Experimental investigation on micro-drilling properties of Mg-based MMCs reinforced with HAP nanoparticles

F Z Sun1,4, G Y Fu2 and J R Shen3

1School of Mechanical and Power Engineering, Nanjing TECH University, Nanjing, Jiangsu 211816, China
2Mechanical Engineering School of Engineering, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK
3School of Material and Science, Shenyang Ligong University, Shenyang, Liaoning, 110159, China

E-mail: sunfuz@njtech.edu.cn

Abstract. Mg-based metal matrix composites (MMCs) reinforced with Hydroxyapatite (Ca10(PO4)6(OH)2, HAP) nanoparticles have been studied as bone substitute materials because of their excellent biocompatibility and biological activity. In this paper, Mg/HAP MMCs with different HAP contents (0.5, 1.0 wt%) were selected and the micro-drilling properties were revealed. Firstly, the chip of MMCs was analyzed. Secondly, the surface roughness of Mg/HAP MMCs under different cutting parameters was studied. The results showed that the surface roughness decreases with the increasing of feedrate and decreases with the increasing of spindle speed, which are contrary to pure Mg. Furthermore, the shapes of burr are all classified as uniform burr, and the burr height increased with the increase of spindle speed and feed. Finally, the size effect of micro-drilling was studied. The minimum cutting thickness per tooth of Mg/HAP MMCs was determined to be 1.0 μm.

1. Introduction

Magnesium (Mg), the sixth richest element in nature, has been studied for nearly 200 years [1]. At the same time, Mg is also the fourth abundant cation in the human body (~1 mol/adult), which is mainly found in bone tissue to stabilize DNA and RNA structures [2]. Mg has been extensively studied as a human implant material due to its excellent biocompatibility and indications of local or systemic toxicity free [3,4]. However, the disadvantages of low strength, low Young's modulus, poor ductility and corrosion resistance at room temperature of pure Mg, which limits its wide application [5]. Matrix metal composites (MMCs) can solve the shortcoming of low ductility and low mechanical resistance of pure Mg by adding other nanoparticles [6]. Hydroxyapatite (Ca10(PO4)6(OH)2, HAP) has chemical and structural similarities to bone and dental minerals and is used as a biomedical material because of its excellent biocompatibility and biological activity [7]. However, HAP is difficult to form in the specific form required for bone repair and implantation due to its inherent hardness and brittleness, which limits its use as a biomedical material. Therefore, Mg-based MMCs reinforced with HAP nanoparticles, combining the advantages of pure Mg and HAP, are considered to be a promising biodegradable implant. Campo et al [8] produced a Mg/HAP MMCs containing 5, 10 and 15% by weight of hydroxyapatite using a dynamic metallurgical method. It was found that the addition of HAP can increase the microhardness of the composite and improve the corrosion resistance of the
Researchers have done a lot of research on MMCs, mainly focusing on tool wear and cutting parameters. Li and Seah [9] studied the tool wear mechanism of Al/SiC MMCs using tungsten carbide tools, and the results showed that tool wear accelerated due to particle interference when the particle weight fraction reached the critical value. Ciftci et al. [10] studied the effects of cutting speed, feedrate and depth of cutting by turning machining methods and found that the tool side wear which cutting speed is 150 m/min was less than that in 100 and 200 m/min. Research on micromachining of Mg-based composites has rarely been published in all MMCs material cutting studies. Teng et al. [11] studied the influence of cutting parameters on the cutting force and surface morphology in micromachining of magnesium-based MMCs reinforced with two types of nanoparticles, namely, titanium (Ti) and titanium diboride (TiB2), as well as studied the size effect and the minimum chip thickness according to the specific cutting energy and surface morphology at different feed per tooth.

In order to reveal the effect of HAP nanoparticles on the machinability of Mg-based MMCs, pure Mg and two MMCs with different contents (0.5, 1.0 wt.%) of HAP nanoparticles were selected for micro-drilling experiments. Firstly, the formation characteristics of burrs and chips in MMCs with different contents were analyzed. Then, the influence of different cutting parameters on the surface morphology was obtained. Finally, the size effect of Mg/HAP was analyzed. The experiment results presented an attempt to fill the gap and provide a comprehensive understanding on the micro-drilling machinability of Mg-based MMCs reinforced with different HAP nanoparticles.

2. Experimental setup

2.1. Workpiece materials
The micromachining experiment was performed on an ultra-precision desktop micro-machine tool (MES5R) consisting of three axes (X, Y, Z) driven by a DC servo motor, shown in figure 1 (to the left). The processing equipment has a 100W (240 V) continuous power driven high-speed spindle with a speed range of 20,000-800,000 rpm. It also has the ability to use high feedrates and small diameter tools with a minimum feed of 0.1 μm. Uncoated tungsten carbide micro twist drill with tool diameter of 1.0 mm and shank diameter of 3 mm were utilized. The geometry of all the new tools used in the experiment was examined by an electron scanning microscope (SEM, Hitachi TM3030) before drilling. The cutting edge radius was estimated to be 1.3 μm by SEM. One new drill was used for each workpiece to ensure the accuracy of the measurement. The characteristics and parameters of micro drill is stated in figure 1 (to the right). Before the drilling experiment, the billet was processed into a rectangular parallelepiped of 60 mm x 7 mm x 4 mm.

| Properties         | Value   |
|--------------------|---------|
| Drill Type         | Twist Drill |
| Tool diameter      | 1 mm    |
| Shank diameter     | 3 mm    |
| Drill Bit Length   | 38 mm   |
| Flute Length       | 9.5 mm  |
| Point Angle        | 140 degree |
| Rake Angle         | 34 degree |
| Number of Flutes   | 2       |

Figure 1. Machine setup with dynamometer (to the left) and micro twist drill properties (to the right).
2.2. Experimental procedure
In order to study the influence of micro-drilling parameters on the hole quality in the micro-drilling experiment, the first experiment used a full-factor design, in which two controlled quantitative factors, that are spindle speed and feedrate. Three spindle speeds were selected to be 20,000, 40,000 and 60,000 rpm, respectively. Three feedrates were selected to be 0.005, 0.01 and 0.015 mm/rev, respectively, and nine combinations were finally formed for micro drilling, as shown in table 1. In order to study the size effect during the drilling process, a second experiment was designed in which 16 different feedrates were selected with constant spindle speed (20,000 rpm), as shown in table 2.

| Table 1. Cutting conditions for the first experiment. |
|-----------------|-----------------|-----------------|
| No.  | Spindle speed (rpm) | Feedrate (mm/rev) |
| 1    | 20000            | 0.005           |
| 2    | 20000            | 0.01            |
| 3    | 20000            | 0.015           |
| 4    | 40000            | 0.005           |
| 5    | 40000            | 0.01            |
| 6    | 40000            | 0.015           |
| 7    | 60000            | 0.005           |
| 8    | 60000            | 0.01            |
| 9    | 60000            | 0.015           |

| Table 2. Cutting conditions for the second experiment. |
|-----------------|-----------------|-----------------|
| No.  | Spindle speed (rpm) | Feedrate (mm/rev) | Feedrate (mm/min) |
| 1    | 20000            | 0.0001           | 4               |
| 2    | 20000            | 0.0002           | 8               |
| 3    | 20000            | 0.0003           | 12              |
| 4    | 20000            | 0.0004           | 16              |
| 5    | 20000            | 0.0006           | 24              |
| 6    | 20000            | 0.0008           | 32              |
| 7    | 20000            | 0.001            | 40              |
| 8    | 20000            | 0.0016           | 64              |
| 9    | 20000            | 0.0022           | 88              |
| 10   | 20000            | 0.0028           | 112             |
| 11   | 20000            | 0.0034           | 136             |
| 12   | 20000            | 0.004            | 160             |
| 13   | 20000            | 0.006            | 240             |
| 14   | 20000            | 0.008            | 320             |
| 15   | 20000            | 0.01             | 400             |
| 16   | 20000            | 0.012            | 480             |

3. Results and discussions

3.1. Chips formation
The chip was first studied because the formation of the chips is closely related to the surface quality, which can reveal the effect of HAP nanoparticles on the quality of the drilled surface. The chips were collected after the end of the processing, and SEM observed the shape and size of the chips. It is necessary to analyze the specific surface morphology of the chip while exploring the shape of the chip due to the chip surface and the machined surface of the workpiece will exhibit similar surface features.

Figure 2 shows the microscopic morphology of the chip when the spindle speed is 40,000 rpm and the feedrate is 0.01 mm/rev. The chip morphology of pure Mg, seen in figure 2(a), shows that the chip shape is regular, the edge is smooth and grooves exist on the chip surface, which is mainly due to the high ductility and low hardness of pure Mg that increases the blurred material between tool and chip
and results in grooves on the inner surface of the chip. Figure 2(b) illustrates the chip morphology of Mg/HAP at 0.5 wt%, in which the chip shape is irregular, the edge of the chip appears serrated, and cracks and fragments exist on the chip. This is because the nanoparticle size of HAP is 1-5 micron and agglomeration inevitably occurs in Mg matrix material, which leads to the discontinuous chip formation [8]. Chip deformation and stress concentration occur along the shear zone due to the existence of hard nanoparticles HAP, so some nanoparticles will debond from the matrix during drilling, which will lead to the formation of cracks and some small voids. The cracks on the chips of Mg/HAP MMCs 1.0wt% become larger, which is the main reason for the chip to become powder and also explains the phenomenon of chip reduction with the increase of HAP.

Figure 2. SEM micrographs of chips morphology when spindle speed is 40000 rpm, feedrate is 0.01 mm/rev.

3.2. Surface morphology
The SEM was used to obtain the microscopic morphology of the drilled hole in order to further explain the variation of roughness with cutting parameters. Figure 3 show the surface morphology of pure Mg and Mg/HAP MMCs 1.0 wt% when spindle speed is and 60,000 rpm, respectively. Significant material flow can be seen on the pure Mg surface when the spindle speed is 20000 rpm and the feedrates are 0.005 mm/rev and 0.01 mm/rev, which proves that the heat generated during the cutting process causes the pure magnesium to soften and flow during the rotation of the tool. Irregular grooves are generated on the surface when the feedrate increases to 0.015 mm/rev, which is a tool mark generated in the cutting process and causes an increase in surface roughness. It is apparent that the flow of the material increases as the spindle speed increases to 60,000 rpm due to the higher spindle speed produces more heat and the softening of the material increases with increasing speed.

Grooves appear on the surface of the chip when the feedrate is 0.01 mm/rev and 0.015 mm/rev, and the deformation is brittle, resulting in better surface quality than plastic deformation, which also explains the phenomenon of roughness variation. Grooves, fragments and micro-pits appear, and the surface is severely damaged when feedrate is 0.005 mm/rev and spindle speed is 60,000 rpm. Grooves on the chip surface become more obvious, and a large number of cracks are produced due to the spalling of the material when the feedrate increases, which results in deterioration of the surface finish. Therefore, in order to obtain high surface quality, high spindle speed and small feed should be selected in pure Mg drilling, while low spindle speed and large feed should be selected in Mg/HAP MMCs drilling.
3.3. Burr formation

The formation of burrs is inevitable in the process of drilling, so the study of burr formation and burr reduction is the focus of micro-machining. Three types were classified according to the shape and size of burrs in the previous drilling research [12]. Burrs with relatively small and uniform height and thickness around the hole are classified as Uniform burrs, burrs with larger size and irregular height distribution are classified as crown burrs, and burrs formed during the transition between uniform burrs and crown burrs are classified as transient burrs, which is used to analyze the shape and height of burrs in this study.

Figure 3. Surface morphology when spindle speed is 60000 rpm.

Figure 4. Burr morphology of pure Mg and Mg/HAP MMCs.
Figure 4 shows the burr types of pure Mg and Mg/HAP MMCs when the spindle speed is 60 000 rpm and the feedrate is 0.01 mm/rev. The size of all burrs is small and the burr height is uniformly distributed, so all can be classified as uniform burr. The lower part of figure 4 is a local enlargement of burrs. It can be seen that the burr size of pure Mg is larger and the surface is smooth, while the burr height of Mg/HAP MMCs decreases with the increase of HAP nanoparticle content, and obvious cracks and fracture sections appear on the burrs. Pure Mg has good ductility and large plastic deformation, so the burr surface is smooth. However, the brittleness of Mg/HAP MMCs increases with the addition of HAP nanoparticles, and the brittleness deformation in drilling is much greater than plastic deformation, so chips are prone to fracture and fracture sections are produced.

3.4. Size effect
Macro machining and micromachining are similar in kinematics, but there are many basic differences as well. When the uncut chips thickness becomes comparable to the radius of cutting edge, the size effects becomes the dominant factor affecting the cutting process. When the thickness of the uncut chip is below the critical value, the material is mainly elastic and will be ploughed out.

Figure 5 indicates the variation of the cutting force and the thickness of the uncut chip. The cutting force of pure Mg and Mg/HAP MMCs has undergone three stages. When the thickness of uncut chips ranges from 0.1 to 0.3 μm, the cutting force increases greatly with the increase of the thickness of uncut chips. In this region, the material has elastic deformation and no chips are produced because the thickness of uncut chips is much smaller than the radius of the tool edge. Therefore, the material will return to its original state after cutting, resulting in the increase of the cutting force between the workpiece and the tool. The cutting force of this three materials decreases dramatically when the thickness of the uncut chip increased to 0.8 μm. In this region, the thickness of uncut chips is close to the critical cutting thickness, and the plastic deformation and elastic deformation occur during the cutting process. The proportion of plastic deformation increases with the increase of the uncut chip thickness, causing the interaction force between workpiece and tool decreases. When the thickness of uncut chips is greater than 0.8 μm, the cutting force increases with the increase of the thickness of uncut chips. Figure 6 shows the variation of the uncut chip thickness and the surface roughness. The surface roughness of pure Mg and Mg/HAP MMCs, shown in figure 6, goes through three stages with the increase of the thickness of uncut chips. The surface roughness of pure Mg increases with the increase of the thickness of uncut chips which ranges from 0.1 to 0.8 μm. The surface roughness decreases when the thickness of uncut chips increases from 0.8 to 6.0 μm, and the reduction rate of surface roughness from 0.8 to 1.7 μm is greater than that from 1.7 to 6.0 μm. Higher cutting force and
worse machined surface quality are obtained at the small feed per tooth ranging from 0.05 to 1.7 μm/tooth in pure Mg and from 0.05 to 1.0 μm/tooth in Mg/HAP MMCs indicating a strong size effect. Considering the influence of cutting force and surface roughness, the minimum cutting thickness of pure Mg and Mg/HAP MMCs should be 1.7 μm and 1.0 μm respectively.

4. Conclusion
The micro-machinability of pure Mg and Mg/HAP MMCs was comprehensively studied by micro-drilling with uncoated cutting tools. The conclusions of the study are as follows:

- The chip shape of pure Mg and Mg/HAP MMCs increases with the increase of feedrate and spindle speed. With the increase of HAP content, the larger the crack produced on chips, and the addition of HAP is beneficial to cutting process.
- The surface roughness of pure Mg increases with the increase of feedrate, but decreases with the increase of feedrate in Mg/HAP MMCs. The surface roughness of pure Mg decreases with the increase of spindle speed, but the change trend of surface roughness of Mg/HAP MMCs is opposite.
- The burrs of pure Mg and Mg/HAP MMCs are all classified as uniform burrs. The burr height increases with the increase of spindle speed and feedrate, in addition, the burr height decreases with the increase of HAP nanoparticles.
- In the study of size effect, the cutting force and surface roughness of pure Mg and Mg/HAP MMCs have undergone three stages with the increase of the thickness of uncut chips. The minimum cutting thickness of pure Mg and Mg/HAP MMCs should be 1.7 μm and 1.0 μm respectively. It is not recommended to micro-drill Mg/HAP MMCs under the minimum cutting thickness per tooth.

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