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# Wear behavior and mechanism of $B_4C$ reinforced Mg-matrix composites fabricated by metal-assisted pressureless infiltration technique

Yan-tao YAO[1], Lan JIANG[2], Gao-feng FU[2], Li-qing CHEN[1]

1. State Key Laboratory of Rolling and Automation, Northeastern University, Shenyang 110819, China;
2. School of Materials and Metallurgy, Northeastern University, Shenyang 110819, China

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**Abstract:** The $B_4C$/Mg composites fabricated by metal-assisted pressureless infiltration technique were used as experimental material, and the wear behavior and mechanism of this material were studied. A pin-on-disc apparatus was used to evaluate the wear behavior where loads of 20, 40, 60 and 80 N, and a sliding velocity of 250 r/min were exerted. The results show that $B_4C$/Mg composites possess superior wear resistance than pure Mg under various applied loads, and the content of Ti, as infiltration inducer, has an influence on the wear resistance of $B_4C$/Mg composites. The dominant wear mechanism for pure Mg is abrasion, while that for $B_4C$/Mg composites under low loads is adhesion and delamination. Under high loads, the wear mechanism of $B_4C$/Mg composites can be attributed to thermal softening and melting or plastic deformation.

**Key words:** Mg-matrix composites; $B_4C$; metal-assisted infiltration; wear behavior; wear mechanism

## 1 Introduction

For several decades of research and development, Al-matrix composites with high wear resistance have been successfully used in automobiles as tribological parts, e.g., brake rotors, piston rings and cylinders [1]. As compared with Al-matrix composites, however, it has long been recognized that ceramic particulate-reinforced Mg-matrix composites have merits in their lighter weight, higher specific strength and excellent wear resistance [2−4], and they can lead to a further weight reduction and find applications in aerospace and automotive industries. Similar to Al-matrix composites, Mg-matrix composites reinforced with ceramic particulates are also the most potential candidates for the structural and functional applications in aerospace, automotive and electronic devices [5].

As far as the density is concerned, $B_4C$ is 2.52 g/cm$^3$, while Mg is 1.74 g/cm$^3$. In this respect, the as-fabricated $B_4C$/Mg composites are extra-light and their density is only ~2.0 g/cm$^3$ even when 50% volume fraction of $B_4C$ particulate is introduced [6]. It is interesting that $B_4C$/Mg composites with higher volume fraction of ceramics exhibit excellent wear resistance, and they show a great potential of application in aeronautical and aerospace industries.

Differing from Al, pure Mg or Mg alloy is chemically active and flammable [7], so careful operation is needed in handling it with processing technology. In processing Mg-matrix composites with usual fabricating techniques, such as powder metallurgy [8], stir casting [9] or squeeze casting route [10], there are two serious deficiencies to be overcome. Firstly, inert gas or $CO_2/SF_6$ is usually used to protect it from flaming or explosion [11]. Secondly, Mg will drastically evaporate in vacuum with powder metallurgy route. Therefore, the processing of Mg-matrix composites with extra light-weight and highly anti-abrasive properties has long been a critical issue and the difficulty involved in processing this material largely originates from the chemically active Mg. As a result, some innovative processing techniques still need to be developed to avoid these problems. To infiltrate the ceramic preform with molten Mg without any external pressure is an easy and cost effective way to fabricate Mg-matrix composites. And this technique has received much attention for the merits in cost effectiveness, near-net shape processing capability and availability of composites with high ceramic volume fraction [3].

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**Corresponding author:** Lan JIANG; Tel: +86-24-83681325; E-mail: jiangl@smm.neu.edu.cn
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It is known that the wear resistance of Mg or Mg alloy is very poor due to their softness, and ceramic reinforcements will have a significant improvement on this performance. In the past decades, extensive researches have been conducted on the wear behavior of Mg or Mg alloy based composites, such as AZ91 [12], AE42 [13], AZ31 [14], AM60 [15], reinforced with particulates, fibers or carbon nano-tube. And many researches about the wear behavior of composites focus on the dry sliding wear resistance [16], but there are also some researches about the wear properties under lubricated conditions [17]. There exist many kinds of wear mechanisms for the wear failure of composites, such as abrasion, adhesion, oxidation, thermal softening and delamination [18,19]. However, research about $B_4C$/Mg composites is still limited. In this work, the wear behavior of $B_4C$/Mg composites fabricated by metal-assisted pressureless infiltration technique was investigated. Moreover, the wear behavior and mechanism were also comparatively studied for the as-fabricated $B_4C$/Mg composites and the unreinforced Mg.

## 2 Experimental

The experimental raw materials are $B_4C$ powder particles (about 28 μm in size, purity>94.66%), Ti powder particles (about 25 μm in size, purity>99.5%) and pure Mg cast ingot (purity>99.95%). The $B_4C$/Mg composites were fabricated by metal-assisted pressureless infiltration technique which consisted of two main steps, i.e., the preparation of $B_4C$ preform with the addition of Ti powder as infiltration inducer and the spontaneous infiltration of Mg melt into $B_4C$ ceramic preform. The processing details can be found in Ref. [6]. It is worth mentioning that different volume fractions of Ti particulates, 4%, 6% and 8%, were added into $B_4C$ powder to study the influence of Ti content on the wear behavior of the as-fabricated composites. The relative density of compacted $B_4C$ preform is thus all about 50%. The $B_4C$/Mg composites were prepared in an electric furnace with argon protective atmosphere by heating at 973 K for 120 min.

The dry sliding wear test was carried out by using a pin-on-disc friction and wear tester, as shown in Fig. 1. The pin specimen was machined from the as-fabricated $B_4C$/Mg composites and has a size of $d$5.95 mm × 12 mm. The steel counter disc is 45 steel with a hardness of HRC 56. The contact surfaces of the pin specimens and counter discs were ground to 800-grit abrasive paper prior to the test. The sliding speed and time were set as 250 r/min and 5 min, respectively. Various loads (20, 40, 60 and 80 N) were applied under dry sliding condition. In order to determine the mass loss before and after the test, the pin specimens and counter discs were washed in acetone by an ultrasonic cleaning machine, and weighted using an electronic balance with a precision of 0.01 mg. The morphologies of the worn pin surfaces of the as-fabricated $B_4C$/Mg composites and pure Mg were characterized by a scanning electron microscope (SEM, FEI Quanta600). The density of the as-fabricated Mg-matrix composites was measured according to Archimedes principle and the hardness was measured using a full-automatic Rockwell type hardness tester. On the basis of the wear resistance test and morphology observations, the wear mechanism was further analyzed.

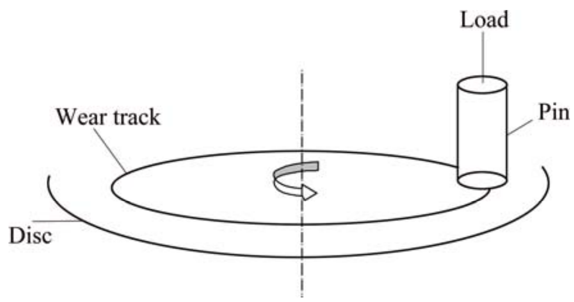


**Fig. 1** Schematic diagram of pin-on-disc friction and wear test machine

## 3 Results and discussion

### 3.1 Wear behavior of $B_4C$/Mg composites

In order to study the wear resistance of the as-fabricated $B_4C$/Mg composites, the mass loss of pin specimens of the composites and matrix Mg were comparatively taken into account after the wear test. Figure 2 presents the abrasion loss as a function of Ti content and externally applied loads. From Fig. 2(a), it can be seen that the wear resistance property of $B_4C$/Mg composites is slightly superior to that of pure Mg. Besides, with decreasing the Ti content added into the $B_4C$ preform, the wear resistance of $B_4C$/Mg composites is slightly improved.

It is obvious that the increased wear property of $B_4C$/Mg composites is mainly due to the superior wear resistance property of the ceramic particulates. The existence of ceramic particulates within the matrix Mg also restrains or reduces the plastic deformation of the Mg matrix to some extent, thus it has a contribution to the improvement of mechanical property of the as-fabricated $B_4C$/Mg composites. It is well recognized that the mild wear regions are suitable for the tribological components to work in and the severe wear regions should better be avoided, so it is of great importance to know the transition load for the as-prepared Mg-matrix composites [1].

The mass loss under various loads is presented in Fig. 2(b), which shows that the wear resistance of both $B_4C$/Mg composites and matrix Mg is better under low loads than under high ones. Besides, the transition load for both pure Mg and the as-fabricated Mg-matrix composites is 60 N, which means the transition from mild wear to severe wear occurs under a load of 60 N.

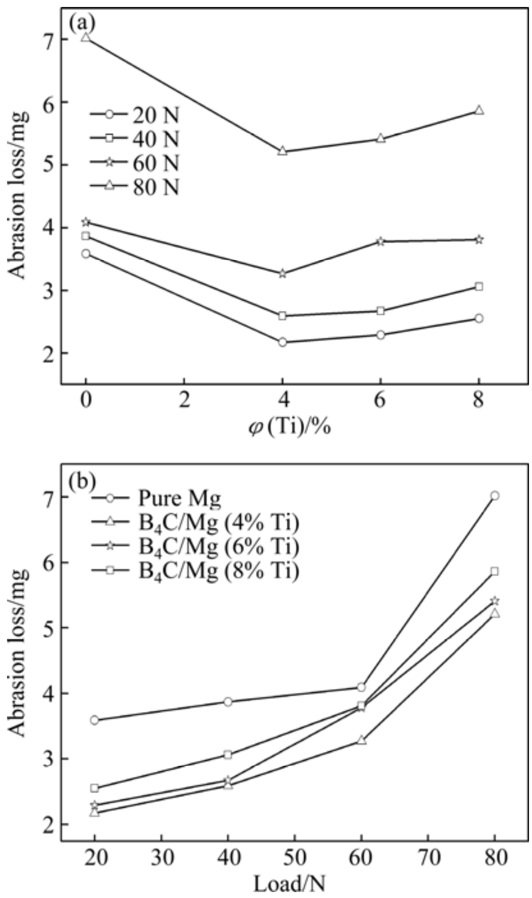


**Fig. 2** Curves of abrasion loss of Mg matrix and $B_4C$/Mg composites as function of Ti volume fraction (a) and applied load (b)

Some physical properties of the as-fabricated $B_4C$/Mg composites under the processing condition are listed in Table 1. From Table 1, it can be seen that the density of $B_4C$/Mg composites is only about 2.1 g/cm$^3$, which is much lighter than that of usual commercial Al matrix composites or Al alloy. The relative density of $B_4C$/Mg composites is about 80%, which indicates that there are some voids or holes within the composites, and this can be seen in Fig. 3. In this case, this suggests that the Mg-matrix composites with micro-holes can be processed by this route and find applications in self-lubricating structures. It is also shown in Table 1 that the hardness of $B_4C$/Mg composites decreases with increasing the Ti content. Therefore, the reason for the improved wear resistance of as-fabricated $B_4C$/Mg composites with decreasing the Ti content can be attributed to the fact that the wear rate of a material is inversely proportional to its hardness or the composites with higher hardness exhibit better wear resistance [20].

**Table 1** Some physical and mechanical properties of as-fabricated $B_4C$/Mg composites

| Ti content (volume fraction)/% | Density/ (g·cm$^{-3}$) | Relative density/% | Hardness (HRC) | Infiltration distance/mm |
|---|---|---|---|---|
| 4 | 2.13 | 81.85 | 77.7 | 6.68±0.95 |
| 6 | 2.10 | 79.36 | 71.0 | 11.14±0.80 |
| 8 | 2.15 | 80.11 | 67.5 | 12.44±0.66 |

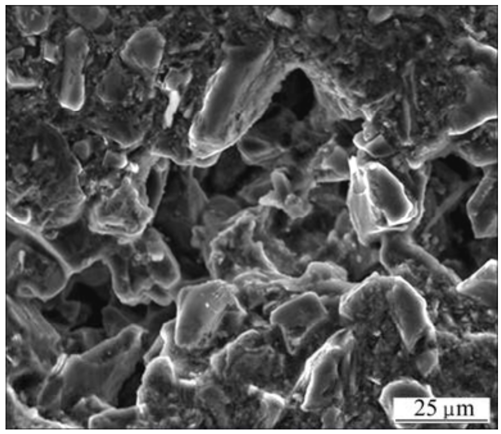


**Fig. 3** SEM micrograph of $B_4C$/Mg composites with 6% Ti content (volume fraction)

### 3.2 Wear mechanism

Generally, the wear mechanisms usually operate in combination for metal-matrix composites. For instance, the wear modes for Al alloy surface hybrid composites reinforced by $MoS_2$ and SiC were delamination and abrasion [21]. The following wear mechanisms: abrasion, oxidation, delamination, adhesion, and thermal softening and melting, were identified for the wear behavior of $SiC_p$ reinforced Mg-matrix composites [22]. In order to analyze the wear mechanisms of the as-fabricated $B_4C$/Mg composites, the worn surfaces of Mg matrix and $B_4C$/Mg composites are observed by SEM.

Figure 4 shows the morphologies of the worn surfaces under dry sliding condition and a load of 20 N, which indicates that the wear modes differ a lot for Mg and Mg-matrix composites. In Fig. 4(a), it is readily to note that the worn surfaces of Mg are filled with grooves paralleling to the sliding direction. This is the characteristic of abrasive wear, where there are hard asperities on the steel disc or hard particles between the contacting surfaces ploughed or cut into the pin, causing wear by removing small fragments or ribbon-like strips of material [22]. Through examining the SEM micrographs of Mg-matrix composites from Figs. 4(b), (c), and (d), it can be seen that grooves are not obvious on the worn surfaces of $B_4C$/Mg composites because the hardness of the as-fabricated composites are greatly improved due to the reinforcement of ceramic particulates, but pits, short cracks and shallow craters are found. The occurrence of pits is due to the pulling out of $B_4C$ particles from the matrix Mg. Short cracks are also found in Fig. 4(c) and they are caused by the increase of friction when adhesion occurs. And the intersections of these cracks may result in the detachment of sheet-like wear particles, leaving behind shallow craters, as shown in Fig. 4(d). This is the characteristics of delamination, and it is a fatigue-related wear mechanism, where repeated sliding induces subsurface cracks and the cracks gradually grow and eventually shear to the surface, forming long thin wear sheets [22]. Therefore, with increasing the Ti content, the wear mechanisms for the as-fabricated composites are transited from adhesion to delamination. In summary, abrasion is the dominant wear mechanism for the matrix Mg while adhesion and delamination are the dominant mechanisms for the as-prepared composites under low loads.

Figure 5 shows the worn surfaces of Mg and as-fabricated $B_4C$/Mg composites under a load of 80 N. As

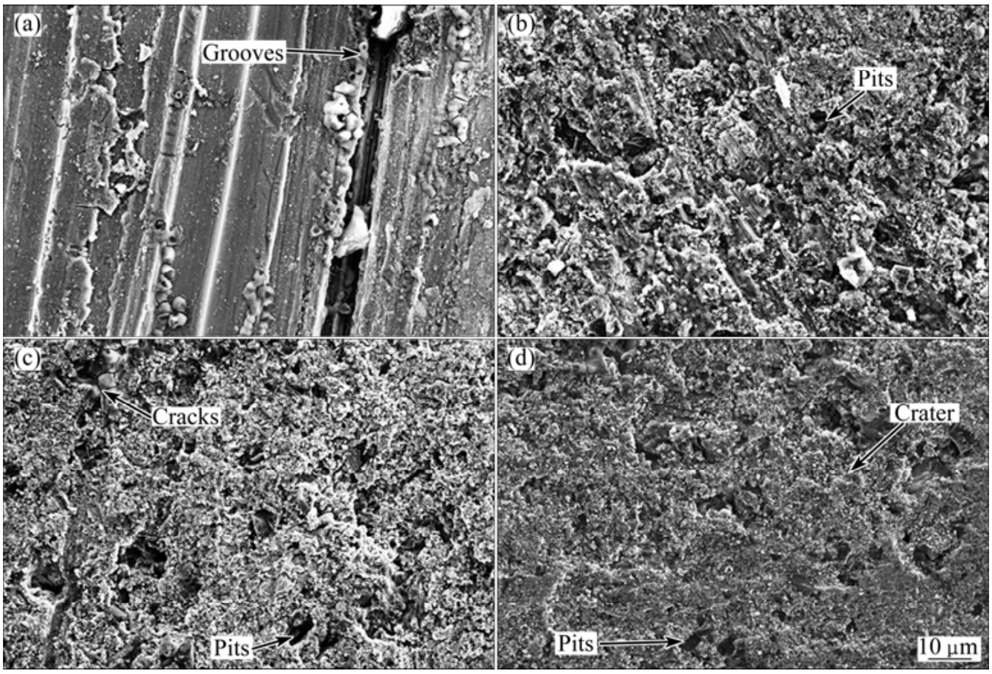


**Fig. 4** SEM micrographs of worn surfaces of pure Mg (a) and $B_4C$/Mg composites with addition of 4% Ti (b), 6% Ti (c) and 8% Ti (d) under a load of 20 N

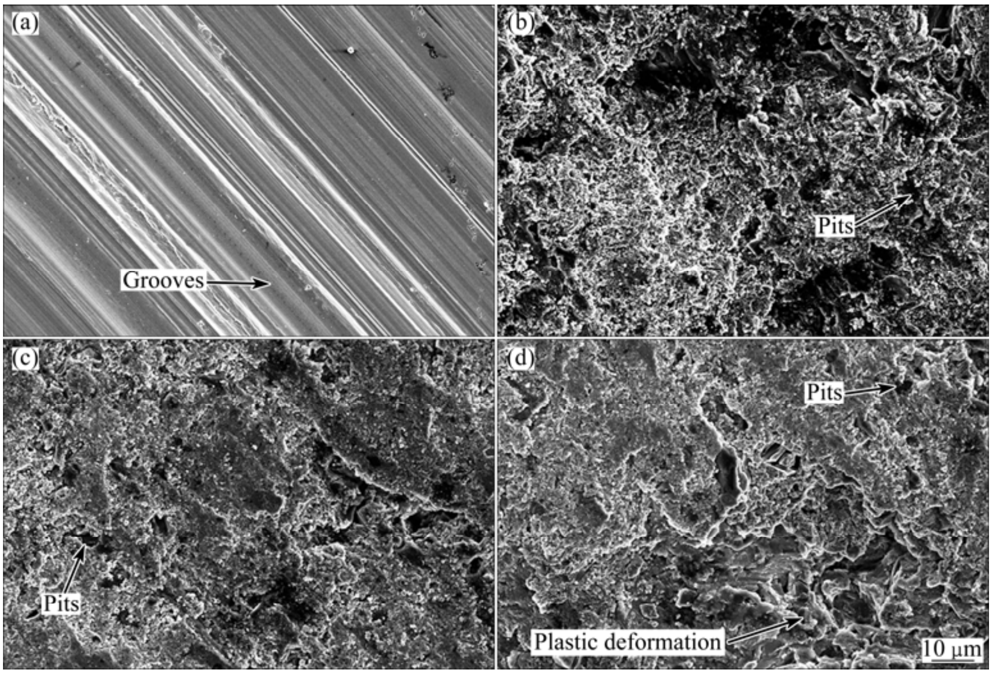


**Fig. 5** SEM micrographs of worn surfaces of pure Mg (a) and $B_4C$/Mg composites with addition of 4% Ti (b), 6% Ti (c) and 8% Ti (d) under a load of 80 N

described above, 60 N is the transition load of this kind of composites, so the wear modes differ with increasing the applied load. From Fig. 5(a), it can be seen that grooves on the worn surfaces of matrix Mg appear severer than those under low loads and the grooves appear wider.

From Figs. 5(b), (c) and (d), it is seen that grooves are not obvious on the worn surfaces of as-prepared composites but pits are easily found on the surfaces. And layers of matrix material are observed to protrude on the worn surface, especially in Fig. 5(d). Under the severest sliding condition of 80 N, gross plastic deformation of the pin surface occurs owing to the large amount of heat produced by large loads or long time sliding, exceeding the melting point of the matrix Mg and causing the softening and melting. And with increasing the Ti content, the softening of the matrix Mg seems to be much severer, thus leading to the decrease of wear resistance of the as-fabricated composites. Therefore, the dominant wear mechanisms for $B_4C$/Mg composites under high loads can be attributed to thermal softening and melting or plastic deformation.

## 4 Conclusions

1) The pin-on-disc wear test of $B_4C$/Mg composites shows that the as-fabricated composites exhibit better wear resistance than pure Mg under different loads. With decreasing the Ti content added into the $B_4C$ powder, $B_4C$/Mg composites exhibit superior wear resistance due to the increase of hardness. Both the matrix Mg and Mg-matrix composites have better wear resistance under low loads than under high ones.

2) The dominant wear mechansim for the matrix Mg is abrasion. Under low loads, adhesion and delamination are in operation for the wear behavior of $B_4C$/Mg composites, while the wear mechanisms of $B_4C$/Mg composites are thermal softening and melting under high loads.

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# 金属诱发无压浸渗技术制备 $B_4C$/Mg 复合材料的磨损行为与机制

姚彦桃[1]，姜 澜[2]，付高峰[2]，陈礼清[1]

1. 东北大学 轧制技术及连轧自动化国家重点实验室，沈阳 110819；
2. 东北大学 材料与冶金学院，沈阳 110819

**摘　要：**利用金属诱发无压浸渗技术制备的 $B_4C$/Mg 复合材料为实验材料，研究该材料的磨损行为与磨损机制。在销盘式实验装置上对施加不同载荷(20、40、60 和 80 N)以及磨损速率为 250 r/min 实验条件下的磨损行为进行评价。结果表明：$B_4C$/Mg 复合材料在所施加载荷下均比纯 Mg 基体表现出更优异的抗磨性能。作为诱发浸渗剂的金属 Ti 颗粒，其含量对 $B_4C$/Mg 复合材料的磨损性能具有一定影响。纯 Mg 基体的主要磨损机制是磨粒磨损；而对于 $B_4C$/Mg 复合材料，当施加载荷较低时，主要磨损机制为粘着和层离；当施加载荷较高时，其磨损机制为加热软化熔化或塑性变形。

**关键词：**Mg 基复合材料；$B_4C$；金属诱发浸渗；磨损行为；磨损机制

**(Edited by Mu-lan QIN)**