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Prediction of Cutting Forces at 2D Titanium Machining

Diana – Andreea Coroni, Sorin – Mihai Croitoru*

Politehnica University, 313 Splaiul Independentei, Bucharest RO 060042, Romania

Abstract

The paper presents aspects related to simulation for optimization of metal cutting for titanium and its alloys. Due to the corrosion resistance, high mechanical strength and low density, titanium and its alloys are currently attractive materials in the industry. For simulations, the software based on finite element method - DEFORM 2D[©] - was used. Cutting process simulations were made for several materials, in the same cutting conditions. Some of the obtained results are presented. Conclusions are presented in terms of comparison.

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1. Introduction

Historically speaking, until recently it was considered that the cutting process of titanium and its alloys would be difficult. With the development of modern manufacturing methods and processes, cutting these alloys and also their use in more and more areas of industrial engineering, became increasingly attractive. Nowadays, in which concerns machining process, there is a widespread trend to use high cutting speeds - "High Speed Machining".

Related to the cutting process there are two important elements: workpiece and cutting tool. Also, other elements should be considered: tool clamping and workpiece, cutting regime parameters and the use of cooling – lubrication liquid.

Cutting processes require high manufacturing accuracy, which also lead to a good quality of the obtained surfaces. Surface low quality is strictly influenced by certain factors, such as inappropriate choice of cutting regime parameters (v_c, f, a_p), dynamic behaviour of the technological system, tool wear etc.

In metal cutting, due to layer by layer removal of the chips, a high dimensional accuracy is obtained.

* Corresponding author. Tel.: +40722623858; fax: +40214029420.
E-mail address: sorin.croitoru@gmail.com

Under the action of the cutting tool edge, the additional material of the workpiece turns to chips. In the workpiece zone of chip formation the distribution of compression stress and friction will influence the cutting forces that occur during the process.

To see these influences and to predict cutting forces in cutting titanium and its alloys, specialized software DEFORM 2D[®] was used to simulate orthogonal cutting [1]. The software uses the finite element method for modelling the dynamics of pure plastic or elastic-plastic deformation processes. The theory of metal cutting processes and phenomena are explained by plastic deformation of the workpiece material, so the cutting process itself is a plastic deformation process. Thus, we can say that conventional manufacturing of metals can be made through plastic deformation processes.

In DEFORM 2D[®] simulation both tool and workpiece can be defined in the software. The incremental movement of the active part of the cutting tool is simulated and, if necessary, the software remodels the mesh automatically and calculations are continued [1, 2, 3]. It should be mentioned that the software reduces simulation problem in a plane, which is possible for orthogonal cutting. For complex surfaces it is recommended to use DEFORM 3D[®] software.

However, considering the processing time calculations, which for DEFORM 2D[®] can take tens of minutes and for DEFORM 3D[®] can take tens of hours (depending on the complexity of the model and the capabilities of the computer), it is recommended that the set of cutting conditions should be made in DEFORM 2D[®] and complex simulation model should be made in DEFORM 3D[®].

2. Simulation of cutting process

There were performed several sets of simulations on two grades of pure titanium (grade 1 and grade 2) and for one of its alloys, Ti6Al4V, considered as the reference titanium alloy. The elasticity of workpiece materials was not considered in the simulations because metal cutting is a process which takes place in the plastic field, even if elastic deformations occur.

The measurement units were considered in the International System, but it can be also used the English System [1].

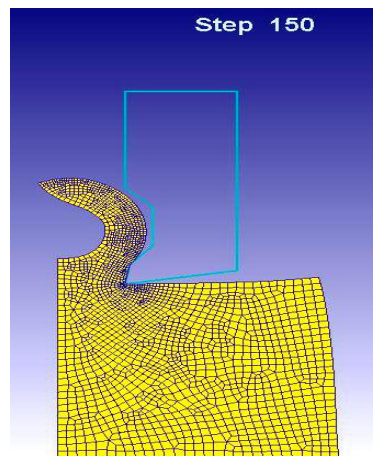


Fig. 1. Simulation of workpiece clamping for studied cases by means of border conditions [1].

From the beginning, DEFORM 2D[®] software sets the conditions for simulation, such as: process type, geometry, temperature and materials of both workpiece and cutting tool, workpiece mesh complexity, cutting tool relative movement to the workpiece, whilst the workpiece is fixed by means of imposed boundary conditions (see figure 1) or by means of a clamping device, considered as the second die.

In processing pure and alloyed titanium, due to small cutting speeds, the way to increase productivity is by increasing the depth of cut. Generally speaking, the roughing of pure and alloyed titanium uses speeds of 60 m/min, and finishing operations are performed at speeds up to 250 m/min.

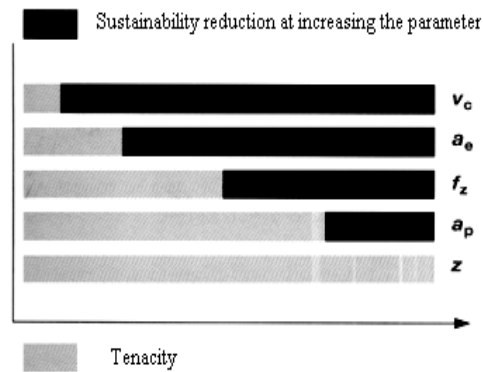


Fig. 2. The influence of cutting parameters variation upon tool durability [4].

When machining titanium and its alloys, in order to remove excess heat that occurs at the contact between cutting tool and workpiece, and also to remove the chips formed in the process of metal cutting, it is highly recommended to use cooling liquid. This means to consider proper friction coefficient and temperature in the process.

Cutting tools used must meet certain conditions for manufacturing, see figure 2 [4], because resulted chips are hardened, which can lead to premature wear of these tools.

Because of the tool durability, manufacturing titanium is directly influenced by temperature of the cutting edge. The correct choice of cutting regime is a balance between cutting speed and chip dimensions (depth of cut and feed).[3]

As mentioned above, under the action of the tool edge, the additional material of the workpiece turns to chips. In the zone of chip formation occurs a state of stress, related to the cutting regime input and output parameters.

Cutting forces are components of total cutting resistance R on the three axes of $OXYZ$ kinematic reference system [5]:

- Force F_z is the main cutting force,
- Force F_x is the feeding force,
- Force F_y is the rejection force.

Determination of cutting forces was the object of many researches, analytical expressions for their determination with different forms: exponential, polynomial etc., considering various parameters of the cutting conditions.

Depending on a very large number of parameters, cutting forces can characterize a workpiece material from the point of view of cutting machinability.

Forms of analytical relationships for determining the cutting forces are shown below, in an exceptional review [5].

Simple models - Linear Functions

J.Hart (1876); H.Fischer (1897)

$$F_c = K_1 \cdot b \cdot h_{cu} \quad (1)$$

H.Friedrich (1909)

$$F_c = K_1 \cdot q + w_R \cdot b_s \quad (2)$$

A.Richter (1954)

$$\frac{F_c}{b} = C_1 \cdot h_{cu} + C_2 \quad (3)$$

Simple models – Exponential Functions

F.W.Taylor (1907)

$$F_c = K_1 \cdot t \cdot s^{K_2} \quad (4)$$

C.Salomon (1928)

$$\frac{F_c}{b} = K \cdot h_{cu}^{(\alpha+1)} \quad (5)$$

O.Kienzle (1951)

$$\frac{F_i}{b} = K_{i1..l} \cdot h_{cu}^{(1-m_i)} \quad (6)$$

H.Viktor (1956)

$$\frac{F_i}{b} = f_i \cdot K_{i1..l} \cdot h_{cu}^{(1-m_i)} \quad (7)$$

M.Hirschfeld (1953)

$$\frac{F_{ij}}{b} = K_{i1..lj} \cdot h_{cu}^{(1-m_i)} \quad (8)$$

L.Deselaers (1970)

$$\frac{F_i}{b} = C_\rho \cdot \frac{\rho_s}{h_{cu}} \cdot K_{i1..l} \cdot h_{cu}^{(1-m_i)} \quad (9)$$

H.Kamm (1977)

$$K_i = \frac{F_i}{b \cdot h_{cu}} = K_{i0} + K_{i1} \cdot \left(\frac{h_{cu}}{h_{cu1}}\right)^{-C_{ik}} \quad (10)$$

K.Langhammer (1972)

$$\frac{F_i}{b} = K_{iHV100} \cdot \left(\frac{HV}{100}\right)^{\alpha_i} \cdot \left(\frac{v_c}{100}\right)^{-m_i} \cdot h_{cu}^{(1-x_i)} \quad (11)$$

Simple models - Combined Functions

U.Klicpera (1972)

$$\frac{F_i}{b} = p_i + g_i \cdot h_{cu} + \frac{q_i}{c_i} \cdot e^{c_i h_{cu}} \quad (12)$$

W.Engelhard (1976)

$$\frac{F_i}{b} = p_i + g_i \cdot h_{cu} + \frac{q_i}{c_i} \cdot e^{c_i h_{cu}} + k \cdot (e^{m_\gamma} - e^{m_{\gamma 1}}) \quad (13)$$

Complex models - empirical

W.Klein (1937)

$$F_c = (g(\text{mat.piesa}) + h_{cu} \cdot f(\text{mat.piesa}, \gamma)) \cdot (1 + \mu_{\gamma} \cdot \text{tg} \lambda) \quad (14)$$

H.Brandenberger (1945)

$$F_c = q \cdot \sigma_{zef} \cdot \lambda_{ch} \quad (15)$$

F.Eckstein (1973)

$$\frac{F_c}{b} = h_{cu} \cdot \sigma_{zef} \cdot \lambda_{ch} \quad (16)$$

Complex models - theoretical

H.Huchs (1951)

$$\frac{F_c}{b} = \tau_0 \cdot h_{cu} \cdot \kappa \lambda \quad (17)$$

K.F.Meyer (1965)

$$\frac{F_c}{b} = h_{cu} \cdot \frac{\tau_\phi}{\text{tg} \phi} + \sigma_\phi; \frac{F_d}{b} = h_{cu} \cdot \frac{\sigma_\phi}{\text{tg} \phi} - \sigma_\phi \quad (18)$$

L.Kazinczy (1974)

$$F_S = t \cdot \tau_B \cdot \frac{s}{\sin \phi}; F = t \cdot \tau_B \cdot \frac{s}{\sin \phi} \cdot \frac{l}{\cos 45^\circ} \quad (19)$$

These relationships were determined analytically, but are based and completed by experimental research. Back in the late 1970's, Professor Stefanuta Enache from University Politehnica of Bucharest, member of CIRP at the time, used a very simple relationship to determine the cutting force:

$$F_c = (3..7) \cdot \sigma_r \cdot f \cdot a_p \quad (20)$$

where σ – tensile strength of the workpiece material, f – feed and a_p – cutting depth, minimum cutting force coefficient = 3 for high strength (ductile) materials (steel), maximum cutting force coefficient = 7 for low strength (fragile) materials (cast iron)[6]. Equation (20) is very useful, considering its simplicity and the significant errors of Taylor's practical equations.

Cutting depth is an important cutting parameter which influences the cutting forces, when all the others are kept identical. When cutting depth is very small cutting pressure is very high, leading to the rise of the cutting forces. In this case a similar relationship to equation (20) can be used, the values of the cutting force coefficient being 2...5 for tenths of millimeters up to 5...10 for hundredths of millimeters [6].

Cutting forces are an important part of the cutting process and are influenced by almost all system parameters:

- active part material for the cutting tool,
- machining process,
- workpiece material,
- cutting regime parameters,
- active part geometry for the cutting tool,
- manufacturing environment conditions, cutting fluids, cutting tool wear condition [3].

Using DEFORM 2D[®] software the prediction of cutting forces was simulated, considering imposed parameters of the cutting regime.

For orthogonal cutting simulation, only the cutting speed and depth were used. In order to simulate the process, the following data were chosen: cutting speed 60 m/min, cutting depth 1 mm and the tool rake angle $\gamma = 5^\circ$.

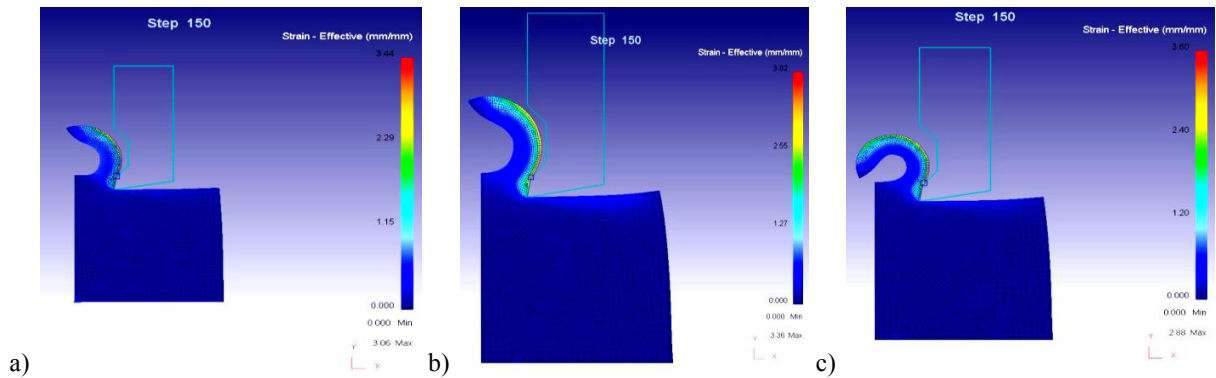


Fig. 3. The state of strain during the simulation for the three studied cases.

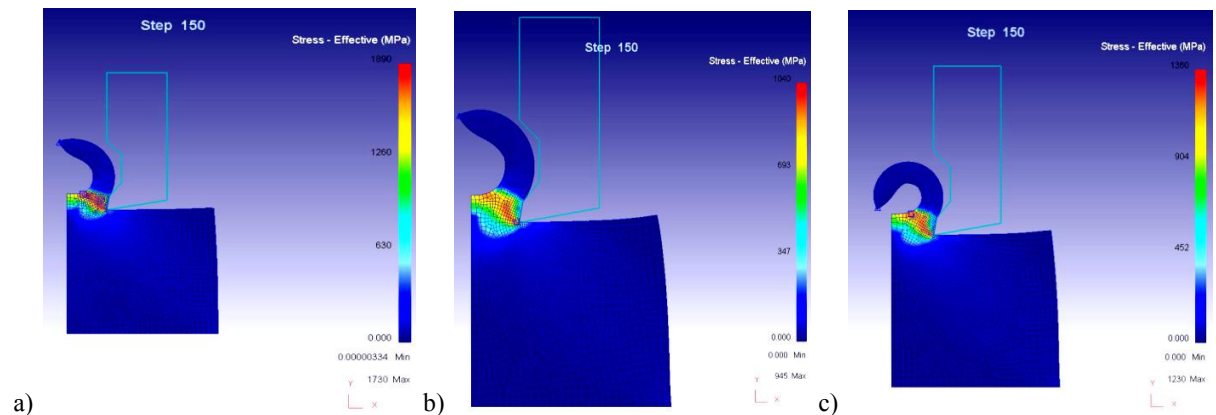


Fig. 4. The state of effective stress for the three studied cases.

The studied workpiece materials were titanium alloy (Ti6Al4V) and two grades of pure titanium (1 and 2), with properties defined in the library of materials found in DEFORM 2D[®] software. The simulation included the following steps:

- naming the studied problem (file),
- setting the load case (symmetrical / asymmetrical) to reduce the case to a 2D problem,
- setting the workpiece geometry,
- meshing the geometrical model,
- choice of the workpiece material,
- setting the boundary conditions,
- setting the cutting tool geometry and, eventually, the clamping device of the workpiece,
- relative positioning elements,
- database generation,
- run of the simulation,
- visualization of results in pre- and post-processor [3].

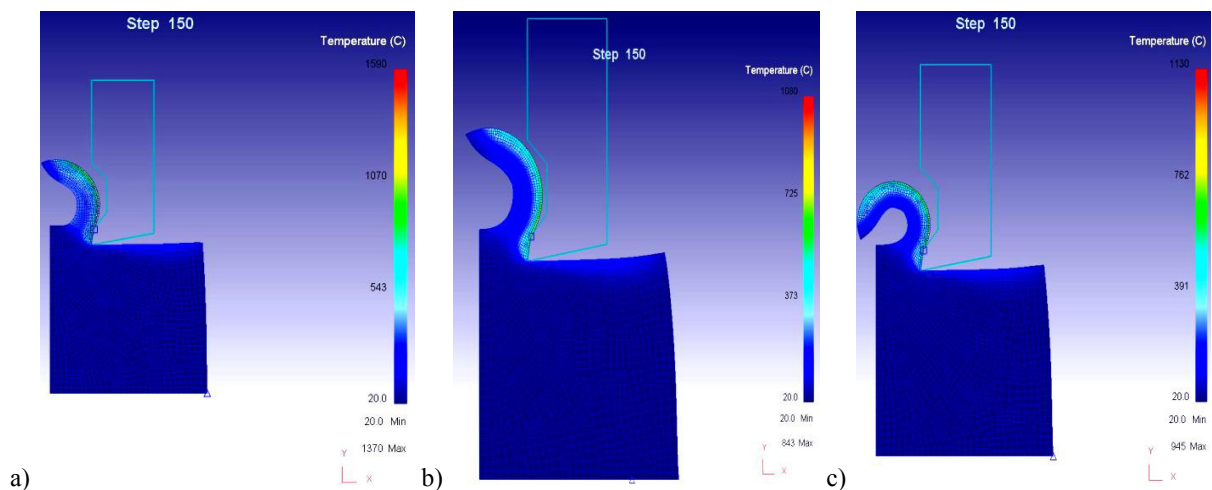


Fig. 5. The state of temperature for the three studied cases.

In the pictures, there are shown the compared results obtained from simulations for all three types of materials mentioned (a) is Ti6Al4V, b) Ti grade 1, c) Ti grade 2), in terms of effective strain (Fig. 3), effective stress (Fig. 4) and temperature (Fig. 5).

Being criteria to evaluate cutting machinability of workpiece materials, it is interesting to mention the values obtained by simulation for effective strain (Fig. 3), effective stress (Fig. 4) and temperature (Fig. 5), see table 1 (maximum values).

Generally speaking, it is obvious that decrease of the purity of titanium leads to the increase of cutting stress and temperature and decrease of strain. Same trend is observed for tensile strength of the same materials, see table 2.

By means of its post – processor, DEFORM 2D[®] provides a series of complex evaluations (output data), including prediction of forces. All measurement units used in the program were considered in the international system.

The software offers output data information vs. time/stroke on X and Y axes, and a step by step video process of cutting. Figure 6 presents the prediction of cutting force along X axis for all three types of materials chosen.

It should be mentioned that there is a relationship between the cutting force and the rake angle, meaning that with increase of the rake angle, the cutting forces decrease. The state of effective stress produced in the chip during simulation of metal cutting process decreases with the increase of the rake angle [3].

Table 1. Simulation results.

Material	Maximum eff. strain [mm/mm]	Maximum eff. stress [MPa]	Maximum cutting temperature [°C]
Ti6Al4V	3.44	1890	1590
Ti gr. 1	3.82	1360	1080
Ti gr. 2	3.60	1590	1130

Table 2. Mechanical properties of pure titanium grade 1 and 2 and titanium alloy Ti6Al4V [7, 8], compared to simulated specific cutting force .

Mechanical properties	Titanium grade 1	Titanium grade 2	Alloy Ti6Al4V
Tensile strength, [Mpa]	240	345	1000
Yield strength, [Mpa]	170	275	110
Elongation, [%]	24	20	15
Area reduction, [%]	30	30	20
Max. simulated specific cutting force, [N]	1200	1500	2200
Max. specific cutting force / tensile strength	5	4.34	2.20

Figure 6 presents the predicted cutting force given by the post-processor of DEFORM 2D[®].

By comparison, related to professor Enache's formula, table 2 [7,8] shows that the more impure titanium is, the greater strength it has and the less value of the cutting force coefficient occurs. Maximum value of the effective stress occurred in contact area, for each case, is closed to strength tensile value for each material multiplied by professor Enache's cutting force coefficient (3...7). Of course, the cutting depth was chosen in the range of tenths of millimeter, so the cutting force coefficient in equation (20) belongs to the lower values, as presented.

Finally, an empiric formula could be used to determine cutting force in practical cases:

$$F_c = (2...10) \cdot \sigma_r \cdot f \cdot a_p, \quad (21)$$

being very similar to professor's Enache formula, the lower value of cutting force coefficient being used for high strength materials and cutting depths of tenths of millimeter and even higher, cutting force coefficient value is being used for low strength materials and cutting depths of hundredths of millimeter.

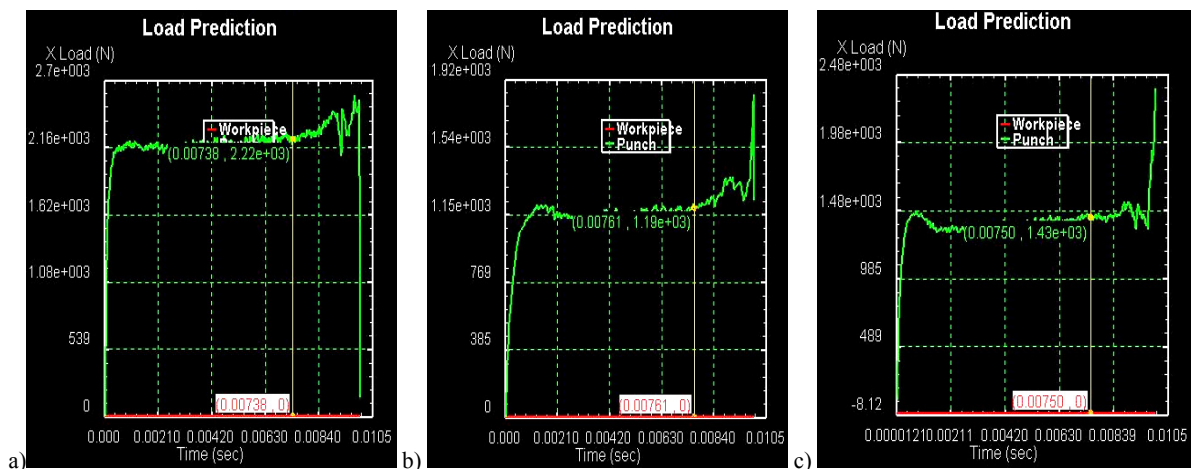


Fig. 6. Prediction of cutting forces along X axis.

Because of such variation of the cutting force it is obvious why determination of Taylor's cutting force formula is made only on small range values of the cutting regime parameters. Still, it is performed experimentally, with cost and time consumption, which justifies the proposed equation (21).

3. Conclusion

DEFORM 2D[®] provides orthogonal cutting or 2D plastic deformation processes simulation results.

In this paper simulations were performed to observe the cutting forces in pure titanium (grade 1 and grade 2) and titanium alloy (Ti6Al4V) cutting process characterization.

Simulated cutting forces in DEFORM 2D[®] are specific cutting forces, meaning cutting force per millimeter of edge, obtained in orthogonal cutting. In real cases (even orthogonal or complex cutting) cutting forces are greater, being proposed an empiric formula (21), depending of the technological parameters of the chip area.

The maximum value of specific main cutting force is equal to the tensile strength of the material, multiplied by technological area of the chip (feed x depth of cut) and a cutting force coefficient (see equation 21).

Professor Enache's formula stated a range of cutting force coefficients considering medium cutting depths. In real cutting processes very small values of the cutting depth occur (hundredths of millimeter). In these cases the cutting force increases for approximately 2 times. This is related to the chip deformation process.

It is well known that values of the cutting depth under 0.01 mm are not possible, because in this case cutting process (chip removal) is replaced by plastic deformation process.

This paper stated that the cutting force coefficient increases with the decrease of the cutting depth, the lower value of cutting force coefficient being used for high strength materials and cutting depth of tenths of millimeter and higher value of cutting force coefficient being used for low strength materials and cutting depth of hundredths of millimeter. It can also be stated the cutting force coefficient increases with the decrease of one technological parameter of the chip, either cutting depth or feed[9].

Comparing the empiric formula (21) to Taylor's equation it can be stated this empiric formula is simpler and it can be used in practical cases. Even when a Taylor's equation is experimentally determined, it has errors, and it is determined for a specific range of cutting parameters values[10]

Also, the simulations were made to obtain other output data, like effective strain, effective stress and cutting temperature, which are evaluation criteria of workpiece material machinability.

It was previously found [2, 3] that there is a relationship between cutting forces and tool rake angle variation, meaning that the optimum value of rake angle leads to an increase of cutting machinability and in the same time, to a decrease of the cutting forces.

The simulation of cutting and deformation processes using DEFORM[®] software can lead to optimum cutting / deformation process conditions related to cutting titanium and its alloys, as well as other workpiece materials, obtaining parts in optimal conditions.

It is obvious the optimization by simulations has advantages, avoiding time and cost consumption which would occur in performing real experiments. Still, there are disadvantages, like software costs and the need for validation in the real life. Of course, this validation could be done only in some cases, not for all planned experiments.

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