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Effect of 3 and 5 wt. % of WO_3 particulates on the properties of Al5Mg5Zn metal matrix

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Abstract. In this research work 3 wt. % and 5 wt. % of tungsten oxide (WO_3) particulates are reinforced the Al-5Mg-5Zn alloy. Two-step liquid stir casting processing route is used for the development of these particulate reinforced aluminium alloy metal matrix composites. The mechanical and the tribological properties such as Brinell hardness, impact toughness and dry sliding wear resistance of the as-cast Al-5Mg-5Zn alloy matrix and the prepared Al-5Mg-5Zn/WO_3 particulate metal matrix composites are analysed according to ASTM standards. The worn-out surfaces of the test samples during the wear test of the developed compositions are also analysed by using optical microscopy to express the patterns of wear. The results show that the addition of WO_3 particulates improved the hardness as well as dry sliding wear resistance of the Al-5Mg-5Zn alloy and these properties are also increased with the increase in the wt. % of WO_3. The value of impact toughness decreases with the addition of WO_3 particulates as well as increasing the wt. % of WO_3 particulates.

Keywords: metal matrix composite; WO_3; hardness; impact toughness; wear resistance

1. Introduction

In this present era, Metal Matrix Composite (MMC) is an advanced material. The MMCs are fabricated by the macroscopic combination of reinforcement and matrix materials. The MMCs includes a desired combination of tribological as well as mechanical properties (Jones 1998, Kaw 2006, Ozben *et al*. 2008, Patel *et al*. 2020c). Aluminium Metal Matrix Composites (AMMCs) hold a very good strength to weight ratio. The AMMCs are mostly applicable in aerospace and automobiles to reduce the required thrust force and to save the fuels requirement (Chen and Tokaji 2004, Feng *et al*. 2008, Patel *et al*. 2018a, 2020a, Shorowordi *et al*. 2003). In particulate reinforced AMMCs, metal forming processes are also applicable because it provides isotropic property in case of the homogeneously distributed particulates between the matrix (Chen and Tokaji 2004, Karamis *et al*. 2003, Patel *et al*. 2021).

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Due to a very good combination of mechanical, tribological as well as corrosion resistance properties at low cost and recyclability of particulate reinforced AMMCs, make them more attractive (Patel *et al*. 2018b, Sujan *et al*. 2012).

Patel *et al*. (2019) evaluated the hardness, toughness and sliding wear resistance after replacing Zn element with SiC in Al-5Mg-5Zn/3WO_3-p MMC and they found SiC particulates improve their mechanical and tribological properties. Feng *et al*. (2008) studied the fabrication and characterization of Al-based hybrid composite reinforced with tungsten oxide particle and aluminium borate whisker by squeeze casting. They reveal that WO_3 has a high atomic no. element (W) which can effectively absorb photons radiation and possess good photo absorbability which can be applied in functional materials, hard alloys, and radiation protection materials etc. The hybrid composite gives improved results on the ultimate tensile strength, yield strength & modulus, but the % elongation of the Al is decreases. The bonding strength is weak at the interface between the reinforcements and the matrix. Feng *et al*. (2009) characterized the properties and microstructure of hybrid composites reinforced with WO_3 particles and $Al_{18}B_4O_{33}$ whiskers by squeeze casting and noted that when the particle/whisker ratio decreases then the ultimate tensile strength and elongation of composites increase. In this hybrid composite WO_3 particles used for radiation absorber and ABO whiskers used to improve the mechanical properties of the composites. So, these hybrid composites have good mechanical properties and good radiation shielding properties and will be potentially useful as structural-functional integration materials in the field of radiation shielding. Hasan *et al*. (2013) also worked on the structural and mechanical properties of nanostructured tungsten oxide thin films. They found improved scratch hardness and wear resistance properties in the case of tungsten oxide thin film coating on the glass at different temperature.

Therefore in this study, the Brinell hardness, impact toughness and dry sliding wear resistance behavior characterization of Al-5Mg-5Zn reinforced by 3 wt. % and 5 wt. % of WO_3 particulates is carried out and obtained results are compared with the unreinforced Al-5Mg-5Zn alloy.

2. Experimental studies

2.1 Materials and methods

The Al-5Mg-5Zn alloy was chosen for the present work, which is the combination of 5xxx and 7xxx series of aluminium alloy. Mg & Zn elements are the principal alloying element for the 5xxx and 7xxx series of aluminium alloy respectively. The 5xxx and 7xxx Al alloys series possess excellent corrosion resistance and high strength property respectively. 5xxx series Al alloys are marine application alloys due to their corrosion resistance property and 7xxx series Al alloys are aerospace application alloy due to their high strength to weight ratio (Dix *et al*. 1958). In this research, this combined grade of Al-5Mg-5Zn alloy matrix was reinforced with 3 wt. % and 5 wt. % tungsten oxide particulates (avg. particle size of 23μm) by simplest and cost-effective two-step stir casting technique. Mg contents present in the Al alloy increases the wettability as well as the distribution of the reinforcing particles (Lin *et al*. 2010). For the development of composites, the required amount of Al-5Mg-5Zn alloy was taken in the clay-graphite crucible and melted at 800°C in the electric resistance furnace for 2 hours. The dross products formed in the molten alloy were removed, after that the molten alloy was cooled to a semi-solid state and then the calculated amount of WO_3 particles (3 wt. % and 5 wt. %) was added in a semi-solid state alloy matrix. With the help of a mechanically developed two-blade stirrer, the reinforcement particulates were mixed with Al-

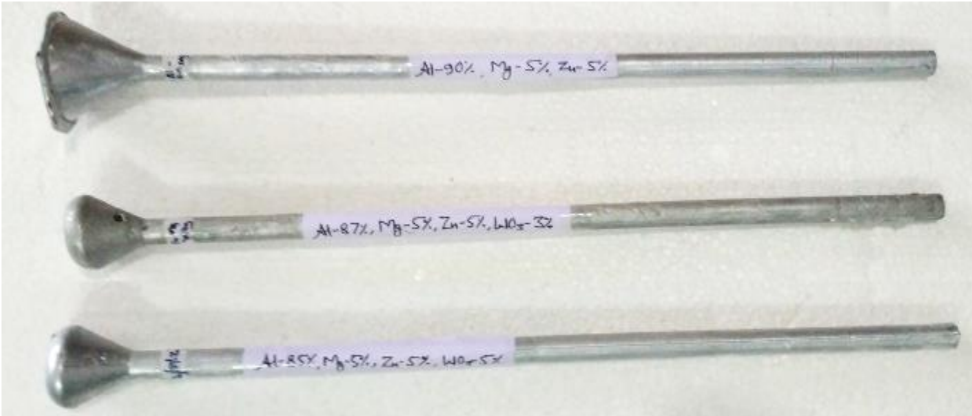


Fig. 1 Developed samples from stir casting

5Mg-5Zn alloy matrix then the composite slurry was again melted at 800°C for half an hour and again stirring was continued for 10 min. at 350 rpm to ensure the homogenous distribution of the added particulate in the molten alloy. After that, the composite slurry was poured in permanent moulds of cast iron of dimension 300×75×15 mm^3 and one another cylindrical mould with dimension 10 mm diameter with 300 mm height then it was allowed to solidify at room temperature. The fabricated cylindrical samples are shown in Fig. 1.

2.2 Hardness test

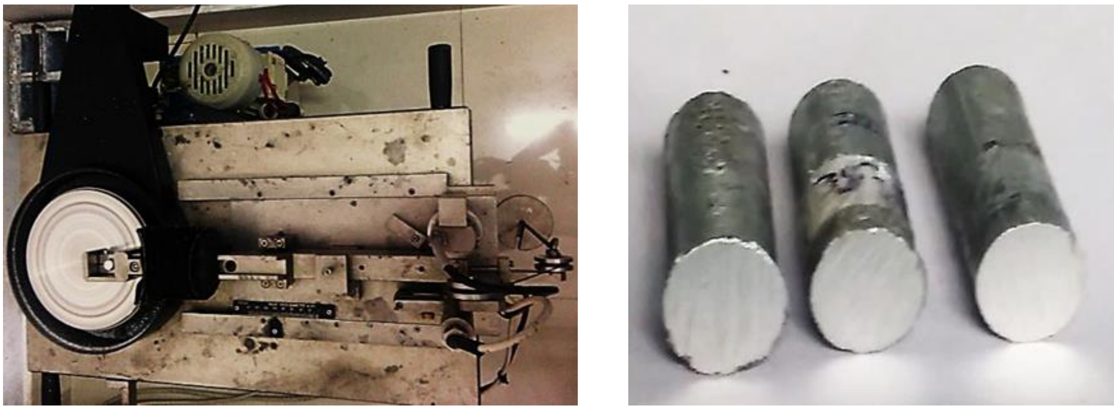
For the Brinell hardness characterization of the developed composites and unreinforced alloy, the test samples were prepared and metallographically polished by P800 grade sandpaper. A definite force of 60 kgf was applied mechanically on the sample for 30 sec. The 5 mm diameter size steel ball indenter was used for doing this test and measured the mean diameter of the impression left on the surface of the test sample by using microscope. Measurements were taken at five different points of each test sample to assess its reproducibility. The Brinell Hardness No. (BHN) is calculated by using Eq. (1)

$$\mathrm{BHN} = \frac{2\mathrm{P}}{\pi D\left(D - \sqrt{(D^2 - d^2)}\right)} \tag{1}$$

where BHN is the Brinell hardness number in kgf/mm^2, P is applied load in kgf, D is the diameter of the indenter in mm, and d is the diameter of indentation in mm.

2.3 Impact toughness test

The impact toughness of the developed compositions was evaluated by the Charpy impact test which was carried out according to ASTM E23 - 07a (ASTM E23-07a 2007). Each test sample had broken by a single blow of freely swinging pendulum or hammer at room temperature. The energy transferred to the material during the blow was indicated by friction pointer on the scale in which result of impact toughness was shown in joules. The dimensions of each Charpy impact test sample were 55x10x10 mm^3 and a V-notch prepared at the mid-span with a notch angle of 45°.



(a) Setup for pin-on-disk wear test (b) Specimens prepared for sliding wear test

Fig. 2 Dry sliding wear test carried out on pin-on-disk wear tester

2.4 Dry Sliding wear test

The wear behavior of the prepared composites was analysed by a computerized pin on disc dry sliding wear test as shown in Fig. 2(a). The tests were performed as per ASTM G99 standard. The wear test was conducted on the test pin of each fabricated composition with dimensions of 10 mm diameter and 30 mm height as shown in Fig. 2(b). The test pin was rotating against EN-32 steel disc having hardness 65 HRC. Test pins were ground to a smooth finish on P800 grit sandpaper before the test. Wear test was conducted at room temperature with an applied load of 20N and at 350 rpm, the wear track diameter is chosen 100 mm for each test sample. The weight loss (Δw) and volumetric wear rate (W_r) of the test samples were calculated by using Eqs. (2) and (3) (Patel *et al*. 2019, 2020b, 2020d, 2020e, 2020f).

$$\Delta w = w_b - w_a \tag{2}$$

$$W_r = \frac{A \times \Delta h}{d} \tag{3}$$

where 'w_b' is the weight of the sample before test in mg, 'w_a' is the weight of the test sample after test in mg, 'A' is the cross-sectional area of the test sample in mm^2, 'Δh' is the change in height of the pin during the test in mm and 'd' is the sliding distance in m.

3. Results and discussion

3.1 Hardness test

The values of BHN at five different points of the as-cast Al-5Mg-5Zn alloy, Al-5Mg-5Zn + 3 wt. % WO_3 MMC and Al-5Mg-5Zn + 5 wt. % WO_3 MMC were measured and listed in Table 1. Avg. Brinell hardness numbers of the developed compositions are plotted in Fig. 3. The average hardness of Al-5Mg-5Zn was found 89.64 BHN and the average hardness of Al-5Mg-5Zn + 3 wt. % WO_3-p MMC was found 98.35 BHN which is 9.7% higher than the avg. hardness of the Al-5Mg-5Zn alloy.

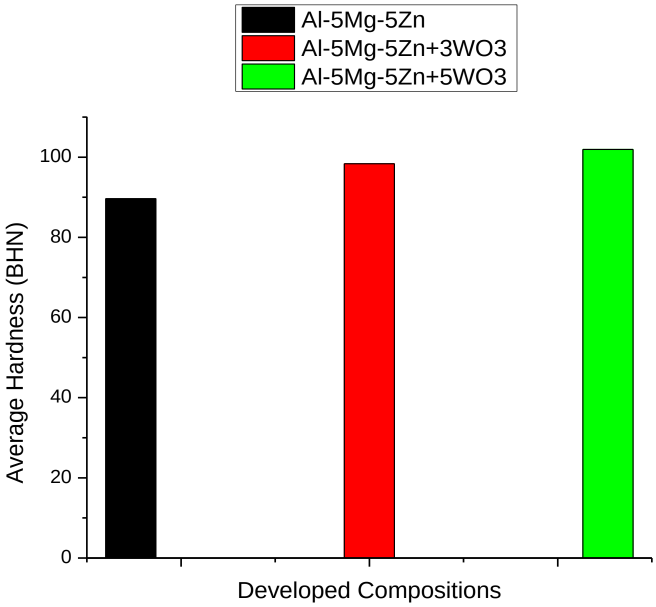


Fig. 3 Average BHN of the developed compositions

Table 1 BHN values at five different points of sample of the developed compositions

Composition	Brinell Hardness No. (BHN)					Avg. BHN
Al-5Mg-5Zn	89.48	93.54	90.34	83.87	90.95	89.64
Al-5Mg-5Zn + 3 wt. % WO_3-p	98.87	95.48	93.58	104.96	98.87	98.35
Al-5Mg-5Zn + 5 wt. % WO_3-p	100.83	102.45	103.51	101.74	100.65	101.84

The average hardness of Al-5Mg-5Zn + 5 wt. % WO_3-p MMC was found 101.84 BHN which is 13.6% higher than the avg. hardness of the Al-5Mg-5Zn alloy. It is observed that when adding the WO_3 particulates as well as increasing the wt. % of WO_3 particulates in Al-5Mg-5Zn matrix then the hardness of the alloy matrix is increased, this is due to the good bonding between the hard WO_3-p reinforcement and Al-5Mg-5Zn alloy matrix. From Table 1, it is also noted that in the sample of Al-5Mg-5Zn/WO_3-p MMC the value of hardness is high at some point due to agglomeration or clustering of the hard WO_3 particles between the used alloy matrix.

3.2 Impact toughness test

Impact toughness test of as-cast Al-5Mg-5Zn alloy and developed AMMCs specimens as per ASTM E23 standard was done by Charpy impact test. Fig. 4 shows the value of impact toughness obtained from the test. From Fig. 4, it is observed that the impact toughness of Al-5Mg-5Zn/WO_3-p MMCs have less value as compare to the unreinforced Al-5Mg-5Zn alloy. Hence it is observed that the addition of WO_3-p in Al-5Mg-5Zn matrix decreases the impact toughness value of the alloy. The impact toughness also decreases with an increase in the weight % of WO_3 particulates. This is because of the brittle nature of the developed AMMC due to hard WO_3-p, which decreases the ductility of the alloy. The impact toughness of the alloy is decreased upto 18% & 22% due to addition of 3 wt. % and 5 wt. % WO_3-p respectively.

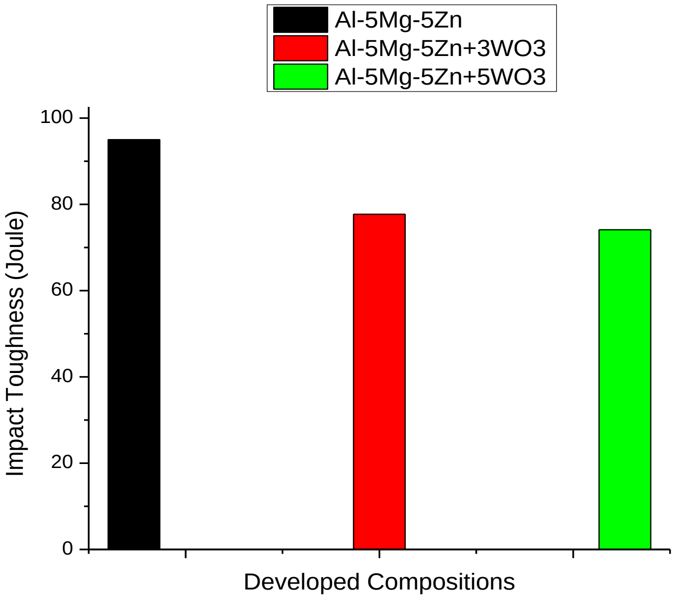


Fig. 4 Impact toughness of the developed compositions

Table 2 Wight loss during dry sliding wear test

Compositions	Weight before wear test (mg)	Weight after wear test (mg)	Weight loss (mg)
Al-5Mg-5Zn	6764.81	6265.59	499.22
Al-5Mg-5Zn + 3 wt. % WO_3-p	6446.30	6149.00	297.3
Al-5Mg-5Zn + 5 wt. % WO_3-p	6417.47	6126.53	290.94

Table 3 Wear rate of the test samples

Compositions	Height change (mm)	Pin area (mm^2)	Sliding distance (m)	Wear rate (mm^3/m)
Al-5Mg-5Zn	1.95317	78.5398	2200	0.06972
Al-5Mg-5Zn + 3 wt. % WO_3-p	1.48162	78.5398	2200	0.05289
Al-5Mg-5Zn + 5 wt. % WO_3-p	1.14173	78.5398	2200	0.04076

3.3 Sliding wear test

According to ASTM G99 standard, test specimens of the Al-5Mg-5Zn alloy, Al-5Mg-5Zn + 3 wt.% WO_3-p MMC and Al-5Mg-5Zn + 5 wt.% WO_3-p MMC are tested under an applied load of 20 N; 100 mm wear track diameter and sliding distance of 2200 m. The results obtained during the dry sliding wear test for the as-cast alloy and developed AMMCs are shown in Fig. 5. The weight loss and wear rate obtained during this test are listed in Table 2 and Table 3 respectively. The wear behaviours of the developed compositions were discussed in terms of wear rate. It is observed that the wear rate and weight loss of the Al-5Mg-5Zn + 5 wt. % WO_3-p MMC and Al-5Mg-5Zn + 3 wt. % WO_3-p MMC are less than the Al-5Mg-5Zn alloy matrix. From Fig. 5 and Tables 2 and 3, it is also observed that the wear, wear rate and weight loss of the Al-5Mg-5Zn + 5 wt. % WO_3-p MMC

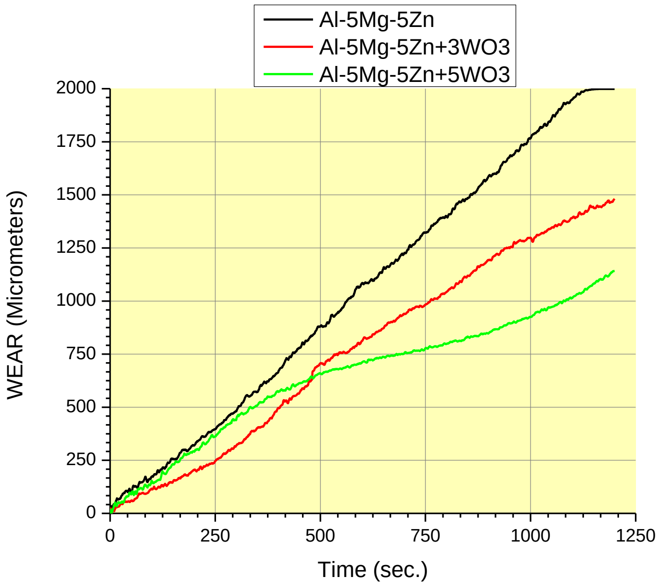
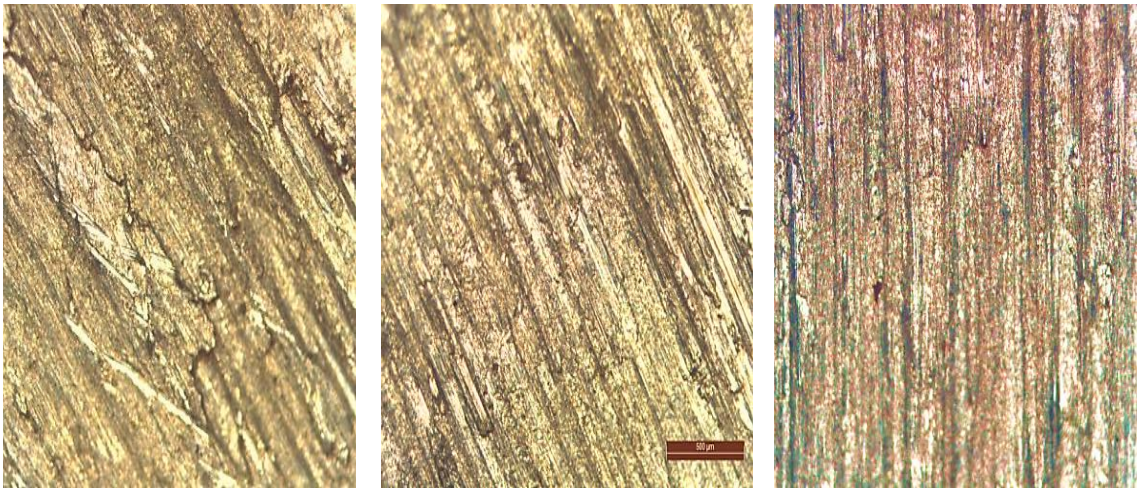


Fig. 5 Dry sliding wear graph of the developed compositions



(a) Al-5Mg-5Zn alloy (b) Al-5Mg-5Zn + 3 WO_3-p MMC (c) Al-5Mg-5Zn + 5 WO_3-p MMC

Fig. 6 Optical micrographs of worn out surfaces

are less than the Al-5Mg-5Zn + 3 wt. % WO_3-p MMC. Hence the dry sliding wear resistance increases with the addition of WO_3-p in the Al-5Mg-5Zn matrix and also increases with an increase in the wt. % of WO_3-p in the Al-5Mg-5Zn matrix. This is due to the high strength bonding between hard WO_3-p and Al-5Mg-5Zn matrix.

The worn-out surfaces were analysed and the mechanism of wear are studied in detail. The micrograph of worn-out surfaces of Al-5Mg-5Zn alloy, Al-5Mg-5Zn + 3 wt. % WO_3-p MMC and Al-5Mg-5Zn + 5 wt. % WO_3-p MMC are shown in Figs. 6(a)-6(c) respectively. From Fig. 6 it is observed that the sliding grooves marked on the surfaces of all developed compositions in the direction of sliding. In the sample of Al-5Mg-5Zn alloy, some micro cracks and delamination between the grooves were also observed. The delamination between the grooves in the as-cast alloy increases the wear rate of the Al-5Mg-5Zn alloy as compared to Al-5Mg-5Zn + 3 wt. % WO_3-p MMC and Al-5Mg-5Zn + 5 wt. % WO_3-p MMC. The grooves marked on the surface of the sample of Al-5Mg-5Zn + 3 wt. % WO3-p MMC was deeper than the grooves formed on Al-5Mg-5Zn + 5 wt. % WO_3-p MMC which results in high wear in Al-5Mg-5Zn + 3 wt. % WO_3-p MMC compared to Al-5Mg-5Zn + 5 wt. % WO_3-p MMC.

4. Conclusions

In this study, 3 wt. % and 5 wt. % of WO_3 particulate is used as a reinforcement of Al-5Mg-5Zn alloy matrix. The AMMCs are fabricated by using a simple and cost-effective two-step stir casting method. The Brinell hardness, Impact toughness and dry sliding wear rate of the as-cast alloy and the developed AMMCs have been investigated. Due to the addition of WO_3 particulate in Al-5Mg-5Zn matrix, the following points are concluded:

- The values of Brinell hardness increased by 9.7% and 13.6% for Al-5Mg-5Zn + 3 wt. % WO_3-p MMC and Al-5Mg-5Zn + 5 wt. % WO_3-p MMC respectively.
- The impact toughness values decreased by 18.2% and 22% for Al-5Mg-5Zn + 3 wt. % WO_3-p MMC and Al-5Mg-5Zn + 5 wt. % WO_3-p MMC respectively as compared to Al-5Mg-5Zn alloy.
- Dry sliding wear rate is decreased by 24.1% and 41.5% for Al-5Mg-5Zn + 3 wt. % WO_3-p MMC and Al-5Mg-5Zn + 5 wt. % WO_3-p MMC respectively as compared to Al-5Mg-5Zn alloy.
- With the increase in the wt. % of WO_3-p in Al5Mg5Zn matrix, results in the improvement of BHN & wear resistance value and diminished in the value of impact toughness. These are due to the good bonding between the hard WO_3 particles and Al-5Mg-5Zn matrix and also increase in the brittle nature of the composites with higher wt. % of WO_3.

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