Study of Chip Morphology and Chip Formation Mechanism During Machining of Magnesium-Based Metal Matrix Composites

Magnesium (Mg) and its alloys are among the lightest metallic structural materials, making them very attractive for use in the aerospace and automotive industries. Recently, Mg has been used in metal matrix composites (MMCs), demonstrating significant improvements in mechanical performance. However, the machinability of Mg-based MMCs is still largely elusive. In this study, Mg-based MMCs are machined using a wide range of cutting speeds in order to elucidate both the chip morphology and chip formation mechanism. Cutting speed is found to have the most significant influence on both the chip morphology and chip formation mechanism, with the propensity of discontinuous, particle-type chip formation increasing as the cutting speed increases. Saw-tooth chips are found to be the primary chip morphology at low cutting speeds (lower than 0.5 m/s), while discontinuous, particle-type chips prevail at high cutting speeds (higher than 1.0 m/s). Using in situ high-speed imaging, the formation of the saw-tooth chip morphology is found to be due to crack initiation at the tool tip. In addition, the influences of tool rake angle, particle size, and particle volume fraction are investigated and found to have little effect on the chip morphology and chip formation mechanism. [DOI: 10.1115/1.4037182]

Keywords: magnesium, metal matrix composite, machining, chip morphology, chip formation mechanism

1 Introduction

Magnetism (Mg) and its alloys are among the lightest metallic structural materials (one-third lighter than aluminum (Al) alloys), which make them very attractive for use in the automotive and aerospace industries [1]. In the automotive industry, Mg has been used where weight savings is critical and has shown a reduction in fuel consumption as high as 60% [2]. As these industries continue to improve the energy efficiency of their products, the need for high-performance materials is expected to rise [1,3]. However, compared to aluminum alloys, Mg alloys are mechanically inferior, especially at high temperatures [1]. Thus, there is a need to improve the mechanical properties of magnesium alloys for use in structural applications within the automotive and aerospace industries.

Recently, ceramic particle reinforcements, such as silicon carbide (SiC) or aluminum oxide (Al2O3), have been embedded into a metallic matrix including Al and Mg, resulting in remarkable improvements in mechanical performance. Such composite materials, known as metal matrix composites (MMCs), have gained popularity due to their increased strength to weight ratio, reduced sensitivity to thermal variation, and improved wear resistance [4,5] when comparing with unreinforced alloys. Moreover, the mechanical and physical properties of MMCs can be tailored to specific applications by varying the reinforcement particle size and volume fraction [6]. While MMC materials may be produced as near-net shape, a number of secondary machining processes are required in order to improve the surface finish and dimensional accuracy.

The objective of this study is to investigate the chip morphology and chip formation mechanisms during machining of Mg-based MMCs embedded with SiC particle reinforcements. Mg-based MMCs are selected for machining since they possess the desirable strength and wear resistance for wide use in the automotive industry where weight savings is desirable [2]. Postmortem metallographic analysis of machined chips and in situ high-speed imaging are implemented to study the chip morphology as well as the chip formation mechanism. High-speed imaging enables instantaneous observation of the chip formation progression and can be considered analogous to quick-stop devices without the deleterious effects of abruptly removing the cutting tool from workpiece. The resulting knowledge is expected to provide the missing physical understanding of the chip formation process during orthogonal machining of Mg-based SiC MMCs.

2 Background

Generally, the chip morphology of MMCs can be classified based on the cross-sectional geometry of postmortem chips using
metallographic analysis as (1) continuous [5,7], representing long chips with uniform thickness; (2) semicontinuous [4], having a reduced length and serrations on one edge; (3) saw-tooth [7,8], consisting of a saw-tooth profile at the free surface, similar to those found during monolithic metal machining; and (4) discontinuous [7,8], appearing as small, discrete segments.

The chip morphology is largely dependent on cutting conditions, particularly the cutting speed, and the volume fraction of particle reinforcements, and most observations are related to Al-based MMC machining. Despite the numerous studies aimed to investigate the chip morphology [5,7,9], there is no consensus regarding the effect of cutting speed on the chip morphology. El-Gallab and Sklad [9] machined an Al-based MMC through a range of cutting speeds greater than 10 m/s and found the chip morphology to change from continuous to saw-tooth as the cutting speed increases. Different chip morphologies were reported when machining similar Al-based MMCs within the speed ranges from $3 < V < 13$ m/s [7] and $0.67 < V < 2$ m/s [5]. Dabade [5] observed discontinuous chips at cutting speeds less than 0.67 m/s, while continuous chips were apparent when the cutting speed was increased up to 2 m/s; discontinuous chips were found to be a result of crack initiation due to particle pinning within the metallic matrix. As the cutting speed increased and thermal softening became more dominant, a local increase in ductility facilitated particle transport, resulting in continuous chip formation. In addition to the effect of cutting speed, the particle reinforcement volume fraction has been reported to influence the chip morphology. The inclusion of particle reinforcements introduces discontinuities within the metallic matrix as the workpiece material passes through the primary shear zone (PSZ), increasing the likelihood of saw-tooth chip formation. Joshi et al. [10] suggested that particle reinforcements increased the likelihood of saw-tooth chip formation. As the particle volume fraction increased, saw-tooth chips became more apparent when comparing with continuous chips during machining of unreinforced materials.

The chip morphology is the result of specific chip formation mechanism(s) occurring during machining. For monolithic metallic materials, the chip formation mechanism has been reported to be primarily due to (1) adiabatic shear localization [11–13] or (2) crack initiation and propagation [14,15]. Adiabatic shear localization occurs when the local rate of thermal softening dominates the local rate of work hardening, which manifests in localized regions of highly deformed material, known as shear bands [11]. Conversely, crack initiation and propagation occur when the machining-induced shear stress along the PSZ reaches a critical level beyond which the workpiece cannot afford, and a crack initiates at/near the free surface and propagates toward the tool tip [14]. It should be noted that crack initiation was also reported to occur at the tool tip and propagate toward the free surface; however, this was only reported at very high cutting speeds [16]. The coexistence of both the adiabatic shear localization and crack initiation mechanisms was also proposed [15]: crack initiation is the primary chip formation mechanism; however, the crack may disperse into multiple microcracks, providing initiation sites for adiabatic shear due to the increased temperature at the moving crack tip.

The inclusion of particle reinforcements into metallic matrix also results in a variation in the chip formation mechanism. Due to this, the chip formation mechanisms of MMCs are expected to differ from their unreinforced counterparts. The reported chip formation mechanism of MMCs is mainly due to crack initiation and propagation [5,10,17,18]. Joshi et al. [10] investigated the chip formation mechanism using a quick-stop device during machining of Al-based MMCs. It was concluded that the inclusion of particle reinforcements increased the propensity for crack initiation compared to the unreinforced alloy. Crack initiation was suggested to be the primary chip formation mechanism due to the observation of gross cracking in the quick-stop metallographs. The gross cracks were assumed to initiate at the free surface and propagate toward the tool tip along the PSZ. Other studies have reported similar cracks in chip metallographs and attributed the chip formation mechanism to be crack initiation and propagation [15,18]. In addition to chip formation by crack initiation and propagation, it is noted that shear localization induced by ductile shear was found to occur during machining of Mg-based MMCs [4]. Pedersen and Ramulu [4] examined machined chips and found chip formation to occur by ductile shear, which was a precursor to shear localization. Regions of highly formed material were found between adjacent segments of relatively undeformed material while facing an Mg-based MMC embedded with SiC particles. This mechanism is similar to the adiabatic shear localization mechanism during machining of monolithic metals [11]. However, the underside of machining chips, which slid along the tool rake face, revealed microvoids and large gross cracks that are typically observed during crack initiation and propagation [15]. Therefore, it is more likely that chip formation is due to void formation and subsequent coalescence to form gross cracks, which may further induce shear localization as the segments slide along one another as suggested by Vyas and Shaw [15] for monolithic materials.

Most MMC machining studies to date are related to Al-based MMCs [5,9,10]. However, little effort has been given to characterizing the chip morphology and chip formation mechanism of Mg-based MMCs. Moreover, the cutting speed range of previous Mg-based MMC studies [4] was limited to low cutting speeds (less than 2 m/s). Furthermore, the effect of particle reinforcement on the chip formation mechanism and resulting chip morphology during Mg-based MMC machining is still elusive. Such understanding is indispensable for the wide adoption of Mg-based MMCs.

### 3 Materials and Methods

#### 3.1 Workpiece Materials and Cutting Conditions

Four Mg-based MMC samples, each embedded with SiC particle reinforcements, were chosen as workpiece materials in this study. They were produced using a ball milling process [19], and the constituents for each MMC used in this study are shown in Table 1. Cutting experiments were carried out to machine the four MMCs and investigate the effect of cutting speed, cutting tool rake angle ($a$), and particle reinforcement size and volume fraction on the chip morphology and chip formation mechanism. Two machining centers were utilized: (1) a Whacheon 435HL manual machine lathe (Whacheon Inc., Long Beach, CA) for the study of chip formation process using high-speed imaging and (2) a Mikron UCP 600 Vario computer-controlled machining center (Georg Fischer AG, Schaffhausen, Switzerland) for the study of effect of cutting conditions. The Whacheon machine lathe, having an open space for imaging instrumentation, was used for the in situ high-speed chip formation imaging study at relatively low cutting speeds (0.1–1.0 m/s only for safety concerns and due to the machine capacity). The Mikron machining center, which cannot accommodate the imaging facility inside its enclosure, was utilized under a single point cutting configuration [20] to complementarily study the chip formation process over a wider range of cutting speeds (0.1–10.0 m/s).

The MMC samples were faced using uncoated NG3125R K313 carbide inserts (Kennametal, Inc., Latrobe, PA) under a dry condition as shown in Fig. 1, and a new insert was used for each experiment to limit the influence of tool wear on the chip formation process. Generally, positive rake angle tools are used for ductile material machining, while negative rake angle tools are used for brittle material machining. The ductility of metallic matrix is greatly reduced when particle reinforcements are introduced. To accommodate the possible ductile and brittle properties of MMCs [19], the cutting tool rake angle was varied from $-10$ deg to $+10$ deg. The feed rate and depth of cut were held constant at 0.1 mm/rev and 1.5 mm, respectively. Table 2 shows the cutting conditions used to machine each MMC. Each MMC was machined using the Whacheon machine lathe in the cutting speed range from 0.1 to 1.0 m/s to study the effect of cutting speed, tool...
rake angle, and particle size and volume fraction on the chip formation mechanism. In addition, MMC 3 and MMC 4 were machined using the Mikron machining center over a large range of cutting speeds (0.1–10.0 m/s) at a constant rake angle to observe the variation in chip morphology with increasing cutting speed; at the same time, the effects of particle size and volume fraction were also investigated since MMC 3 has the highest particle volume fraction and MMC 4 has nanoparticles. Due to geometric constraints, the MMC workpieces as received were cast in a machinable urethane prior to machining, which provided easy work holding during machining.

### 3.2 Image Acquisition and Optics for Chip Formation Study

To observe the chip formation progression in situ, a high-speed camera system was implemented onto the Whacheon machine lathe as shown in Fig. 1. The data were acquired using a 1024 x 1024 pixel resolution Photron SA-5 high-speed camera (Photron, Inc., San Diego, CA) aligned along the z-direction of the machine lathe. During the machining test, a frame rate of 50,000 frames per second was used to image the chip deformation at the tool cutting edge. For enhanced image resolution, a Navitar 12 x zoom lens system (Navitar Inc., Rochester, NY) together with a 1 x lens attachment and a 2 x lens extender was also implemented, resulting in an approximate magnification of 15 x and a spatial resolution of approximately 0.5 x 0.5 mm, respectively. The Navitar lens system was focused on the radial edge of the workpiece, and the tool height was aligned with its center. As shown in Fig. 1, the imaging system was mounted on an adjustable xy fixture, which isolated the camera from vibration produced during machining. The focal length of the entire lens system was approximately 50.8 mm (2 in), and fine focus was achieved by a manual adjustment on the lens. At high frame and magnification rates, the cutting area must be well illuminated in order to obtain a well-defined image. As such, two SugarCUBE light-emitting diode-based light sources (Nathaniel Electronics, Vergennes, VT) were introduced to illuminate the cutting area: one SugarCUBE was coupled with the Navitar lens system using coaxial illumination and the other provided an off-axis illumination of the chip area.

![Schematic representation of the experimental machining setup](image)

### 4 Results

#### 4.1 Chip Morphology

The chip morphologies during the machining of the microparticle-based MMCs (MMC 1–3) and the nanoparticle-based MMC (MMC 4) are shown in Figs. 2 and 3, respectively. The cutting speed is found to have the most significant effect on the chip morphology, while the cutting tool rake angle, particle size, and particle volume fraction have little influence.

As shown in Figs. 2(a)–2(j), machining of the microparticle-based MMCs at low cutting speeds (V < 1.0 m/s) results in the formation of saw-tooth chips, which have a relatively smooth surface along the chip-tool side but serrated along the chip-free surface.
side. While there is little difference microscopically, the chips are separated into small segments along the chip flow direction whose length increases up to approximately 1 mm as the cutting speed increases up to 1.0 m/s. In addition, the particle size, particle volume fraction, or tool rake angle has little effect on the chip length. It should be noted that while these chips are separated into small segments, these are not considered strictly discontinuous since each segment contains many saw-tooth segments. At low cutting speeds, the frictional force on the tool rake face results in significant chip curl, leading to the breakup of resulting chips as small

<table>
<thead>
<tr>
<th>Condition</th>
<th>Material</th>
<th>Cutting speed (m/s)</th>
<th>Rake angle (°)</th>
<th>Chip morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MMC 1</td>
<td>0.1</td>
<td>-10</td>
<td>Free surface</td>
</tr>
<tr>
<td>2</td>
<td>MMC 1</td>
<td>0.1</td>
<td>0</td>
<td>Tool surface</td>
</tr>
<tr>
<td>3</td>
<td>MMC 1</td>
<td>0.1</td>
<td>+10</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>MMC 1</td>
<td>0.5</td>
<td>-10</td>
<td>Free surface</td>
</tr>
<tr>
<td>5</td>
<td>MMC 1</td>
<td>0.5</td>
<td>0</td>
<td>Tool surface</td>
</tr>
<tr>
<td>6</td>
<td>MMC 1</td>
<td>0.5</td>
<td>+10</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>MMC 2</td>
<td>0.1</td>
<td>-10</td>
<td>Free surface</td>
</tr>
<tr>
<td>8</td>
<td>MMC 2</td>
<td>0.1</td>
<td>0</td>
<td>Tool surface</td>
</tr>
<tr>
<td>9</td>
<td>MMC 2</td>
<td>0.1</td>
<td>+10</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>MMC 2</td>
<td>0.5</td>
<td>-10</td>
<td>Free surface</td>
</tr>
<tr>
<td>11</td>
<td>MMC 2</td>
<td>0.5</td>
<td>0</td>
<td>Tool surface</td>
</tr>
<tr>
<td>12</td>
<td>MMC 2</td>
<td>0.5</td>
<td>+10</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>MMC 3</td>
<td>0.1</td>
<td>-10</td>
<td>Free surface</td>
</tr>
<tr>
<td>14</td>
<td>MMC 3</td>
<td>0.5</td>
<td>0</td>
<td>Tool surface</td>
</tr>
<tr>
<td>15-18</td>
<td>MMC 3</td>
<td>1.0-10.0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2  Representative chip morphologies of microparticle-based MMCs

<table>
<thead>
<tr>
<th>Condition</th>
<th>Material</th>
<th>Cutting speed (m/s)</th>
<th>Rake angle (°)</th>
<th>Chip morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>MMC 4</td>
<td>0.1</td>
<td>0</td>
<td>Free surface</td>
</tr>
<tr>
<td>20</td>
<td>MMC 4</td>
<td>0.1</td>
<td>0</td>
<td>Tool surface</td>
</tr>
<tr>
<td>21-24</td>
<td>MMC 4</td>
<td>1.0-10.0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3  Representative chip morphologies of nanoparticle-based MMCs
segments. Increasing the cutting speed to \( V \geq 1.0 \text{ m/s} \) results in the formation of the discontinuous, particle-type chip morphology as shown in Figs. 2(k) and 2(l). At high cutting speeds, the increased energy input in the PSZ facilitates crack propagation by increasing its speed and distance propagating within a chip. The result is that the conditions are favorable for crack propagation through the entire chip thickness. The particle-type chip morphology is a distribution of both small and large segments, ranging from 20 to 150 \( \mu m \) in size. Thus, there is no observable trend in the chip morphology as the cutting speed increases within the speed range of \( 1.0 \text{ m/s} \leq V \leq 10.0 \text{ m/s} \). In addition, Fig. 2 shows a negligible change in the chip morphology with changes in the cutting tool rake angle, particle size, and particle volume fraction when comparing Figs. 2(a), 2(e), and 2(i). With respect to the effect of particle volume fraction on the chip morphology, it was reported that the saw-tooth profile became more prominent during machining Al-based MMCs when the SiC particle reinforcement volume fraction increased from 10% to 30% [21]. Since the particle size in this study is large compared to the undeformed chip thickness, relatively small changes in the particle volume fraction (5–15%) may not significantly alter the chip morphology.

The chip morphologies observed in this study at low cutting speeds (\( V < 0.5 \text{ m/s} \)) are similar to those observed during machining 2ZK60A-T5 Mg embedded with SiC microparticles [4]. However, as shown in Fig. 2, a transition in the chip morphology from saw-tooth to particle-type, discontinuous chips is observed herein when the cutting speed increases beyond \( V = 1.0 \text{ m/s} \). This observation contradicts the transition observed during machining of Al-based MMCs [5,8], which reported the discontinuous and continuous chip morphologies as the cutting speed varied. The transition between two chip morphologies is primarily influenced by the matrix material; the Al matrix used in previous studies [5,10] is more ductile than the Mg matrix used in this study. At high cutting speeds, the local ductility of the matrix increases, which facilitates particle transport. Thus, particles align themselves along the shear direction, and the formation of saw-tooth instead of discontinuous chips ensues [8].

As with the microparticle-based MMCs, the chip morphology of the nanoparticle-based MMC (MMC 4) is saw-toothed at cutting speeds lower than \( 1.0 \text{ m/s} \) and discontinuous, particle-type at cutting speeds from 1.0 to 10.0 m/s, which indicates a change in the deformation characteristics as the cutting speed increases. Figures 3(a) and 3(b) show that the resulting chips are heavilyerrated at the free surface, and large gross cracks are observed to propagate through both the thickness and width directions. As the cutting speed increases, the overall chip length is reduced and more individual segments are produced, which indicates that an increase in cutting speed facilitates crack propagation and bifurcation. As with the microparticle-based MMCs, the particle-type chips are statistically random and no conclusion can be drawn about the size of the chips as the cutting speed increases. By comparing the chip morphologies of MMC 1, the microparticle-based counterpart and MMC 4, it is found that there is no noticeable difference in the chip morphology (Figs. 2(a) and 2(b) versus Figs. 3(a) and 3(b)) under the cutting conditions as investigated when reducing the particle size from micrometers to nanometers.

In addition to the chip morphology, the chip saw-tooth spacing of each MMC is also investigated. The projected saw-tooth spacing was found by averaging ten spacing measurements along the chip flow direction on the chip-free surface (see the inset of Fig. 1) as implemented in previous studies [21,22]. The shear-band spacing can be calculated based on the saw-tooth spacing and crack initiation angle [21]. For simplicity, the crack initiation angle is assumed constant, and the projected saw-tooth spacing is assumed equal to the actual saw-tooth spacing. The results from this investigation are summarized in Fig. 4. In general, the cutting speed has negligible effect on the saw-tooth spacing of the microparticle-based MMCs as well as the nanoparticle-based MMC (MMC 4). Increasing the cutting tool rake angle (more positive) results in a decrease in the saw-tooth spacing when machining MMC 1 and MMC 2 regardless of the cutting speed. Comparing the saw-tooth spacing of MMC 1 (microparticle particles) and MMC 4 (nanoparticle-based particles) machined using a neutral rake angle tool at the cutting speed of 0.1 m/s reveals a smaller spacing of the MMC 4 chips, which is about 4 \( \mu m \) smaller (around 15%).

### 4.2 Chip Formation Mechanism

As mentioned previously, both the saw-tooth and particle-type chip morphologies are observed during machining of Mg-based MMCs, and each chip morphology reflects a specific chip formation mechanism. In general, saw-tooth chips occur due to crack initiation at the free surface followed by propagation toward the tool tip. Similarly, particle-type chips form due to crack initiation; however the cracks are observed to occur at the tool tip followed by propagation toward the free surface.

#### 4.2.1 Formation of Saw-Tooth Chips

Figure 5 shows representative schematics illustrating the chip formation progression of a saw-tooth chip during machining microparticle-based MMC (MMC 1: 18 \( \mu m \), 5%) using a 0° rake angle tool at the cutting speed of 0.1 m/s. The chip formation progression shown in Fig. 5 is representative at low cutting speeds (conditions 1–14 in Fig. 2 and conditions 19 and 20 in Fig. 3). In general, the chip formation mechanism under these conditions is due to crack initiation at the free surface and subsequent crack propagation toward the tool tip. This mechanism agrees well with the reported chip formation mechanism during machining of Al-based MMCs [10,18]. While it is difficult to visualize the propagating crack in the high-speed camera images due to its size, this mechanism will be further confirmed by investigating saw-tooth fracture surfaces as discussed in Sec. 5. From the high-speed image sequence, the chip formation process is classified into three stages: (1) wedge-shaped compression, (2) crack initiation and propagation, and (3) segment sliding. As shown in Fig. 5(a), stage 1 occurs when a wedge-shaped volume of material is compressed against the tool rake face before entering the PSZ. The compressive stress along the PSZ is a minimum at the free surface [23], which leads to crack initiation (stage 2) as shown in Fig. 5(b). Joshi et al. [10] suggested that the bonding between the particle reinforcements and the metallic matrix is of the mechanical type. Thus, the matrix material is in a state of compression, while the particle reinforcements are in a state of tension [10]. The stress-state mismatch results in the formation of a crack at point B at the free surface, and a crack propagates toward the tool tip (point O). During monolithic metal machining where crack initiation is believed to be the primary chip formation mechanism, the crack propagates toward the tool tip until it is hindered by the high normal stress near the tool tip. During MMC machining, however, the distribution of particle reinforcements within a matrix influences crack propagation along the PSZ. As shown in Fig. 2, the tool side of the chips shows that some surface cracks propagate all the way to the tool tip and bifurcate across the chip width. Dahade and Joshi [5] suggested that particles align along the shear direction and favor crack propagation. Thus, it is apparent that in some cases where a large number of particles exist across the width of cut of the PSZ, a crack propagates from particle to particle until it reaches the tool tip (Fig. 5(c)). Figure 5(d) shows that a segment slides along the cracked surface as well as up the tool rake face (stage 3), appearing saw-toothed from the chip-free surface side. This stage occurs regardless of how far the crack propagates along the shear plane since this plane is already weakened.

The chip formation progression shown in Fig. 5 can be compared to the saw-tooth chip formation process during machining of monolithic metallic materials such as Ti–6Al–4V [11] and 4340 steel [15,24]. Regardless of the underlying mechanism, saw-tooth chip formation begins with free surface upsetting followed by instability. Free surface upsetting occurs when the chip-free surface rises above the horizontal due to the development of heterogeneous shear strain. However, during machining of Mg-based
MMCs, the particle reinforcement reduces the workpiece ductility such that free surface upsetting is minimal. While Fig. 5(a) shows slight upsetting (surface A), this is attributed to compression against the tool rake face, and free surface upsetting is not considered to be influential during saw-tooth chip formation of Mg-based MMCs.

4.2.2 Formation of Discontinuous Chips. Figure 6 shows representative schematics describing the chip formation progression of discontinuous, particle-type chips of a microparticle-based MMC (MMC 1: 18 μm, 5%) using a 0 deg rake angle tool at the cutting speed of 1.0 m/s. The chip formation progression shown in Fig. 6 is representative at high cutting speeds (conditions 15–18 in Fig. 2 and conditions 21–24 in Fig. 3). In general, the chip formation mechanism under these conditions is due to crack initiation at the tool tip followed by propagation toward the free surface. As shown in Fig. 6(a), the material at the free surface (surface A) is initially compressed by the tool rake face. The compression stage is very short due to the formation of a crack at the tool tip, which is aided by the friction in the secondary shear zone due to sliding along the tool rake face as shown in Fig. 6(b). Thus, the material at the tool tip is under a state of compression, while the material at the workpiece-free surface is under a state of tension as it is being pulled away from the workpiece due to crack propagation. As seen from Fig. 6(c), the crack is observed to propagate nearly to the free surface as the segment moves up along the tool rake face. At this time, no relative sliding between the segment and the workpiece occurs. Eventually, the segment flows up along the rake face of the tool as a discontinuous particle as shown in Fig. 6(d), and the cycle begins again.

While it is difficult to image the chip formation process at cutting speeds higher than 1.0 m/s due to the rotational capacity of the Whacheon lathe herein, Fig. 6 gives some insight into the chip formation mechanism at high cutting speeds during machining of both micro- and nanoparticle-based MMCs. As shown in Fig. 2 (condition 18) and Fig. 3 (condition 24), when a cutting speed of 10.0 m/s is used, particle-type, discontinuous particles are formed for both micro- and nanoparticle-based MMCs, respectively. It is hypothesized that the chip formation progression of discontinuous chips produced at cutting speeds of 10.0 m/s is the same as that shown in Fig. 6 (1.0 m/s); however, the resulting particles may have a much larger cross-sectional area.

Compared with the progression of the saw-tooth chip morphology, several differences are observed during the formation of discontinuous, particle-type chips. First, crack initiation occurs at the tool tip rather than the free surface due to the increase in the cutting speed. The formation of discontinuous particles indicates that increasing the cutting speed facilitates gross crack propagation due to the increase in shear strain rate at the tool tip. Second, no relative sliding occurs between each individual segment and the adjacent workpiece, indicating that the segment is under a state of tension once the crack is initiated and propagates toward the free surface. During monolithic material machining, tensile cracks can form at the free surface during discontinuous chip formation; however, the crack changes to be a shear crack as the segment slides along the cracked surface [16]. During MMC machining, the segment is pulled away from the cracked surface, and no relative sliding occurs.

5 Discussion on Saw-Tooth Chip Fracture Surface

Recently, Zhang et al. [18] reported three modes of crack initiation during machining of MMCs: the formation of matrix defects/ internal voids, particle debonding/decohesion, and particle fracture. Figure 7(a) shows the fracture surface of saw-tooth segments of a microparticle-based MMC (MMC 1) machined at a cutting speed of 0.1 m/s. For comparison, Fig. 7(b) shows the machined workpiece surface. On examination, there are two distinct textures of the free surface side of saw-tooth segments. The upper region (labeled 1) shows a dimpled or textured surface, while the lower region (labeled 2) shows a relatively smooth fracture surface. This fracture surface is apparent in all saw-tooth chip morphologies for all materials under all cutting conditions in this study. The dimpled texture (region 1) is assumed to be due to the formation of internal voids, which coalesce to form gross cracks. As shown in Fig. 2, large gross cracks are observed on the free surface side.
of the saw-tooth chips formed at low cutting speeds (such as $V < 0.5 \text{ m/s}$), and most of these cracks only extend halfway along the chip width. It is possible that these cracks are a result of bifurcated crack propagation and form due to the coalescence of internal voids.

During machining at low cutting speeds, the thermal softening effect is negligible [5], and internal voids formed within the matrix due to the immobilization of particle reinforcements result in microcrack formation and propagation across the chip width [18]. Thus, the introduction of particle reinforcements reduces the workpiece ductility such that particles are trapped within the matrix, giving rise to brittle fracture at the particle-matrix interface [5]. In addition to the formation of microcracks within the metallic matrix, particle debonding/decohesion occurs when MMC undergoes a large amount of shear deformation. It is known that for MMCs, bonding between the reinforcement and the metallic matrix is of mechanical type [10]. Therefore, the resultant interface has lower shear strength, and plastic flow results in void formation around particles, resulting in a dimpled or textured surface (region 1).

On the other hand, as the cutting speed increases, the cutting-induced temperature increases the workpiece ductility and reduces
the propensity for crack initiation at the particle/matrix interface via particle transport within the matrix. While this phenomenon may result in the formation of continuous chips, this is not observed during machining Mg-based MMCs at higher cutting speeds in this study. Despite previous observations of the formation of continuous [5] or saw-tooth chips [10] at high cutting speeds ($V > 0.5\text{ m/s}$), it is assumed in this study that microcracks initiate at voids formed by particle debonding at the particle/matrix interface, which aids in gross crack propagation. Such particle debonding may be promoted as the cutting speed increases. This particle debonding and void formation-induced microcrack initiation mechanism instead of thermal softening is assumed to be the primary cause of crack initiation and propagation during machining at high cutting speeds.

6 Conclusions and Future Work
Mg-based MMCs, embedded with both nano- and microparticles, were machined using a cutting speed ranging from 0.1 to 10.0 m/s. In situ high-speed imaging along with postmortem metallographic analysis was used to evaluate both the chip morphology and chip formation mechanism(s). During machining, two chip morphologies are observed: saw-tooth chips at low cutting speeds (such as $V < 0.5\text{ m/s}$) and discontinuous, particle-type chips at high cutting speeds ($V > 0.5\text{ m/s}$). The formation of discontinuous, particle-type chips is attributed to the propagation of microcracks initiated at voids formed by particle debonding at the particle/matrix interface.
chips at high cutting speeds (such as \( V > 1.0 \text{m/s} \)). The chip morphology is influenced primarily by the cutting speed, while changes in the tool rake angle, particle size, and volume fraction show little influence.

The chip morphology is the result of specific chip formation mechanism(s) occurring during machining, so high-speed imaging was used to elucidate the difference during the chip formation progression when the cutting speed increased. In general, crack initiation and propagation is found to be the primary chip formation mechanism throughout the cutting speed range, regardless of the tool rake angle, particle size, or volume fraction. At low cutting speeds (such as 0.1 m/s), crack initiation occurs at the free surface and propagates toward the tool tip, whereas at higher cutting speeds (such as 1.0 m/s), the crack initiates at the tool tip. The change in the location of crack initiation from the free surface to the tool tip is attributed to the increase in strain rate at the tool tip due to higher cutting speeds.

For this research, each of the Mg-based MMCs was investigated using a relatively low particle volume fraction compared to those reported for other metallic MMC machining [10]. While the resulting knowledge from this study offers some insight into both the chip morphology and chip formation mechanism for some Mg-based MMCs, the influence of higher particle volume fractions should be investigated in a future study. Moreover, the cutting speed effect should be investigated at a finer speed resolution in order to identify the exact transition speed when the chip morphology and formation mechanism changes. Due to the current experimental setup, only a spatial resolution of 0.5 \( \mu \text{m} \) is achievable, making it difficult to resolve key features in the chip cross section using high-speed images. Future studies should improve the spatial resolution to have better image quality and identify key features within the chip cross section. Furthermore, the effect of workpiece microstructure on machining performance [25,26] should be investigated numerically or analytically for better implementation of MMC machining.

Acknowledgment

The authors would like to acknowledge Dr. Jinshan Yang of Florida State University for the preparation of the MMC samples and Dr. Nancy J. Ruzycki of the University of Florida for experimental support.

References


