Optimization on the Johnson-Cook parameters of Ti-6Al-4V used for high speed cutting simulation

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Abstract—The Johnson-Cook (J-C) parameters obtained from the conventional mechanical tests are usually adopted directly for the high-speed cutting simulations. However, the conventional J-C parameters can not describe the exact plastic deformation under the coupling effect of large strain and high strain rate occurred in high speed cutting. In this paper, the response surface approximation method was used to optimize the Ti-6Al-4V’s J-C parameters for high speed cutting simulation, and the experimental results obtained from our previous work were further adopted to validate the optimized parameters. The simulated chip size error obtained at the cutting speed of 15 m/s could reduce from 16% with using the conventional J-C parameters to 8% with using the optimized J-C parameters. Furthermore, the simulated chip morphologies achieved based on the optimized J-C parameters were compared with the experimental results with cutting speed ranging from 0.05 m/s to 86.5 m/s. The results show that the simulated chip morphologies could give good agreements with the experimental results, and the chip morphology transitions can be well predicted with using the optimized J-C parameters.

1. Introduction

Ti-6Al-4V alloy is widely used in the fields of aerospace, automotive and medical equipment due to its excellent properties such as high toughness, high temperature resistance, corrosion resistance and high strength [1]. However, due to the low thermal conductivity and high chemical activity, the Ti-6Al-4V alloy is taken as one of the most typical difficult-to-cut materials [2]. It is easy to form the serrated or segmented chips in Ti-6Al-4V alloy machining. Both the serrated and segmented chip could reduce the machining quality and accuracy significantly. So it is of significant importance to study the mechanical phenomena occurred in Ti-6Al-4V alloy machining, so as to understand the mechanism of serrated and segmented chip formation.

The finite element method is widely used to study the cutting mechanism, since it can be used to observe some phenomena that hard to be observed in experiments, such as the shear band evolution, fracture initiation, etc. Considerable efforts have been carried out to study the cutting phenomena using finite element method. Gholamzadeh [3] developed a finite element model to study the effect of cutting parameters, such as cutting speed and feed rate, on the tool tip temperature. Chen [4] presented another finite element cutting model using energy-based ductile failure criterion, which can give good predictions on the cutting force and chip morphology for Ti-6Al-4V alloy.

It can be noted that, the Johnson-Cook (J-C) model, which can describe the coupling effects of strain hardening, rate hardening and thermal softening on plastic flow for most metallic materials, is usually
adopted in the finite element simulations [5,6]. By using the J-C model, Li [7] studied the formation process of serrated chip in orthogonal turning of Ti-6Al-4V. Zhang [8] proposed a modified J-C model to describe the plastic flow behaviors of aluminum alloy with introducing the strain rate hardening coefficient, which can be validated by a large number of experimental data. Zhang [9] evaluated two sets of J-C parameters for Ti-6A-4V using three types of metal cutting models. The results showed that the best set of J-C parameters, which could give acceptable chip thickness, is not unique for the three numerical models.

It is worth noticing that the J-C parameters used in most published cutting simulations are obtained directly from the conventional mechanical properties tests, such as the static compression experiment and Split Hopkinson Pressure Bar (SHPB) test. It should be pointed out that, the strain and strain rate achieved in the conventional tests can only reach to about \(10^{-1}\) and \(10^{4}\) s\(^{-1}\), respectively. However, the cutting processes can be characterized by large strain, high strain rate and high temperature. The strain and strain rate occurred in metal cutting can reach to the order of \(10^{1}\) and \(10^{7}\) s\(^{-1}\), respectively. So, the J-C parameters obtained from the conventional tests cannot describe the exact plastic behavior occurred in metal cutting. And the finite element models developed based on the conventional J-C parameters are not able to give good predictions for the cutting process [10].

To give a good prediction of the cutting process, a correct set of J-C parameters, which could accurately describe the plastic flow occurred in metal cutting under large strain and high strain rate, should be achieved first. In this work, a 2D finite element model is established to simulate the orthogonal cutting of Ti-6Al-4V alloy. The response surface approximation method was used to optimize the J-C parameters, based on which the finite element model could give reasonable predictions on the chip morphology compared with the experimental results.

2. Finite Element Model

In this work, the Abaqus/CAE software Explicit module was used to establish the 2D orthogonal cutting model for Ti-6Al-4V. The finite element model includes four parts: workpiece base, uncut chip layer, joint layer, and tool, as shown in Fig. 1. A 45° angle with respect to the x-direction is preset in the uncut chip layer, which facilitates the chip formation [11]. The preset angle could also eliminate the mesh distortion as the tool touch the uncut chip. The four-node thermal-mechanical coupling plane strain quadrilateral (CPE4RT) element was adopted, since the CPE4RT element is suitable for temperature-displacement coupling problems and has reduced integral and hourglass control features. The bottom and left side of the workpiece are completely fixed. The tool is set as a rigid body during the whole simulation process. The front and back angles of the tool are set as 0° and 7°, respectively. The tools move along the negative direction of the x-axis, and the cutting speed ranges from 0.5 m/s to 86.5 m/s. The thickness of the uncut chip layer is kept as 0.1 mm. The modified Coulomb-Tresca model is adopted to describe the friction between the tool and chip [12].

Here the J-C model is adopted to describe the plastic behavior of the Ti-6Al-4V, which can be given by

\[
\sigma = A + B (\varepsilon_p)^n \left[ 1 + C \ln \left( \frac{\varepsilon_p}{\varepsilon_0} \right) \right] \left[ 1 - \left( \frac{T-T_r}{T_{melt}-T_r} \right)^m \right] 
\]

(1)

where \(A, B, C, n,\) and \(m\) are the five parameters of the J-C constitutive model, which represent the initial yield strength, hardening modulus, strain rate correlation coefficient, work hardening coefficient, and thermal softening coefficient, respectively. \(\sigma\) is the equivalent plastic stress, \(\varepsilon_p\) is the equivalent plastic strain, \(\varepsilon_0\) is the reference plastic strain, \(T_r\) is the temperature of the workpiece material, \(T_r\) is the reference temperature, which is taken as 300K, and \(T_{melt}\) is the melting temperature. The J-C parameters \((A, B, C, n,\) and \(m)\) of the Ti-6Al-4V will be optimized in the next section to make it be suitable for the cutting simulation.

In order to realize the separation between the chip and workpiece material as well as the generation of segmented chip, a fracture model based on the classic cumulative damage law is introduced [11]
where $D$ is the failure parameter, $\Delta \varepsilon$ is the equivalent plastic strain increment and $\varepsilon_f$ is the failure strain. When the accumulated equivalent plastic strain is equal to the failure strain, that is, when the failure parameter $D=1$, the element fails and will be deleted in the next calculation. The failure strain $\varepsilon_f$ can be defined by the J-C damage model [13], that is

$$\varepsilon_f = \left[ D_1 + D_2 \exp(D_3 \tilde{\sigma}) \right] \times \left[ 1 + D_4 \ln \left( \frac{\tilde{\varepsilon}_p}{\varepsilon^*} \right) \right] \left[ 1 + D_5 \left( \frac{T - T_e}{T_{melt} - T_e} \right)^n \right]$$

(3)

where $\tilde{\sigma}$ is the triaxial stress, which represents the ratio of hydrostatic pressure $P$ to the von Mises stress $\sigma ( P/\sigma )$, and $\tilde{\varepsilon}_p/\varepsilon^*$ is the dimensionless plastic strain rate. $D_1, D_2, D_3, D_4$ and $D_5$ are the J-C damage parameters.

The material properties and Johnson-Cook damage parameters of the Ti-6Al-4V are given in Table 1.

### 3. Optimization of Johnson-Cook Constitutive Parameters

In this section, the response surface approximation method based on multi-objective genetic algorithm is used to optimize the J-C parameters of the Ti-6Al-4V alloy. The optimized constitutive parameters are further used for the Ti-6Al-4V alloy cutting simulation to verify its reliability.

Response surface approximation method is an optimization method based on mathematics and statistics [14]. It usually uses first-order or second-order polynomial regression equations to fit the surface, with assuming that the test variance conforms to the normal distribution. The specific form of the response surface approximation method can be given by

$$y(x) = \phi_0 + \sum_{j=1}^N \phi_j x_j + \sum_{j=1}^N \phi_{ij} x_j^2 + \sum_{j=1}^N \phi_{ij} x_j$$

(4)

| Physical and mechanical properties | Value  |
|-----------------------------------|--------|
| Density (kg/m$^3$)                | 4430   |
| Elastic modulus (GPa)             | 105    |
| Poisson’s ratio                   | 0.34   |

TABLE I. LIST OF PARAMETERS USED IN THE FE SIMULATIONS OF Ti-6AL-4V ALLOY [9, 11]
Thermal conductivity (W/(m·K)) 7.4
Expansion coefficient (m/K) 9x10⁻⁴
Specific heat (J/(kg·K)) 520
Melting temperature (K) 1880
Initial failure strain in J-C damage model $D_1$ -0.09
Exponential coefficient in J-C damage model $D_2$ 0.25
Exponential coefficient of stress triaxial in J-C damage model $D_3$ -0.5
Strain rate factor in J-C damage model $D_4$ 0.014
Temperature factor in J-C damage model $D_5$ 3.87

where, $x_j$ is the optimization variable, $N$ is the number of target variables, and the regression coefficient $\phi$ can be expressed as $\phi=(N+1)(N+2)/2$.

As for the five parameters ($A$, $B$, $C$, $n$, and $m$) in the J-C model, the initial yield stress $A$, work hardening modulus $B$ and strain rate dependence coefficient $C$ affect the cutting simulation much more significant compared to $n$ and $m$ [15,16]. So, in this work, the J-C parameters $A$, $B$, and $C$ were set as the optimization variables in (4), while the parameter $n$ and $m$ were set respectively as 0.28 and 1 according to the reference [16]. And the shear band spacing $L_c$ and tooth root thickness $h$ (The distance between the tooth valley and the bottom of the chip.) were chose as the target variables. The shear band spacing and tooth root thickness are schematically shown in Fig. 2. As show in Fig. 2, $a_c$ is the uncut chip thickness, $L_c$ is the shear band spacing, $H$ and $h$ are the entire chip thickness and tooth root thickness, respectively.

The Design-Expert software was further used to select the target point to fit the target function. Firstly, the variation ranges of the three optimization variables $A$, $B$, and $C$ were respectively defined, and then the target point was selected by obtaining equal points and corner points within the variation range. Then, the number of target points was gradually increased, and a multiple coefficients of determination ($R^2$) to evaluate the reliability of the explicit expressions of the target variable (The shear band spacing $L_c$ and tooth root thickness $h$) obtained by different numbers of target points. The multiple determination coefficient $R^2$ is given by

$$R^2 = \frac{\sum_{i=1}^{N} (\hat{y}_i - \bar{y})^2}{\sum_{i=1}^{N} (y_i - \bar{y})^2} \quad (5)$$

Figure 2 Schematic diagram of the serrated chip geometry
where \( K \) is the number of test points, \( y_i \) is the true value of the test point, \( \hat{y}_i \) is the predicted value, and \( \bar{y}_i \) is the average value of the true value of the test point.

When \( R^2 \) approaches to 1, reliable results are achieved, as thus the explicit expression of the shear band spacing \( L \) and tooth root thickness \( h \) with respect to \( A, B, \) and \( C \) can be obtained, that is

\[
L = -0.11 + 2.33 \times 10^{4} A + 1.36 \times 10^{4} B + 1.51 C
- 1.42 \times 10^{-7} AB - 1.41 \times 10^{-3} AC - 7.51 \times 10^{-3} BC \quad (6)
- 6.02 \times 10^{-7} A^2 + 1.79 \times 10^{-6} B^2 - 8.27 \times 10^{-2} C^2
\]

\[
h = -0.19 - 2.79 \times 10^{-4} A + 1.36 \times 10^{-4} B - 2.08 C
- 3.32 \times 10^{-8} AB + 1.71 \times 10^{-3} AC + 1.01 \times 10^{-3} BC \quad (7)
+ 1.92 \times 10^{-7} A^2 - 1.40 \times 10^{-7} B^2 + 0.77 C^2
\]

where the value of \( A, B, \) and \( C \) are in the ranges 700 MPa ~ 1200 MPa, 300 MPa ~ 900 MPa and 0.01~0.1, respectively.

The multiple determination coefficients of the expressions (7) and (8) are \( R^2_L = 0.996 \) and \( R^2_h = 0.994 \), respectively, which are very close to 1. This means that the fitted expressions obtained from the response surface method could match well with the simulation results (the target points). The expressions (7) and (8) give reasonable relationships of the chip morphology (shear band spacing \( L \) and tooth root thickness \( h \)) with respect to the J-C parameters \( A, B, \) and \( C \).

According to the expressions (7) and (8), a fast-multi-objective genetic algorithm was used to obtain the Pareto optimal solution, and that can be expressed as \cite{17}

\[
\min \, \hat{f}(\bar{x}) = \left[ \hat{f}_1(\bar{x}), \hat{f}_2(\bar{x}), \ldots, \hat{f}_M(\bar{x}) \right]
\]

subject to \( \bar{g}(\bar{x}) \leq 0 \) and \( \bar{h}(\bar{x}) = 0 \) \quad (8)

where \( \bar{x} \) is the optimization variable, \( \bar{g}(\bar{x}) \) and \( \bar{h}(\bar{x}) \) are the target functions.

The pareto optimal solution obtained by the fast-multi-objective genetic algorithm is shown in Fig. 3. Each data point in Fig. 3 corresponds to a set of J-C parameters. It can be found from Fig.3 that, at the same cutting speed, the shear band spacing and tooth root thickness are always inversely proportional, no matter what J-C parameters are used. The larger the shear band spacing, the smaller the corresponding tooth root thickness.

In our previous work \cite{18}, we have conducted the high-speed cutting experiments on Ti-6Al-4V based on a light gas gun with cutting speed \( V \) ranging from 0.05 m/s to 210 m/s, and the chip morphology at different cutting speeds were investigated. It was observed that the shear band spacing \( L \) and tooth root thickness \( h \) obtained at \( V=15 \) m/s were 0.054 mm and 0.05 mm, respectively. In order to obtain the optimal J-C parameters of Ti-6Al-4V for the high-speed cutting simulation, we compared the optimized curve with the experimental results, and an optimal point \( (L=0.05 \text{ mm}, \ h=0.047 \text{ mm}) \) was obtained, which matches the experimental data best, as shown in Fig. 3. The corresponding optimal J-C parameters are \( A=790 \text{ MPa}, \ B=478 \text{ MPa} \) and \( C=0.032 \), which can be used for the Ti-6Al-4V’s high-speed cutting simulation. The optimized J-C constitutive parameters were further used to simulate the high-speed cutting of Ti-6Al-4V, and the simulated values of \( L \) and \( h \) are 0.056 mm and 0.046 mm, respectively, with an error less than 8%.

Table 2 gives the optimized J-C parameters for Ti-6Al-4V, together with other two sets of commonly-used J-C parameters obtained from conventional material tests [20,21]. The simulated \( L \) and \( h \) with using these three different sets of J-C parameters are shown in Table 2. It can be seen that the chip size error obtained by using two commonly used constitutive parameters is about 16%, while the error with using optimized parameters is only 8%. It shows clearly that the optimized J-C
parameters can be used to predict the chip morphology much more accurately compared with the conventional parameters.

4. Simulation Results and Analysis

We further compared the simulated chip morphology with the experimental results from 0.05 m/s to 86.5 m/s, as shown in Fig. 4. The experimental results are obtained from our previous work, the detail of which can be found in reference [22]

| Set number | Johnson–Cook constitutive parameters | Chip size | Error value (%) |
|------------|--------------------------------------|-----------|-----------------|
|            | $A$ (MPa) | $B$ (MPa) | $C$ | $n$ | $m$ | $l_c$ (mm) | $h$ (mm) | $l_c$ (mm) | $h$ (mm) | $l_c$ | $h$ |
| Optimized value | 790 | 478 | 0.032 | 0.28 | 1 | 0.056 | 0.046 | 3.7 | 8.0 |
| Ducobu [20] | 870 | 990 | 0.011 | 0.25 | 1 | 0.061 | 0.042 | 12.9 | 16.0 |
| Molinari [21] | 782.7 | 498.4 | 0.028 | 0.28 | 1 | 0.049 | 0.057 | 9.2 | 14 |

It can be observed that as the cutting speed increases, the degree of chip sawtooth increases, and the chip changes from continuous ($V=0.5$ m/s) to sawtooth-like ($V=15$ m/s). And when the cutting speed increases to 86.5 m/s, the adjacent saw teeth separate from each other, giving rise to the discontinuously
segmented chips. It shows clearly that, with using the optimized J-C parameters, the simulated chips agree well with the experimental ones, no matter the chip is continuous, sawtooth-like or discontinuously segmented.

Moreover, from Fig.4 it also can be noted that, the value of the equivalent plastic strain (PEEQ) in the primary shear zone (PSZ) or at the tool-chip contact surface is much greater than that at any other places. The maximum PEEQ decreases gradually as the cutting speed increases. When the cutting speed is changed from 0.5 m/s to 86.5 m/s, the maximum PEEQ decreases from 5.612 to 4.532. The reason is that when the cutting speed is extremely high, the workpiece material will become brittle, and cracks take place before large plastic deformation occurs, thereby reducing the plastic strain.

In what follows, the simulated results will be compared with the experimental results quantitatively.

Here, the degree of serrated $G_s$ is defined to describe the geometric characteristics of the serrated chips [11], which is given by

$$G_s = \frac{H - h}{H} \quad (9)$$

where $G_s$ is the degree of serration, $H$ is the entire chip thickness, and $h$ is the tooth root thickness.

Fig. 5 gives the degrees of chip serration at different cutting speeds.

![Figure 5 The degree of chip serration evolving with cutting speed](image)

As shown in Fig. 5, it can be seen that the simulated results are in good agreement with the experimental ones obtained from our previous work [22], which further validates the reliability of the optimized J-C parameters. The degree of chip serration increases with the increase of cutting speed. When the cutting speed increases to 86.5 m/s, $G_s$ reaches 1, which indicates that the adjacent saw teeth have been completely separated, resulting in the emergence of discontinuously segmented chip, as shown in Fig. 4e.

5.Conclusion
In this study, a special focus has been attached to optimize the J-C constitutive parameters of Ti-6Al-4V in 2D orthogonal cutting simulation, which was carried out based on a response surface approximation method. The optimized J-C constitutive parameters were used to establish a 2D orthogonal cutting model of Ti-6Al-4V, which was validated by experimental results. The optimized J-C constitutive parameters can be used to describe the whole process of chip morphology transitions from continuous to sawtooth-like, and then to discontinuously segmented in Ti-6Al-4V’s cutting simulations.

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