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An investigation into finite element modelling of micro machining of nano Mg/SiC metal matrix composites

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Abstract
Metal matrix composites (MMCs) present a high strength-to-weight ratio, superior wear resistance and mechanical properties. MMCs have been utilised in various industrial applications. In this work, a heterogeneous two-dimensional finite element model (FEM) was established to simulate microscale orthogonal machining of magnesium based MMCs reinforced with nano-sized SiC particles using ABAQUS/Explicit. The results present simulated chip formation process and local effect of particles during cutting process and it is observed to be different from that in conventional machining of MMCs with micro-sized particles. Finally, segmented chips with different geometry were observed in both circumstances.

Keywords: Finite element models; Micro machining; Nanocomposite; Magnesium; Nanoparticles; Tool–particle interaction

1. Introduction

Metal matrix composites (MMCs) reinforced with micro-sized particles have been widely applied in many industrial areas including electronics, aerospace and automobile owing to its high fracture toughness, high strength-to-weight ratio, excellent fatigue and corrosion resistance [1]. With the development of MMCs, the mechanical properties (especially, the tensile ductility) of MMCs with small volume fraction nano-sized particles is found to be even superior to that with larger content of micro-sized particles [2]. Additionally, with the increasing demands on the miniaturised size and complex features, micro machining, as an emerging technology has received growing attention in fabricating MMC components. However, the superior mechanical properties achieved through addition of hard reinforcement brings tremendous challenges in the machining process such as excessive tool wear, surface and sub-surface damage. Numerous numerical investigations on conventional machining of micro-sized MMCs can be found in the past two decades to reveal the behaviour of both matrix and reinforcement phases during machining process, but little investigations regarding the micro-machining of MMCs reinforced with nano-sized particles can be found. It is believed that the chip formation mechanism and local effect of particles can be altered significantly due to the reduced machining scale and the existence of nano-scale particles.

In this investigation, a fully coupled thermo-mechanical finite element model was developed to study the chip formation and particles debonding mechanism during micro orthogonal machining of MMCs with nano-sized particles. The size effect, namely, the effect of cutting edge radius was included in simulation process. Additionally, the results obtained in this study are compared with that obtained from conventional machining of MMCs with micro-sized particles in terms of chip formation and stress distribution.

2. Finite element modelling procedure

2.1. Modelling steps

A two-dimensional plane strain fully coupled thermos-mechanical finite element model was developed in ABAQUS/Explicit version 6.14.1 and the schematic representation of the model setup was illustrated in Figure 1. Quad-dominated continuum element with advancing front algorithm was utilised in cutting area A with mesh size of 0.04 µm as shown in Figure1. In order to overcome the excessive mesh distortion caused by large plastic deformation in cutting process, the Arbitrary Lagrangian-Eulerian (ALE) adaptive meshing techniques is applied.

In this model, two phases material were assigned and sheared nodes method was used to simulate the interface of matrix and particles and the average distribution of SiC particles with diameter of 100nm was constructed. The cutting parameters is listed in Table 1. The surface-to-surface contact model was applied between the external surface of the tool and node points of cutting area A.

Table 1. Cutting parameters applied in finite element models

Cutting speed, V_c (m/min)	31.4
Uncut chip thickness, t_u (µm)	1
Tool rake angle, α (Degree)	10
Tool clearance angle, β (degree)	6
Cutting edge radius, (µm)	1.0

2.2. Material constitutive equations

The cutting tool was regarded as an analytical rigid body and moved horizontally into workpiece. The matrix material Mg was modelled as a deformable elastic-plastic component with fracture criterion. Johnson-Cook material constitutive model (equation 1) and fracture model (equation 2) were employed to describe plastic behaviour and the fracture criterion respectively and the constant are listed in Table 2. The SiC particles were assigned as an elastically deformable body without failure. The mechanical properties of the matrix (Mg) and particles (SiC) are listed in Table 3.

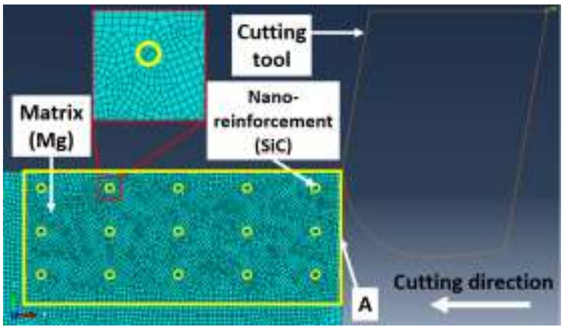

Figure 1. FEM model setup for micro-orthogonal machining of MMCs with nano-sized particles.

Table 2. Johnson-Cook materials constitutive models & failure constants of Pure Mg

A (MPa)	B (MPa)	n	m	c
153	291.8	0.1026	1.5	0.013
d1	**d2**	**d3**	**d4**	**d5**
0.5	0.2895	-3.719	0.013	1.5

Table 3. Mechanical properties assigned in FEM analysis

Materials	Mg	SiC
Density	1738 kg/m^3	3200 kg/m^3
Young's Modulus	39.82×10^9 Pa	40.8E10 Pa
Poisson's Ratio	0.35	0.183
T_{melt}	873K	873K
$T_{transition}$	293 K	293 K
Thermal expansion	25×10^{-6} K^{-1}	NA
Thermal Specific Heat	914 J/kg*K	750 J/kg*K
Conductivity	156 W/m*K	120 W/m*K

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

$$\overline{\varepsilon_f^{pl}} = (d_1 + d_2 e^{d_3\eta})\left[1 + d_4 \ln\left(\frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\varepsilon}_0}\right)\right]\left[1+d_5\left(\frac{T-T_{room}}{T_{melt}-T_{room}}\right)\right] \quad \textbf{(2)}$$

3. Results and discussion

Figure 2 illustrates the simulated chip formation process in micro orthogonal machining of MMCs with nano-sized particles. Instead of an obvious primary shear zone found at the initial engagement between cutting tool and workpiece (Figure 3a), an irregular shear zone with relatively large stress distribution was closely located in front of cutting edge (Figure 2a).

As the tool continuously moves (Figure 2b), a partially debonding of particle is observed above the primary shear zone which becomes more obvious than that in first engagement and a crack is initiated at the same time. Moreover, according to the observation of von Mises stress distribution on the particles along the crack area, relatively large stress amplitude was found on the area in the particles at vicinity of primary shear zone which is same as that in conventional machining.

As the tool moves forward, Figure 2c illustrates that a large area of stress is distributed beneath the clearance face of cutting tool. Consequently, the workpiece material is squeezed out in the opposite of cutting direction which is different from that observed in conventional machining (Figure 3b). A large crack is initially formed from the workpiece surface and then progress downward into the chip-root. In the meantime, the particles embed within chip root come contact with cutting edge.

The brittle failure tends to be more significant due to the addition of particles which results in segmented chips in both micro and conventional machining (Figure 2d & 3). However, the geometry of chips is different in these two circumstances.

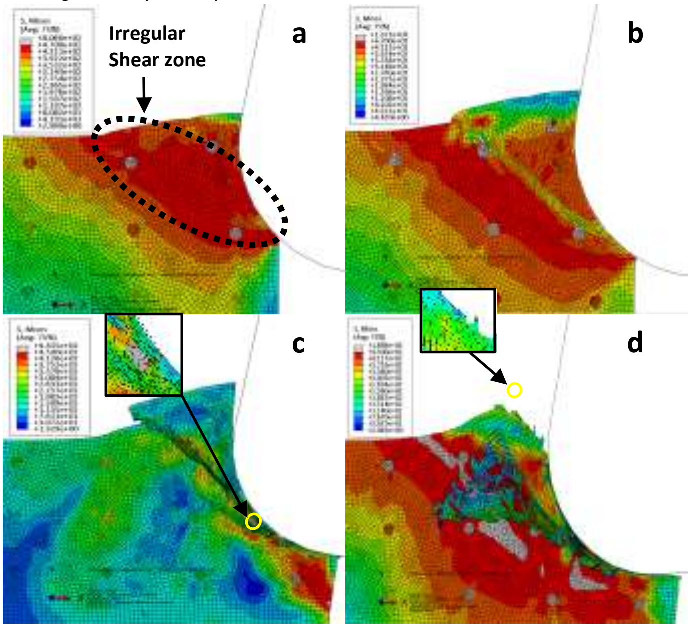

Figure 2. Chip formation process of micro orthogonal machining of MMCs with nano-particles

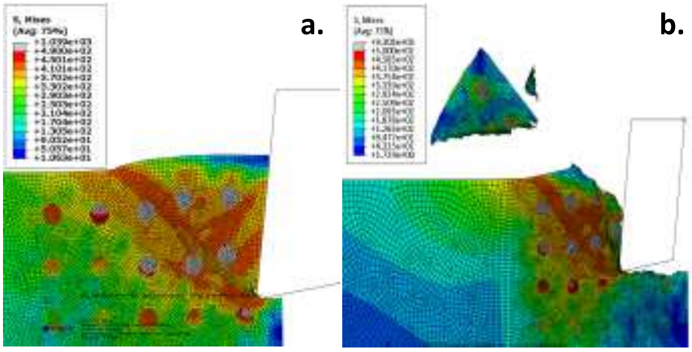

Figure 3. *Chip formation and deformed mesh in conventional machining of MMCs with micro-particles*

4. Conclusions

The two-dimensional finite element model was developed to simulate the chip formation process of micro orthogonal machining of MMCs with nano-sized particles with consideration of cutting edge radius. Several distinct differences were found through the comparison with conventional machining of MMCs with micro-particles. For the further works, the effect of cutting parameters (e.g. cutting speed, diameter of particles) on the chip formation process will be investigated. Meanwhile, the simulated results will be compared with that from experiment considering chip morphology and cutting force.

References

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