Numerical study of microstructural effects on chip formation in high speed cutting of ductile iron with discrete element method

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ABSTRACT

Microstructural deformation and fracture process is important for chip formation and finished surface quality during metal cutting. In this paper, discrete element method (DEM) is introduced to establish a heterogeneous material model for cutting simulation to understand the microstructural deformation and fracture behaviors. A typical heterogeneous engineering material, ISO 450-10 ductile iron, was selected for modeling and experiments. Graphite nodules and ferrite grains were modeled respectively for studying their deformation behaviors. Cutting force and chip morphology obtained by simulation were compared with the experimental results. It shows that lamellar structure and unequal segments form at the chip free surface, which was also observed by optical microscope (OM) and scanning electron microscopy (SEM). The deformed degree of graphite nodules is much higher than that of ferrite grains. In addition, cracks are prone to produce and the chip size becomes smaller as the cutting speed increases. The velocity field and stress distribution of material near the rake face were investigated and the relationship between stress and cutting speed was further discussed. The velocity fluctuation of discrete particles in heterogeneous model is more obvious due to the microstructures compared with that in homogeneous model. Furthermore, the stress of material changes significantly with the increase of cutting speed since velocity vortexes may occur, resulting in the occurrence of the fracture. The results demonstrate that the influences of microstructure on crack initiation and chip formation are more significant at high cutting speeds.

1. Introduction

Metal materials commonly used in mechanical engineering are generally composed of various microstructures, which impose great influences on cutting process and surface quality of machined parts. During the cutting process, the breakage of chip depends on the weakest microstructure in materials. Therefore, the characteristics of microstructure deformation and fracture are very important to explore the chip formation and other physical phenomena in cutting process.

Much attention has been devoted to the effects of microstructure on machining process in recent years. The study of Poulachon et al. (2005) pointed out that the segmented chips and thin white layers on machined surface would be generated easily in coarse-grained materials. The relationship between the size of soft phase and the roughness of surface was established by Grum and Kisin (2003) through the analysis of the results obtained by fine turning of aluminum-silicon alloys. In these studies, although the influences of microstructure on machining process have been investigated, the researchers have not developed a physical model for the quantitatively description of these factors by experiments. However, many physical quantities that could not be

directly measured real-time during cutting process could be easily characterized by simulation. Thus, many researchers have discussed the effects of microstructure through finite element (FE) simulation.

For the microstructural behavior of heterogeneous materials in localized area could not be characterized by homogeneous model, Chuzhoy et al. (2002) firstly proposed the model of ductile iron with three phases at the microscale and conducted the cutting simulation. The results of stress-strain distribution showed that the plastic strain follows a preferred path by traveling between graphite nodules, and the cutting force is primarily from the deformation of pearlite. But chip is not formed due to the extremely short cutting distance. Simoneau et al. (2006) developed heterogeneous and homogeneous models of AISI 1045 steel, respectively, to investigate the effect of microstructure on chip formation. He demonstrated that the plumes form at chip free surface due to the concentrated plastic strain on the grain boundaries. Ljustina et al. (2014) also pointed out that chip morphology changes with the graphite nodularization degree. Furthermore, the simulation results of Zhang et al. (2012) showed that aperiodic chip segmentation may occur due to the different grain orientation angles at low cutting speeds. Mohammed et al. (2011) utilized the cohesive zone technique

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Nomenclature

E	Young's modulus (GPa)
F	Resultant contact force of particle (N)
F^n, F^s	Normal and tangential force of spring (N)
F_{max}	Yield strength of bond connection (N)
F_{max}^n, F_{max}^s	Normal and tangential spring strength (N)
F_{load}	External force (N)
F_t, F_r	Tangential and radial cutting force (N)
F_x, F_y	Measured milling force (N)
$F_{i(N)}$	Contact force acting on the particle from its neighbors at the Nth step (N)
f_u	Friction coefficient
h	Thickness of particle (mm)
I_i	Rotational inertia of particle (kg m^2)
K_n^t, K_n^c, K_t^s	Tensile, compressive and share stiffness of spring in contact model (N/m)
l_c	Cutting distance (μm)
M_{load}	External moment (N m)
N	Calculation step number
U	Displacement of particle (m)
U_e, U_p, U_{pmax}	Elastic, plastic and ultimate deformation of spring (mm)
v_c	Cutting speed (m/min)
x_i, y_i	Center coordinates of particle

Greek symbols

α_0	Clearance angle (°)
γ_0	Rake angle (°)
θ	Angular displacement of particle (rad)
ν	Poisson ratio
ρ	Density (kg/m^3)
ρ_0	Density of particle (kg/m^3)
σ_s	Yield strength (MPa)
σ_b	Tensile strength (MPa)
σ_{bc}	Compression strength (MPa)

to simulate segmented chip formation of graphite iron, showing the cracks that initiate at graphite or graphite-matrix interface and propagate into the matrix are the main cause of chip segmentation. In addition, the cutting forces and torques of carbon steel (Abouridouane et al., 2012) and the residual stress of bearing steel (Umbrello et al., 2010) are also affected by workpiece microstructures through the FE cutting simulation. Compared with homogenous model, the heterogeneous models including material microstructures can predict these physical quantities or phenomena more accurately.

However, these FE simulations were conducted at conventional cutting speeds from 3 to 400 m/min, and little research has been carried out on the effects of microstructure at higher speeds. With the increase of cutting speed, the physical phenomena in cutting process always change, such as the stress-strain state in the primary deformation zone and the transformation of chip morphology. Many studies, such as the work by Gu et al. (2016) and Zhanqiang and Guosheng (2012), demonstrated that the chip morphology changes from continuous to segmented and then to fragmented with the increase of cutting speed. However, there is no unified interpretation or a thorough understanding on this phenomenon. Furthermore, the internal defects,

including micro-voids and grain boundaries, make the material become discontinuous at the microscale. The continuum based FE method is difficult to solve problems with complex discontinuity, which leads to a problem of singularity due to the spatial derivative at the discontinuities. The mesh distortion and adaptive remeshing may introduce errors in resolution and impose a high computational load.

Discrete element method (DEM) proposed by Cundall and Strack (1979) is a mesh free method. The discontinuity or crack initiation is the natural outcome of the breakage of connecting bond. This method specializes in large deformation, fracture and breakage problems, and it has been widely used in machining simulations. The chip can separate from the workpiece without chip separation criterion or predefined crack path, which is reasonably consistent with the real cutting conditions. Many cutting simulations of heterogeneous materials, such as rock (Van Wyk et al., 2014), carbon fiber-reinforced polymer (Iliescu et al., 2010) and polycrystalline SiC (Tan et al., 2009), have been conducted to study the cutting force, machinability and crack propagation. However, the workpiece materials used in these investigations are non-metal, and few simulations have been performed on metal cutting with high cutting speeds. Therefore, the purpose of this paper is
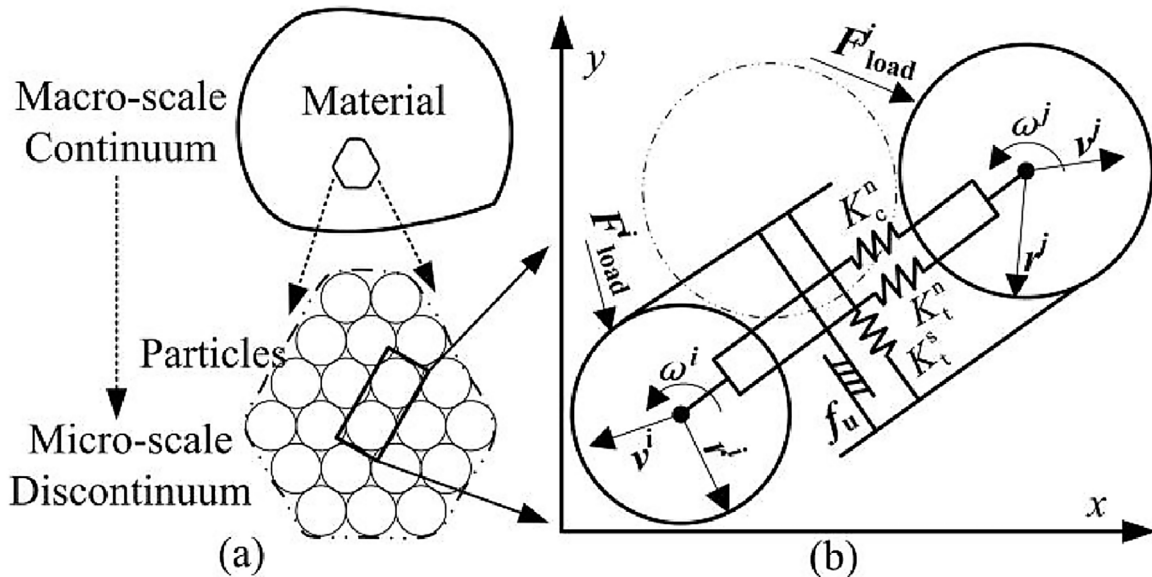

Fig. 1. (a) Schematic of DEM. (b) Contact constitutive model of particles. Superscripts *i* and *j* represent particles number, *v* is the translational velocity, *r* is the radius and ω is the angular velocity.