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# Study of Abrasive Wear and Abrasion Heating of Mg and Al Matrix Composites Reinforced with $B_4C$ and Cr

Sakshi Singh* and Nathi Ram Chauhan
MAE Department, Indira Gandhi Delhi Technical University for Women, Delhi, India

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This paper has focused on abrasive wear and abrasion heating of Mg- and Al-based $B_4C$ and Cr reinforced composites. The $B_4C$ and Cr have been added in 5% in the Mg- and Al-matrices and their composites have been fabricated by a squeezed stir casting method. The matrices and composites are evaluated and characterized for microstructure, hardness and X-ray diffraction. The abrasive wear and temperature rise during abrasive wear tests are carried out using a tribo-tester machine. The microstructure of Mg- and Al- matrices and their composites mainly show a uniform distribution of the $B_4C$ and Cr reinforcements. The hardness of the composites enhanced upto 72% by including $B_4C$ and 30 to 37% in the case of Cr composites in comparison to Mg- and Al- matrices. Temperature rise during abrasive is found more in the case of $B_4C$ reinforced composites in comparison to Cr amalgam composites and the abrasive resistance of $B_4C$ composite is high in comparison to Cr amalgam composites. The wear rate of boron carbide composites is approximately 2–6 times lower than the Mg matrix under different conditions. SEM image analysis mainly shows the cutting and ploughing material removal mechanism in abrasive wear.

**Keywords:** Casting, Hardness, Microstructure, Squeezed stir casting, XRD

## Introduction

The automotive and aircraft applications demand distinct mechanical and wear abilities such as high hardness, light-weight, and wear resistance. Such materials should also satisfy the favorable physiochemical properties because the materials have to withstand environmental conditions such as high temperature and corrosion in cylinder head cover (made of Al-based composites) encountered with heating, scratching wear and fatigue effect.[1]

Aluminium and magnesium-based parts are being used frequently in the automobile sector due to their light-weight properties. Material's abilities can be modified by reinforcing hard material with particulates or fibers. There are numerous hard particulates feasible such as $Si_3N_4$, $Al_2O_3$, graphite, SiC, TiC, $TiB_2$ etc., the addition of which can enhance and modify the properties of aluminium and magnesium-based alloys.[2–5] These materials can be synthesized with different processing paths such as powder metallurgy and stir casting. The key difference between them is that in the stir casting method there is a proper amalgamation of reinforced particulates in the matrix material.[6]

Praveenkumar *et al.*[7] preferred the use of stir casting methods for mixing the reinforcement and with the treatment of Mg/Al as composite materials. Gasali *et al.*[8] evaluate the wear behavior of the Mg matrix with boron carbide at different pressure and sliding speeds. Their study reveals that with the increase in the wt. % of boron carbide, the coefficient of friction and abrasion heating has been decreased. Suresh Babu *et al*.[9] deals with the influence of microstructural and wear rate of $Al/B_4C$ hybrid matrix amalgam by friction stir casting process. They highlighted that the hybrid forms less abrasion heating with high friction coefficient value. Also, the wear rate has been dropped in the higher sliding speed of $Al/B_4C$ hybrid composites.

Pei *et al*.[10] also evaluated mechanical strength for varied Cr particles in AZ91D Mg alloy. It was reported that after the 6 wt% tendencies of amalgamation have been representing in the melt, homologues images of Cr were not retrieved. This leads to a declination in mechanical strength. However, 2 wt% of Cr particles results showed the homogeneous distribution which leads to enhanced mechanical properties.

Mg/SiC/graphite composites revealed a better coefficient and wear resistance.[11] The inclusion of titanium carbide reinforced particulates also improves

*Author for Correspondence
E-mail: singh.sakshi0408@gmail.com

the abrasive properties of Mg alloy.[12] Yan *et al.*[13] evaluated a rise in tensile strength of Al hybrid specimens after the agglomeration of $Cr_2O_3$. It was concluded that Cr particulates are uniformly segregated in the Al matrix and evaluated that the incorporation of $Cr_2O_3$ improves the tensile strength up to 5%.[14] Shankar *et al.*[15] studied the response of the addition of $B_4C$ carbide particulates of stir cast Al6061 composites and reported an increment in the hardness of composites with the inclusion of $B_4C$ particles. The sliding velocity concerned by the micro-size and configuration of reinforcement micro-particles used in the fabrication of composites.[16] Apart from this, the scratching velocity for minimal abrasive wear rate has been calculated by the intermittent interconnection between the reinforcement and matrix.[17] As the reinforced percentage increases, the composite material showed good hardness and indicate that the addition of reinforcement micro particles causes difficulty in synthesizing process.[18] For better results, the optimum selection of the wt.% of the material is reported. From the above literature, it is found that very few studies have been reported on abrasive wear on Al and Mg composites with other reinforcements.[19,20] In this work, the abrasive wear study of the fabricated Al and Mg composites using $B_4C$ and Cr (reinforcements) have been carried out.

## Experimentation

### Materials and Methods

The pure Al and Mg ingots have been considered as the base material for developing Mg- and Al-matrix composites. The chemical compositions of Al and Mg base materials are presented in Table 1. The mechanical properties of $B_4C$ and chromium micro-particles have been selected as reinforcement for the synthesis (fabrication) of composites as represented in Table 2. The micro-particles are placed in an electric oven at 250°C for preheating purpose of the reinforcements.[21]

Table 1 — Compositions and properties of materials involved

| Matrix Material | Elements | Thermal Conductivity[22] ($Wm^{-1}K^{-1}$) |
|---|---|---|
| Magnesium | 99% purity with1% residual impurities | 156.0 |
| Aluminium (AA1100) | 99% purity with1% residual impurities like Fe, Cu, Si | 385.0 |

The Mg- and Al-composites are prepared by squeezed stir casting process with proportions as Mg-5% $B_4C$, Mg-5%Cr, Al-5% $B_4C$, and Al-5%Cr reinforced with $B_4C$ and Cr particles. In the process, initially under continuous stirring, the matrix metal (Mg/Al ingots) was placed in a vacuum-based preheated muffle furnace with a supply of argon with $SF_6$ cover gas to extinguish from fire. Then reinforcements ($B_4C$/Cr) were dropped into the molten melt of Mg/Al with continuous stirring. About 750–850°C of stirring temperature and constant 450 rpm of stirring speed was applied to the setup to attain a homogeneous arrangement. After 10–15 minutes of stirring, the composite melt was dropped into the mould by the bottom pouring approach. In the bottom pouring approach, a preheated small inclined runway (300°C) was attached below the muffle furnace to maintain the temperature of the composite melt. Then the composite melt was poured into the mould and instantaneously squeeze pressure (250 MPa) was applied by the hydraulic press for a few minutes to remove the residual defects. After solidifying at room temperature, fabricated specimens were taken out from the mould and slice out as per testing dimensions.

### Metallographic Study

The matrix and composite samples were cut as per ASTM 766 in the transverse direction for microstructure study. The microstructure study samples were prepared using the standard polished metallographic procedure. The general purpose etchant of the composition of 1 mL Nitric Acid, 60 mL Ethylene Glycol, 20 mL Acetic Acid and Water was used for the study.[22] The microstructure of all the composites was investigated using an electron microscope.

### Diffraction Study

The diffraction (XRD) samples were also prepared by ASTM E1508 as discussed without etching. The study was carried out from up to 80° at a speed of 2°/min. The peaks were identified by the software.[23]

Table 2 — Properties of $B_4C$ and Cr reinforced particles

| Properties Reinforcement | Elastic modulus (GPa) | Density ($kg/m^3$) | Thermal expansion coefficient ($K^{-1}$) | Thermal conductivity ( $Wm^{-1}K^{-1}$) |
|---|---|---|---|---|
| Boron Carbide | 362 | 2520 | $4.2–4.6×10^{-6}$ | 42.3 |
| Chromium | 279 | 7150 | $6.0–6.2×10^{-6}$ | 93.7 |

### Hardness Testing

The dimensions of each specimen were 10 mm × 10 mm × 10 mm i.e. length × breadth × height. Rockwell hardness test was executed on the Rockwell Hardness machine with an applied load of 100 kgf for 15 seconds for matrix and their composites. The hardness is measured using the ASTM E18-scale having the intender ball of 3.175 mm (1/8”). The average value of hardness was used for analysis.

### Abrasive Wear and Abrasion Heating Study

Abrasive wear tests were operated using a wear testing apparatus i.e. Pin on disc (DTU, Delhi India) under 20 N and 30 N load and sliding speed of 5 m/s as represented in Fig.1. In this investigation, a solid rectangular specimen of 50 mm long, 10 mm wide and 10 mm high was held strongly against a rotating SiC emery’ of different abrasive sizes. The disc was rotated at 5 m/s, test temperature was measured with a thermocouple (K-type). The abrasive test was conducted as per ASTM G99 standard using different abrasive sizes (in 35, 27, 23 and 18 microns) by the applied load (20 N and 30 N) and 300 m and 500 m distance with a speed of 5 m/s. The speed of the disc was regulated with the help of the speed control switch of the motor and managed by a regulator. All the samples are rinsed with acetone before and after each of the test. An electronic balance was used for weighing the specimens to 0.0001g of accuracy. The weight loss was used as a measure of wear. Friction develops whenever surfaces rub against each other. It is acknowledged that frictional heating was focused on the real contact areas within the bodies having relative motion.[24] Abrasion heating was recorded using a thermocouple attached to the test pin after regular intervals. Scanning electron microscopy is also used for abrasive wear study of the composites for wear mechanism analysis.

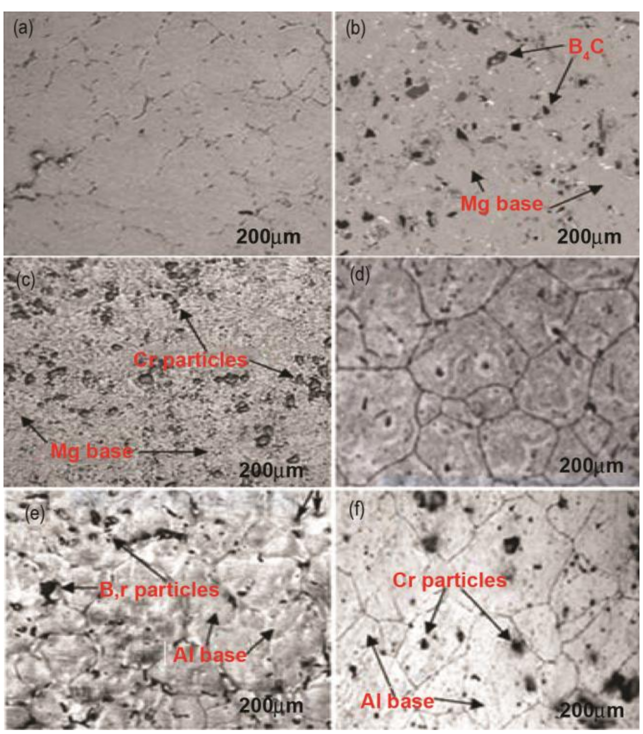


Fig. 1 — Microstructural images of (a) Mg-matrix, (b) Mg-5%$B_4C$ composite, (c) Mg-5%Cr composite, (d) Al-matrix, (e) Al-5%$B_4C$ composite, (f) Al-5%Cr composite

## Results and Discussion

### Metallographic Analysis

The microstructure of cast matrices and their composites containing $B_4C$ and Cr (5 wt% each) are shown in Fig. 1(a-f). The SEM images show a uniform and homogeneous microstructure of both pure Mg and Al-based matrices and their composites. Boron carbide particles are more homogeneously distributed as compared to chromium particles. This may be due to the lower density of boron carbide (2520 kg/$m^3$) as compared to chromium (7150 kg/$m^3$) as lower density takes more time to settle down as compared to higher density materials. Some agglomeration has also been observed in the composites (Fig. 1c and f). Furthermore, the microstructures of the Mg matrix and its composites (Fig.1a-c) are fine as compared to aluminium and its composites (Fig. 1d-f). This may be because the melting temperature of Mg is lower than Al as lower temperature results in a fast cooling rate.[25] The fast cooling rate results in a fine microstructure.

### Diffraction Analysis

Each of the profiles of composite specimens reveals α-Mg as the highest peak due to the presence of the matrix material but somewhere small peaks of MgO are also observed. $B_4C$ reinforced composite shows α-Mg and $\beta$ $MgB_2$ phases while Cr reinforced composite shows α-Mg and $\beta$-$Mg_5Cr$ phases. However, other elements such as Cr and $Cr_2O_3$ are also presented in the MgMCs at different diffraction angles as shown in Fig 2a and 2b.

For Al-composites and its XRD analysis showed the highest peaks of the single phase of α-Al and small peaks of Mg, Cu as in the form of impurities are also observed. α Al and $\beta$ $Al_3BC$ phases and small amounts of $AlB_2$, $B_{13}C_2$ phases have also been observed. α-Al and $\beta$-$Al_{13}Cr_2$ and $\beta$-$Al_{13}Cr_2$ are

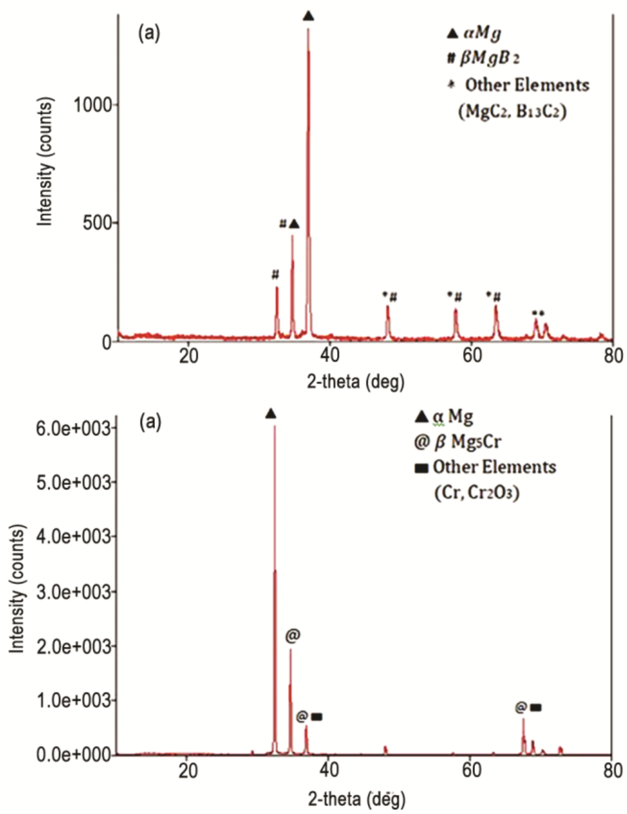


Fig. 2 — Diffraction images of (a) Mg-5%$B_4C$ composite, and (b) Mg-5%Cr composite

having more small peaks, which is due to the addition of Cr in the Al-matrix.

**Hardness Analysis**

The hardness of the casted matrices and their composites as presented in Fig. 3. The hardness of the matrix is low in both cases (Mg and Al) while the hardness increases significantly with the inclusion of $B_4C$ in both cases. An increase in hardness is less with the inclusion of Cr in both cases. The hardness is increased by 72% in the case of $B_4C$ composites in both Mg- and Al- matrices whereas there is only 30 to 37% increase in hardness in the case of Cr composites of Mg and Al matrices. This is because of the addition of hard reinforced particles ($B_4C$ and Cr) in both Mg and Al matrices.

**Abrasive Wear Loss Rate Analysis**

The abrasive loss of wear rate of the pure Mg and Al matrices with their composites have been carried out using 18, 23, 27 and 37 microns abrasive size. The load of 20 and 30 N are used for siding distance of 300 and 500 m for each case separately. The wear loss

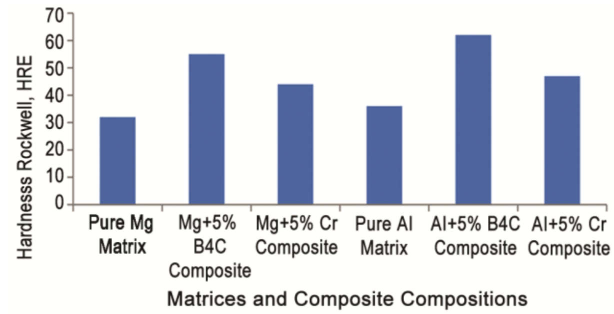


Fig. 3 — Hardness of Mg- and Al-matrices based composites

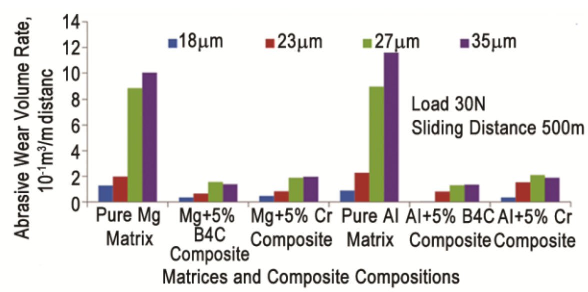


Fig. 4 — Wear rate of fabricated composites for 30N Load at 500 m

rate of these composites is shown in Fig. 4. This investigation explains that the wear loss rate increases with the rise in the grit/abrasive size.[25,26] The abrasive rate of wear loss of the Mg matrix and Al matrix is higher at each load and under each sliding distance as compared to their composites. The boron carbide reinforced composites reveals a higher wear resistance in comparison to Cr based composites. This is due to the high hardness of the boron carbide composite. The rate of wear loss of boron carbide composites is approximately 2–6 times lower than the Mg matrix under different conditions as shown in Fig. 4. The rise in abrasive wear rate with the increasing load is evident from Fig. 4. This is because load increases with the penetration depth of the abrasive grit which results in a higher wear rate of matrix and their composites. Similarly, higher abrasive size results in more material removal of the matrix and their composites. A similar explanation can be applied for the sliding distance which results in a rise in the rate of wear with the enhancement of distance.[27]

**Temperature Rise Analysis**

The temperature analyses of the pure Mg and pure Al with their composites have been carried out using 18, 23, 27 and 37 microns abrasive size. The load of 20 and 30 N is used for siding distance of 300 and 500 m for each case separately. The temperature analysis of these composites as presented in Fig. 5.

These investigations reveal the rise in temperature with the rise in the grit/abrasive size.[28] The temperature rise of the Mg matrix and Al matrix are lower at each load and under each sliding distance in comparison to their composites. This is because of the higher thermal conductivity of matrices (Table 1). The boron carbide reinforced composites shows a higher temperature rise in comparison to Cr based composites. This is because of the lower thermal conductivity of the boron carbide composite (Table 1). The temperature rise of boron carbide composites is approximately 20°C higher than the Mg matrix under different conditions as shown in Fig. 5.

#### Microscopic Analysis of Worn Surfaces of Composites

The microscopic images of the abrasive wear surfaces help to analyze the abrasive wear and material removal mechanisms in the composites and matrices. The SEM images in Fig. 6 show the worn images for Mg-composites and Al-composites respectively. From the analysis of images, it has been found that with the increase in load the grooves become wider as compared to lower load. Similarly, grooves are wider as abrasive size increases. Both these factors increase the abrasive wear of the composites. The main material removal mechanisms in the matrices (pure Mg and pure Al) are mainly observed as cutting and ploughing. The ploughing mechanism is due to the soft nature of the matrices (Fig.6 (a) and Fig. 6(e)). However, with the increase in hardness of composites, the wear material is mainly a cutting mechanism. Also with the increase in hardness, the material removal is found lower as compared to matrices.[29,30]

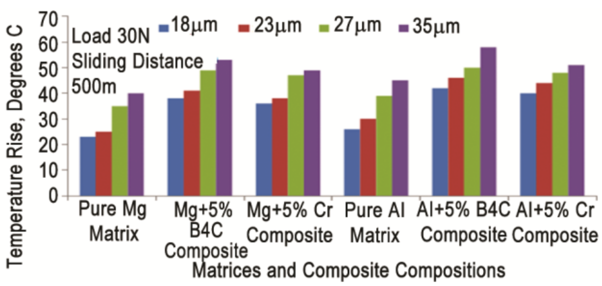


Fig. 5 — Abrasion Heating of Fabricated Composites for 30N Load at 500 m

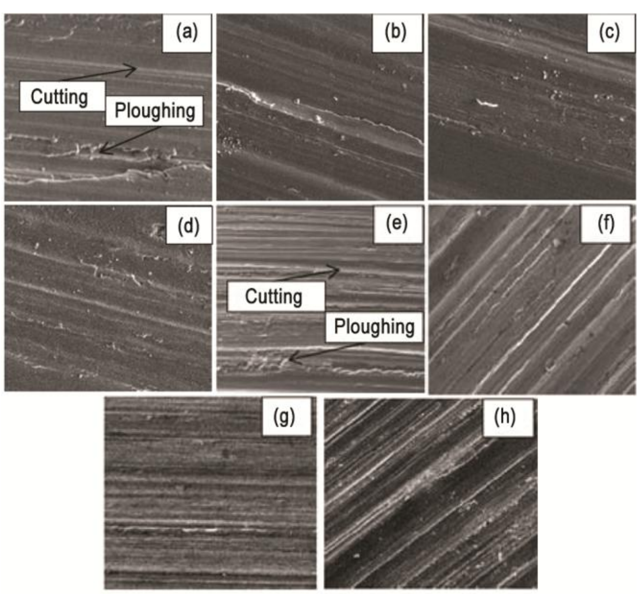


Fig. 6 — Worn surface images of fabricated composites for the load and sliding distance of (a) 20 N and 300 m, (b) 30 N and 300 m, (c) 20 N and 500 m, (d) 30 N and 500 m, (e) 20 N and 300 m, (f) 30 N and 300 m, (g) 20 N and 500 m, (h) 30 N and 500 m at 500 x.

## Conclusions

Mg- and Al-based composites are successfully fabricated and analysed with the inclusion of $B_4C$ and Cr reinforcements. The following outcomes are recorded from this research work:

i) The microstructure of Mg- and Al- matrices and their composites show the uniform distribution of $B_4C$ and Cr reinforcements. However, in Cr reinforced composites, some non-uniform distribution has been observed due to the high-density difference of Cr.

ii) The composites' hardness rises with the addition of $B_4C$ and Cr. The hardness has increased by 72% in the case of $B_4C$ composite while there is only 30 to 37% increase in hardness in the case of Cr composites in comparison to pure form Mg- and Al- matrices.

iii) Rise in temperature during abrasive is found more in the case of $B_4C$ reinforced composites in comparison to Cr reinforced composites because of the low thermal conductivity of $B_4C$.

iv) The results of abrasive wear resistance of $B_4C$ composite is higher than Cr reinforced composites due to the high hardness value of the $B_4C$ reinforced composite. The wear rate of boron carbide composites is nearly 2–6 times decreased than the Mg matrix under variable conditions.

v) SEM image analysis of both Mg- and Al-based composites mainly shows the cutting and ploughing material removal mechanism in abrasive wear.

Thus these results give new divergence towards small-size surveillance aeroplane parts such as aileron, wing flaps due to their suitability for abrasion wear and heating of Mg-based composites under variable load and speed conditions. But during actual modelling analysis of such design parts, conditions may vary due to its validity as per requirements.

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