Teng X, Huo D, Chen W, Wong E, Zheng L, Shyha I. [Finite element modelling on cutting mechanism of nano Mg/SiC metal matrix composites considering cutting edge radius](#). *Journal of Manufacturing Processes* 2018, 32, 116-126.

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DOI link to article:

<https://doi.org/10.1016/j.jmapro.2018.02.006>

Date deposited:

28/03/2018

Embargo release date:

20 February 2019

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Finite element modelling on cutting mechanism of nano Mg/SiC metal matrix composites considering cutting edge radius

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Abstract

In the last two decades, metal matrix composites (MMCs) have been utilised in various industrial applications owing to their high strength-to-weight ratio and superior wear resistance. However, these superior mechanical properties bring poor machinability. The purpose of this paper is to perform a simulation study on the cutting mechanism of magnesium based MMCs reinforced with SiC nanoparticles. A two-dimensional micromechanical finite element (FE) model is established using ABAQUS/Explicit to simulate the micro machining process with consideration of cutting edge radius. The simulated results present tool-particles interaction, chip formation process, cutting force, Von Mises stress and strain distribution within workpiece under the effect of uncut chip thickness. The model is validated by comparing with experimental data in terms of cutting force and chip morphology.

Keywords: metal matrix composite; finite element model; nanocomposites; cutting; chip formation

1 Introduction

With the increasing demand on advanced lightweight structural materials, traditional metal matrix composites (MMCs) reinforced with micro-sized particles have become important materials in many industrial areas including aerospace, electronics, automobile and bioengineering due to their high fracture toughness, high strength-to-weight ratio and superior fatigue and corrosion resistance [1]. However, the ductility of traditional MMCs with micro-sized particles is found to be much lower than their matrix materials and therefore being restricted in specified applications [2]. With the development of MMCs, magnesium based MMCs with small volume fraction of nano-sized particles are found to exhibit even better mechanical properties than that reinforced with larger volume fraction of micro-sized particles without compromising in ductility [3]. As one of the lightest of engineering materials, magnesium and its composites attract broad research attention in terms of weight saving potential in engineering applications [4]. Besides this, it also exhibits the satisfactory biocompatibility.

Normally the MMCs components are fabricated in near net shapes, however mechanical machining, such as turning, milling and drilling is still necessary to achieve a desired accuracy and to generate complex features. The abrasive ceramic reinforced within the matrix would act as very sharp cutting edge and finally results in a premature tool wear during the interaction between cutting tool in high speed machining process. Another obstacle is identified as the poor machined surface due to particle debonding. Therefore, the improved mechanical properties and the nature of heterogeneous and anisotropic of MMCs bring tremendous complexities in machining process [5, 6]. In order to satisfy increasing demands on components with miniaturised size and high accuracy, micro machining is recognised as one of the most versatile micro manufacturing process. It is believed that those aforementioned obstacles will become significant in micro machining process with the decreasing ratio of uncut chip thickness and cutting edge radius.

A comprehensive understanding for materials removal mechanism in machining MMCs is highly desired. Numerous research has been conducted in machining of particle reinforced MMCs both experimentally and numerically. Finite element modelling method exhibits better capability in predicting actual machining characteristics such as the behaviour of matrix and interaction between cutting tool and particles during cutting process and therefore produces more visible details of materials removal mechanism when compared to experimental approach. As one of the most commonly used numerical approaches, finite element modelling has received growing attention on investigating the machining process of MMCs in the past two decades.

As an early attempt, Monaghan and Brazil [7] conducted a numerical investigation of micromechanics during machining A356 aluminium alloy with 35% volume fraction of SiC particulate based MMC using FORGE2 code. They split the whole simulation process into two stages. A homogeneous material was modelled to obtain the hydrostatic pressure in the first stage and the resultant loading output was applied in second stage which is accomplished using ANSYS, an elastoplastic FEA code. By using the pressure data from aluminium alloy simulation, the failure at the particle-matrix interface, tool wear and residual stress in the machined surface were studied. Later, Ramesh et al. [8] performed a transient dynamic FE simulation to analyse the diamond turning process of Al6061/SiC_p MMCs. Within this model, four possible types of encounters for tool ploughing through workpiece, namely, tool facing/ploughs particles and matrix and tool facing/ploughs matrix. Based on the analysis for the normal and shear stress within the cutting zone, they found that the position of particles relative to the tool can greatly affect the stresses field. Mariam et al. [9] developed a FE model considering thermal effect with the aim of optimising experimental parameters that minimise surface and subsurface damage and tool wear. A solid model of the machined workpiece was constructed. Both thermal and mechanical induced stress was studied. They found that the damaged layer depth in subsurface can increase by increasing the cutting speed. Moreover, the ratio of hydrostatic stress beneath the machined surface to the shear flow strength can reflect the extent surface damage. The higher the ratio (>1.0) is, lesser the damage occurs in the subsurface. A plain strain thermo-elastic-plastic FEA model on orthogonal machining of Al6061 reinforced with Al₂O₃ composites was developed by Zhu and Kishawy [10]. Particles were distributed within matrix randomly. The distribution of temperature and shear stresses in the matrix and around the particles at chip, primary and secondary deformation zone were investigated. Moreover, the debonding of particles was found and used to explain the formation of tool wear. Although particles were involved in this model, some workpiece behaviours such as tool-particles interaction and chip formation process were not simulated. Unlike previous research works, a more comprehensive model describing the behaviour of workpiece materials in machining was established by Pramanik et al. [11]. The interaction between particles and cutting tool was studied through three scenarios: particles above, along and below the cutting path. The variation of tensile and compressive stresses at the particles and its surrounding matrix as the tool move advance was investigated in these three scenarios, and were used to explain the particles fracture and debonding from the matrix. Additionally, the machined surface was considered to be hardened owing to the indentation of particles into machined surface caused by the interaction with the cutting tool. A 3D fully-coupled thermos-mechanical FE model on machining of particulate MMC with multi-step approach was established by Dandeker et al. [12]. In the first step, equivalent homogenous materials (EHM) model was utilised to predict the cutting force, stress and temperature distributions in machining MMC. For the second step, the results from first step were applied in a multi-phase sub-model with particles and matrix separated by a layer of cohesive zone element. As a result, the damage prediction was obtained resulting in a better understanding of the failure mechanism, void formation of matrix and particle fracture and debonding at interface. Meanwhile, a relation between damage depth and cutting force was established. More recently, Zhou et al. [13] carried out an investigation on the formation mechanism of edge defects near the exit of orthogonal cutting using a thermo-mechanical FE model during machining aluminium based SiC particulate MMCs. The effect of machining parameters on the size of edge defects was studied. Wang et al. [14] established a meso-scale FE model on milling process of Al/SiC MMCs with high volume

fraction. Their research showed that the formation mechanism of machined surface defects was contributed by particles failure behaviours such as debonding, micro fracture, big cleavage and cutting through of particles. In order to obtain an in-depth understanding regarding the chip formation process and tool-particles interaction, Ghandehariun et al [15, 16] developed a micromechanical FE model on machining Al/Al₂O₃ MMCs using cohesive zone element method. In their research, three main phases, namely matrix, particles, interface between matrix and particles were simulated separately. Also, the effect of cutting speed on cutting process was studied. With the increasing demands on miniaturised components with complex features in various areas, micro machining technique have emerged to satisfy such demands. At the same time, materials removal mechanism would change dramatically with decreasing of machining scale. Based on the references mentioned above, comprehensive finite element models on machining MMCs reinforced with micro-sized particles has been widely studied. Nevertheless, none of the currently available FE models studied the micro machining process of MMCs, especially the MMCs reinforced with low volume fraction of nano-sized particles.

This paper attempts to establish a novel micro-mechanical finite element (FE) model to simulate the micro machining process of nano Mg/SiC MMCs considering the cutting edge radius in this paper. Unlike the previous research, the nano particles (100nm in diameter) is modelled with a volume fraction of 1.5%. It is clear that the uncut chip thickness will make significant effect on the machining process, especially in micro machining process under size effect. This paper will particularly focus on the behaviour of MMCs such as chip formation mechanism, tool-particles interaction, stress distribution and cutting force at small depth of cut. A validation has been made with the experimental results for a range of uncut chip thickness.

2 Experimental procedures

Magnesium based metal matrix composites reinforced with nano-sized SiC particles with a volume fraction of 1.5% is employed in micro milling experiment. The average particle size is around 100 nm. Disintegrated melt deposition (DMD) technique is utilized as the fabrication method. A set of micro milling experiments is conducted on an ultra-precision desktop micro machine tool (Nanowave, MTS5R) fitted with a high speed spindle. Different feed per tooth of 1 and 2 μm at constant spindle speed of 80,000 rpm and depth of cut of 30 μm are selected during machining. Two-flutes AlTiN coated tungsten carbide end mills with cutting diameter of 500 μm , rake angel of 10°, cutting edge radius of 1 μm are employed. The cutting force is measured using piezoelectric dynamometer (Kistler 9256C2). The chips collected from experiments are observed by a SEM benefiting the validation with simulated results in terms of chip morphology.

3 Finite element modelling procedures

3.1 Simplification of 2D milling to orthogonal machining process

An assumption has been made for simplifying 2D micro milling process to orthogonal machining process. In micro milling experiment conducted within this study, the maximum uncut chip thickness t (less than 2 μm) is much smaller than the diameter of micro endmill (500 μm) as shown in Figure 1 (a), which results in relatively small variation of uncut chip thickness (2 μm) when compared with the travel distance of cutting edge in 180° of tool rotation (~392.5 μm), i.e. the variation of uncut chip thickness will not make significant influence on results (cutting force, chip morphology, etc.). Therefore, the uncut chip thickness in micro milling process can be considered to be equivalent to that in orthogonal machining process as shown in Figure 1 (b).

Figure 1. (a) Schematic diagram of 2D milling process in 180° of tool rotation; (b) Relationship between 2D milling process and orthogonal machining process (adapted from [17]).

3.2 Model setup

A two-dimensional micro-mechanical finite element model is established to simulate the micro-orthogonal machining process of nano Mg/SiC MMCs using commercially available software ABAQUS/Explicit v6.14-4. Since the nonlinearity, large strain and strain rate are involved in machining process, Arbitrary Lagrangian Eulerian (ALE) formulation is selected to avoid severe distortion of elements. The schematic representation of the established model is shown in Figure 2. Analytical rigid body is assigned to the cutting tool which moved horizontally into workpiece with a predefined speed. In order to get a better understanding of details of machining process, two phases materials including matrix and particles are assigned individually in this model. The particle diameter is defined as 100 nm with volume fraction of 1.5%. The machining parameters are listed in Table 1.

Table 1. Machining parameters in FE model

Cutting speed, V_c (m/min)	125.64
Uncut chip thickness, t (μm)	0.1, 0.2, 0.5, 1, 2
Tool rake angle, α (Degree)	10
Tool clearance angle, β (degree)	6
Cutting edge radius, (μm)	1

Figure 2. (a) Schematic representation of the established models for micro orthogonal machining of Mg/SiC MMCs; (b) local zooming of mesh element

A particles distribution strategy that makes the particles distributed at different relative locations of cutting path is used in this model as shown in Figure 2 (a). Within this strategy, the distance between each particle in X and Y direction is same, while the distance between the uppermost particles and top surface of the workpiece is 50 nm larger in Y direction than the last column from right to left side. For example, particles along line A distribute further away from bottom cutting edge limits, which simulate the diversity of particles locations relative to the cutting path in reality.

3.3 Materials modelling

Magnesium matrix is treated as a deformable thermo-elastic-plastic material with quadrilateral continuum element and fracture criteria. As one of the most commonly used constitutive models for predicting flow stress within metallic materials subjected high strain, strain rate and temperature, the Johnson-Cook constitutive model is used to describe the plasticity behaviour of magnesium matrix during machining process. Strain harden, strain rate effects and thermal softening are combined in the J-C model:

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

Where $\bar{\sigma}$ is the flow stress, $\bar{\epsilon}^{pl}$ is the plastic strain, $\dot{\bar{\epsilon}}^{pl}$ is the plastic strain rate, $\dot{\epsilon}_0$ is the reference strain rate, T is the workpiece temperature, T_{melt} and T_{room} are the material melting and ambient temperature. Coefficient A is the yield strength, B is the hardening modulus, C is strain rate sensitivity coefficient, n is the hardening coefficient, m is the thermal softening coefficient and these material constants are normally determined by static tensile test, torsion test and dynamic Hopkinson bar tensile test. The mechanical properties and material constants of Mg in J-C model are listed in Table 2.

Johnson-Cook fracture equation is used to define the materials failure criterion for magnesium matrix. It is a function of strain and strain rate hardening effect and temperature softening. It has been widely used to define the fracture criterion in metal machining. The equivalent plastic strain at the onset of fracture, $\bar{\epsilon}_f^{pl}$ is defined as:

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

Where $d_1 - d_5$ (listed in Table 2) are fracture parameters obtained from experiments, η is the stress triaxiality and $\dot{\epsilon}_0$ is reference strain rate.

$$D = \sum \frac{\Delta \epsilon^{pl}}{\epsilon_f^{pl}} \quad (3)$$

$\Delta \epsilon^{pl}$ is the change of equivalent plastic strain in each integration increment. A damage parameter D is defined in each analysis increment and the element would be deleted once damage parameter D reaches unit value.

Table 2. Mechanical properties and materials constant in J-C model for magnesium matrix [18]

Density (ton/mm ³)	1378×10 ⁻¹²
Young's Modulus (MPa)	39820
Poisson's Ratio	0.35
T _{melt} (K)	873
T _{transition} (K)	293
Thermal expansion (K ⁻¹)	25×10 ⁻⁶
Thermal Specific Heat (mJ/ton*K)	914×10 ⁶
Conductivity (mW/mm*K)	156
A (MPa)	153
B (MPa)	291.8
n	0.1026
m	1.5
C	0.013
d ₁	0.5
d ₂	0.2895
d ₃	3.719
d ₄	0.013
d ₅	1.5

SiC particles were assumed to be brittle cracking body with brittle shear and brittle failure definition in order to investigate its behaviour during cutting process. The mechanical and brittle cracking properties are shown in Table 3.

Table 3. Mechanical and brittle cracking properties for SiC particle

Density (kg/mm ³)	3200
Young's Modulus (MPa)	408000
Poisson's Ratio	0.35
Thermal Specific Heat (J/kg*K)	755
Conductivity (W/m*K)	120
Compressive Strength (MPa)	3900

3.4 Boundary conditions and contact definitions

Free thermal-displacement quad-dominated meshing technique is used with combination of advancing front algorithm for both matrix and particles (Figure (2b)). Mesh size of particles and matrix surrounding particles is defined to be 25 nm and 40 nm. Cohesive element and shared nodes are two common methods employed to model the interface between the particles and matrix. A cohesive layer

with appropriate properties and fracture criterion is essential to generate accurate results. However, this method is not available for modelling Mg-MMC due to the absence in material properties. As a result, share nodes method was employed to model the interface. The interface nodes of magnesium matrix and SiC particles are tied together, resulting that the matrix and particles will exhibit the same behaviour at initial deformation. The bottom surface of the models was fixed in all directions.

The surface-to-surface contact model is applied between the external surface of the tool and node points of machining area. In this study, due to the high cutting speed and high friction contributed by size effect, the high temperature generated is believed to make a significant contribution to plasticity behaviour of matrix material. This would make the sticking zone obvious during chip formation process. Therefore, Coulomb friction law combining with sticking-sliding theory is used to simulate friction stress.

$$\tau_{sticking} = \mu\sigma_n \text{ when } \mu\sigma_n < \tau_{lim} \quad (4)$$

$$\tau_{sliding} = \tau_{lim} \text{ when } \mu\sigma_n \geq \tau_{lim} \quad (5)$$

where τ_{lim} is the limiting shear stress on the interface, σ_n is normal stress distribution along the rake face, μ is the coefficient of friction, $\tau_{sticking}$ is friction shear stress along the sticking region, $\tau_{sliding}$ is friction shear stress along sliding region. A sticking region forms at the vicinity of cutting tool and the equivalent shear stress (Equation 4) can be determined by the coefficient of friction, μ and normal stress distribution along the rake face σ_n . Once the shear stress at interface reaches a critical value τ_{lim} , sliding regime (Equation 5) governs the friction process. A constant friction coefficient of $\mu = 0.5$ is used in this simulation.

4 Results and discussion

4.1 Chip formation process analysis

According to previous studies on macro machining of micro-sized MMCs [13–16], addition of hard particles into matrix materials could greatly alter the cutting mechanism comparing with homogeneous materials. In fact, cutting tool edge radius is becoming one of the important factors governing the machining mechanism in micro machining process. In this section, the chip formation process in micro machining process will be studied in terms of chip morphology, stress/strain distribution within matrix and tool-particles interaction with consideration of cutting edge radius.

Figure 3 illustrates the simulated chip formation process under the uncut chip thickness of 1 μm . As shown in Figure 3 (a), when the tool firstly engages with the workpiece, a highly concentrated stress is induced leading to an irregular shear zone closely formed in front of the cutting edge, which is different from that in macro machining of MMCs where an obvious primary shear zone can be formed at initial cutting stage.

Figure 3. Chip formation process during micro-machining of nano Mg/SiC MMCs

Figure 4. Effect of addition of nano-particles on distribution pattern of von Mises stress contour

As the tool advances, the primary shear zone can be observed in Figure 3 (b). Additionally, it is clear that the particles take more stress than matrix material, especially those particles located near the primary shear zone. This might be attributed to the high elasticity of SiC particles. The maximum von Mises stress is found at the particles located under cutting edge which is 3109 MPa. This is different

from that in machining monolithic materials where the maximum stress occurs in the primary shear zone. Moreover, another difference can be obtained through observing the von Mises stress distribution pattern in Figure 4. The addition of nano-particles greatly alters the pattern of stress field within matrix. A distorted stress contour can be found at vicinity of each particle. This observation can be explained by the existence of particles in the matrix restricting the progression of plastic stress flow within matrix during machining. The stress is therefore accumulated and hence results in a high plastic strain field at particle interface as shown in Figure 5. The existence of nano-particles also fragments strain field. Similar phenomena was reported by Pramanik et al. [11] in machining of micro-sized Al/SiC MMCs.

Figure 5 Distribution of equivalent plastic strain within nano Mg/SiC MMCs.

As the tool continuously moves, Figure 3 (c) shows the behaviour of particle located immediately under the flank face of the cutting tool when the tool is approaching to it. By comparing with the original position of this particle, it moves horizontally with the highly deformed matrix in cutting direction without any direct contact with the cutting edge. Evolution of von Mises stress on the matrix element surrounding the particle with approaching of cutting edge is studied in Figure 6 in details. Initially, the von Mises stress is found to increase to maximum value of 454 MPa (C) with advancement of the tool. At this stage, the particle is found at primary shear zone. As mentioned earlier, this particle acting as a barrier restricts the progression of plastic stress within matrix which results in a high compressive stress acting on the matrix close to particle interface. This is different to macro machining process where the maximum stress usually happens at the matrix between cutting edge and particles due to the indentation caused by the cutting edge [11]. Consequently, this results in a concentrated stress ranging from 540 to 650 MPa acting at particles. A sudden drop in von Mises stress is followed from C to E as the primary shear zone moves horizontally passing through this particle. At this period, the restricting behaviour on plastic stress flow of particle becomes less dominant as particles moves with surrounding matrix with further advancement of the tool. It is believed that the matrix element experiences a highly plastic deformation within this stress drop process (C to E). Finally, von Mises stress releases and decreases to 0 MPa when the cutting edge is passing through it, resulting in a failure of matrix surrounding this particle. As a result, this particle is subjected to debonding from matrix.

The premature tool wear caused by the high contact stress between cutting tool and hard particles has been recognised as one of the important factors affecting the machinability of MMCs. The interaction process between cutting tool and particles should be better analysed to predict the tool wear. Figure 7 (a-d) illustrates the stress distribution on the particles located immediately below the cutting edge with advancement of the tool. Based on the observation of Figure 7 (a) and (b), the increase in von Mises

stress can be observed on the particle due to the compressing of surrounded matrix with tool approaching to the particle. The direct contact between tool and particles can be found in Figure 7 (c). A highly concentrated stress on the upper part of particle is generated due to the ploughing between particle and flank face. This particle is then debonded and slide over the flank face (Figure 7 d). During the sliding process, particle acting like a sharp cutting edge scratches the flank face leading to abrasive wear. Smoother wear at flank face is expected due to the nano-sized particles. Additionally, it is evident from this figure that the particle is still intact which is different with that in machining of micro-sized MMCs where particle fracture is observed.

Upon the advancement of cutting tool, the chip is completely formed (Figure 3 d). A complete chip-tool contact area is achieved with chip flow happening along the rake face. In this stage, the particles located above the flank face of cutting tool initially move with surrounding matrix and enter into the formed chips as the cutting edge approaches. Figure 3 (d) also illustrates a continuous chip with saw tooth appearance. This phenomenon can be explained by studying the equivalent plastic strain distributed in the chip as shown in Figure 8. A large deformation is observed at the interface of chip and cutting tool. Moreover, it can be seen that several highly strained bands are distributed across the chips at vicinity of particles, which can be considered as the main reason contributing to the lamellate structure of chips. Essentially, those highly strained bands are caused by localised high plastic von Mises stress bands (Figure 9). Figure 9 illustrates the formation of high stress bands within chip with advancement of cutting tool. At initial stage, primary shear zone is observed in Figure 9 (a). As the tool further moves, transition stage is achieved (Figure 9 b). The concentrated stress field is observed at interface of particles as primary shear zone passing through due to particles' restricting behaviour to plastic stress flow as mentioned earlier. Figure 9 (c) shows eventually the high stress bands is formed within chips.

Figure 6 Evolution of von Mises stress distribution on the matrix element close to interface of particle

Figure 7 Evolution of von Mises distribution on the particle located immediately below cutting edge with advancement of cutting tool

Figure 8. Distribution of equivalent plastic strain within formed chips

Figure 9. Formation of high stress bands within chips with advancement of cutting tool

4.2 FE model validation

A validation of the finite element model is performed by comparing the simulated cutting force and chip morphology with experimental results. Figure 10 illustrates the cutting force obtained from simulation and experiment under different uncut chip thickness. As expected, the cutting force is found to increase with increase of uncut chip thickness. A satisfying agreement can be obtained between the predicted and experimental cutting force. At lower uncut chip thickness of $0.1\ \mu\text{m}$, the absolute average percentage error is 39.3% for the predicted cutting force. As the uncut chip thickness increasing, the absolute average percentage error decreases to 30.2%, 26.5%, 20.3% and 15.6% at uncut chip thickness of 0.2, 0.5, 1 and $2\ \mu\text{m}$ respectively. It can be attributed to the constant friction coefficient used in this model which should be larger in realistic machining at small uncut chip thickness due to the ploughing effect. Moreover, because of the ideally sharp cutting edge without considering tool wear used in this model, the simulated cutting force is observed to be smaller than that obtained from experiment at each defined uncut chip thickness which meet the expectation.

Figure 10. Comparison between simulated and experimental cutting force at different uncut chip thickness

Figure 11. Chip morphology comparison between (a) simulation; (b) experiments

Figure 12. Cutting force comparison between simulation and experiments

FE model is also quantitatively validated in terms of the chip morphology. Small and fragile chips are collected from the micro milling experiment on nano Mg/SiC MMCs at uncut chip thickness of $1\mu\text{m}$ (Figure 11 (b)). The distinct lamellar structure is observed on the free surface of the chips. As mentioned earlier, highly strained bands distributed across the chips at vicinity of particles obtained from simulation can be considered as the main reason contributing to the lamellate structure of chips. Therefore, the validation is performed by comparing the thickness of lamellae on the chip obtained from experiment (Figure 11 (b)) with the width of highly strained bands from simulation results (Figure 11 (a)). The thickness of each lamellae is calculated by averaging the thickness of ten lamellar structure. Comparison results are shown in Figure 12. The average difference between simulation and experiment is 20.4%.

4.3 Effect of uncut chip thickness

4.3.1 Specific cutting force

Figure 13 shows the specific cutting force at different uncut chip thickness obtained from machining experiment and simulation model. Specific cutting force is calculated by dividing the resultant cutting force by the section area of cutting area. Based on observation, size effect can be found according to the non-linear decrease of specific cutting force with increase of uncut chip thickness.

Figure 13 Specific cutting force at different uncut chip thickness

4.3.2 Chip morphology

Several differences will appear when the machining features decrease from macro to micro scale. One of the significant concerns is the size effect leading a transitional regime associated with intermittent shearing and ploughing in material removal process [19]. In this section, chip morphology of micro machining on nano Mg/SiC MMCs under various uncut chip thickness is investigated through FE models (Figure 14). Minimum chip thickness is determined based on the studying of chip morphology. The uncut chip thickness is selected to be 0.1, 0.2, 0.5, 1 and $2\mu\text{m}$. As shown in Figure 14, the highly concentrated stress region which can be considered as primary shear zone can be observed within workpiece materials with different location underneath the cutting edge at all uncut chip thickness.

At uncut chip thickness of $0.1\mu\text{m}$, it can be found from Figure 14 that there is no continuous chip formed in the cutting process. The small amount of material is initially elastically ‘pushed’ and accumulated in front of cutting edge (Figure 15 (a)). With the tool continuously moves, the equivalent strain at the chip root increase resulting the onset of plastic deformation. Figure 15 (c) illustrates the continuous cutting stage. The maximum equivalent plastic strain is distributed at the accumulated

material which finally leads to a complete failure and stress within workpiece is released. The fragmented chip is therefore formed by this discontinuous removal mechanisms. The chip formation process at uncut chip thickness of $0.2\text{ }\mu\text{m}$ exhibits the similar behaviour as that in uncut chip thickness of $0.1\text{ }\mu\text{m}$. When the uncut chip thickness increase to 0.5 to $2\text{ }\mu\text{m}$, an irregular segmented chip is formed. Based on these results, the minimum chip thickness can be proposed to be $0.5\text{ }\mu\text{m}$ ($0.5R$) under the input parameters utilised in this FE model. This result is consistent with that obtained from research carried by Teng et al. [20], which is $0.53R$ in micro machining of Mg/TiB_2 with volume fraction of 1.98% . Moreover, an increase in the shear angle can be found with the uncut chip thickness (Figure 16).

Figure 14. Chip morphology at uncut chip thickness of (a) $0.1\text{ }\mu\text{m}$; (b) $0.2\text{ }\mu\text{m}$; (c) $0.5\text{ }\mu\text{m}$; (d) $1\text{ }\mu\text{m}$; and (e) $2\text{ }\mu\text{m}$.

Figure 15. Stress and strain distribution within workpiece at material removal process under uncut chip thickness of 0.1 μm

Figure 16 The variation of shear angle with uncut chip thickness in FE model

5 Conclusion

A novel micro-mechanical finite element (FE) model is established to investigate the micro machining process of magnesium based metal matrix composites reinforced with nano-sized silicon carbide particles. The micro mechanism of Mg/SiC such as chip formation process, tool-particles interaction, stress and strain distribution and cutting force with consideration of cutting edge radius is investigated. The validation of FE model is conducted by comparing with experimental data. The following conclusions can be draw from this paper:

1. The particles can be recognised as the obstacle restricting the progression of von Mises stress within matrix, resulting the highly strained field at particles interface.
2. The investigation on tool-particles interaction provides a better understanding for premature tool wear. The concentrated stress acting on the particle is generated due to the ploughing between particle and flank face. During the machining process, particle is still intact without fracture.
3. A continuous chip with saw tooth appearance is obtained at the uncut chip thickness above 1 μm . Highly strained bands at vicinity of particles are observed at chips, which can be recognised as the cause of this lamellate structure.
4. The cutting force and chip formation process are obtained in this FE models. Minimum chip thickens is determined as 0.5R according to simulated results.
5. The validation of FE models is performed by comparing the simulated and experimental results in terms of cutting force and chip morphology and a satisfactory correlation is achieved.

Acknowledgment

The authors gratefully acknowledge support of the Engineering and Physical Sciences Research Council (EP/M020657/1).

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