide only few detailed information about the dynamics of the entire machine structure [6]. In this paper a revision of actual stage in modelling cutting processes generally and milling processes particularly is made. Economically speaking, the ability of predicting key process parameters such as cutting forces, temperature, tool life, wear, vibrations etc. means cost savings, increased productivity and more efficiency for industry. Early work of scientists in field of modelling of metal cutting presents simple analytical models which represent just the basic physics and mechanics of metal cutting through mathematical equations [7]. Nowadays these simple models became complex and hard to describe. However, the research is far to be finished and scientists try to create more reliable and accurate models.

In order to help modelling machining processes, the computer-based simulation and the finite element analysis (FEA) were developed. FEA is a method known since 1970 and has been used to analyze forming processes and designing tools [8].

Finite Element Method (FEM) permits the prediction of cutting forces, stresses, tool wear, and temperatures of the cutting process so that the cutting tool can be designed. With this method the best cutting parameters are determined. First this method was used by Tay et al. [9] in 1970 and then taken by many other manufacturing researchers. FEM has some advantages such as [10]:

- solves contact problems;
- uses bodies made from different materials;
- a curvilinear region can be approximated by means of finite elements or described precisely etc.

The researchers developed also finite element software for simplifying working with FEM. Nowadays the right choice of finite element software is very important in determining the scope and quality of the analysis that will be performed. The most important software codes used for simulation of metal cutting are: Abaqus, Deform and AdvantEdge.

2. BRIEF HISTORY OF DIFFERENT CUTTING MODELS

When speaking about cutting models researchers consider analytical models, orthogonal models, genetic models, dynamic models and other.

2.1. Analytical models

Analytical models are mathematical models, described through analytical functions. These models describe complex systems. Table 1 gives a summary of most popular analytical models of cutting forces.

E. Budak [101 and 102] described in his papers some analytical models of force, tool deflection, form error and analytical models which can be used to suppress chatter vibrations. These models help improving productivity in milling. He showed the importance of properly selection of milling conditions and also described some common errors that appear during milling, form errors, also known as the deviation of a surface from its intended, or nominal, position. He concluded that the developed

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Table 1

Summary of the most popular relationships for cutting forces calculation [100]

	Author	Analytical Models (theoretical)	Observations
1	TIME, 1870	$F_N = b \cdot l \cdot \tau_r$; $F_z = b \cdot l \cdot \tau_r \cdot \frac{\sin\delta}{\sin\omega \cdot \sin(\omega-\gamma)}$; $\varphi = \arctan\left(\frac{\cos\gamma}{C_D - \sin\gamma}\right)$.	$\omega = 90^\circ + \delta$; and δ – cutting angle; l – shear line length; C_d – plastic deflection coefficient
2	ZVORÎCHIN, 1893	$F_\tau = \frac{\tau_r \cdot b \cdot t \cdot [2 \cdot \mu \cdot \cos\delta + \sin\delta(1-\mu^2)]}{\sin\varphi[\sin(\delta+\varphi)(1-\mu_1 \cdot \mu) + \cos(\varphi+\rho)(\mu+\mu_1)]}$.	Considers friction μ, μ_1 on the clearance face and between chip elements.
3	TAYLOR, 1907	$F_z = k_1 \cdot t \cdot s^{0.933}$ (steels); $F_z = k_2 \cdot t^{0.933} \cdot s^{0.75}$ (cast iron) .	$F_z = k \cdot t^{xF} \cdot s^{yF}$
4	KLOPSTOCK, 1926	$F_z = C_{ks} \cdot A^m$.	A – sectional chip area[mm^2]
5	ERNST-MERCHANT, 1945	$F_N = F_f \cdot \cos\rho \cdot \cos(\varphi+\rho-\gamma)$; $F = F_f \cdot \sin\rho \cdot \cos(\varphi+\rho-\gamma)$; $F_{fn} = F_f \cdot \tan(\varphi+\rho-\gamma)$; $F_f = K \cdot b \cdot \frac{a}{\sin\varphi}$; $F_z = \frac{K \cdot a \cdot b \cdot \cos(\rho-\gamma)}{\sin\varphi \cdot \cos(\varphi+\rho-\gamma)}$; $F_y = F_z \cdot \tan(\rho-\gamma)$.	$\varphi = 45^\circ + \frac{\gamma}{2} - \frac{\rho}{2}$; $\varphi = \arctan\frac{F_y + F_z \cdot \tan\gamma}{F_z - F_y \cdot \tan\gamma}$
6	KUZNEȚOV, 1944	$F_N = \sigma_c \cdot s \cdot t \cdot C_d^n$.	σ_c – flow limit of chip material
7	JUKOV, 1956	$F_N = \sigma \cdot h \cdot b$.	h – contact length chip/clearance area; b – chipped layer width; σ – normal effort on the clearance face
8	KLUȘIN-GORDON, 1952	$R = \frac{\sigma_f \cdot a \cdot b}{\cos(\rho+\beta_1-\gamma) \cdot \sin\beta_1}$; $F_n = \frac{\sigma_f \cdot a \cdot b \cdot \cos\rho}{\cos(\rho+\beta_1-\gamma) \cdot \sin\beta_1}$.	R – resultant of forces on the clearance face; β_1 – shear angle; ρ- friction angle on the clearance face
9	KIENZLE, 1952	$F_z = b \cdot h \cdot k_s = b \cdot h^{1-m} \cdot k_{s1,1}$	$k_{s,1.1}$ – specific force for a chip section with b = 1 mm and h = 1 mm
10	ROSENBERG-EREMIN, 1953	$F_N = \frac{\sigma_0}{n} \cdot a \cdot b \cdot \frac{\sigma^{n \cdot 0,4} \cdot \frac{C_d^2 - 2C_d \sin\gamma + 1}{C_d \cdot \cos\gamma - 1}}{1 - \frac{\sin\rho}{C_d \cdot \cos(\rho-\gamma)}}$.	n – hardening exponent; σ_0 – flow-compression effort; C_d - plastic deflection coefficient; ρ – external friction angle
11	KRAVCENKO, 1956	$F_N = \frac{\tau \cdot a \cdot b}{[\cos(\beta_1-\gamma) - \mu\sin(\beta_1-\gamma)] \cdot \sin\beta_1}$; $F_z = F_C = 2\sigma_c \cdot a \cdot b \cdot C_d^n \cdot \frac{C_d^2}{1+C_d^2}(\cos^2\gamma - 0.4\sin\gamma)$.	t – shear chip effort; μ – friction coefficient on the rake face; β_1 – shear angle; $\sigma_c = \frac{2\tau}{\sin 2\varphi}$; $\varphi = \beta_1$
12	ZOREV, 1963 KATTWINCKEL	$F_N = \frac{b \cdot l_c \cdot \sigma_{max}}{n+1}$; $n=2\left\{\frac{l_c}{a \cdot C_d[\mu+\tan(\varphi-\gamma)]}\right\}$.	Efforts distribution: $\sigma_c = \sigma^2_{max}\left(\frac{x}{l_c}\right)$
13	ZOREV, 1967	$F_d = \frac{\tau_f \cdot a \cdot b}{\cos(\varphi+\rho-\gamma)\sin\varphi}$; $F_d = \frac{\sigma_r \cdot a \cdot b}{\cos(\varphi+\rho-\gamma)\sin\varphi}$.	For a simplified model of the thick plastic zone; σ_f, τ_f – consistent efforts in terms of conventional shear zone
14	KRONENBERG, 1967	$F_N = \tau_f \cdot t \cdot s \cdot M_N$; $M_N = C_d \frac{\cos\rho}{\cos(\rho+\varphi-\gamma)}$.	

15	McADAMS-ROSENTHAL, 1961	$F_y = F'_y y + F_{yu} \rightarrow F'_y y = F_y - F_{yu}$; $F'_f = mF_y$; $F'_z = mF_z$; $F'_y = mF_y$.	Based on the Merchants model for worn and unworn tool
16	ALBRECHT, 1961	$\tau = \frac{Q}{b_1 \cdot t_1}\sin\varphi\cos(\gamma+\varphi); \overline{Q} = \overline{F}_N + \overline{F}$.	t – shear effort in the presence of the rounding radius
17	VIDAL, 1967	$F_d = \frac{F_{dL}}{E} = \frac{1}{E}\frac{F_f \cdot \sin\varphi}{\cos(\rho-\gamma)-\sin(\rho-\gamma)}; E = \frac{F_{dL}}{F_{dM}}$.	F_{dL} – resultant force by Lee-Schafer; F_{dM} – resultant force by Merchant; E – efficiency parameter
18	OXLEY-WELSH, 1967	$F_N = \frac{\sigma_A + \sigma_B}{2}\cdot\frac{t}{\sin\varphi}\cdot b$; $F_f = \tau\cdot\frac{t}{\sin\varphi}\cdot b$.	Merchants model: $\tau = \tau_0 + n\sigma$, $n \approx 0.23$ (experimental)
19	RUBENSTEIN, 1972	$F_z = \mu\cdot p_m \cdot b \cdot l_c + b\tau\left(2t + \overline{DA}\right)$; $F_y = p_m \cdot b \cdot l_c + b\cdot\sigma_1\cdot\overline{DA}$; $\overline{DA} = L = t(ctg\varphi - 1)$. Dynamic components: $(F_z)_\upsilon = (F_z)_i\cos\delta - (F_y)_i\sin\delta$; $(F_y)_\upsilon = (F_y)_i\cos\delta - (F_z)_i\sin\delta$.	p_m – unified contact effort t – depth of cut b – cutting width
20	ARNDT, 1973	$F_N = F_m\sin\left(90^\circ - \varphi + \gamma\right) + F_z\cos\gamma - F_y\sin\gamma$; $F_m = \frac{b\,t\,\upsilon^2\rho_d}{\cos\varphi}\left[\frac{1}{1+\tan\varphi\tan\gamma}\right]$.	F_m – inertia force when high speed cutting and F_z, F_y – according to Merchant
21	MOORE, 1975	$F_N = b\cdot\int p_A dx = = l\ p_{\max l\left(\frac{n}{l}\right)^{k_1} dx} = p_{\max}\cdot b\cdot l\cdot\frac{l}{l+k_2}$.	
22	ARMAREGO-BROWN, 1977	$F_p = F_z = F_s\left[\frac{\cos(\beta_N - \gamma_N)\cos i\cdot\cos\eta_s}{\cos(\varphi_N + \beta_N - \gamma_N)} + \sin\eta'_s\cdot\sin i\right]$; $F_Q = F_y = \frac{F_s\cos\eta'_s\cdot\sin(\beta_N - \gamma_N)}{\cos(\varphi_N + \beta_N - \gamma_N)}$; $F_R = F_x = F_s\left[\frac{\cos(\beta_N - \gamma_N)\sin i\cos\eta'_s}{\cos(\varphi_N + \beta_N - \gamma_N)} - \sin\eta'_s\sin i\right]$; $\tan\varphi_N = \frac{\gamma_t\cos\gamma_N}{l - \gamma_t\sin\gamma_N}$; $\gamma_t = \frac{t}{t_1}$.	Oblique cutting model F_s – shear force η'_c – chip deviation angle η_c – blade tilt angle
23	KOTELNIKOV-CIUIKO, 1978	$P_0 = 2\tau_s\left[t_0\left(0.5 - \frac{\pi}{4}\right) + H\right] + \tau_s H\frac{\frac{\pi}{2} + \left(1 + z_A^2\right)\arctan z_A}{M}$; $z_A = M - 1$ (method of balance equations for plastic area)	P_0 – cutting press τ_s – flow of chipped material t_0 – cutting depth
24	KIRK, ANAND, McKINDRA, 1977	$F_x = \frac{\tau_f\cdot b\cdot t\cdot\cos(\rho-\gamma)}{\sin\varphi\cos(\varphi+\rho-\gamma)}$; $F_y = -\cos\eta\cdot\frac{\tau_f\cdot b\cdot t\cdot\sin(\rho-\gamma)}{\sin\varphi\cos(\varphi+\rho-\gamma)}$; $F_z = \sin\eta\cdot\frac{\tau_f\cdot b\cdot t\cdot\sin(\rho-\gamma)}{\sin\varphi\cos(\varphi+\rho-\gamma)}$.	3D model with η angle between rake face and chip flow direction
25	NIGM, SADECK, TOBIAS, 1977	$C_d = e\sin\gamma + (1 - f\sin\gamma)\left[g + \frac{h}{(10^3 s)^k} l_n\left(\frac{s\upsilon^n}{Q}\right)\right]$; $C = -e'\sin\gamma + (1 - f'\sin\gamma)\left[g' + \frac{h'}{(10^3 s)^k} l\ n\left(\frac{s\upsilon^n}{Q'}\right)\right]$; $F_z = \frac{b\cdot s\cdot\tau_f}{\sin\varphi(\cos\varphi - C_d\sin\varphi)}$; $F_y = C\cdot F_z$; $\rho = \gamma + \arctan C$; $\tan\varphi = \frac{C_d\cos\gamma}{1 - C_d\sin\gamma}$.	Merchants model: $C_d = f(\gamma, s, \upsilon)$; $C = f(\gamma, s, \upsilon)$ – experimental determinations

26	WILLIAMS, 1978	$\tau_1 = \frac{F}{A}$; $A_1 = \frac{b \cdot t_1}{\sin\varphi}$; $\upsilon_1 = \frac{\upsilon \cdot \cos\gamma}{\cos(\varphi - \gamma)}$; $\frac{dE_1}{dt} = F_1 \cdot \upsilon_1$; $\tau_2 = \frac{F_2}{A_2}$; $F_2 = \tau_2 \cdot l_2 \cdot b$ $\upsilon_2 = \frac{\upsilon \sin\varphi}{\cos(\varphi - \gamma)}$; $\frac{dE_2}{dt} = F_2 \cdot \upsilon$; $\frac{dE_{3A}}{dt} = F_{3A} \cdot \upsilon$; $A_{3A} = \frac{hb}{\sin\varphi}$; $\frac{dE_{3s}}{dt} = F_{3s}\upsilon_1$.	Considers three areas of plastic deformation (*P*, *CD*, *SS*)
27	KAYABA- KATO, 1979	$p_x = \tau \sin\varphi' \cos\theta' + \sigma \sin\varphi \cos\theta$; $p_z = \tau \cos\varphi' + \sigma \cos\varphi$; $F_x = A\int_{l2}^{l1}\int_{\theta 2}^{\theta 1} p_x(\varphi,\theta) \cdot f(\varphi) \cdot g(\theta) d\varphi d\theta$; $F_y = A\int_{l1}^{l2}\int_{\theta 1}^{\theta 2} p_y(\varphi,\theta) \cdot f(\varphi) g(\theta) d\varphi d\theta$; $F_z = A\int_{l1}^{l2}\int_{\theta 2}^{\theta 2} p_z(\varphi,\theta) \cdot f(\varphi) g(\theta) d\varphi d\theta$.	Mathematical model in a contact point, where σ and τ are the acting efforts over the *xyz* – axis system. *A* – contact area for a multiple contact
28	ZAIKOV, 1978	$\sigma_n = \sigma_{SE}\left(1 + \frac{c}{y_1} m l_n - \tan\varphi\right)$; $c_1 = \frac{\sqrt{2}}{2} \cdot \frac{a'}{\sin\beta_z \cos\varphi}$; $a' = a \cdot \frac{\cot\beta_1 + \tan\gamma}{\cot\beta_2 + \tan\gamma}$; $F_N = \int_0^{c_1} b \cdot \sigma_n dy$; $F = \int_0^{c_1} b \cdot \tau_\mu$; $\tau_\mu = \mu \cdot \sigma_n$.	σ_n – specific press; β_1- primary shear angle; β_2 – shear angle on the φ_n direction; σ_{SE} – flow effort
29	GRASSO- NOTO LA DIEGA, 1980	$\frac{F_z}{A_0} = M + B\frac{F}{A_0}$; $M = \frac{M_0}{1 + \tan\gamma_n}$; $\left(\frac{F_z}{A_0}\right)_{\min} = M = \frac{2\tau_f}{1 + \tan\gamma_n}$.	Method of minimum mechanical work for chip detachment M_0 – minimum mechanical work for $F = 0$ and $\gamma_n = 0$
30	KRAVCENKO, 1989	$F_N = \frac{F_y(1 + \mu \cdot \tan\gamma) - F_z(\mu - \tan\gamma)}{1 + \mu^2 \cdot \tan\gamma - \mu^2}$.	Close results to those of Gordon 1978
31	LIN- WEIG, 1990	$\tau = \frac{F_y \cos\varphi - F_z \sin\varphi}{a \cdot b}$, $\sigma = f(\tau)$.	Merchants model for: $\varphi = \frac{k}{2} + \frac{\gamma}{2} - \frac{\rho}{2}$
32	AMARANDEI, 1993	$\mu = \frac{\sqrt{\left(\frac{F_x}{F_z}\right)^2 + \left(\frac{F_y}{F_z}\right)^2} + \tan\gamma_N}{1 - \tan\lambda \cdot \sqrt{\left(\frac{F_x}{F_z}\right)^2 + \left(\frac{F_y}{F_z}\right)^2}}$. If $\lambda = 0$ and $F_x = 0 \Rightarrow$ Merchants relation: $\mu = \frac{F_y + F_z \tan\gamma_N}{F_z - F_y \tan\gamma_N}$.	3D model
33	GILORMINI	$F_z = 2 \cdot \tau_{\max} = \cdot s \cdot t \cdot tg\left(\frac{\pi}{4} + \frac{\rho - \gamma}{2}\right)$; $C_d = \frac{a_1}{a} = \frac{\cos\left(\frac{\pi}{4} + \frac{\rho - \gamma}{2}\right)}{\sin\left(\frac{\pi}{4} - \frac{\rho - \gamma}{2}\right)}$; $l_c = \xi \frac{\sin(\varphi + \rho - \gamma)}{\sin\varphi \cos\rho}$; $l_c = \xi \frac{t}{\cos\rho} \tan\left(\frac{\pi}{4} + \frac{\rho - \gamma}{2}\right)$.	Merchants model: $\varphi = \frac{\pi}{4} - \frac{(\rho - \gamma)}{2}$
34	GILORMINI	$F_Z = \frac{2 \cdot \tau_{\max} \cdot s \cdot t}{1 - \tan(\rho - \gamma)}$; $a_1 = \frac{\cos\left(\frac{\pi}{4} - \rho\right)}{\sin\left(\frac{\pi}{4} - \rho + \gamma\right)}$.	Lee-Shaffer model: $\varphi = \frac{\pi}{4} - \rho + \gamma$
35	GILORMINI	$\rho = \gamma + \arctan\frac{F_y}{F_z}$; $\tau_{\max} = \frac{\sin^2\varphi}{s \cdot t}\left(F_z \cot\varphi - F_y\right)$; $\varphi = \arctan\frac{\cos\gamma}{\frac{a_1}{a} - \sin\gamma}$; $\overline{m} = \frac{a}{l_c} \cdot \frac{\sin\rho}{\sin\varphi \cos(\varphi + \rho - \gamma)}$.	F_y, F_z, a_1 – experimental values $\overline{m}$ – friction coefficient of Tresca

models can be extended to more complex milling processes such as ball end and five-axis milling. The models provide general information about the relations between the process performance and the process parameters and can be used to simulate real cases, and the best set of parameters to improve the process performance can be selected.

2.2. Orthogonal models

Orthogonal cutting means that the cutting edge of the tool is straight and normal to both cutting and feed direction [11]. The orthogonal cutting concept appeared in 1930, when Piispanen presented a so called "card model" [12] and described the workpiece material being cut as a 'stack of cards' (Fig. 1), where thin lamella's are produced which slip against successive elements as the tool penetrates the workpiece.

Ernst and Merchant used this basic model to develop another model which is used widely today known as the „idealized" orthogonal cutting model describing the mechanics of chip formation [14].

With his model, Figs. 2 and 3, Merchant showed that the shear angle is related to the tool rake angle α and friction angle λ by Eq. (1):

$$\phi = \frac{\pi}{4} - \frac{1}{2}(\lambda - \alpha)\,. \tag{1}$$

Unfortunately, when applied to a range of workpiece materials, the model does not provide accurate results.

Lee and Shaffer [15], Fig. 4, added the slip line theory to Ernst and Merchant's model, which provides the solution for φ as:

$$\phi = \frac{\pi}{4} + \alpha - \beta\,. \tag{2}$$

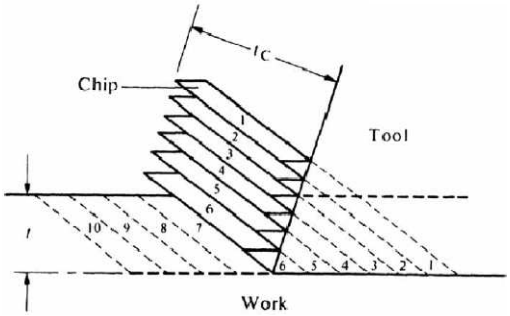

Fig. 1. Piispanen's [12] 'card stack' model of chip formation.

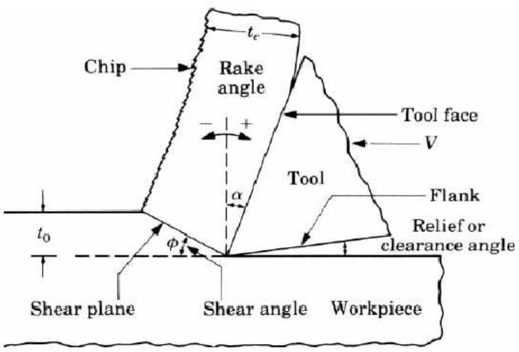

Fig. 2. "Idealized" orthogonal cutting model [14].

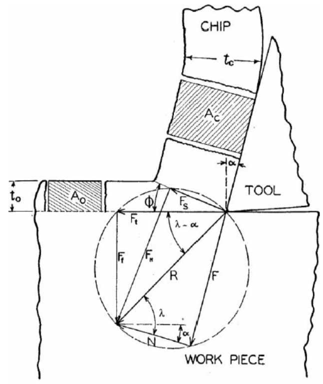

Fig. 3. Merchant's circle force diagram.

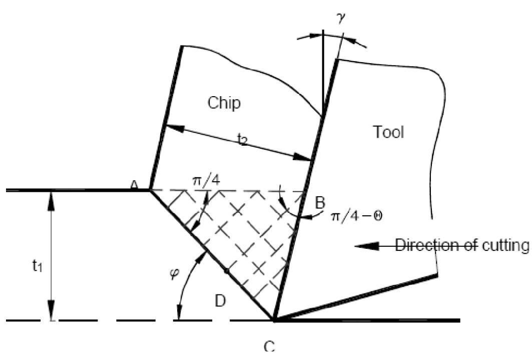

Fig. 4. Lee and Shafer's slip-line field configuration with the built-up edge [15].

Kececioglu's approach was similar to Merchant's model but assumed the primary and secondary deformation zones within parallel-sided boundaries. He assumed a uniform stress distribution in these deformation zones, [16]. In 1961 Okushima and Hitomi [17] made an analysis when applying an orthogonal cutting to discontinuous chip.

Another important model is the Oxley's model. Oxley based his work on the Merchant's model and discovered that when a wide range of cutting conditions is applied Merchant's theory showed very poor quantitative agreement with experimentally measured values [18]. Oxley and Welsh [19] developed a new predictive analytical model with a direct description of the chip formation and they concluded that the shearing took place within a finite plastic zone Fig. 5. The analysis described by Oxley and Welsh involved a determination of the stresses as function of the shear angle and work material properties. Despite the improvements brought up by Oxley and Welsh's model, the lack of sufficient strain and stress data is a significant limitation.

Over the years there had been many other important theoretical models developed for the prediction of cutting forces and temperatures, such as those of Trigger and Chao [20], Boothroyd [21], Hou and Komanduri [22] etc.

A list of the most known orthogonal cutting models is presented in Fig. 6.

In the recent publication by Shamoto and Altintas [24] the Ernst and Merchant approach was applied to oblique cutting. The authors mentioned that when three-dimensional oblique cutting model is applied to two dimensional orthogonal cutting, it yields the following shear angle expression similar to the Ernst and Merchant's solution.

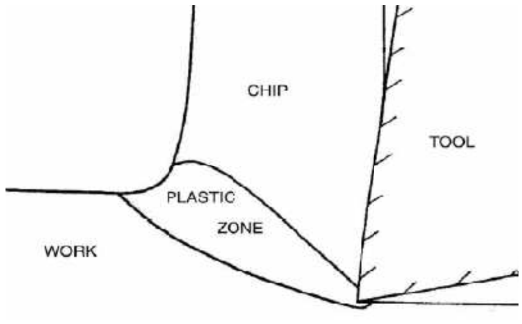

Fig. 5. Chip formation within a finite plastic zone [19].

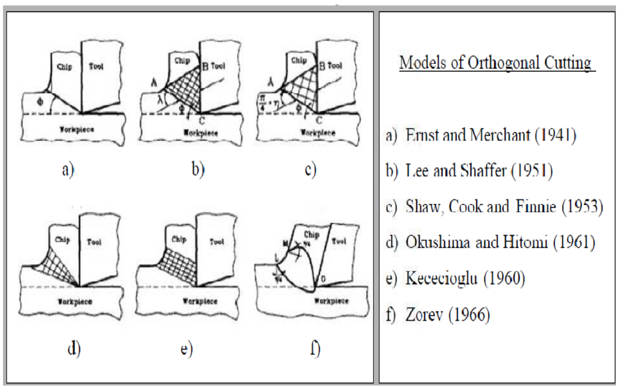

Fig. 6. Models of Orthogonal Cutting [23].

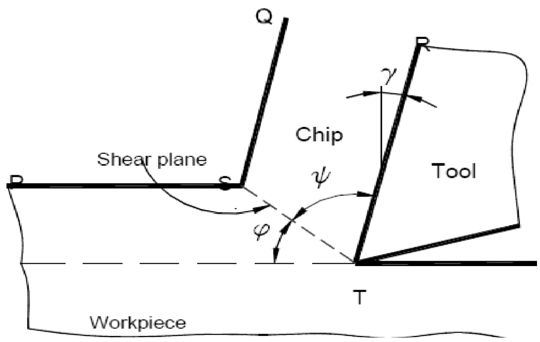

Fig. 7. Hill's model [25].

$$2\varphi_{sp}+\theta-\gamma=\frac{\pi}{2}, \tag{3}$$

Furthermore Hill [25] investigated the possibility of steady states in which the zone of deformation is concentrated in a single plane (ST) springing from the tip of the tool (T), Fig. 7. The inclination of this shear plane to the surface of the workpiece is denoted as φ and its inclination to the tool face by ψ.

2.3. Dynamic models

When speaking of dynamic models we can quote the paper of J. W. Sutherland [64] in which the author presents a dynamic model of the cutting force system in the end milling process, Fig. 8. His model describes: the dynamic transverse response of the end mill via a distributed parameter model, the chip load geometry and the dependence of the cutting forces on the chip load and has some unique features: a model for the instantaneous chip load which includes the effects of past and present displacements of the end mill relative to the workpiece and the effects of cutter run out and a model for the dynamic response of the end mill which describes the dynamic response via a distributed parameter representation of the end mill.

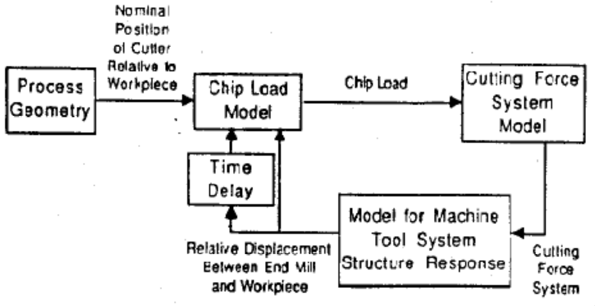

Fig. 8. Elements of the dynamic end milling cutting force [64].

It is a representative work, next to similar works of J. Tlusty et al. [65, 66, 67, 68, and 69]. Recent researches of Zhou [63], Daud et al. [70], Ko et al. [71], Ispas et al. [72], etc., help improving the dynamic models.

Anna Araujo et al. [103] present in their paper a dynamical analysis of the milling process using a smoothness system for the mathematical description of the system dynamics. The general aspects of the milling process are captured by the proposed model that can be used to identify unproper system response. The system dynamics is investigated by considering different operational conditions of the milling process. The idea is to represent different aspects related to proper and improper functioning. In order to describe these conditions, different machine tool velocities and workpiece material are used.

2.4. Genetic models

An interesting development is made by Milfelner et al. [95]. The paper presents the development of a genetic equation for the cutting force in a ball-end milling process using some measured cutting forces and the genetic programming.

Genetic algorithms (GAs) [96] are a part of evolutionary computing and were invented and developed by John Holland [97]. GA is a model of machine learning which derives its behavior from a metaphor of the processes of evolution in nature.

The genetic equation developed by exploring the advantages of the artificial intelligence methods can be used for the cutting force estimation and optimization of cutting parameters. This equation (4) is seen as a direct modeling method when predicting cutting forces for the ball-end milling operations

$$\begin{aligned}F_{max} &= 11.04 + R_D - A_D + V_C \cdot R_D \cdot A_D - 58.50 \cdot (-8.2466 + A_D) \cdot A_D \\ &+ \frac{58.50 \cdot (-8.25 + A_D) \cdot (0.0058 + A_D) + V_c \cdot (-0.79 - 0.28 \cdot f_z)}{V_c \cdot (2.802 + R_D) \cdot (2.7956 - A_D) \cdot f_z^2} \\ &+ \frac{V_C \cdot R_D \cdot (2.802 + R_D)}{0.10 \cdot V_C - 2 \cdot R_D - A_D + f_z - 0.57 \cdot V_C \cdot f_z}.\end{aligned} \tag{4}$$

As seen in Fig. 9, the results from the proposed genetic programming approach prove their effectiveness and resemble with the experimental results.

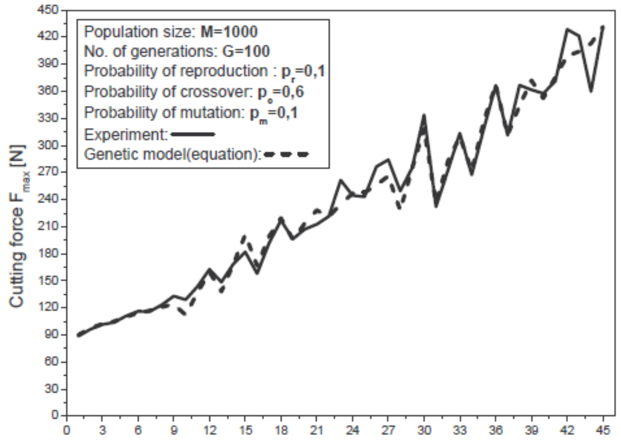

Fig. 9. Experimental and genetic data [95].

Other examples of genetic models are presented in the papers of S. Gallova [104] and of K.-D. Bouzakis et al. [105]. Bouzakis [105] uses a multi-objective optimisation procedure, based on genetic algorithms to obtain the optimum cutting of milling. Objectives functions, like machining cost and machining time and technological constrains are simultaneously taking into consideration.

A Pareto-optimization approach is used to determine the optimum cutting parameters. The proposed approach can be applied on various cases of milling (single pass or multi-pass, roughing or finishing). Optimum machining parameters obtained from this procedure can be intended for use by commercial CAD-CAM systems or directly by CNC machines.

3. FINITE ELEMENT MODELING

3.1. Brief history of FEA

As previously shown, Finite Element Analysis (FEA) technique was first introduced in early 1970s and has been widely used since then. Many researchers developed their own FEM codes in order to help improving the analysis of metal cutting processes [26, 27, and 28]. Usui and Shirakashi [26] assumed a rigid sharp tool and elasto-plastic workpiece, and defined a node separation criterion based on the geometry of the element approaching the cutting edge. Iwata [27] established a rigid-plastic cutting model and used a ductile fracture criterion for node separation. However, the effects of temperature were excluded. Stenkowski et al. [28] used the NIKE-2D software and assumed fracture strain criterion to determine the separation of the predefined plane near the tool cutting edge. All of these early FEM models for metal cutting assumed perfectly sharp tool.

In 1990, automatic remeshing methods were developed to allow FEM cutting models to consider the tool edge geometry [29, 30, and 31]. These remeshing methods use similar procedures, which start by detecting mesh distortion, dividing the contact boundary, adding up internal nodes and then interpolating stress and strain data for the new mesh. Marusich [30] developed a FEM cutting model using six-node quadratic triangular elements, based on dynamic Lagrangian formulation. His model was later transformed into an explicit FEM software code called Third Wave AdvantEdge. Ceretti [31] used an early version of commercial software named DEFORM-2D. This code uses four-node quadrilateral elements and is based on static Lagrangian formulation. Today, both DEFORM-2D and AdvantEdge codes are commonly used by researchers and industry. Their simulation results are widely discussed in the literature. A number of researchers pointed out that after repetitive remeshing the errors may accumulate in the Lagrangian approach. Some researchers proposed the cutting models using Arbitrary Lagrangian-Eulerian (ALE) formulation to simulate steady state cutting [32 and 33].

Applications of FEM models for machining can be divided into six groups: 1) tool edge design, 2) tool wear, 3) tool coating, 4) chip flow, 5) burr formation and 6) residual stress and surface integrity.

Tool design can be improved by prediction of tool stresses and tool temperature. A study of tool edge design using FEM [34] shows that tool edge radius has a small effect on cutting forces but influences chip flow direction, tool stresses and surface finish.Modelling of tool wear has been studied only recently using FEM by incorporating tool wear data from experiments [35]. Modelling tool wear using FEM has some advantages over statistical approach because it requires less experimental effort and it provides useful information such as normal tool stress and tool temperature. These variables can approximately determine how cutting parameters affect tool life and tool performance.

A vast majority of cutting tools and inserts today are coated in order to increase the tool life. Several experimental studies have analyzed the effects of coatings referring to their thermal barrier and low friction properties [36].

Several studies have been conducted using FEM for modelling serrated chip, chip curling, chip breakage, and the 3D chip flow [26, 31, and 37]. Modelling burr formation using FEM was initiated by Dornfeld and his associates [38]. However, this initial work was limited by the assumption of a sharp tool and a need of element-separation criterion. The predictions of residual stresses and surface integrity are significant to access the fatigue life and the performance of machined components. A number of researchers have attempted to use FEM simulation to predict and obtain desirable residual stresses due to machining [39 and 40].

3.2. Model formulation

This refers to the way in which the finite element mesh is associated with the workpiece material. There are three main types of finite element formulations: Lagrangian, Eulerian and the Arbitrary Lagrangian–Eulerian (ALE) [41].

3.2.1. Lagrangian formulation. This formulation is widely used. In a Lagrangian analysis, mesh grid deforms with the material, because the mesh is attached to the workpiece material. This is suitable for solid mechanics analysis [33]. This is also preferred for metal cutting simulations because it simulates the entry, exit, intermittent and discontinuous chip formation phases and the geometry of the material boundaries don't have to be predetermined [42]. When speaking of disadvantages one can find an important one: the elements generally experience severe deformations [43], geometrical and material non linearity is introduced and the computational load is considerably increased. This means that the mesh has to be regenerated often to prevent the simulation breakdown and this affects the efficiency and accuracy of the analysis. The chip detachment from workpiece is achieved by separation of nodes in front of the tool tip along the depth of cut [44, 45, 46, and 47] but this method has its own problems like a tendency for the nodes in front of the tool to be pushed out of position, or premature node separation, which is caused by inappropriate specifications. Such problems affect the accuracy and validity of results. Recently, many researchers investigated these problems and tried developing alternative methods such as element deletion [48 and 49] and adaptive remeshing [50].

3.2.2. Eulerian formulation. In this approach the finite element grid is fixed in space [51] and the material flows through the meshed control volume. This approach can't simulate the intermittent and discontinuous chip formation phases but the Eulerian based models haven't any element distortion problems, so no remeshing is necessary, which is a key benefit in terms of efficiency [52]. Among the disadvantages of this approach is reminded that the initial shape of chip and the contact conditions must be known or assumed in advance, that implies the manually adjusting of the free surfaces of the chip [53]. This Eulerian method is well suited for the study of steady-state cutting [54]. Although good predictions have been made by several researchers like Strenkowski and Moon [55] and Strenkowski and Athavale [56], it is agreed that this approach is more suitable for fluid mechanics than machining.

3.2.3. Arbitrary Lagrangian Eulerian Formulation (ALE). ALE formulation is a combination between Lagrangian and Eulerian approaches, and was developed in order to take full advantage from the benefits of the two formulations into one complex approach. The finite element mesh is neither fixed in space nor attached to the material, but is allowed to move relative to material [57].

The ALE approach can be reduced to Eulerian or Lagrangian approach when needed [58]. In case of metal cutting simulations, the ALE formulation applies features of the Eulerian type for modelling the area around the tool tip, while the Lagrangian formulation should be applied for modelling the flow of material and the free boundaries [59]. An early description of this approach can be found in the paper of J. Donea [60]. ALE formulation has been used extensively for fluid structure interactions problems [61].

4. 2D AND 3D FEM SIMULATION OF MACHINING PROCESSES

Up to 1990 the majority of researchers concentrated themselves on the two-dimensional FEM simulations, plane strain descriptions, making comparisons with orthogonal cutting of conventional workpiece materials such as carbon and steels. Despite of the great improvements of computational methods many researchers still use the 2D formulations [73–77].

Although initially the focus was mainly on simulating the continuous chip formation and prediction of stress and strain distributions, today researcher developed their works and models in such matter that they present specific aspects associated with the cutting process: effect when varying tool geometry [78], evaluation of workpiece and chip temperatures [79 and 80], modelling the effect of coatings on temperatures generated [81–83], predictions on different chip morphologies [84], simulation of discontinuous chip formation [85–88].

In his paper Bäker [87] uses a different approach: an algorithm that triggered automatic remeshing as a result of heavy distortion when a shear band occurred. This remeshing technique changed the mesh topology by adding "free" nodes where necessary in order to create the chip segment.

Later researchers headed to 3D simulations, especially when speaking of turning processes. Among the first 3D investigations is the research of Maekawa et.al. [89], an investigation on the machinability of leaded Cr-Mo and Mn-B steel.

The simulation of other cutting processes such as drilling and milling started to gain space since year 2 000, because the three-dimensional models are necessary in order to fully understand and resolve problems.

G. Pitalla and M. Mono, in their paper [90], proposed a 3D model of a milling operation considering the real geometry of the insert. The FEM simulation was carried out with the commercial code DEFORM3D (Fig. 10).

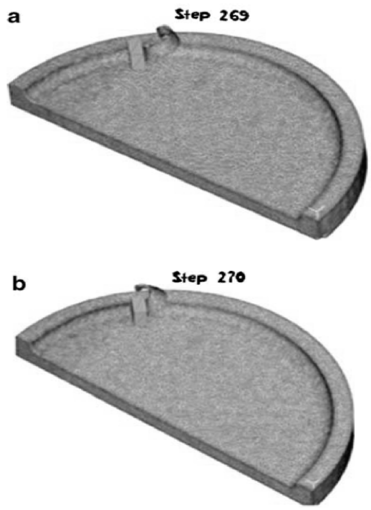

Fig. 10. Chip morphology friction coefficient [90]: a – 0.6; b – 0.1.

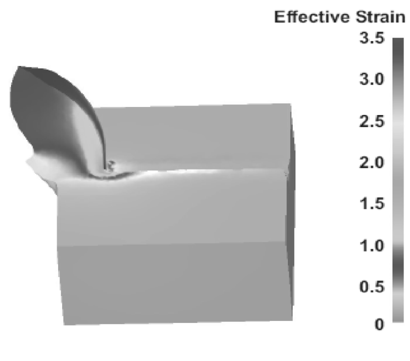

Fig. 11. Result with continuous adaptive remeshing [91].

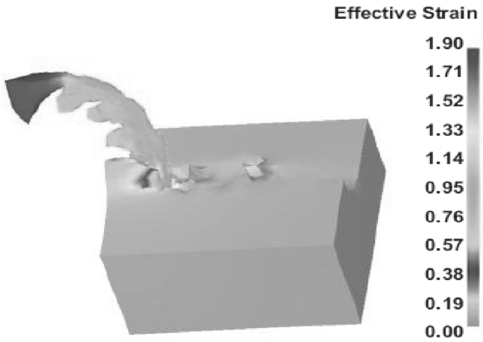

Fig. 12. Result with modelling of fracture [91].

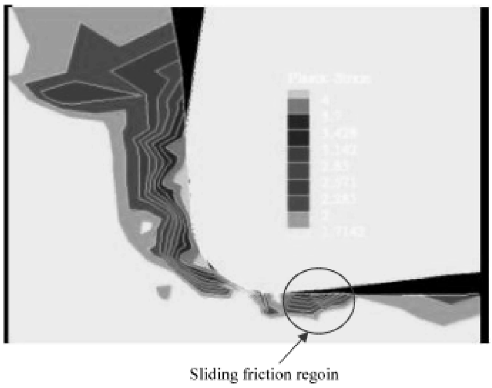

Fig. 13. Sticking friction [92].

Aurich et al. [91] created a 3D coupled thermo-mechanical finite element model for the simulation of segmented chip formation. And the results conclude: the method of thermal softening produces a brief segmentation and was able to predict narrow shear localization in the chip (Fig. 11) and crack initiation and propagation, on the other hand, predicted severe segmentation in the chip, Fig. 12, creating more segments for the same tool stroke.

Kadirgama et al. [92] tried to highlight the effect of milling parameters when milling hastelloy C-22HS using two methods: a FEM and a statistical method, Fig. 13. They concluded in their paper that cutting speed, feed rate and axial depth of the milling process play the major role in producing high friction force, coefficient, angle and stress and that the combination of numerical analysis and statistical method are very used in analyzing the distribution of friction in milling.

In their paper, T. Schermann et al. [93] used commercial software named ABAQUS/Explicit (Fig. 14). Their simulation results proved to be similar to the experimental ones (Fig. 15).

In a recent paper Andrew Otieno and Clifford Mirman [94] tried to emphasize FEA of cutting forces and temperatures when micromachining aluminium alloys using third commercial software AdvantEdge (Fig. 16). They concluded that the depth of cut has the most significant influence on the machinability of a material in micromachining applications. When the depth of cut is tripled, the cutting forces increase by 3.5 to 4 times. On the other hand, when the feed is tripled the cutting forces increase by 2.5–3 times. The preliminary results from their study can be used in an optimization process to determine optimum cutting conditions.

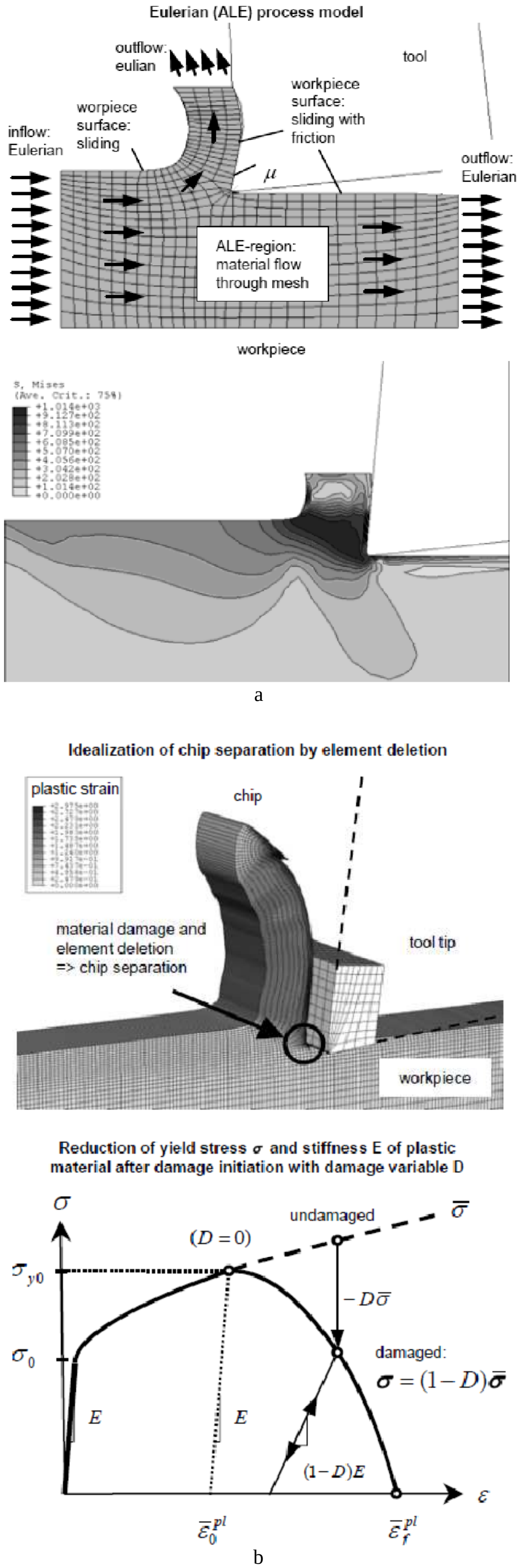

Fig. 14. Process models and results [93]: *a* – Eulerian (ALE) process model/ example results; *b* – Lagrangian process model with damage/ element deletion.

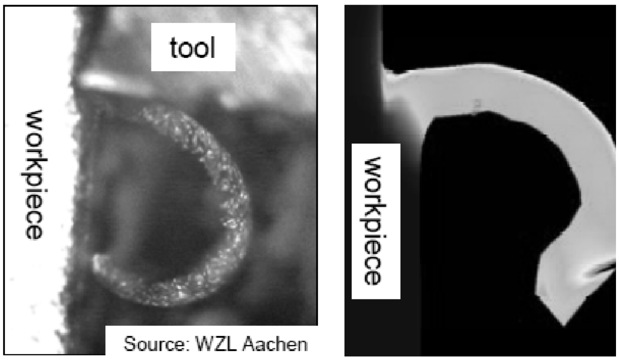

Fig. 15. Chip formation in experiment versus simulation [93].

5. COMMERCIAL SOFTWARE USED

In recent years finite element method became the main tool for the analysis of metal cutting because it has important advantages as follows:

- Material properties can be handled as a function of strain, strain-rate, and temperature;
- Nonlinear geometric boundaries, such as free surfaces, can be modelled;
- Other than global variables like cutting force, thrust force; local variables like strains, strain-rates, stresses, etc. can be obtained;
- Interaction of chip and tool can be modelled in different forms.

From 1990s massive use of commercial software when modelling the cutting processes starts. Examples of such software are: NIKE2, ABAQUS, MARC, DEFORM 2D and 3D, AdvantEdge, FORGE 2D, ALGOR, FLUENT, LS DYNA.

Table 2

Comparison between Abaqus, AdvantEdge, and Deform [62]

	Advantages	**Disadvantages**
Abaqus	- high level of detail - manual design of work-piece and tool, free modelling - allows configure the material with lot of details - basic solver function can be modified	- has no support for any materials - it takes a lot of time to “setup” simulations as the user has to manually set many of the simulation parameters like mesh refinement and boundary conditions - not much fine control in adaptive meshing
Advant Edge	- the solver is optimized for metal-cutting processes - simple tool and work-piece geometries, - allows import of complex geometries - extensive material library, - allows specifying new materials - uses adaptive meshing to increase the accuracy of solution	- gives the user less flexibility in configuring the controls of the solver, this means that the user is restricted to the preset controls of the software - the software also has no support for drilling operations
Deform	- set up of standard machining processes - adjusts solver parameters - extensive material library - capability of defining new materials - uses adaptive meshing controls	- some tool geometries need to be imported - the drilling module has a few deficiencies: the simulation solver runs very slow and stops periodically

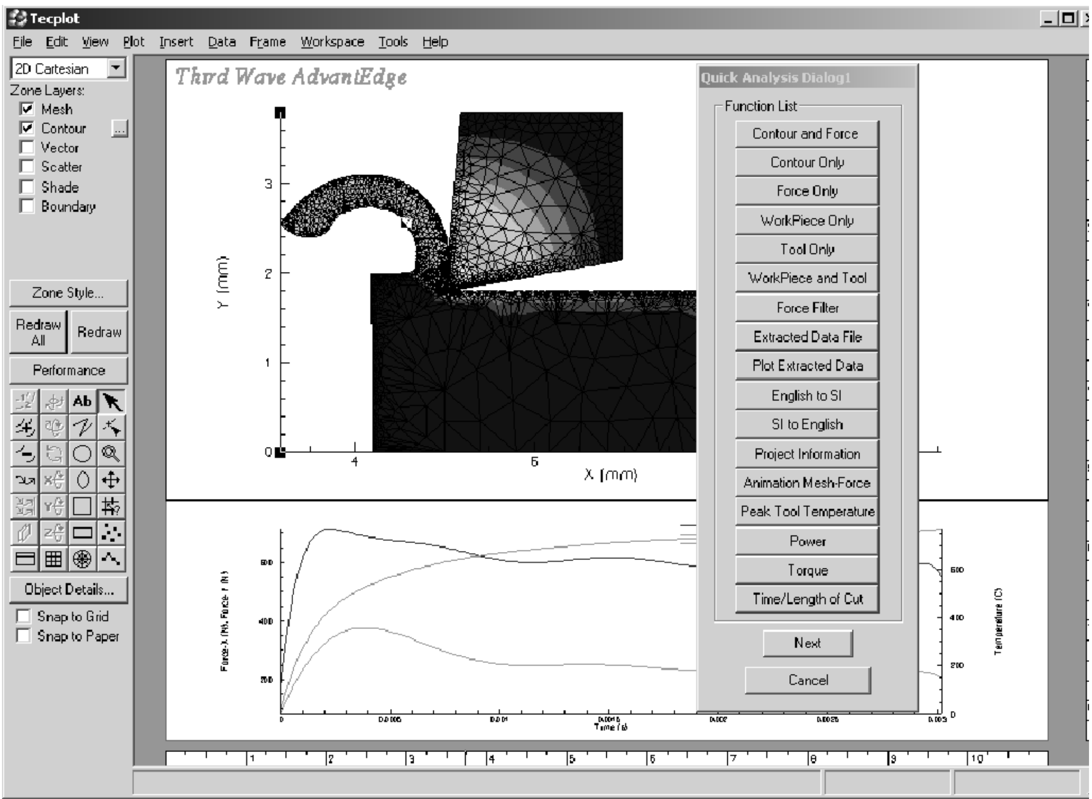

Fig. 16. Steady state cutting forces and temperatures [94].

The right choice of finite element software is very important in determining the scope and quality of the analysis that will be performed. The most important software codes used for simulation of metal cutting are: Abaqus, Deform and AdvantEdge, Table 2.

6. CONCLUSIONS

The use of FE modelling techniques as a design or optimization tool for machining processes is growing.

Current commercial packages are not able to predict with reasonable reliability and accuracy aspects such as workpiece surface integrity post-machining, which is of big importance when speaking of safety critical components such as aero-engine parts. There is, however, a growing interest in developing suitable expertise within this area. Another related area that has received significant attention is the effect of tool geometry (in particular tool edge radius) and associated cutting parameters in relation to workpiece residual stress [98 and 99]. But modelling has important advantages. The most well known reasons for modelling are: design or planning of processes, optimisation of processes, control of processes, simulation of machining processes, and design of equipment.

In principle, only quite simple models would be needed for selection of the proper type of operation (turning, milling, drilling), type and main dimensions of the cutting tool and the class of tool material. The difficulty is of a different nature, e.g. if the intended operation can be performed without disturbances. To answer this, an investigation of the boundary conditions for safe machining, which increases the demands of the model is necessary. The best available solution are certain rules, e.g. rules deciding the level of stiffness needed to prevent too large deflections and vibrations.

The optimisation of processes requires more complicated models. Some of these models are designed for technical or economical aspects. An example of a pure technical aspect would be a model for calculation of maximum feed for a specific cutting force.

The application of models for control of metal cutting processes has so far not been shown much attention. This is remarkable since the use of appropriate models can prevent rejects due to scatter of results from metal cutting.

In the area of simulation of machining processes the models became more reliable and the results accurate.

There are today models that are convenient for use for design of equipment. Examples are models used for estimations of expected values of cutting forces, torque, power and spindle speeds. Other examples are models used for studying elastic and thermal deformations as well as the dynamic behaviour of machine tools.

Accurate predictions of the result from manufacturing processes have today a great interest due to the interest of useful strategies for the control of processes. This interest is supposed to grow even further in the future due to the desire in being able to predict the accuracy of shape and dimensions, surface roughness, properties of the subsurface layer of produced parts, required machining time and cost of different operations but the primary objective of modelling of machining processes is the development of the capability of predicting the machining performances. This aim is desirable in order to facilitate effective planning of machining processes to achieve optimum productivity, quality and costs.

ACKNOWLEDGEMENTS: The work has been funded by the Sectoral Operational Program Human Resources Development 2007-2013 of the Romanian Ministry of Labour, Family and Social Protection through the Financial Agreement POSDRU/ 88/1.5/S/61178.

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