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TECHNICAL PAPER

Simulation machining of titanium alloy (Ti-6Al-4V) based on the finite element modeling

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Abstract Titanium alloy is the most significant material used in the aviation industry because of their properties such as high strength and corrosion resistant. However, it is considered one of the most challenging areas for all industrialists due to their poor machinability. Therefore, machining process needs to be controlled by selecting the optimal cutting conditions to obtain the best machining responses at the same time which is very difficult and involves high cost. Hence, this review paper presents the investigation of an agreement between the simulation results and experimental findings to evaluate the finite element modeling (FEM) for prediction of the machining parameters of titanium alloy (Ti-6Al-4V). Computer-aided engineering tools, especially software which was used to perform the simulation. Four types of finite element software have been focused during the machining process of titanium alloy (Ti-6Al-4V) such as AdvantEdge, ABAQUS/EXPLICIT, DEFORM, and FORG software. The simulation results of FEM proved an agreement with the experimental data during the machining process of titanium alloy (Ti-6Al-4V). The FEM permits to reduce the cost of manufacturing in terms of prolonging the cutting tool life and saving machining time.

Keywords Finite element modeling · Simulation software · Machining · Titanium alloy (Ti-6Al-4V)

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List of symbols

A	Initial yield stress (MPa)
B	Hardening modulus (MPa)
C	Strain rate dependency coefficient (MPa)
d	Depth of cut (mm)
f	Feed rate (mm/min)
F_c	Cutting force (N)
F_t	Feed force (N)
m	Thermal softening coefficient
n	Work-hardening exponent
v_c	Cutting speed (m/min)
γ	Rake angle (deg)
α	Clearance angle (deg.)
σ	Flow stress
ε_ρ	Strain
ε	Strain rate
ε_o	Reference strain rate (1/s)
σ	Stress (Von-Mises)
T_r	Room temperature
T_m	Melting temperature

Abbreviations

FEM	Finite element modeling
J–C	Johnson–Cook model

1 Introduction

Titanium alloy (Ti-6Al-4V) is a lightweight, corrosion resistant and high temperature material. It has the highest strength to weight ratio of all commonly used metals up to 550 °C. It is used extensively in the aerospace industry because of their excellent combination of high specific strength, which is maintained at elevated temperature, their fracture resistant characteristics, and their exceptional resistance to corrosion. Many aircraft components made from titanium alloys are produced during the machining processes. Pittalà and Monno [23] presented that titanium alloys are also used increasingly in other industries and commercial applications, such as military, racing and medical.

Numerical simulation method is very useful to predict and/or optimize the machining parameters and it leads to reducing experimental cost testing during the machining process. It has a good chance of choosing the optimal cutting conditions such as feed rate, cutting speed and depth of cut and other during machining processes. A numerical simulation modeling method is not reliable enough to predict machining response results. This is because many researchers use different laws, rules, and technique or procedure of numerical simulation modeling. Therefore, it is very important to know the limitations and efficiency of the simulation process. Thus, it will be provided all the machining parameter's value with feedback which allows to validate the outcomes with the experimental data. Hence, according to Calamaz et al. [8] a valid simulation enables good predictions in terms of the machining responses such as cutting force components, temperature, stress and strain components. Therefore, a numerical simulation method such as finite element modeling (FEM) contributes to cost reduction for the machining process which includes saving machining time and minimizing industrial cost.

Finite element modeling is predicted the machining parameters such as chip formation, cutting force components, temperatures, stress–strain and other during the cutting process of titanium alloy (Ti-6Al-4V). For instance, Umbrello [25] used two dimensions (2D) of FEM during high-speed machining of titanium alloy (Ti-6Al-4V). On the other hand, Baker et al. [4] used ABAQUS/EXPLICIT software for prediction of cutting forces and chip formation during machining of titanium alloy (Ti-6Al-4V) and studied the adiabatic shearing phenomenon. On the other hand, Li and Shih [20] conducted three dimensions (3D) of FEM for machining titanium alloy (Ti–6Al-4V) using Third Wave System's AdvantEdge. It can be seen that most of the researchers are focused to prediction of the cutting forces, cutting temperatures and how they can configure the chips from the workpiece surface. There are some studies found on the FEM for machining parameters of titanium alloy such as the challenges involved in modeling of machining for practical applications by assisting in the selection of the right cutting parameters Klocke et al. [17]. One of their suggestions was to utilize the modeling outputs of stresses, relative velocities, cutting temperature and strains by arriving at the possible tool wear rate. Dandekar et al. [9], Hua and Shivpuri [15] used DEFORM software (2D) to study chip segmentation when machining process of titanium alloy (Ti-6Al-4V) at different cutting conditions. In addition, Ceretti et al. [7] developed a model for turning process using DEFORM software (3D) to predict cutting forces, cutting temperature, stress distributions, and chip flow.

2 Simulation of machining using FEM

Researchers are seeking to enable a wide range of tools and/or techniques to ensure that the designs they create are safe. However, accidents sometimes happen and when they do in the factories or laboratories, industries need to know if a product failed because the design was inadequate or, if there is another cause such as a user error. However, they have to ensure that the product works well under a wide range of conditions, and try to avoid maximum failure produced by any cause. One important method to achieve this goal is by doing the finite element method. FEM is a very good platform for researchers as it improves cutting processes and is a technique used to discretize model equations for complex engineering problems. Besides that, FEM can also provide accurate results which saves money and time by estimating the events in computer programs and not in real life.

In modeling the plastic material flow there are two basic approaches in assigning elements; both of them follow Boothroyd and Knight [5]:

1. Fixing the elements in space and allowing the material to flow through them (Eulerian technique).
2. Dividing the material into elements that move with the flow (Lagrangian technique).

3 Finite element modeling

3.1 Third Wave systems AdvantEdge

Dandekar et al. [9] used machining simulation software by applying cutting parameters in FEM. The turning model used three dimensions (3D) through Third Wave systems AdvantEdge software. This model best approximates an actual turning process, since it accounts for the nose radius of the tool and represents cutting by the primary and secondary cutting edges of the cutting tool. Dandekar et al. [9] updated Lagrangian technique of FEM by applying the continuous re-meshing and an adaptive meshing technique to their model. The model of workpiece and cutting tool was used with 4-node, 12 degrees of freedom tetrahedral of FEM. A mesh convergence study was conducted to arrive at the best possible values for the meshing. Generally, standard mode was used with a minimum element edge length for the chip bulk and the cutter edge at 0.0198 and 0.01 mm, respectively. In this respect, the boundary conditions were specified such that the top and back surfaces of the cutting tool were fixed in all directions. On the other hand, the workpiece was constrained in vertical and lateral directions on the bottom surface and the workpiece moves at the specified cutting speed in horizontal direction.

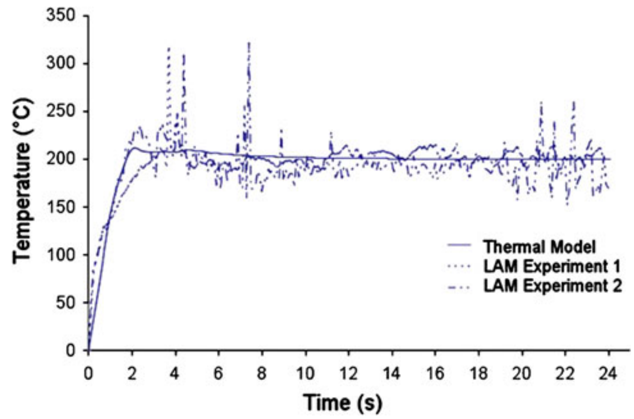

Fig. 1 Comparison of the thermal model predictions and the IR camera measurements in the cutting process

3.1.1 Titanium alloy (Ti-6Al-4V)

When the researchers decide to run the simulation correctly, first and foremost, they must know the material properties. It is one of the most crucial aspects. Two material formulations were used to check for discrepancies in the results. One constitutive model selected for the material was obtained from the following formula and keyed in into AdvantEdge as a user-defined model with power law hardening. The second material selected for the simulation was used from the default material library. The constitutive equation used for titanium alloy (Ti-6Al-4V) is shown in Eq. (1). Therefore, from the high stress and strain rates with a high adiabatic shearing, the Johnson–Cook model coefficients were obtained from conducting split Hopkinson bar compression tests.

$$\sigma = \left(A + B\varepsilon_{\rho}^{n}\right)\left(1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{o}}\right)\left(1 - \left(\frac{T - T_{\mathrm{r}}}{T_{\mathrm{m}} - T_{\mathrm{r}}}\right)\right)^{m}\right) \quad (1)$$

where σ is flow stress, ε_{ρ} and ε are strain and strain rate, ε_{o} is the reference strain rate (1/s) and n, m, A, B and C are constant parameters for Johnson–Cook model as detailed in nomenclature and T is a workpiece material temperature, T_{r} room temperature, and T_{m} melting temperature. The model verification and validation of the thermal model were conducted by measuring the temperature of the laser irradiated, graphite coated, and surface using a non-contact FLIR SC3000 infrared camera. The IR camera tracked the maximum temperature along the centerline of the workpiece at 10 frames/s. Hence, good agreement was found between the predicted and measured data as shown in Fig. 1.

3.1.2 Validation of simulation results

Dandekar et al. [9] validated the mode between the simulation results and experimental data through the default material model and the user defined model. The final results indicated that there was good agreement between the simulated results and experimental data for the cutting forces. However, there was poor agreement between the simulated and experimental values about the thrust force when using the default material model, to tune approximately 50–74 %. On the other hand, by selecting, the user-defined material model yielded a better engagement between the simulated and experimental of cutting force where the maximum discrepancy in the thrust force was reduced to 26 % as shown in Fig. 2. Therefore, the trend observed in this case was similar to the simulation under predicting the cutting force by 7–8 %, while over predicting the thrust force by 20–24 %. In conclusion, FEM could yield a reduction in overall machining costs and saves time through an economic analysis by applying the simulation software to predict the machining response parameters of titanium alloy (Ti-6Al-4V).

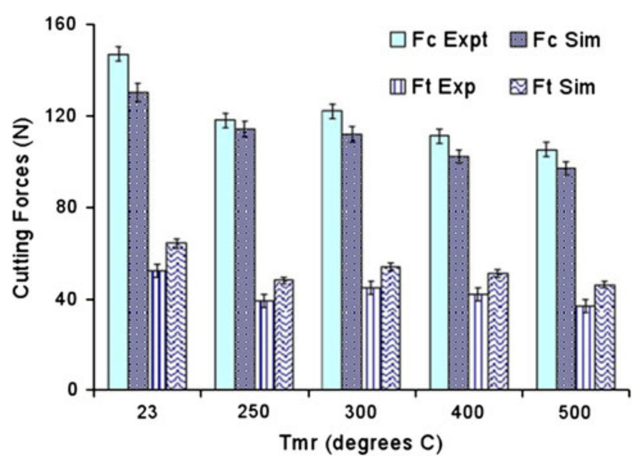

Fig. 2 Comparison of simulated and experimental results for cutting forces

3.2 ABAQUS/EXPLICIT

3.2.1 Material modeling

ElTobgy et al. [10] used a FEM to predict erosion process. This is because simulating the erosion process through finite element enables the prediction of the erosion behavior of materials under different conditions, which will substitute the need for experimentation. The workpiece material was modeled from titanium alloy (Ti-6Al-4V) based on Johnson and Cook [16] model as shown in Eq. (1). In detail, the flow stress was expressed as a function of the strain hardening index n, strain rate, reference strain rate, temperature room (T_r), temperature melting (T_m), and strain rate sensitivity index m. The constants A, B, and C were acquired experimentally by Leseur [18] from compressive split Hopkinson bar tests in the punching shear configuration on titanium alloy (Ti-6Al-4V).

3.2.2 Dynamic explicit

Modeling of erosion process was performed using FEM and employed with Lagrangian technique through "ABAQUS/EXPLICIT-version 6.3". Hence, ElTobgy et al. [10] concluded that the present finite element model offers a unique advantage of modeling the residual stresses generated during the erosion process.

3.2.3 Meshing elements and boundary conditions

FEM easier to apply complex mathematical analysis by developing a model and obtaining a finer mesh to avoid mesh distortion problems, get accurate results and time saving when program is running. In this respect, ElTobgy et al. [10] achieved eight-nodded linear brick elements. Hourglass control was used to mesh the target workpiece and to reduce integration, while four points tetrahedral elements were employed for the impacting particles with mesh biased toward the impact region as shown in Fig. 3. Besides that, only a half-model was evaluated and constraints were set at the boundaries to achieve the symmetry conditions in which the bottom plane was fixed. The particles were constrained from displacement in the Z (3) direction and rotated around the X (1) and Y (2) axis as shown in Fig. 3. On the other hand, WU et al. [26] used ABAQUS software for the orthogonal cutting process of FEM. The final results proved that the material model estimated the adiabatic effect more precisely to respond to the physical phenomena in the cutting process of titanium alloy (Ti-6Al-4V). WU et al. [26] further found that the J–C model agreed with the experimental curve at low strain rate, but did not agree well at high strain rate as shown in Fig. 4. This was because the static compressive experiment

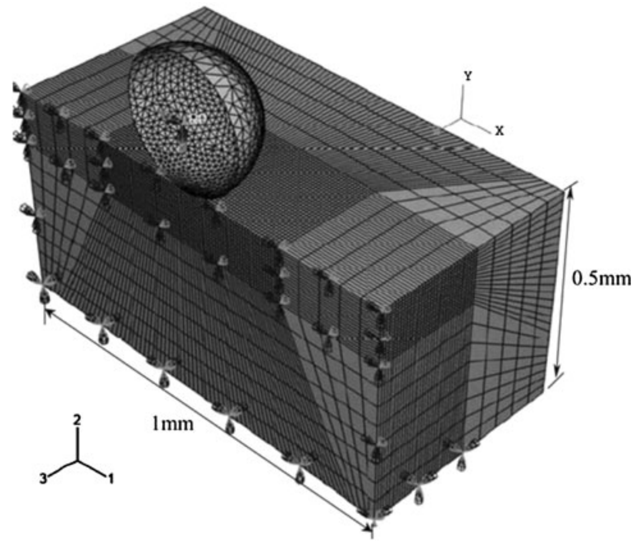

Fig. 3 Meshing elements and boundary conditions for the finite element model

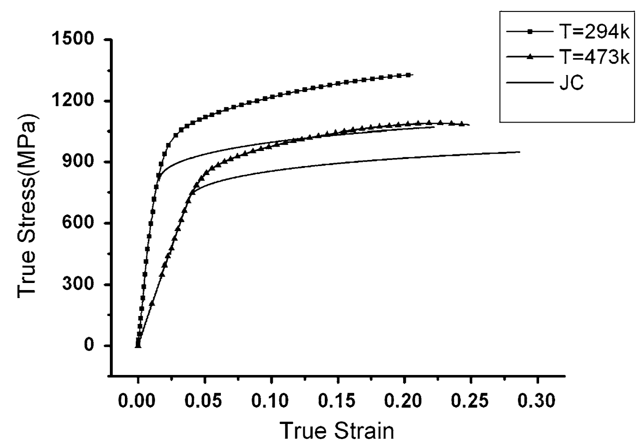

Fig. 4 Comparison of John–Cook model and experiment curve at strain rate 0.001 s^{-1}

was an isothermal process and the SHPB experiment was an adiabatic process.

Generally, sometimes the user subroutine is required to predict cutting temperature using FEM when creating a thermocouple technique. For instance, the Vumat user subroutine was added with a coupled temperature–displacement analysis in connection with (2D) adaptive mesh facility Hong and Ding [13], Zhang et al. [28]. However, a new interesting technique is provided by a new version of ABAQUS software that is called "Dynamic, temperature-displacement, Explicit". It is considered a fully thermo-mechanically coupled technique for estimating the cutting forces and cutting temperature at the same time, so that it saves time and effort when creating the module. In fact, researchers who studied finite element method to develop

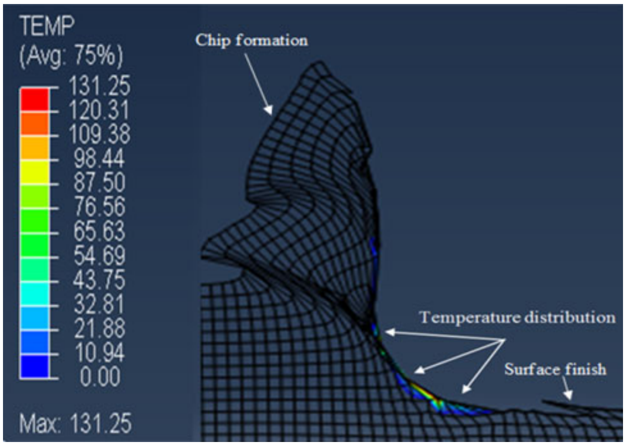

Fig. 5 Temperature distribution estimated at spindle speed 600 rpm, feed rate 120 mm/min and depth of cut 0.6 mm

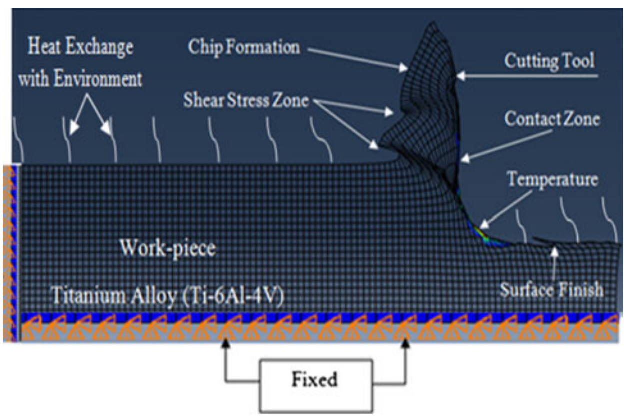

Fig. 6 Boundary conditions during machining simulation process of titanium alloy (Ti-6Al-4V)

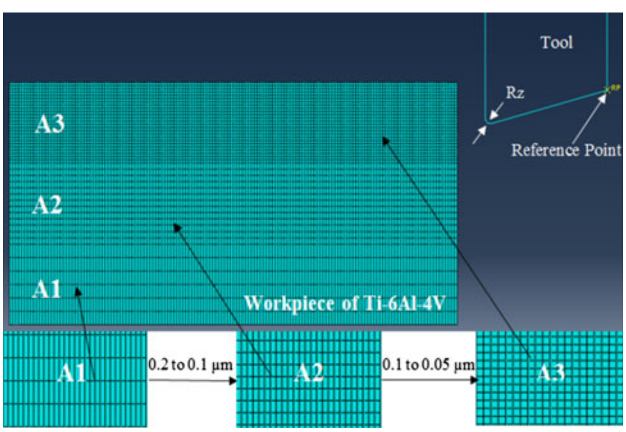

Fig. 7 Mesh elements during machining simulation process of titanium alloy (Ti-6Al-4V)

modeling for estimating machining parameters have always faced problems. One of these problems is the need to separate the model into two steps: the first step

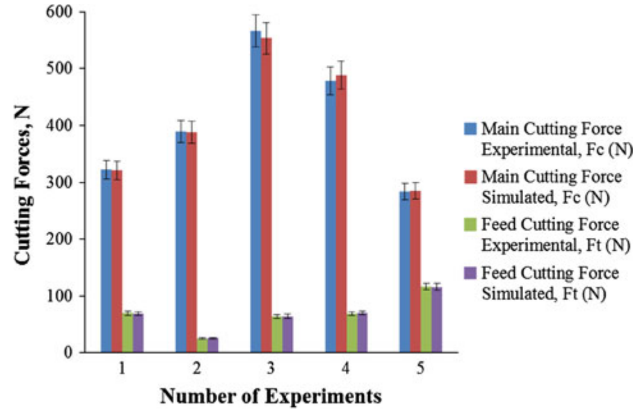

Fig. 8 Comparison between the experimental and simulation results of cutting forces when machining of titanium alloy (Ti-6Al-4V) during the face milling operation

determines to estimate cutting forces as an example and the second step sets to estimate temperature which is considered a long procedure. Hence, Ali et al. [1, 2] used a new interesting step which is called "Dynamic, temperature-displacement, Explicit" through FEM during the machining process of titanium alloy (Ti-6Al-4V) as shown in Fig. 5. Machining face milling process was carried out through the CNC milling machine (OKUMA MX-45VA) under dry cutting conditions. He developed the model in an orthogonal cutting process by modifying machining parameters, while the boundary conditions and meshing elements were created as shown in Figs. 6 and 7. He obtained a very good agreement between the simulation results and the cutting experimental data using the FEM of titanium alloy (Ti-6Al-4V). For instance, as shown in Fig. 8 the accuracy of both cutting experimental data and predicted model values was about 97 %.

3.3 DEFORM Software

Ozel et al. [22] investigated the machining process of titanium alloy (Ti-6Al-4V) with multi-layer coated inserts. He used a finite element model to predict cutting forces, temperature, chip formation and tool wear on these inserts. He simulated the chip formation with finite element analysis and investigated temperature fields for coated inserts by modifying material models with strain-softening effect. He used an updated Lagrangian technique with DEFORM software. A plane strain-coupled thermomechanical analysis was performed during this simulation. Then, the serrated chip formation process was performed from the incipient to the steady state using adiabatic shearing based on strain (flow) softening Elasto-viscoplastic work material assumption. The comparison of simulated and measured serrated chip formation is shown in Fig. 9.

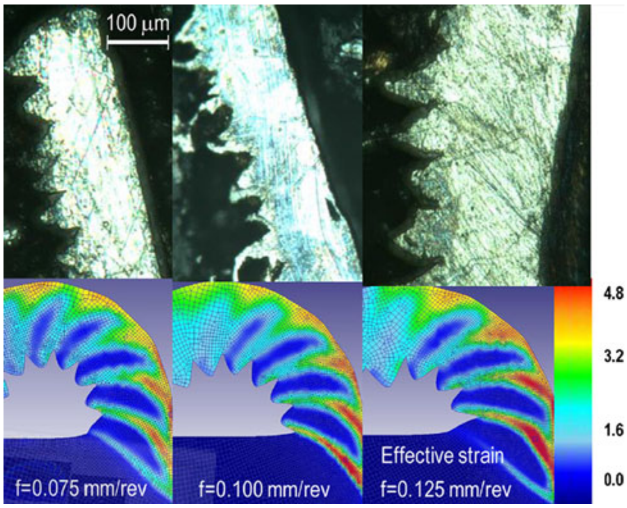

Fig. 9 Comparison of simulated and measured serrated chip geometry

3.3.1 Orthogonal cutting process

Ozel et al. [22] selected turning operation during machining titanium alloy (Ti-6Al-4V) to perform his experiment using uncoated and TiAlN-coated tungsten carbide (WC/Co) cutting tools. The cutting forces were measured with a force dynamometer and high-speed data acquisition devices. The modifications to the J–C model included strain (flow) softening effects at elevated temperatures as proposed by Calamaz et al. [8]. In addition, Ozel et al. [22] applied modifications to the strain hardening part of the J–C model by including strain softening at higher strain values and proposed a thermal softening part. The model is given in Eq. (2).

$$\sigma = \left[A + B\varepsilon_\rho^n\left(\frac{1}{e^{\varepsilon^a}}\right)\right]\left[1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_o}\right)\right]\left[\left(1-\left(\frac{T-T_r}{T_m-T_r}\right)\right)^m\right] \times \left[D + (1-D)\left[\tanh\left(\frac{1}{(\varepsilon+p)^r}\right)^s\right]\right] \quad (2)$$

where $D = 1 - (T/T_m)^d$; $p = (T/T_m)^b$, σ is flow stress, ε_ρ is true strain, ε is true strain rate, ε_o is reference true strain, and T_m, T_r are working material melting and ambient temperatures, respectively.

Ozel et al. [22] predicted the cutting forces using an orthogonal cutting process of titanium alloy (Ti-6Al-4V) and compared it with his experimental results as shown in Fig. 10. Therefore, the cutting forces were in close agreements with 5 % prediction error. However, the main cutting force prediction that showed 10–15 % prediction error could be further improved with a finer adjustment of friction regions and their values.

In this review, Aurich and Bil [3] presented the segmented chip formation by using finite element analysis on turning processes. Tool geometry was modeled as rigid with a mesh containing 2,500 elements. Besides that, tool wear zone showed that cBN-coated WC/Co inserts depicted the smallest wear zone. Hence, cBN coatings might lead to a reduction in tool wear in dry machining conditions of titanium alloy (Ti-6Al-4V). Therefore, Fig. 11 shows the comparison of simulated and measured tool wear zones.

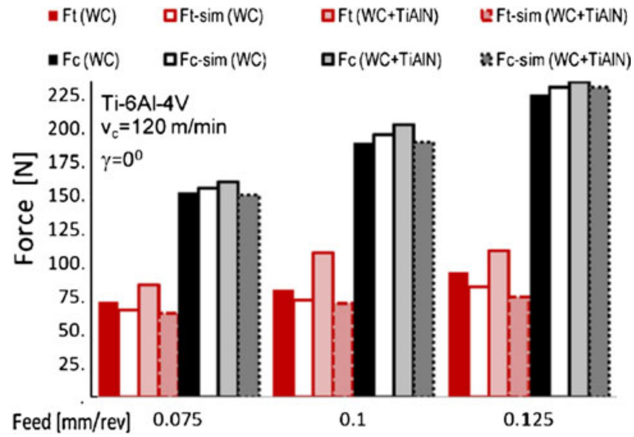

Fig. 10 Comparison of simulated and measured forces in an orthogonal cutting test

On the other hand, Pittalà and Monno [23] used FEM of machining process during face milling operation of aluminum material in dry cutting conditions. They developed the temperature field module of the workpiece for titanium alloy (Ti-6Al-4V) through DEFORM software by modifying the Johnson–Cook law as shown in Eq. (1). Therefore, a sensitivity analysis was performed to estimate the influence of the discretization of thermal boundary conditions as shown in Fig. 12. FEM allows obtaining the relation between chip thickness and cutting forces for different feed rates, as well as cutting speed. Therefore, a good agreement was found when the simulation results of this model and the experimental data were compared as shown in Fig. 13. Furthermore, infrared thermal imager considers a new approach was used during the experimental tests for measuring cutting temperature.

3.4 FORGE-2005 software

Calamaz et al. [8] studied the influence of two different strain-softening levels and machining parameters on cutting forces and chip morphology for titanium alloy (Ti-6Al-4V). Generally, there are two theories applied in the sawtooth chip formation predominate. Firstly, the initiation and propagation of cracks inside the primary shear zone of the workpiece material, and then secondly the thermoplastic instability. Hence, Calamaz et al. [8] found different methods to simulate the sawtooth chip formation in machining such as the pure deformation model without

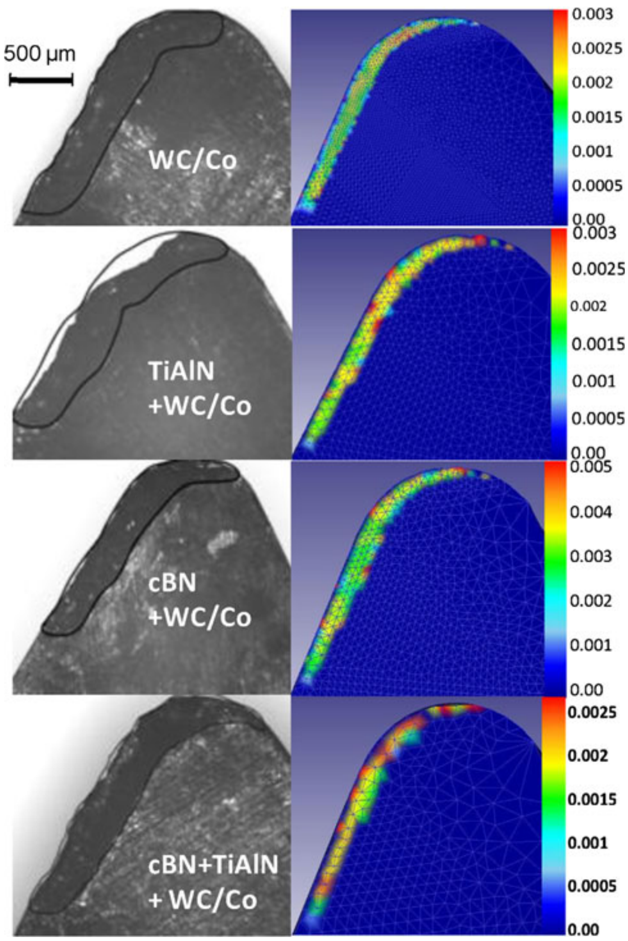

Fig. 11 Predicted and experimental wear rate distributions

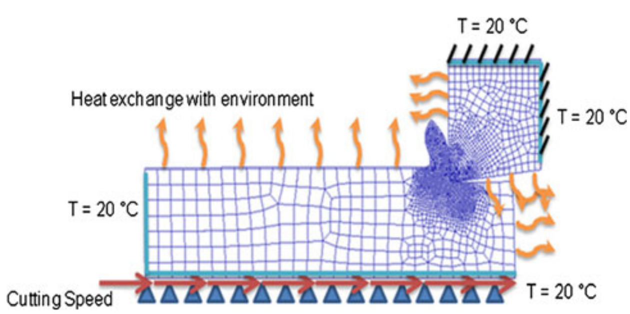

Fig. 12 Thermal boundary condition of FE model

taking into account any fracture criterion based on Baker et al. [4] and Yen et al. [27], through applied (J–C) material law, Baumann–Chiesa–Johnson (BCJ) law by referring to Guo et al. [11], Obikawa and Usui [21], Rhim and Oh [24] models. In addition, the J–C damage law with a fracture criterion such as in Li and He [19], Guo and Yen [12]. In addition, deformation energy-based criterion according to Hua and Shivpuri [14], Ceretti et al. [6], and ductile fracture criterion according to Obikawa and Usui [21]. In this respect, apart from the pure deformation model of Baker

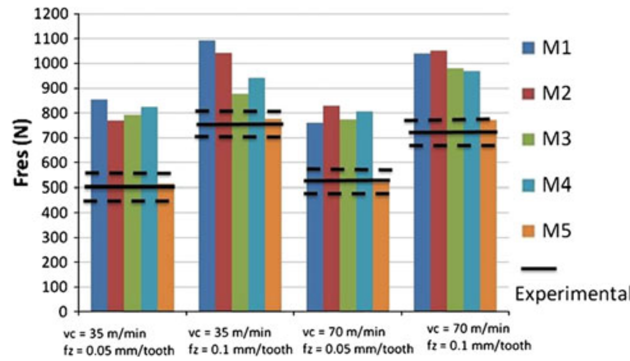

Fig. 13 Main cutting force during the machining process changing the cutting conditions

et al. [4] and Yen et al. [27], a fracture criterion was implemented in most numerical simulations to obtain the sawtooth chip geometry such as in Obikawa and Usui [21], Li and He [19], Guo and Yen [12], Hua and Shivpuri [14], Ceretti et al. [6]. Furthermore, Calamaz et al. [8] studied the influence of both the strain-softening phenomenon and the friction coefficient at the tool–chip interface on the appearance of shear localization giving rise to segmented chips. However, the main feature of the new mathematical formulation named TANH (Hyperbolic TANgent) was to add a new term to the J–C law to model the strain-softening effect as was carried out by Calamaz et al. [8] presented in Fig. 14. The methodology modeled the workpiece material using two different levels of strain softening as previously described. Calamaz et al. [8] focused on the friction at the tool–chip interface by varying both the Coulomb and Tresca friction coefficient. Furthermore, they estimated chip morphology, and cutting forces were compared with experimental results. Calamaz et al. [8] found that the predicted chip morphology and the strain field distribution in the chip were in good agreement with experimental results as shown in Fig. 15. Therefore, through FORGE-2005 software of (2D) for FEM is able to solve complex mechanical problems for titanium alloy (Ti-6Al-4V).

4 Summary

The final results were observed from different simulation softwares applied in the machining simulation process for titanium alloy (Ti-6Al-4V) using the FEM method which was obtained a good agreement with the experimental data. The results were taken from different research works and from the researcher's own specialization in the field of FEM for titanium alloy (Ti-6Al-4V). It was found that there is a significant difference in terms of simulation technique using FEM and modifications of the J–C model. However, a little difference was observed between them in

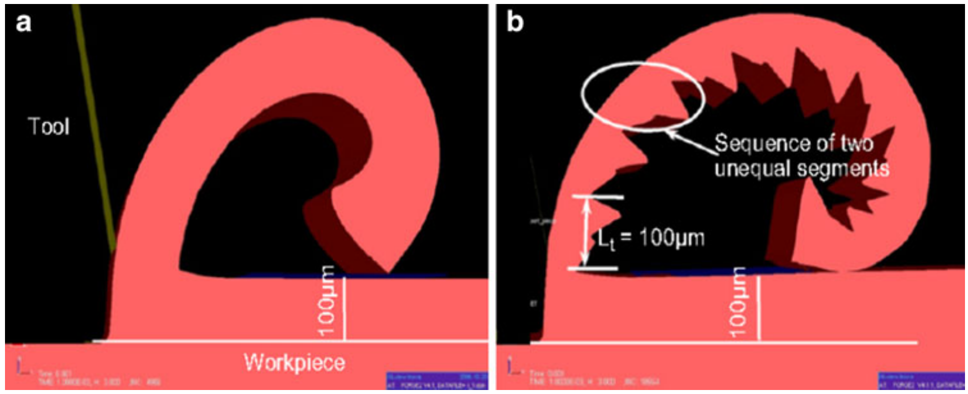

Fig. 14 Simulated chips at a cutting speed of 60 m/min and a feed of 0.1 mm: **a** Johnson–Cook material law and **b** new TANH material model

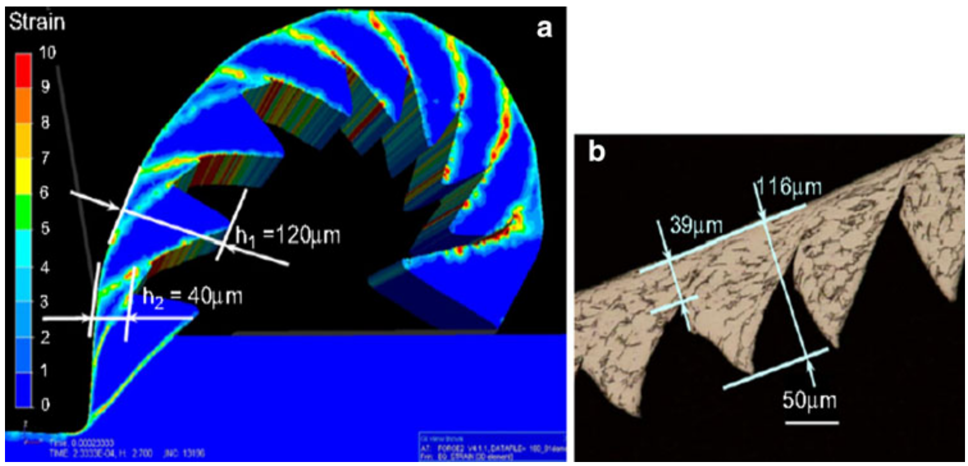

Fig. 15 Predicted (**a**) and experimental (**b**) chips under a cutting speed of 180 m/min and a feed of 0.1 mm

Table 1 Comparison among the machining simulation software

Machining simulation software	Chip formation	Predicted successful 100 %	Cutting forces	Mechanical and thermal problems
Third Wave systems AdvantEdge	Fair	Fair	Good	Good
ABAQUS/EXPLICIT	Very good	Very good	Very good	Good
DEFORM	Good	Very good	Good	Very good
FORGE-2005	Very good	Good	Good	Very good

terms of procedures. Furthermore, the true criterion was defined to find the lowest error between the experimental cutting findings and estimation values using FEM. In this respect, all researchers in this review obtained their goals by verifying the simulated and experimental results during the machining process. Table 1 illustrates the comparison between different machining simulation software using FEM for predicting the machining response parameters of titanium alloy (Ti-6Al-4V).

Finite element modeling is considered a famous method and belongs to numerical simulation methods. It can contribute to reducing the cost of manufacturing by prolonging the cutting tool life and saves machining time. However, AdvantEdge software observed poor agreement between the simulated and experimental results for the thrust force when using the default material model. On the other hand, ABAQUS/EXPLICIT shows a very good agreement on the comparison between the experimental data and simulation results which is approximately more than 95 %. Otherwise, DEFORM software has a close agreement for machining parameters with 5 % prediction error, especially while predicting the mechanical-thermal problems. In addition, FORGE software can solve complex thermomechanical problems. It is also useful for investigating the sawtooth chip formation predominates.

5 Conclusions

Through a research review, the following conclusions were drawn regarding the application of FEM on the machining simulation of cutting parameters for titanium alloy (Ti-6Al-4V). FEM has been reviewed with a new vision by applying it in different simulation software.

- Finite element modeling is a very good platform for researchers as it improves cutting processes and is also considered a technique used to discretize model equations for complex engineering problems.
- Finite element modeling can contribute in reducing the cost of manufacturing by prolonging the cutting tool life and saving machining time by predicting the machining parameters very well such as cutting forces, chip formation, temperature, stress–strain analysis and other.
- The results of the experiment from the machining process of titanium alloy (Ti-6Al-4V) are in agreement with the simulation values of finite element method. The simulation modeling was proved through verification with the experimental findings, and the accuracy based on the most of researchers between the experimental data and simulation results was more than 90 %.
- It was found that there is a significant difference in terms of simulation technique using FEM and modifications of the J–C model. However, a little difference was observed between them in terms of procedures.

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