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# Physics-Based Model to Predict Forces and Chip Morphology in the Machining of a Ti-6Al-4V Alloys for Aeronautical Applications

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## Abstract

The understanding of the cutting process for Ti-6Al-4V alloys is a substantial challenge for process planning in the aerospace industry due to their large-scale utilization. The recent advances in physics-based simulation tool show great capabilities to reduce the operating cost while maintaining the desired product properties. This paper presents a new physics-based materials model capable of capturing accurately the plastic deformation behavior of a Ti-6Al-4V alloys. The model uses the so-called mechanical threshold stress (MTS) theory as a basis for the predictions. The model's ability to predict the dimensions of the shear band is evaluated by comparing finite element simulation and experimental results. The results show good predictability for both the cuttings forces and chip morphology. Overall, it is suggested that the model can be used for planning of machining processes in industrial practice.

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*Keywords:* Titanium Alloys; orthogonal cutting; Shear band; Fracture.

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## 1. Introduction

The high performance cutting of Titanium alloys specifically Ti-6Al-4V has been investigated extensively by industry and academia. Titanium alloys present high strength, low density, low thermal conductivity and heat capacity. They are considered hard to machine alloys. During the machining, a chip segmentation phenomena is observed. Different problems related to severe tool wear and process instability are associated to the chip segmentation. On the

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other hand, one might think that the chip segmentation is a beneficial aspect because of cutting forces reduction. For many years, researchers presented innovative solutions to achieve stable machining process such as the development of new materials and geometries for the cutting inserts or innovative lubrication solutions, cryogenic cooling as an example. Aerospace industry has adopted high speed machining of Titanium due to the increasing productivity requirements. New issues related to tool wear, high vibration as well as alternated surface properties are observed. For these reasons, the need of a physics based understanding of the chip formation during the machining of Titanium alloys is still a hot topic. Revealing the fundamental understanding of the chip segmentation in the machining of titanium alloys will enable a better understanding and control of the surface integrity. Pioneering work of Shaw et al [1] investigated some aspects of the chip formation. They explained that the segmented chip is a result of a competing thermal softening and work hardening of the material in the primary deformation zone. Later, Shaw et al [2] introduced the concept of Adiabatic Shear Bands (ASBs) are the results of the thermal properties of titanium alloys. Later, Komunduri and Turkovich [3] proposed a step by step analysis based on experimental results obtained through varying the cutting speed in orthogonal configuration. The deformation was recorded under scanning electron microscope (SEM) and video camera at higher speeds. Their main finding is that high strain are mainly confined to the shear bands. It is clear that the understanding of the chip formation process in the machining of Titanium is key to achieve higher productivity and better surfaces. Another mechanism is proposed as dominating the chip segmentation due to ductile fracture. A crack initiation and propagation is observed experimentally. Shaw et al [1], after the proposition of the competing softening/hardening, concluded that a ductile fracture on the free surface of the chip is at the origin of this behavior during the machining. Large number of report confirmed this assumption through simulations and experimental work. In an early work by Nakayama [4] the saw tooth chip formation during the machining of hard steel is interpreted by the fracture initiation on the free surface. The reason behind this is interpreted through the weak value of hydrostatic pressure in these locations. Using a ductile fracture criteria, Obikawa and Usui [5] proposed a finite element model capable of predicting the chip morphology. The model included the effect of stress, strain, strain rate and temperature in the prediction. Gente [6] presented a controlled experimental work to support the fact that the Catastrophic Adiabatic Shear (CAS) is no happening during the machining of Titanium alloys. Instead, the thesis of a fracture is supported.

Based on the recent review and state of the art in the machining of titanium alloys, it is clear that the understanding of the chip formation is not yet elucidated. Different issues related to the formation of adiabatic shear bands and fracture locus in the segmented chip is to be answer. In this study, we propose a physics based model to help answer these questions. The numerical model based on finite element is validated through a comparison of the simulated and experimental cutting forces. The model is also validated through a comparison of the length of the shear band. The state of stress is simulated to better interpret the chip morphology and the fracture locus. Finally, the model is utilized to investigate the obtained chip at different cutting conditions.

## 2. Materials and experiments

Orthogonal machining of Ti6Al4V is performed on an OKUMA Genos L200E-M machine. The insert and materials properties are presented in Table.1. The insert has a rake angle of  $0^\circ$ . The chamfer is measured to be  $6^\circ$  as shown in the model in Fig.1.

Table 1: Materials and cutting insert properties.

mechanical properties	E(Gpa)	G(Gpa)	$\nu$	$\rho(\text{kg/m}^3)$	$T_m(\text{K})$	Thermal conductivity (W/m k)	specific heat (J/kg.k)
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Workpiece (Ti6Al4V)	110	49.02	0.3	4430	1905	16	670
Tungstencarbide	534	*	0.22	11900	*	50	400

Three cutting conditions are performed for the purpose of this study. Machining at different cutting speeds is performed.  $V_c=15$  m/min,  $V_c=30$  m/min and  $V_c=60$  m/min. The feed is fixed to  $f=0.12$  mm. The cutting forces are measured using a Kistler dynamometer. The obtained chip are characterized using optical microscope in terms of morphology and shear band.

### 3. Physics modeling

#### 3.1 Finite Element Modeling

A standard implementation of a 2D orthogonal cutting model based on the Lagrangian approach is developed in Abaqus/Explicit software and inspired by the previous work of Atlati et al [7], both to simulate the cutting process using de MTS model and segmentation prediction in the chip by coupled MTS-damage JC. The Lagrangian-FE formulation has been seen as an interesting method to simulate discontinuous chip formation under a steady state condition. It mainly enables the simulation with the need of a separation criteria, such as a critical stress state achieved at a specified distance ahead of the tool tip or a damage evolution parameter for the elements deletion. Each layer of the workpiece mesh is defined with specific behavior. In Part1, MTS with damage, in Part2, MTS without damage. Part3 MTS damage with element delete. Finally, in Part4 MTS without damage is implemented (see Fig. 1). This separation in different section is implemented to reduce the computational time.

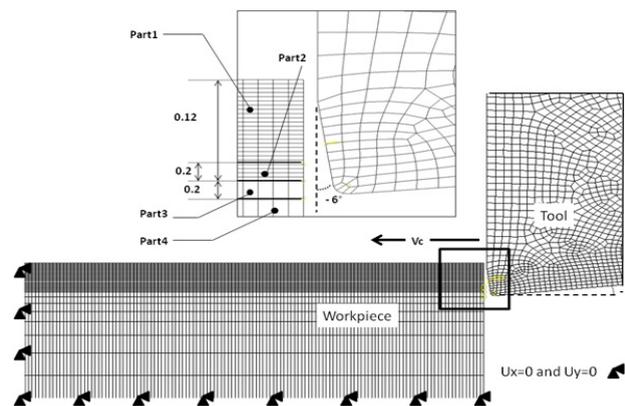


Fig. 1. Description of the finite element model with mesh, tool geometry and boundary conditions

The contact behaviour at the tool–workpiece interface is defined by the relationship between the normal friction stress  $p$  and the shear friction stress  $\tau_f$ . The friction value is selected to be 0.4. The details about the friction coefficient selection Atlati et al [7].

#### 3.2 Mechanical Threshold Flow Stress (MTS)

During the machining process, the complex thermomechanical loading will lead to a complex material deformation and microstructure evolution. The capacity of the model to capture these changes is therefore critical. In this work, we base the flow stress prediction on an approach to predict the variation of dislocation energy at stage III hardening of the materials, here Ti6Al4V. For many years, the Johnson Cook model is used to predict machining forces and deformation. However, the JC model presents clear limitation due to the simplification in terms of microstructure

dynamics. In this study, we propose to integrate a physics based model based on the Mechanical threshold flow. The so called Kocks-Mecking to predict the flow stress of the material during the machining process.

$$\sigma_y = \sigma_a + S_I(\dot{\epsilon}, T)\hat{\sigma}_I + S_S(\dot{\epsilon}, T)\hat{\sigma}_S + S_D(\dot{\epsilon}, T)\hat{\sigma}_D \quad (1)$$

where  $\sigma_a$  is the athermal stress,  $\hat{\sigma}_I$ ,  $\hat{\sigma}_S$ , and  $\hat{\sigma}_D$ , are the threshold stresses that represent respectively dislocation-interstitial, dislocation-solute and dislocation-dislocation interactions.  $S_I(\dot{\epsilon}, T)$ ,  $S_S(\dot{\epsilon}, T)$  and  $S_D(\dot{\epsilon}, T)$  represent the ratios between the yield stress at a specific strain rate and temperature and the yield stress at 0 K for each dislocation obstacle. The physics interpretation of the four terms represented in Eq (1) are respectively: athermal strength, the strengthening due to dislocation-interstitial interactions, the strengthening due to dislocation-solute interactions, and the dislocation-dislocation. The proposed model constants are reported for the case of Ti6Al4V in Da Silva and Ramesh [8]. The model behaviour under different temperature is simulated and compared to the experimental work of Hammer [9]. Fig.2 shows the comparison results. The model show good capacity in capturing the measured stress-strain behaviour. Other test are performed for higher strains in order to further validate the model. The obtained results suggest that the model is good at capturing the materials behaviour at low and moderate temperature. For the case of 600°C, the model is not capable of predicting accurately the yield stress. Further investigation for the model capacity at high strain rate is under consideration.

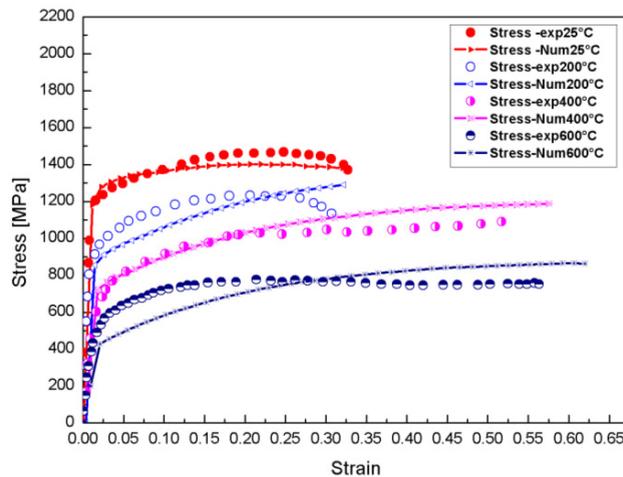


Fig. 2. Flow stress validation under compression for strain rate of  $1s^{-1}$  at different temperatures

### 3.3 Damage Model and Stress Triaxiality

During the machining of Titanium alloys and specifically the Ti6Al4V. Fracture happening in the shear band has been observed. It is therefore important to reflect this behaviour in the modelling of the machining approach. The stress triaxiality could play based on the work of Bao [10] an important role in the explanation of the fracture behaviour. Depending on the material, ductility may decrease when stress triaxiality decreases from 1/3 in the case of a pure tension to 0 for pure shear. Garrison and Moody [11] described the step by step ductile fracture as void nucleation, void growth and finally void coalescence. To capture the damage accurately, a JC damage model is proposed in this work. The model capture the initiation and propagation of the damage as described by Fig. 3.

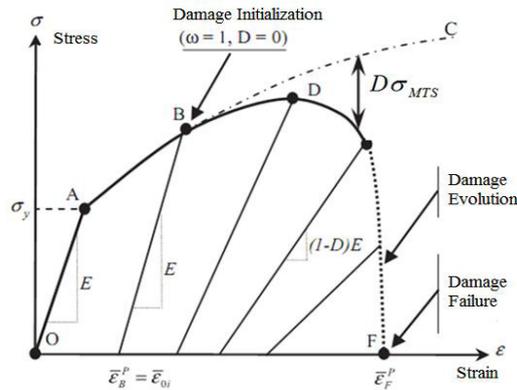


Fig. 3. Damage evolution based on Abaqus [12]

The initialization of damage is described by the following relationship where strain is given by:

$$\bar{\epsilon}_i = [d_1 + d_2 \exp(d_3(P/\bar{\sigma}))] \left[ 1 + d_4 \ln \left( \frac{\dot{\bar{\epsilon}}_p}{\dot{\bar{\epsilon}}_0} \right) \right] \left[ 1 - d_5 \left( \frac{T - T_0}{T_f - T_0} \right) \right] \quad (4)$$

Where  $\bar{\sigma}$  is equivalent von Mises stress,  $P$  is the hydrostatic pressure. The  $P/\bar{\sigma}$  refers to the stress triaxiality. The variables are the parameters of initiation of damage to the machined material to determine experimentally. The damage is initiated when  $\omega_d = 1.0$ . The JC damage coefficient used in this study are (d1: -0.09, d2: 0.25, d3: -0.5, d4: 0.014 d5: 3.87) as reported from the previous work of Johnson and Cook [13]. Previous investigation by Xue et al [14] of the fracture in the shear band of the machined chip concluded that the three stages of the fracture are observed. He reported experimental evidences of nucleation, growth and coalescence of fracture in the ASBs. He concluded that these sites are idea fracture locus during the machining of Ti6Al4V as shown in Fig. 4.

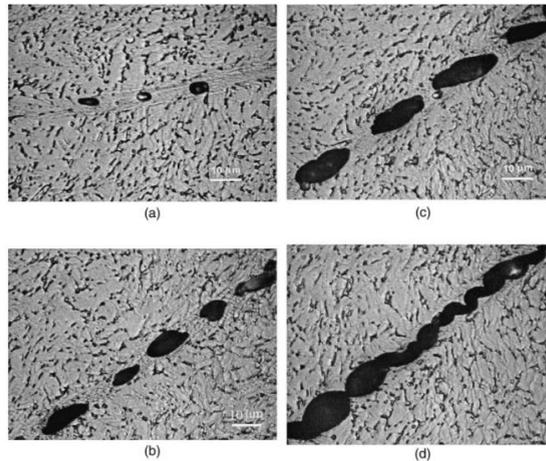


Fig. 4. Void initiation, growth and coalescence based on the work of Xue et al [14]

## 4. Results and Discussions

### 4.1 Model validation using forces and shear band

The predicted and measured forces are compared after calibration. The calibration procedure consisted in using the experimental collected data from  $V_c = 15\text{m/min}$  and adapted the model to make it capable of predicting accurately the value. This was done through a very small adaptation of the friction coefficient. Then, the experimental data are measured to the average as due to the chip segmentation, some variations are observed. Fig.5 shows the obtained results for the case where  $V_c = 60\text{m/min}$ . It is clear that the model was capable of capturing the cutting forces in both directions. The prediction model is also capable predicting the variation of cutting forces associated to the chip segmentation phenomena. These in some cases are substantial as variation of 50% can be observed in some cases. This might be associated more to a fracture initiation in the shear band rather than the apparition of the adiabatic shear band. In the next section, physics based interpretation of the fracture initiation described initially in the literature is discussed.

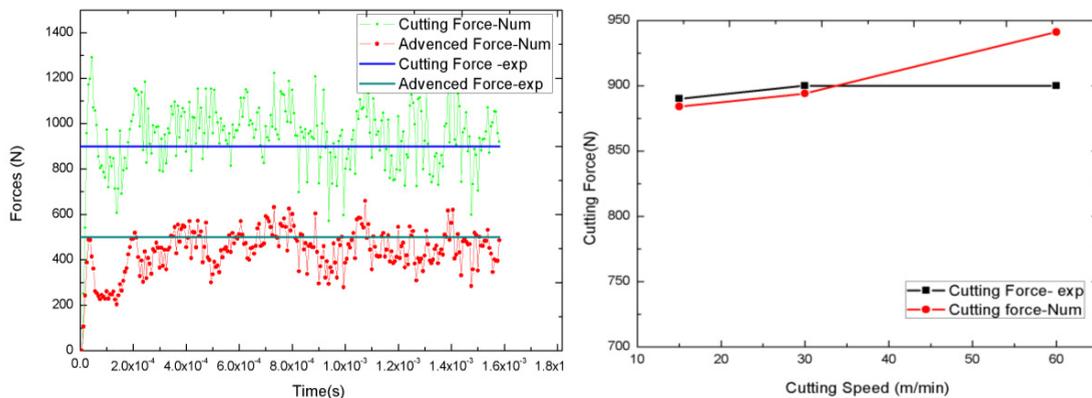


Fig. 5. Comparison between the predicted cutting forces and the average of measured forces using dynamometer

The formation of segmented chip is inherent to the machining of Titanium alloys. The segmented sections of the chip are separated by a shear band. It is reported that the adiabatic shear band (ASB) shape changes following the variation of the cutting parameters. The ASB can be characterized by its width. In this work, microscope image of the shear band is compared to the obtained simulated results. Fig.6 shows the obtained shear band for the case of  $V_c=60\text{m/min}$ . Severe deformation is observed in the shear band. The simulated shear strain is found to be 5 on average. The shear band was measured to be  $12.2\ \mu\text{m}$ , the average simulated results in found to be  $12\ \mu\text{m}$ . The accurate results are attributed to the capacity of the materials deformation model to capture the deformation.

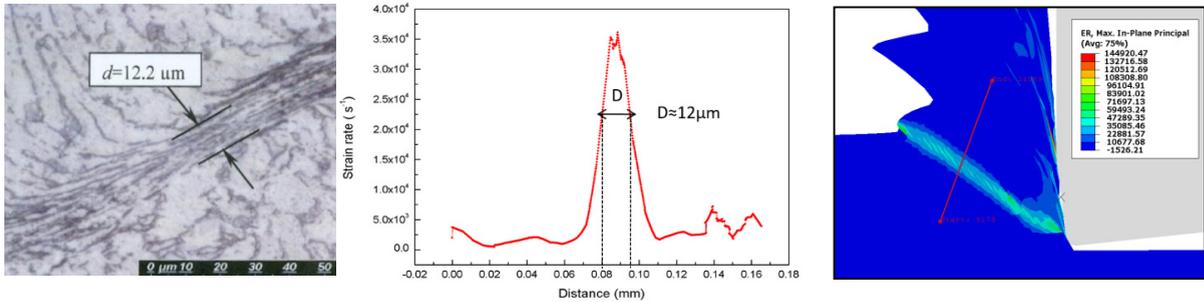


Fig. 6. Comparison between measured shear band in the obtained chip and the predicted using the simulation for the  $V_c=60\ \text{m/min}$

#### 4.2 State of stress and strain

Fig. 7 (b) shows the typical fracture obtained in a shear band. The initiation of fracture locus on the shear band is important to capture to plan a stable machining process. The state of the stress through stress triaxiality is part of the damage model. We investigate the stress triaxiality in each machined sample. Based on Bao [15], if the value of stress triaxiality is higher than  $1/3$ , the fracture locus could appear, the shear band becomes therefore an ideal spot for fractured shear. For the case of  $V_c=60\ \text{m/min}$ , the simulation predicted very high strain in the shear band between 4 and 5 (Fig.7 (a)). Also, stress triaxiality values are presented in Fig.7 (b). The ideal condition for observing a fracture locus are obtained. Results from the experiments confirm the predicted data. Fracture locus and fracture along the shear band could be clearly seen.

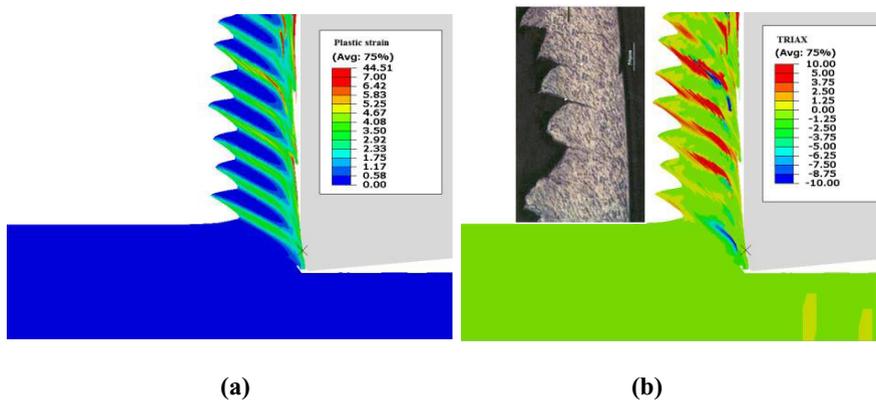


Fig. 7. (a) Plastic strain, (b) Stress triaxiality and associated obtained chip

The fracture mechanism happening in the segmented chip specifically at the ABSs can be explained by the nature of the machining operation. The homogenous shear stress associated to a compressive stress the second half of the shear plan and a tensile on the other create an instable deformation experienced by the materials at the shear band. In addition to the stress triaxiality, Fig. 8. shows the state of hydrostatic stress in the ASB. It appears that the hydrostatic stress are very weak. This association of high stress triaxiality and very weak hydrostatic pressure can be at the origin of the fracture locus in the ASB.

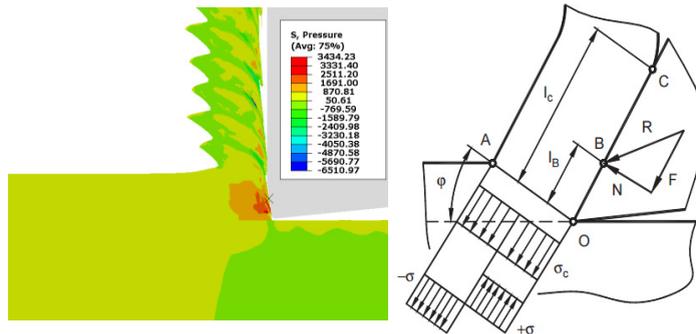


Fig. 8. Predicted hydrostatic pressure in the chip shear bands

The results presented in Fig.9 demonstrate the influence of the cutting speed on the stress triaxiality in the chip. It is evident from the simulation results that the increase of the cutting speed is at the origin of the tension and compression profile inside the chip as clearly shown in the case of  $V_c=500\text{m/min}$ . Using low cutting speeds, the chip is under only one type of stress (compression) as it is showed in the case of  $V_c=90\text{m/min}$ . This is clear evidence that the stress triaxiality will play a key role in the chip segmentation. It can also be used as a parameters to predict the fracture in the chip.

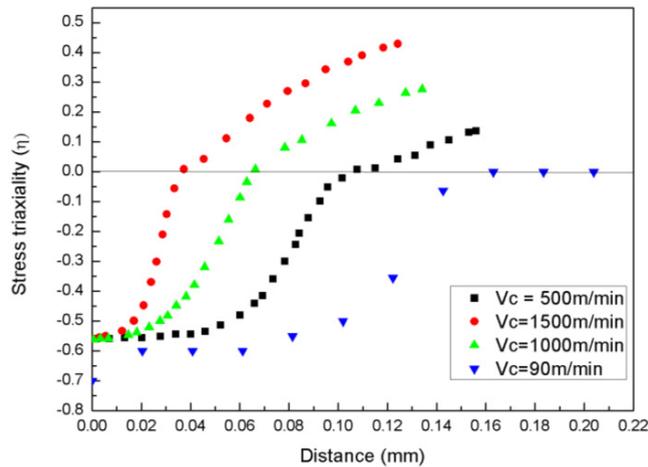


Fig. 9. Predicted hydrostatic pressure in the chip shear bands

### 4.3 Chip morphology and frequency

The developed model in this study is used to explore the the chip morphology behavior at different cutting speeds. Chip morphology can be defined by the deformed chip thickness  $H$ , the orthogonal peak to valley length  $h$  and finally, the inclined peak to valley  $L$ . These parameters are defined in Fig.10. Using the numerical model, the values of  $H$ ,  $h$  and  $L$  are evaluated for each cutting speed. Results showed in Fig.10 suggest that the increase of the cutting speed reduces drastically the value of  $H$ . However, slight variation of  $h$  and  $L$  are observed during the increase of the cutting speed.

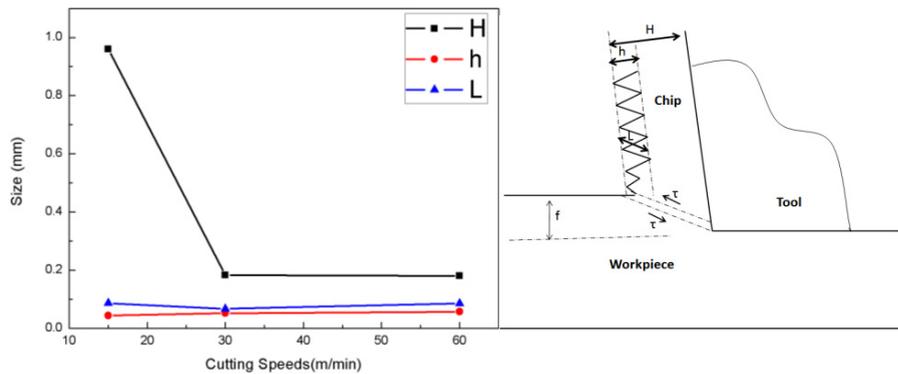


Fig. 10. Predicted parameters defining the chip morphology

## 5. Conclusion

In this work, a new physical model to capture the material deformation based on microstructure attributes is implemented in a numerical code using FORTRAN subroutine. The model is used to simulate and predict the orthogonal machining of Titanium alloys. The model is validated experimentally using machining experiments. The results of this work can be summarized as follow:

- MTS based flow stress model showed high capacity to predict deformation of Ti6Al4V accurately.
- The materials model enabled the model to capture the chip segmentation accurately. The cutting forces, the chip morphology and the size of the shear band are validated experimentally.
- The severe deformation experienced in the shear band can lead to the formation of fracture locus. This is explained through the analysis of the stress state and triaxiality. It is found also that the increase of the cutting speed induces more fracture locus in the shear bands
- The proposed model showed ability to predict chip morphology for different cutting conditions. The frequency of fracture can also be predicted thanks to the accurate prediction of stress triaxiality.
- Further investigation is in progress for higher speed in order to achieve optimal process planning for high productivity machining.

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