Engineering Analysis with Boundary Elements 59 (2015) 129–143

Contents lists available at ScienceDirect

Engineering Analysis with Boundary Elements

journal homepage: www.elsevier.com/locate/enganabound

MPM simulations of high-speed and ultra high-speed machining of titanium alloy (Ti–6Al–4V) based on fracture energy approach

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ARTICLE INFO

Article history:
Received 25 October 2014
Received in revised form
13 May 2015
Accepted 28 May 2015
Available online 26 June 2015

Keywords:
Material point method
Hillerborg's fracture energy criterion
Chip morphology

ABSTRACT

Based on material point method (MPM), two dimensional (2D) orthogonal chip model on titanium alloy is established. Unlike finite element method (FEM) with seriously distorted meshes during the simulation of large strains such as the formation of shear band, the MPM is especially suitable for the numerical simulation of large deformation and high strain rate of metal material at high temperature. The generalized interpolation material point (GIMP) contact algorithm, Johnson–Cook model and Hillerborg's fracture energy criterion are used to simulate the cutting process on Ti–6Al–4V alloy. The parameters option and simulation process are first discussed, then the corresponding chip force and temperature field etc. are analyzed and compared with experimental data available. A good agreement has been found between them. Finally, the evolution of the temperature and cutting force are studied, and the effects of cutting speed and cutting feed rate on the chip morphology and cutting force are also investigated. It was the first time to simulate the serrated and discontinuous chips with the MPM and obtain relatively satisfactory results. The transition from serrated to discontinuous chips has been well captured in this paper.

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1. Introduction

High-speed machining is an advanced manufacturing technology with high efficiency, high quality and low consumption, and has been considered as the development direction of machining technology. Comparing with the traditional cutting process, high speed cutting leads to the cutting force to be decreased by 30–90%, and more cutting heat to be carried off by the chip. It can significantly improve the tool life and avoid the large thermal deformation of workpiece. Therefore, the machining precision and surface quality of workpiece [1] can be greatly improved. But the process of high speed machining often causes the periodic vibration, which can affect the service life of the cutting tool and the accuracy of the machined surface. At present, the mechanism of the serrated chip formation has not yet been well understood. Currently, two theories, i.e. the adiabatic shear theory and the periodic brittle fracture theory [1] have been used in the field of the high speed machining. Burns et al. [2,3] proposed a one-dimensional model of a simple isotropic material and revealed the serrated chip process of thermal-mechanical mechanism. Feng and Meng [4] calculated the critical velocity of titanium alloy material of saw-tooth chip by using elastoplastic theory and numerical methods. Mabrouki [5] investigated the thermo-mechanical effect on the chip morphology by using ABAQUS/Explicit software. Based on the fracture mechanism, Mabrouki et al. [6] and Zhang et al. [7] simulated the serrated chip, and analyzed the distribution of the chip damage factor. Ng and Aspinwall [8] and Ng et al. [9] established two-dimensional and three-dimensional models, respectively. For two kinds of different materials, their work showed that when fracture criterion is not considered, chip morphology is continuous. However, the chip becomes a discontinuous formation and the crack will be found at the shear band when the fracture criterion is used. Therefore, the discontinuous chip formation can be attributed to the periodic fracture theory. Although many studies about metal cutting have been done using the finite element method (FEM) [10–13], most of them did not carry out comparison with the experimental results [10,11,13]. Compared with the FEM, the meshless method has more advantages in dealing with the impact and penetration problems, and has achieved successful application [14–17] in recent years. The MPM uses particles to dissociate the objects. Therefore, it actually belongs to the particle type meshless method. The advantage of the MPM is that it is easy to describe the object with large deformation or break such as high speed cutting process [17]. In numerical implementation of the MPM, it only uses regular background grid to compute the momentum equations. As a result, it is not restricted to mesh distortion. The aim of this work is to develop the 2D MPM for investigating the high speed to ultra high speed cutting process on Ti–6Al–4V alloy. To this end, the Fortran

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http://dx.doi.org/10.1016/j.enganabound.2015.05.005
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computing code using the 2D MPM has been written. Numerical examples are presented to verify the present method by means of comparison with the experimental results available.

This paper is organized as follows. The review of the formulations of the MPM is given in Section 2. The description of classical Johnson–Cook constitutive model without damage is presented in Section 3. The introduction of the energy-based fracture criterion developed from the JC constitutive model is shown in Section 4. The cutting process simulations and discussion appear in Section 5. Finally, the conclusion is obtained in Section 6.

2. Basic formulations

The MPM belongs to the particle type meshless method since it uses a set of discrete particles to represent the continuum. Particle movement represents the movement and deformation of the continuum body. By using updated Lagrangian scheme, it is easier for the MPM to describe dynamic problems involving large material deformation [18].

2.1. The basic formulations of the MPM

Based on continuum mechanics, the following governing Eqs. (1)–(3) must be satisfied in the updated Lagrangian deformation and movement. In addition, the tensor is adopted here to facilitate description of the problem, the Cauchy stress $\boldsymbol{\sigma}$ and deformation rate tensor $\boldsymbol{D}$ are used to describe the stress and strain rate,

$$\text{Conservation of mass}: \ \frac{d\rho}{dt}+\rho\nabla\cdot\mathbf{v}=0 \tag{1}$$

$$\text{Momentum equation}: \ \rho\mathbf{a}=\nabla\cdot\boldsymbol{\sigma}+\rho\mathbf{b} \tag{2}$$

$$\text{Energy equation}: \ \rho\frac{de}{dt}=\boldsymbol{\sigma}:\mathbf{D} \tag{3}$$

where $\rho(\mathbf{x},t)$ is the density of the material; ∇ represents the Hamilton operator; $\mathbf{v}(\mathbf{x},t)$ and $\mathbf{a}(\mathbf{x},t)$ respectively denote the velocity vector and the acceleration vector; $\boldsymbol{\sigma}(\mathbf{x},t)$ and $\mathbf{D}(\mathbf{x},t)$ respectively express the Cauchy stress tensor and the deformation rate tensor; $\mathbf{b}(\mathbf{x},t)$ indicates the body force vector; $e(\mathbf{x},t)$ shows the internal energy of unit mass; $\mathbf{x}$ means the particle position vector at time t.

In the MPM, continuum is dispersed into a series of particles, as shown in Fig. 1. The particle carries density, velocity, stress and other physical quantities. In the domain, it is very difficult to directly solve the momentum Eq. (2) of the differential form. Therefore, the numerical simulation is often based on the weak form of the differential equation in a general way, i.e. virtual work equation. Here Ω represents the spatial domain occupied by an object at time t. Γ represents the surface of an object, and it consists of two parts Γ_t and Γ_u in which Γ_u is the displacement boundary and Γ_t is the stress boundary. As a virtual displacement vector, $\mathbf{w}$ satisfies the displacement boundary conditions. Then, the virtual work equation is as follows:

$$\int_\Omega \rho\mathbf{a}\cdot\mathbf{w}d\Omega+\int_\Omega \boldsymbol{\sigma}:\nabla\mathbf{w}d\Omega=\int_\Omega \rho\mathbf{b}\cdot\mathbf{w}d\Omega+\int_{\Gamma_t}\tilde{\mathbf{t}}\cdot\mathbf{w}d\Gamma \tag{4}$$

where $\tilde{\boldsymbol{t}}=\boldsymbol{\sigma}\cdot\boldsymbol{n}$ in which $\boldsymbol{n}$ is the unit normal vector to Γ_t.

In the MPM, the subscript i expresses the node variable, the subscript p denotes particle variables. With the discrete particle, the density of the object can be approximately expressed at time t as

$$\rho=\sum_{p=1}^{N_p} m_p\delta(\mathbf{x}-\mathbf{x}_p) \tag{5}$$

where m_p expresses the mass of the particle p, $\mathbf{x}_p$ means spatial situation at time t, N_p indicates the number of all the particles. Eq. (5) can be inserted directly into Eq. (4) to give

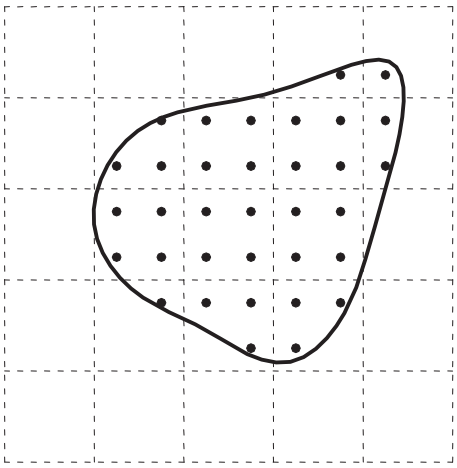

Fig. 1. Material point method diagram: continuous thick line – body boundary; dash line – background grid; bold dot -- material point.

$$\sum_{p=1}^{N_p} m_p\mathbf{a}(\mathbf{x}_p,t)\cdot\mathbf{w}(\mathbf{x}_p,t)+\sum_{p=1}^{N_p}\frac{m_p}{\rho(\mathbf{x}_p,t)}\boldsymbol{\sigma}(\mathbf{x}_p,t):\nabla\mathbf{w}|_{x=x_p}=\sum_{p=1}^{N_p} m_p\mathbf{b}(\mathbf{x}_p,t)\cdot\mathbf{w}(\mathbf{x}_p,t)+\int_{\Gamma_t}\tilde{\mathbf{t}}\cdot\mathbf{w}d\Gamma \tag{6}$$

When solving the momentum equation, material points move with background grid. So the mapping relation between particle and background grid nodes can be established through the finite element shape function. If we use the regular background grid of the same square cells, a cell with four nodes will be established. The shape functions are given by

$$N_i(\xi,\eta)=\frac{1}{4}(1+\xi\xi_i)(1+\eta\eta_i) \tag{7}$$

where ξ, η are the coordinate values for the particle under local coordinate system, and ξ_i,η_i are 1 or -1 according to the different node values.

If S_{ip} expresses the value of shape function of node i at particle p, and $\mathbf{G}_{ip}$ denotes the gradient vector of shape function of node i at particle p, considering the arbitrary displacement, the momentum equation at node i is

$$\sum_{j=1}^{N_n} m_{ij}\mathbf{a}_j=\mathbf{f}_i^{ext}+\mathbf{f}_i^{int} \tag{8}$$

In Eq. (8), m_{ij} is the component of mass matrix, $\mathbf{f}_i^{ext}$ denotes the external force vector of node i, $\mathbf{f}_i^{int}$ represents the internal force vector of node i, these equations are given by

$$m_{ij}=\sum_{p=1}^{N_p} S_{ip}S_{jp}m_p \tag{9}$$

$$\mathbf{f}_i^{ext}=\sum_{p=1}^{N_p} m_pS_{ip}\mathbf{b}_p+\int_{\Gamma_t} N_i\tilde{\mathbf{t}}d\Gamma \tag{10}$$

$$\mathbf{f}_i^{int}=-\sum_{p=1}^{N_p}\frac{m_p}{\rho_p}\boldsymbol{\sigma}_p\cdot\mathbf{G}_{ip} \tag{11}$$

If the lumped mass matrix is adopted, the momentum equation of the node can be written as

$$m_i\mathbf{a}_i=\mathbf{f}_i^{ext}+\mathbf{f}_i^{int} \tag{12}$$

where m_i is the mass of the node i.

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