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Comparison of Johnson-Cook and Modified Johnson-Cook Material Constitutive Models and their Influence on Finite Element Modelling of Ti6Al4V Orthogonal Cutting Process

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Abstract. Titanium alloys such as Ti6Al4V are widely used and are well known as hard-to-machine material. The material behavior that is described by the constitutive equation plays a pivotal role in modeling and simulation of machining process. The Johnson–Cook material model is widely used for analysis of material flow stress, especially for those materials with a flow stress highly influenced by high values of temperature and strain rate. A continuous improvement on constitutive models for accurate prediction of the work material behavior under machining conditions is observed in the literature. The purpose of this study is to show the influence of the constitutive model by comparing and investigating Johnson-Cook constitutive model with calibrated or modified Johnson-Cook constitutive models that take into account temperature dependent hardening factor and its coupled effects between strain and temperature. This paper deals with the simulation of orthogonal cutting process with those constitutive models. The three constitutive models are included in a Lagrangian cutting finite element model to highlight their influence on the results. Cutting forces and chip morphology are mainly used in the comparison of the numerical results and their validation with an experimental reference.

INTRODUCTION

Titanium and its alloys have received considerable interest with wide range of applications in aerospace, biomedical fields etc. Ti6Al4V has excellent properties such as high strength-to-weight ratio, low coefficient of expansion, excellent corrosion resistance even at very high temperature. Typically, titanium alloys are hard to machine materials because of their high chemical reactivity and low thermal conductivity. The low thermal conductivity, low modulus of elasticity and dynamic deformation of Ti6Al4V alloy during high speed machining makes it a complex phenomenon for simulation using finite element method [1].

Finite element simulation has been employed to the high-speed machining process. Due to many factors that affect the machining precision and surface integrity, the finite element simulation of machining is a very complicated process. In addition, it is essential to establish the models of flow stress, strain, strain rate and temperature for workpiece materials. Material models are the most critical input that directly affects the accuracy of cutting process simulations. The major difficulties encountered in finite element simulation of machining process is the lack of suitable constitutive equations than can describe accurately the variations of flow stress with strain, strain-rate and temperature.

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A valid material constitutive model that describes the behavior of the material during the orthogonal cutting process is required in finite element analysis, which always remains a challenge and is a key factor influencing the prediction accuracy in cutting process. Many material constitutive models have been developed in the past years. Among those, the Johnson-Cook (JC) [2] models are widely utilized in modeling and simulation studies.

In this paper finite element simulation of Johnson-Cook model (JC) is compared with the Modified Johnson-Cook models from Chen et al (MJC1) [3] and Hou et al (MJC2) [4] that take into account temperature dependent hardening factor and its coupled effects between strain and temperature. The parameters for these models are acquired from the corresponding references, contributing to the originality of the paper as they are not modified for the orthogonal cutting process simulation. Cutting force and chip morphology are compared and they are validated with an experimental reference.

MATERIAL CONSTITUTIVE MODELS

Johnson–Cook Constitutive Model

The Johnson-Cook model [2] is well-accepted, numerically robust and heavily utilized in modeling and simulation studies. This model describes flow stress as a product of strain, strain-rate and temperature dependent terms. Among the material constitutive models, the Johnson-Cook model (JC) has been commonly employed for analyzing the material flow stress because of its simple form and is given by Eq. 1.

$$\sigma = [A + B\, \varepsilon^{n}] \left[1 + C ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right]\left[1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^{m}\right] \quad (1)$$

where $\dot{\varepsilon}_0$ is the reference plastic strain rate, T_{room} the ambient temperature, T_{melt} the melting temperature and A, B, C, n and m are constants that depend on the material and are determined by material tests. The expression in the first set of brackets represents power-law work hardening curve with n assumed to be constant. The expression in the second set of brackets represents the semi-logarithmic dependence of stress on strain rate while that in the third set of brackets represents the reduction in strength due to the increase in temperature (thermal softening) resulting from plastic work. However, the JCM is meaningful in certain operating ranges of strains and strain-rates (strains up to 0.5 and strain rates lower than 10^4 s^{-1}) but fails to capture high strain material behavior in machining, where the flow stresses are difficult to measure by existing material testing device.

Modified JC material constitutive models

Numerous models are proposed for Ti6Al4V alloy to describe the dynamic deformation behavior in machining [1]. Several correcting functions which account for temperature effect have proposed to modify the JCM for orthogonal cutting of Ti6Al4V alloy. Chen et al (MJC1) and Hou et al (MJC2) introduced a temperature function into the work hardening term to describe the phenomenon of temperature dependent hardening effect for better prediction of flow stress behavior of Ti6Al4V alloy under loading condition of high strain rate and temperature.

Modified JC model 1 (MJC1)

Chen et al (MJC1) [3] suggested a modification term to the J–C model is given by Eq. 2. This modification includes temperature dependent strain hardening effect at elevated strains and temperatures. Chen et al [3] model describes the work hardening rates decrease gradually with the increase of the temperature, at high strain rate conditions and 500°C (T_0) was approximately considered as the critical temperature for Ti6Al4V alloy deformation and microstructure evolution mechanism, for the deformation involves machining and hot working. Genetic algorithm optimization method was implemented to obtain the material parameters from the compression test conditions on split Hopkinson bar system.

$$\sigma = \left[A + B\left(\frac{T_0 - T/2}{T_0}\right)^{n_2} \varepsilon^{n}\right]\left[1 + C ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right]\left[1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^{m}\right] \quad (2)$$

The domains of constant T_0 and T are related with the temperature range of the compression tests. Where $450 < T_0 < 700$ °C, $0 < T < 1000$ °C and n_2 ($0 < n_2 < 1$) is an exponential coefficient.

Modified JC model 2 (MJC2)

Hou et al (MJC2) [4] proposed a modified JC model (Eq. 3) by coupling logarithmic strain hardening rate and thermal sensitivity coefficient along with the strain function of JC model as they concluded that strain hardening rate Q of Ti-6Al-4V alloy has no noticeable strain rate sensitivity but has apparent temperature sensitivity. The strain or work hardening rate Q is a function of temperature $Q = f(T^*)$.

$$\sigma = \left[A + B\left(1 + m_1 \ln\frac{T}{T_{room}}\right)\varepsilon^n\right]\left[1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right]\left[1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^m\right] \tag{3}$$

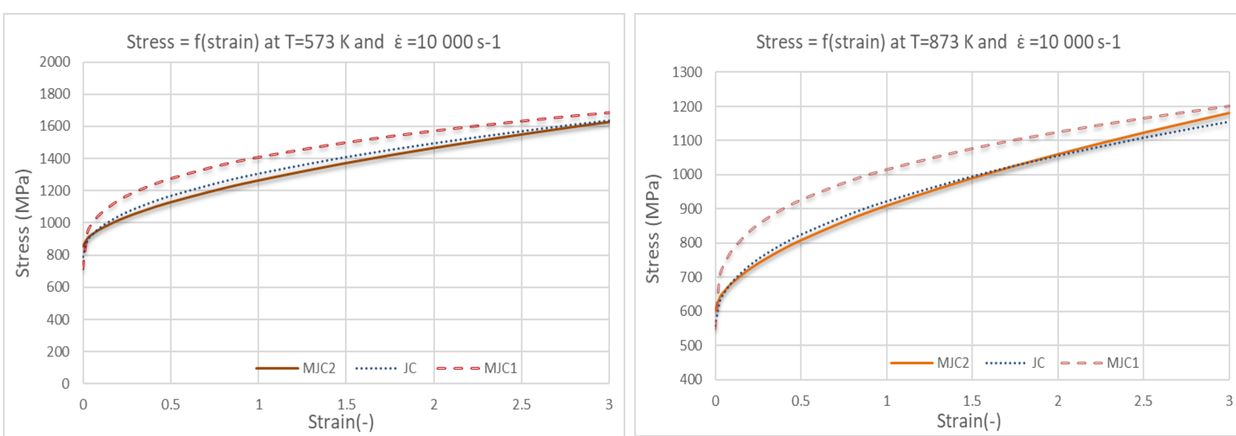
In addition to the parameters from JCM, m_1 is thermal sensitivity coefficient with the increasing strain.

The set of parameters adopted for three models are reported in Table1.

TABLE 1. Parameters adopted for JC model [5], Modified JC model 1 (MJC 1) [3] and Modified JC model 2 (MJC2) [4].

JC Model		Modified JC model 1 (MJC 1)		Modified JC model 2 (MJC2)	
A (MPa)	997.9	A (MPa)	789.566	A (MPa)	920
B (MPa)	653.1	B (MPa)	911.446	B (MPa)	400
C	0.0198	C	0.012	C	0.042
m	0.7	m	0.952	m	0.633
n	0.45	n	0.306	n	0.578
T_{room} (K)	298	n_2	0.349	m_1	0.158
T_{melt} (K)	1878	T_{room} (K)	293	T_{room} (K)	293
		T_{melt} (K)	1933	T_{melt} (K)	1933
		T_0 (K)	735.314		

The evolution of stress vs strain curve for the three constitutive models at fixed temperature and strain rate is plotted in Fig 1. The evolution of the stress strain curve from the two modified constitutive models that take into account on temperature dependent hardening effect shows a notable difference in the evolution of stress with respect to strain at higher temperature and strain rate.



(a) (b)

FIGURE 1. Stress-strain curves of JC, MJC1 and MJC2 (a) at T=573 K and $\dot{\varepsilon}_0 = 10\,000$ s^{-1} (b) at T=873 K and $\dot{\varepsilon}_0 = 10\,000$ s^{-1}

FINITE ELEMENT MODEL PRESENTATION

The commercial FEA software ABAQUS, with the Lagrangian explicit code is used to simulate Ti–6Al–4V alloy orthogonal cutting process. The FE model is composed of the workpiece and the tool. The orthogonal cutting process simulation of Ti-6Al-4V is performed by a two-dimensional (2D) plane-strain thermo-mechanical coupled analysis using orthogonal assumption.

The tool geometry and the cutting conditions defined for this study are the rake angle is 15°, the clearance angle is 2° and the cutting-edge radius is 20 µm. The cutting speed is set to 30 m/min and the uncut chip thickness is 60 µm. The work piece is modeled as a rectangular block of 1 mm long and 1 mm wide and is fixed in space. The workpiece is meshed with 5 µm×5 µm [5] square linear quadrilateral elements of type CPE4RT leads to 12200 elements and 12462 nodes. The basic geometry and the boundary conditions are illustrated in Fig 2. Tungsten carbide is selected as a tool material and the linear elastic law is imposed. As the interest is not put on tool wear, Coulomb's friction law is employed to model friction between the tool-chip interface with a friction coefficient of 0.2 [6]. The thermal properties are taken from the reference [6]. The initial temperature for tool and workpiece is set to 293 K.

The chip formation, by ductile failure phenomenon, occurs in two steps. In first step the Johnson–Cook shear failure model was used as a damage initiation criterion, whereas the second one concerns damage evolution based on the fracture energy approach. In this model, two different values of fracture energy are used as input data in Abaqus/explicit where fracture energy in region I $(G_f)_I$ is defined by tensile mode (mode I: opening mode normal to the plane of the fracture) and fracture energy region II $(G_f)_{II}$ is defined by shearing one (mode II: sliding mode acting parallel to the plane of the fracture) [7, 8]. The chip is mainly found in region 1 and region 2 is the tool passage layer (its thickness depends on the cutting-edge radius (20 µm), it is 25 µm thick in this study) [7]

The fracture energy is given by equation 4 [8]

$$\left(G_f\right)_{I,II} = \left(\frac{1-\nu^2}{E}\right)\left(K_c^2\right)_{I,II} \tag{4}$$

Where K_c is fracture toughness, E is the Young's modulus and ν is Poisson's ratio.

The predictive model is developed for the above cutting conditions, only the constitutive equations are changed for MJC1 and MJC2 models. The parameters for JC, MJC1 and MJC2 are taken from the corresponding references where they are observed from experiments result performed by corresponding authors and they are not altered for the simulation purpose. Those parameters are given in Table 1.

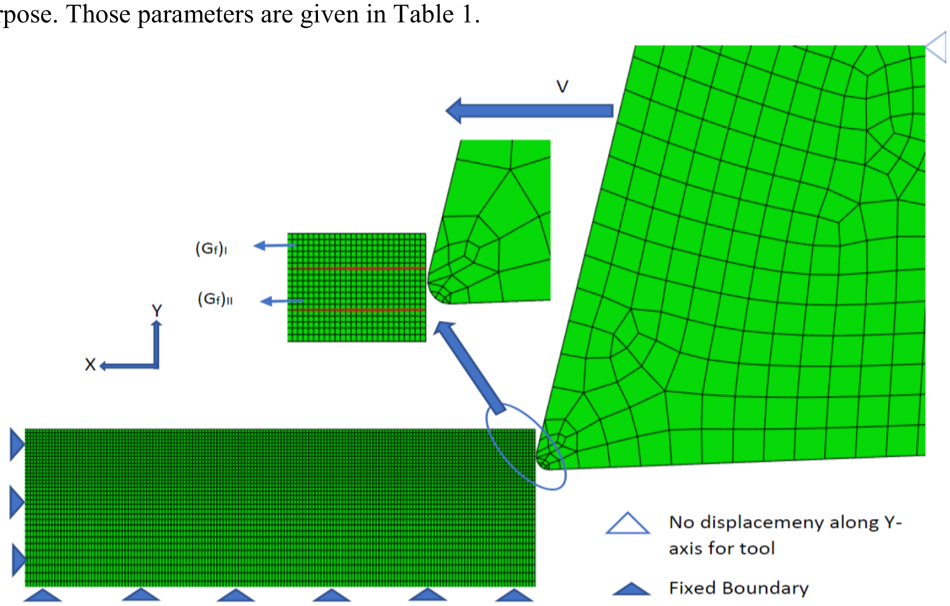


FIGURE 2. Initial geometry, initial mesh structure, boundary conditions and fracture energy in region 1 and 2

RESULTS AND DISCUSSION

The cutting force value, feed force value and chip morphology are acquired from the experiment work performed by Ducobu et al [5] on orthogonal cutting of Ti6Al4V on a high-speed milling machine with the same cutting condition for uncut chip thickness of 60 µm. A continuous chip was observed from the experimental results for the cutting condition. It is shown in Fig 3. The RMS values of cutting force (F_c) was in the range of 111 ± 2 N/mm and the feed force (F_f) is 44 ± 1 N/mm.

The chip morphology and the temperature differences are analyzed and compared for the three different constitutive models. All the numerical chips are continuous and are same as the experimental reference [5]. Differences are however noted as deformed and elongated elements at the crack tip (elements get distorted near the tool tip in the beginning of chip formation) are observed in MJC1 and MJC2 are highlighted in Fig 3.

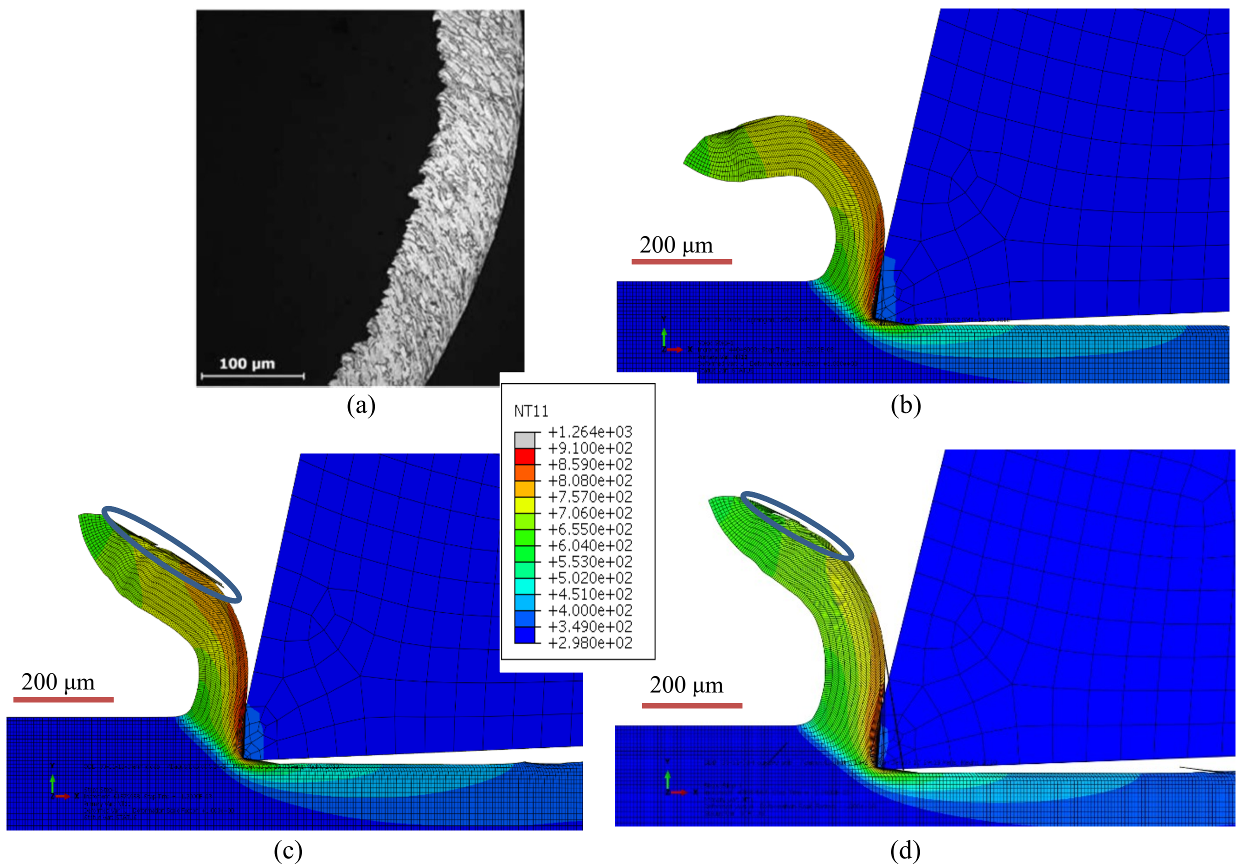


FIGURE 3. Chip morphology for uncut chip thickness of 60 µm (a) Experimental reference [5] and Temperature contour (in K) of the numerical chip at 1200 µs (b) JC model (c) MJC1 (d) MJC2

The RMS forces values are calculated and compared in Table 2. The feed force RMS value of MJC1 and MJC2 are similar and near to the experimental value when compared with JC model. The thickness of the chip is reduced when the feed force is higher as the feed force is inversely linked with chip thickness.

The temperature of the numerically computed chip for JC, MJC1, MJC2 are analyzed at 1200 µs. As expected, the temperature is maximum in the secondary deformation zone. The temperatures for the MJC1 is higher than JC, MJC2 and that can be explained by the high level of stresses. The RMS cutting force value of MJC2 and MJC2 are quite close to the experimental reference when compared with JC model. The cutting force RMS value and the temperature are compared, and it is observed that temperature directly linked with cutting force.

TABLE 2. RMS cutting force (F_c), feed force (F_f) and chip thickness (h′) summary and Δ_x differences with the experimental forces [9] results

Models	F_c (N/mm)	Δ_{Fc} (%)	F_f (N/mm)	Δ_{Ff} (%)	h' (mm)	$\Delta_{h'}$ (%)
Experiments	113 ± 2	-	44 ± 1	-	0.080 ± 0.04	-
JC	106	8	48	4	0.077	3
MJC 1	116	3	46	2	0.078	2
MJC 2	111	2	46	2	0.079	1

Overall the RMS value of cutting force and feed force of MJC1 and MJC2 is close to the experimental result, but the chip morphology of MJC2 is consistent when compared with MJC1 and JC model.

CONCLUSION

In this study, a FEM model was developed with the JC and modified JC constitutive material (MJC1, MJC2) models. The results of JC, MJC1 and MJC2 models have been verified by comparing the simulated forces, chip morphology, chip thickness with the experimental reference. From the results, the predictive model along with the cutting condition adopted in this study is well capable to accurately predict the cutting forces (within 2-3 % error) and the feed force (within 2% error) for the modified JC constitutive models (MJC1, MJC2). The parameters of these models are directly taken from the literature and are not adapted for the cutting process simulation. The cutting forces, feed forces and chip thickness are influenced by the constitutive models. A direct link was observed between the RMS value of the cutting force and the temperature in the secondary shear zone and an inverse link between chip thickness and the RMS value of the feed force. This study shows the importance of temperature dependent strain hardening effect on the material deformation behavior of Ti-6Al-4V alloy during machining process.

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