Effect of Boron Addition on the Wear Properties of As-Cast AZ91 Magnesium Alloy

N Akram, K M Shorowordi, S Roy and A Mahmud

Department of Materials and Metallurgical Engineering, Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh

Abstract. AZ91, AZ91-0.5B and AZ91-1.0B magnesium alloys are produced in an inert atmosphere to investigate the influence of B on microstructure and properties of AZ91 alloy. Microstructural study is carried out using optical microscopy. Microhardness measurements are conducted by Vickers hardness tester. Using a pin-on-disk type apparatus, wear tests are conducted under dry sliding condition to assess the beneficial effect of boron on the wear properties of AZ91 alloy in relation to the resulted hardness and microstructures. The worn surface and wear particles morphology are also investigated. It is observed from microstructural investigation that the grains become finer with the addition of boron. The hardness is also found to increase with the addition of boron in AZ91 alloy, however maximum hardness is achieved with the addition 0.5 % B addition. The wear resistance is found to be better in the boron added alloy and maximum resistance is found with the addition of 0.5 % B. Wear mechanisms are also investigated.

1. Introduction
Magnesium alloys have shown greater demand in structural applications for its lightweight and higher strength-to-weight ratio compared to many other structural metals (such as steel, aluminium) [1,2]. These properties of magnesium alloys have attracted the attention in the automotive sector and aerospace industries to reduce fuel consumption and emissions. However, even after the recent developments of magnesium alloys, they are still not used as widely as aluminium alloys because of its poor formability arising from their h.c.p. crystal structure, inadequate mechanical properties, high susceptibility to hot tearing during permanent mould casting and relatively low corrosion resistance [3].

AZ91 is a widely used commercial magnesium alloy containing 9% aluminium and 1% Zn alloy but its mechanical properties are relatively low [4]. Grain refinement and secondary phase formed in this alloy can enhance the mechanical properties by the formation of fine equiaxed grains at the expense of dendrites. The studies on the grain refinement of magnesium based by melt superheating, rapid cooling, FeCl₃ addition, carbon inoculation, melt agitation have been reported [5]. It is found that the addition of inoculation is an effective method of refining the Mg based alloys. For the improvement of mechanical properties minor addition of alloying elements have also been studied such as Pb, Sr, RE, Th, Si, B and Ca [6-8]. Addition of some of these elements were found to be effective in improving the mechanical properties by refining the magnesium alloy with the formation of second phases. Boron is thought to be one of the potential element in improving the properties. Generally boron as in the form of master alloys, is added to Al-Si alloys for grain refinement [9]. Suresh et. al. have shown that small amount of boron addition in the form of Al-4B master alloy can cause grain refinement which can lead to improved mechanical properties [2].
Despite these studies, literatures on effective addition of boron in magnesium alloys is not enough to use boron at commercial scale. The present attempt has been taken to investigate the effect of small addition of boron on the properties of AZ91 alloy.

2. Experimental
Three different Mg alloys AZ91, AZ91-0.5B (0.5% Boron), AZ91-1B (1% Boron) were prepared through casting process using pure ingots of magnesium, aluminum and zinc, and Al-B master alloy (92%Al-8%B) as raw materials. Melting of the starting metals was done in an induction furnace under Ar atmosphere. The melt was then poured into the steel mold and this was also done in Ar protecting atmosphere.

Small pieces of sample were cut from each cast ingot. Samples were prepared by following standard metallographic technique to investigate the microstructure of cast magnesium alloys using optical microscope. Samples were finally etched in acetic-picral reagent (5 ml acetic acid; 10 ml distilled water; 100 ml ethanol and 6 gm picric acid). The micro-hardness of AZ91, AZ91-0.5B and AZ91-1B samples were measured by a Vickers hardness tester under 1 kg load for the dwell time of 10 seconds. For each of the samples, at least ten measurements were taken from different locations of the sample.

For study of the wear properties of magnesium alloys, pins of 5 mm diameter and 12 mm length were machined out from the cast AZ91 alloy plates. The end surface of the pin specimen was polished using a grit paper 1200, cleaned in distilled water and then dried in acetone. A pin-on-disc type setup was used for the wear test in which AZ91 alloy pin was pressed against a horizontal rotating disc made from the hardened steel (HRC 53). Tests were conducted for a total duration of 30 minutes in an ambient air of relative humidity 64±5% and temperature 25±2°C. Three contact loads, viz. 5, 10 and 15 N were used, while the linear speed was kept constant at value of 0.75 m.s$^{-1}$. After the test, the specimens were cleaned in water, dried in acetone and weighed and wear rates (gm.m$^{-1}$) of the specimens were calculated from weight loss measurements. An average of at least six tests for each sliding condition was taken for wear rate measurements.

3. Results and discussion
Figure 1 displays optical micrographs of as cast AZ91, AZ91-0.5B and AZ91-1B. It is seen that white phases have encircled the grains in all the as cast samples. It is reported that the white phase is intermetallic compounds of $\beta$-Mg$_{17}$Al$_{12}$ phase while the grain is of $\alpha$-Mg [10]. This intermetallic is formed during solidification of liquid metal in permanent mold. Figure 1 also reveals that the grains are almost same in size in AZ91 and AZ91-1B. The grain size of AZ91-0.5B alloy is observed finer than the other two Mg alloys. This indicates in the present study that the 0.5 weight percent boron addition is effective in grain refinement of AZ91, while 1.0 percent boron addition has almost no effect in grain refinement.

Suresh et. al. also studied the addition of boron in AZ91 and found that small addition of boron refines the grains [2]. This is attributed to the presence of AlB$_2$ particles. They reported that the particles are formed at early stage of liquid Mg alloy in the mold and acts as nucleation site for the solidification of liquid melt. The fine particles also have pinning effect which resist the growth of grain during solidification. Thus, it is thought that in the present case, grain size become finer for the addition of 0.5 weight percent boron due to the synergistic effects of fine AlB$_2$ particles early stage of nucleation and its pinning effect during solidification. In previous study, boron addition was limited to in the narrow range of 0.008 to 0.04 weight percentage. They also reported that no further grain refinement was observed beyond 0.032 weight percentage of boron addition [2]. On the contrary, Figure 1(b) shows clear refinement of grains at 0.5 weight percent of boron addition. Joshi et. al. have added boron through Al-5B master alloy and have found that 1%wt boron addition does indeed refine grains significantly. They attribute that the refinement occurs due to Al addition through the master alloy rather than AlB$_2$ particles. Also grain refinement was not very significant at any amount higher than 1 weight percent boron addition [11]. Present study reveals that 1% weight addition of boron does refine the grain. However, 0.5% B addition is found to be more effective in grain refinement (compare between Figure 1a and Figure 1b).
Figure 1. Optical micrograph showing the structure of as cast (a) AZ91 (b) AZ91-0.5B and (c) AZ91-1B.

Figure 2 shows a new phase in AZ91-0.5B at high magnifications which is revealed as black phase in boron added sample in Figure 1. This phase is not present in the AZ91 and AZ91-1%B. This phase seems to have a laminar structure and may be stronger than the α-Mg phase. Further study is required to identify the phase.

Figure 2. Showing a phase of laminar structure in as cast AZ91-0.5B alloy
The hardness of AZ91, AZ91-0.5B and AZ91-1B is shown in Figure 3. It can be seen from the figure that the average hardness of boron added alloys AZ91-0.5B and AZ91-1B is higher than the AZ91 alloy. The hardness of 0.5 weight percent boron added sample is higher than the 1.0 weight percent boron added sample. The lowest hardness is found in AZ91 alloy due to its coarse grain structure and absence of second phase particles or laminar structure like phase which are found in the 0.5% boron added sample. The highest hardness is observed in AZ91-0.5B alloy mainly for its fine grained structure, although AlB2 and laminar structure may also have increased the hardness. The hardness of AZ91-1.0B is higher than AZ91 alloy despite having almost same grain size, possibly due to the presence of AlB2 and laminar phase (See Figure 1). The lower hardness of AZ91-1.0B compared to 0.5% B addition can be attributed mainly to the increase of grain size when 1% B is added. The laminar phase found in AZ91-0.5B may also be responsible for its high hardness compared to AZ91-1.0B but cannot be said for certain without further investigation on that phase.

![Figure 3. Showing the comparison of hardness of AZ91, AZ91-0.5B and AZ91-1B alloy](image)

Figure 4 shows the variation of wear rate of AZ91, AZ91-0.5B and AZ91-1B with normal load. The wear rates of three alloys are found to increase as the normal load increases. The wear rate of AZ91-0.5B is seen to be lower than that of AZ91 and AZ91-1B. The AZ91 alloy shows the higher wear rate than the AZ91-1B. The lowest wear rate found in AZ91-0.5B is due to the higher hardness as compared to both the AZ91 and AZ91-1B alloys. The wear properties of materials is dependent on the strength of materials,

![Figure 4. Wear rate of AZ91, AZ91-0.5B and AZ91-1B under different normal loads.](image)
mainly hardness. In this study three alloy shows the wear properties according to their hardness property i.e. AZ91 alloy being of the lowest hardness shows the highest wear rate. The difference in wear rates between the alloys also becomes more pronounced as the load increases.

The morphology of the worn surface of AZ91, AZ91-0.5B and AZ91-1B samples is shown in Figure 5 tested at normal load of 5 N. Parallel ploughing marks along the sliding direction are visible on the worn surfaces of three samples. The ploughing marks on the worn surface and the positive correlation with wear rate suggest that abrasive wear mainly operates under the present experimental conditions. The abrasive wear is found to occur in lesser extent in AZ91-0.5B compared to the AZ91 and AZ91-1B as the ploughing marks are less deep.

**Figure 5.** Optical micrographs of the worn surfaces of (a) AZ91, (b) AZ91-0.5B and (c) AZ91-1B tested under the normal load of 5 N.

**Conclusion:**
In the present study, grain refinement is found with the addition of 0.5 weight percent boron AZ91 alloy, while less refinement is observed in the sample with 1 percent boron addition. Boron addition significantly increases the hardness and wear resistance of AZ91 magnesium alloy, especially in the case of 0.5% B addition. The AlB2 particles also increase the wear resistance of AZ91-1.0B as compared to AZ91 despite the same grain size. It is also found that abrasive wear is found to be the predominant wear mechanism which occurs at a lesser extent on AZ91-1.0B than that of other two alloys.

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