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Study of Microstructure and Mechanical Properties of Magnesium Metal Matrix

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ABSTRACT

In this study, we have manufactured AZ91D magnesium-based alloy and its composite reinforced with boron carbide (B4C) and ZrO2 at various weight percentages by bottom pouring stir casting process. The work is aimed at comparing the microstructure and mechanical properties of developed composites with its matrix AZ91D magnesium alloy. We added 0.3 weight percentage of B4C reinforcement particles with matrix material and also 2 weight percentage of zirconium dioxide (ZrO2) into composite. Density, Rockwell Hardness Test, Tensile Test, Wear and Optical Microstructure were evaluated. The developed composites reveal increased hardness when compared to base material, which could be accredited to the occurrence of B4C particles. Also, this study indicates that increase in percentage addition of B4C and zirconium dioxide (ZrO2) leads to increase in density and tensile strength of the developed composites. Optical microstructure images show the uniform distribution of particles into matrix.

***Keywords:** AZ91D magnesium-based alloy, composite, boron carbide (B4C), ZrO2, microstructure*

1. INTRODUCTION

In current era there is a massive require of the materials that are lighter in weight, have superior strength, further durable and have superior wear resistance. Elevated anxiety on material for enhanced on the complete recital has led to widespread research and enlargement effort in the composite fields. Considering this in the model few decades, general research has been carried out into metal matrix composites (MMC) [1-3]. Al MMCs, Mg-MMCs are some of the composites that are lighter in weight than erstwhile metals and their alloys. As a consequence of this they discover enormous appliance in sectors like Automobiles and Aerospace [4-6]. As a result, magnesium alloys warm incredibly elevated specific strength amid predictable engineering alloys. In adding together, magnesium alloys posse's admirable damping capacity, excellent castability, and superior machinability. Further research done in this field says that Mg-MMCs were nearly 17-22% lighter than the Aluminium composites and are also used in defence systems like missiles and their components etc [7-10]. A small decrease in hardness is observed for the hybrid composite when compared to Mg–SiC composite due to the presence of soft Gr particles [11]. Adding of B4C into AZ91D magnesium matrix composite mechanical properties were slightly increased as compared to AZ91Dmagnesium alloy. It might be observed that there is increase in hardness reported on use of B4C and Zr02 particulates on the mechanical properties of magnesium AZ91D alloy. The current effort expected to examine the

$$\rho_{mmc} = \frac{m}{m - m_1}\rho_w$$

$$v_{Al} = 1 - (v_{Sic} + v_{Tic})$$

$$v_r = \frac{\rho_m - \rho_{mmc}}{\rho_m - \rho_r}$$

result of addition of B4C and Zr02 on the microstructures and mechanical properties of AZ91D magnesium alloy at room temperature.

2. LITERATURE REVIEW:

m	Mass of the composite sample in air
m_1	A mass of the same composite sample in
	Distilled water
w	Density of the distilled water
v_{Al}	Volume fractions of aluminium alloy
v B_4C	Volume fractions of B_4C
v Zro_2	Volume fractions of Zro_2
vr	Volume fractions of reinforcement
m	Density of the matrix
r	Density of reinforcement
th	Theoretical densities
a	Actual densities
$AZ_{91}D$	Density of the Magnesium alloy
B_4C	Densities of B_4C
	Densities of Zro_2

Density and Porosity measurement

The density of a composite is one of the most important physical properties used to characterize the composite material. In a composite, the proportion of matrix and reinforcement is expressed either as a volume fraction or as a weight fraction. The theoretical density is calculated by the rule of the mixture, and expressed in Equations. The actual density of the hybrid composite is calculated by Archimedes principle with Equation. The fabricated hybrid metal matrix composite is immersed in distilled water apparently in equal weight of the water so that the composite gets displaced. From the theoretical and actual densities, the porosity of composite is also calculated by using Equation.

$$\rho th = \rho AZ91D v AZ91D + \rho\ B4C\ v\ B4C + \rho\ Zro2 v\ Zro2$$

$$\rho_a = \frac{m}{m_1}$$

where MMC - density of composite

Density details of composite materials

Density(kg/m3)							
Sample	$AZ_{91}D$	$\%AZ_{91}D$	ZrO2	2%ZrO2	B_4C	$3\%B_4C$	HYBRID COMPOSITE
AZ91D	1809.1		5680	0	2520	0	1809.1
AZ91D+3%B4c	1809.1	1754.827	5680	0	2520	75.6	1830.427
AZ91D+2% Zro2+3%B4c	1809.1	1718.645	5680	113.6	2520	75.6	1907.845

Calculated Weighted Amount of AZ91D/B4C/ZRO2 Reinforcement

Material	$AZ_{91}D$(g)	B_4C reinforcement(g)	ZrO_2 reinforcement(g)
AZ91D	1085.4	-	-
AZ91D+3%B4c	1052.83	35.62	-
AZ91D+2% Zro2+3%B4c	1028.07	35.62	21.708

3.METHODOLOGY:

The flowchart of the experimental procedure followed for the current investigation. Important aspects such as material (matrix and reinforcement) selection for composite production, identification of composite manufacturing process, density, microstructure studies, tensile of the AZ91D and its composites of the present research are detailed.

FABRICATION OF AMCs

Two-step stir casting route is used to fabricate the AZ91D+B4C+ZrO2 hybrid MMCs. It is the simplest method for composite preparation. The AZ91D metal matrix and the reinforcements (B4C) used for casting. Reinforcement and molten alloy have poor wet ability. The hard ceramic particles float on the aluminium

Composition (AZ91D+B4C+Zr02)	$AZ_{91}D$ (weight%)	B_4C (weight %)	ZrO_2 (weight %)
$AZ_{91}D$	100	0	0
AZ91D+3%B4C	97	3	0
AZ 91D+3%B4C+2%ZR02	95	3	2

Table: Calculated Weighted Amount of AZ91D+B4C+Zr02

molten surface because of the surface gas layers around the particles. In the two-step stir casting method, surface gas layer around the hard reinforcement particles is removed in the first step and the particle distribution into molten metal is improved in the second step (Zhou & Xu 1997). The proportion of the AZ91D matrix and the reinforcement of B4C and ZrO2 materials are determined by calculating the weight percentages. 3% and 2% of hard reinforcement particles are added into the AZ91D to prepare AZ91D - B4C and AZ91D - B4C+ ZrO2 hybrid composite material. The composition details of the hybrid metal matrix composites are given in Table.

Muffle furnace is used to melt AZ91D and fire-resistant stirring motor arrangement with speed regulator is used to perform the stirring process. Stir casting setup for AZ91D hybrid composite preparation is shown in Figure. The AZ91D material is first heated above the liquids temperature to melt completely. It is then slightly cooled below the liquid temperature to maintain the slurry in the semi-solid state. Preheated B4C and ZrO2 particles are added into AZ91D molten metal and mixed manually. Then the composite slurry is reheated to a liquid state and mechanical mixing is carried out for about 10 min at an average mixing speed of 200 rpm. The final temperature is controlled to be within 750°C±10 °C. Finally, the composite is transferred to a mild steel die with a dimension of 200x 120 x 25 mm as shown in Figure

STIR CASTING

4. DESIGN OF EXPERIMENTS WITH SIMULATION TOOL

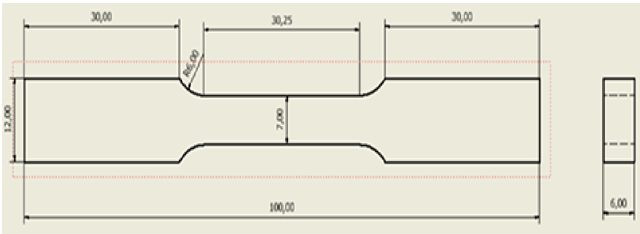


Figure ASTM E8 Tensile Specimen,

STATIC ANALYSIS USING FEA

It is very difficult for human brain to examine critically the behavior of a complex structure subjected to different conditions. To overcome this, scientists started to divide the complex structure into individual components, whose behavior can be understood intuitively. This individual component is then assembled to study the behavior of the entire structure. This method of discretizing a complex structure and then making analysis on it is termed as Finite Element Method.

Need for Finite Element Analysis

The tendency of structure or a component in a machine to fail increased with the complexity of structure. This necessitated the analysis of the machine during design, a building before and after construction, to ensure proper functioning and reduce production losses. The analysis becomes difficult and time consuming as the complexity of the model increases. This dictated the need for an efficient method that gives a reasonably good result and require less time. Finite element methods give possible solutions to such problems and are much widely in use because the techniques can be adapted to digital computers. In many situations, an adequate model is obtained by dividing it into a finite number of well-defined components called elements. Such problems are termed discrete. Whereas in some cases, the discretization is finite and can only be defined by fictional mathematical equations. Such problems are termed continuous. It becomes difficult to solve such equations even by fast digital computers. This imposed the need for finite element methods, which uses equations that can be solved easily by the computers. All these factors called for a need for Finite Element Methods.

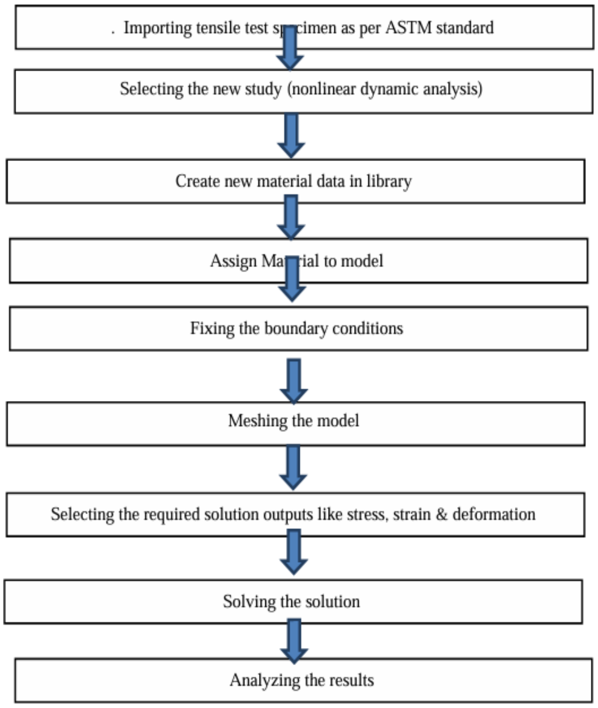
Introduction about Ansys:

Ansys R19.2 Mechanical finite element analysis software is used to simulate computer models of structures, electronics, or machine components for analyzing strength, toughness, elasticity, temperature distribution, electromagnetism, fluid flow, and other attributes. Ansys is used to determine how a product will function with different specifications, without building test products or conducting crash tests. For example, Ansys software may simulate how a bridge will hold up after years of traffic, how to best process salmon in a cannery to reduce waste, or how to design a slide that uses less material without sacrificing safety. Most Ansys simulations are performed using the Ansys Workbench system, which is one of the company's main products. Typically, Ansys users break down larger structures into small components that are each modelled and tested individually. A user may start by defining the dimensions of an object, and then adding weight, pressure, temperature and other physical properties. Finally, the Ansys software simulates and analyzes movement, fatigue, fractures, fluid flow, temperature distribution, electromagnetic efficiency and other effects over time. Ansys also develops software for data management and backup, academic research and teaching. Ansys software is sold on an annual subscription basis.

Step by Step procedure in Static Structural Analysis:

There are many steps involved in the Ansys for structural Analysis is given below in the form of flow chart.

Flow chart of solid works explicit dynamic Analysis



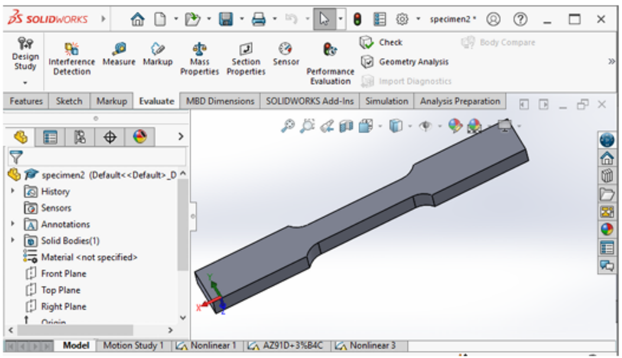
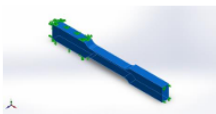
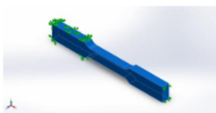
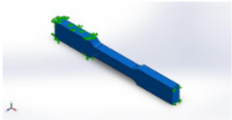


Fig. Solid modelling

Properties of composite materials:

Model Reference	Properties
	**Name:** **AZ91D** Yield strength: 7.1e+07 N/m^2 Tensile strength: 6.21e+07 N/m^2 Elastic modulus: 2.62953e+09 N/m^2 Poisson's ratio: 0.35 Mass density: 1,809.1 kg/m^3 Shear modulus: 0 N/m^2 Thermal expansion coefficient: 2.5e-05 /Kelvin
Model Reference	Properties
	**Name:** **AZ91D +3%B4C** Yield strength: 7.5e+07 N/m^2 Tensile strength: 1.091e+08 N/m^2 Elastic modulus: 2.62959e+09 N/m^2 Poisson's ratio: 0.35 Mass density: 1,821.38 kg/m^3 Shear modulus: 0 N/m^2 Thermal expansion coefficient: 2.5e-05 /Kelvin

Model Reference	Properties
	Name: AZ91D +3%B4C +2% ZrO2 Yield strength: 7.864e+07 N/m^2 Tensile strength: 1.95229e+08 N/m^2 Elastic modulus: 2.63e+09 N/m^2 Poisson's ratio: 0.35 Mass density: 1,934.98 kg/m^3 Shear modulus: 0 N/m^2 Thermal expansion coefficient: 2.5e-05 /Kelvin

Analytical Results:

$AZ_{91}D$:

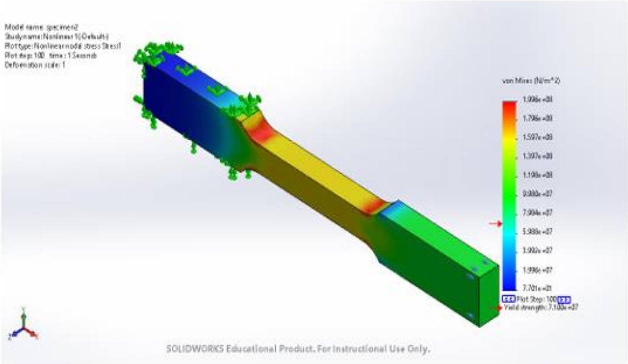


Fig. Yield and **Equivalent** stress:

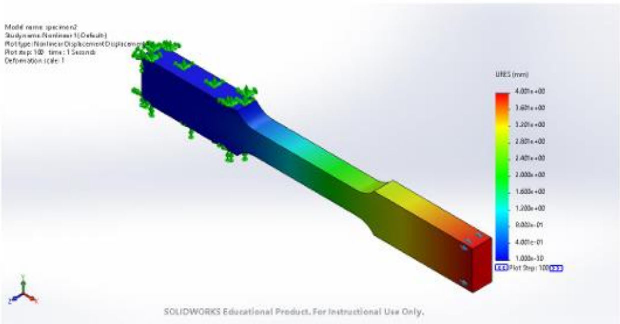


Fig. **Total Deformation:**

Analytical results of $AZ_{91}D$+3%B_4C:

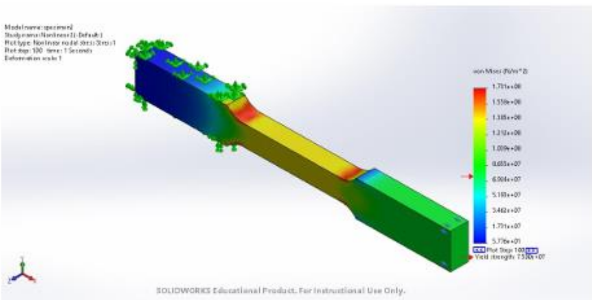


Fig. **Yield and Equivalent stress**

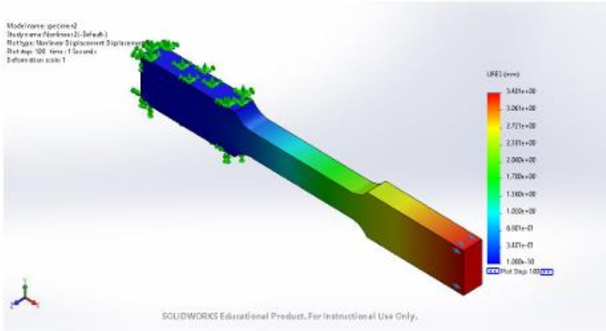


Fig. Total Deformation

Analytical results of $AZ_{91}D$+3%B_4C + 2%ZrO_2

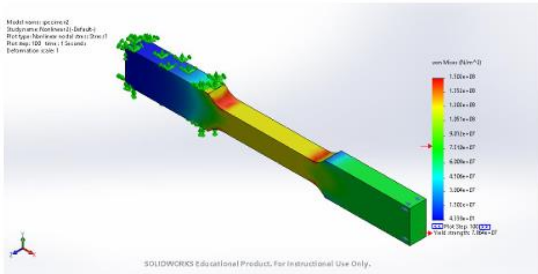


Fig. Equivalent Von-Mises Stress

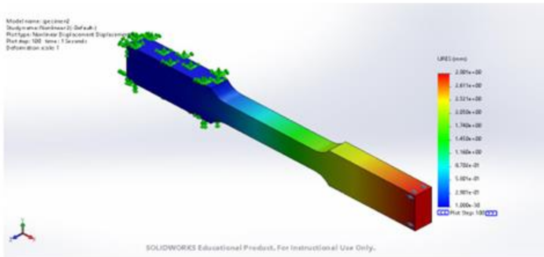
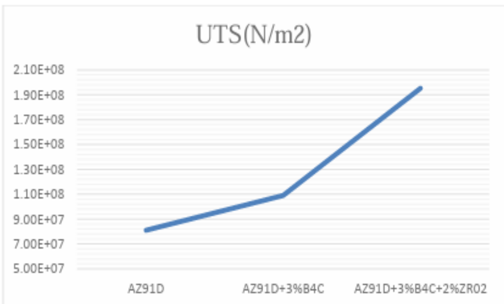


Fig. Total Deformation

5. Finite Element Analysis Results:

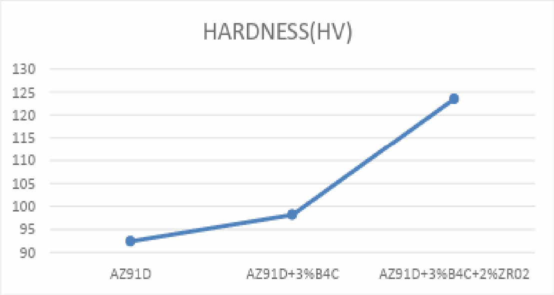
Ultimate tensile strength:

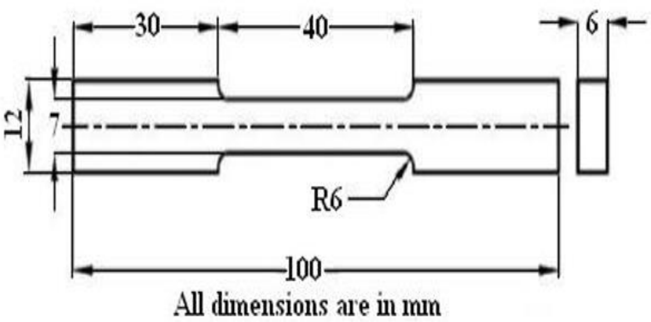
Specimen	UTS(N/m2)
AZ91D	8.10E+07
AZ91D+3%B4C	1.09E+08
AZ91D+3%B4C+2%ZR02	195229000



MICRO HARDNESS:

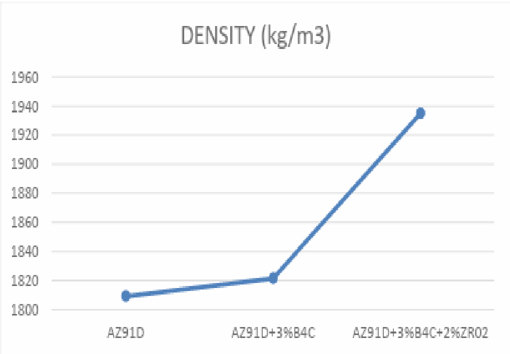
Specimen	HARDNESS(HV)
AZ91D	92.38
AZ91D+3%B4C	98.15
AZ91D+3%B4C+2%ZR02	123.5





DENSITY:

Specimen	DENSITY (kg/m3)
AZ91D	1809.1
AZ91D+3%B4C	1821.3815
AZ91D+3%B4C+2%ZR02	1934.9815



6. MICROHARDNESS TESTING :

Tensile Testing:

Tensile strength is one of the mechanical properties; it is tested as per the ASTM E8M- 13a sub size standard shown in Figure. From the casted composite, 6mm thickness of rectangular bar given in Figure is cut and sliced into four pieces. In CNC machine, the sliced samples are machined and the tensile test samples are prepared as per the standard size shown in Figure. The tensile test sample prepared is shown in Figure. The test is done with the computerized universal testing machine with the strain rate of 1 mm/min. Four tests are conducted for each composition and the result and values re averaged

Figure break the specimen after applied load

Specimen	UTS(N/m2)
$AZ_{91}D$	8.10E+07
$AZ_{91}D$+3%B_4C	1.09E+08
$AZ_{91}D$+3%B_4C+2%ZrO_2	195229000

Experimental values of Ultimate tensile strength

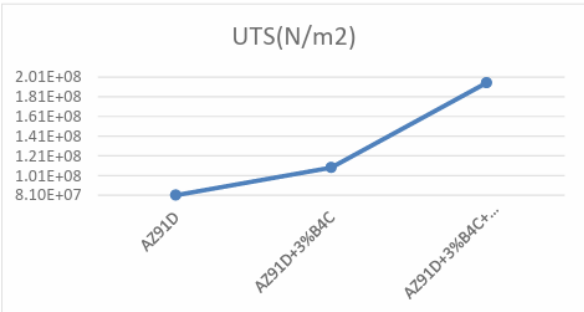
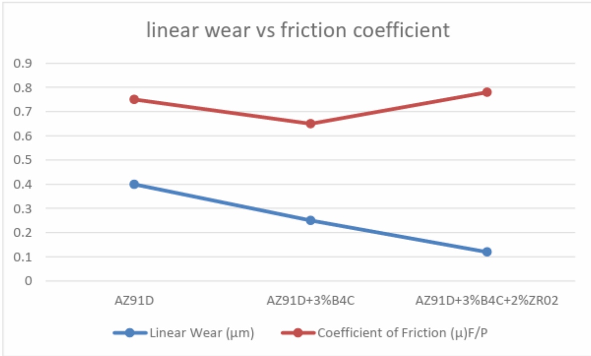


Figure shows the graphical representation of UTS of developed samples. From fig. we observed that whereas increasing B4C contents in AZ91 magnesium alloy ultimate tensile strength values faintly increased, also increasing ZrO2 content into AZ91D magnesium composite ultimate tensile strength of the sample faintly Increased. This is because of hard ceramic B4C and ZrO2 elements.

Figure :Pin on Disc Friction and wear test rig

$$Wear\ rate = \frac{Mass\ Loss/Density}{sliding\ distance}$$

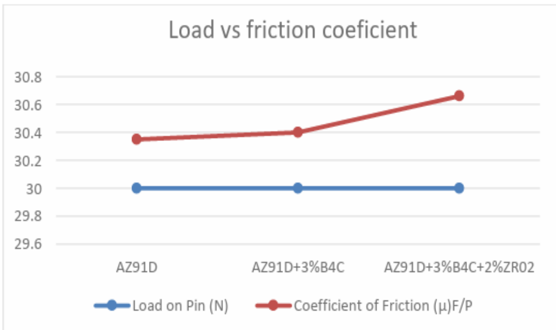
Figure: Specimen after the Tensile Test

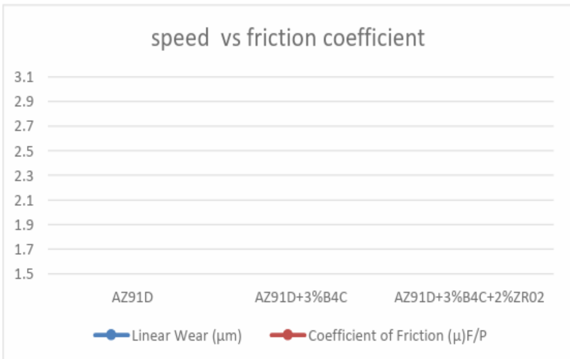


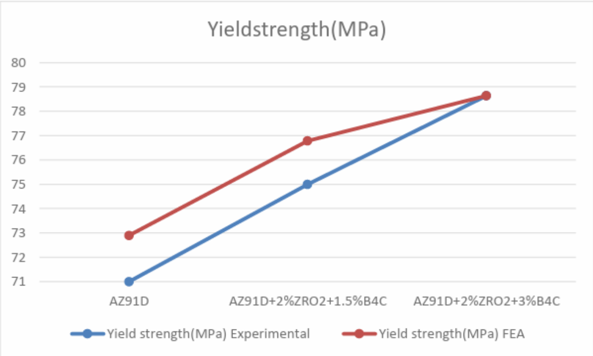
Observation

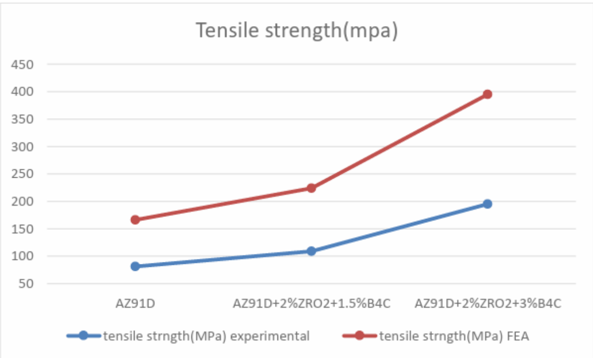
Specimen Material	Load on Pin	Speed	Frictional Force (F)	Linear Wear	Surface Speed (S)	Frictional Torque (T)	Frictional Power (P)	Coefficient of Friction (μ)	Rate of Wear
	N	RPM	N	μm	$\frac{\pi DN}{60}$ m/min	FxR Nm	$\frac{2\pi NT}{60}$ Watts	F/P	microns/min
AZ91D	30	200	0.22	0.4	1.5072	0.01584	0.331584	0.35	0.026
AZ91D+3%B4C	30	200	0.34	0.25	1.5072	0.02448	0.512448	0.4	0.016
AZ 91D+3%B4C+2%ZR 02	30	200	0.56	0.12	1.5072	0.04032	0.844.32	0.66	0.008

Time period = 15 min Rate of Wear = Linear Wear / Time Period =









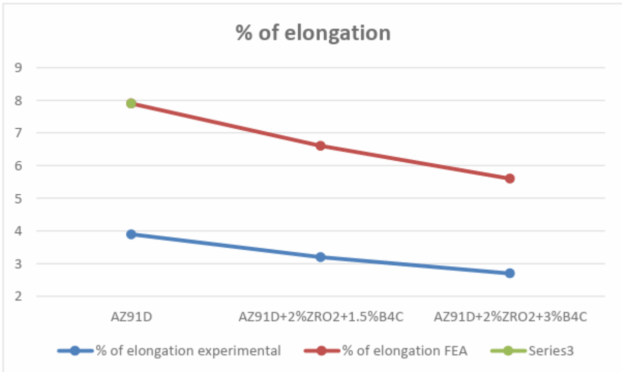
Specimen Material	Load on Pin (N)	Speed(RPM)	Frictional Force (F)	Linear Wear (μm)	Surface Speed (S)	Coefficient of Friction (μ)F/P	Rate of Wear microns/min
$AZ_{91}D$	30	200	0.22	0.4	1.5072	0.35	0.026
$AZ_{91}D$+3%B_4C	30	200	0.34	0.25	1.5072	0.4	0.016
AZ_91D+3%B_4C+2%Zr02	30	200	0.56	0.12	1.5072	0.66	0.008

Wear Test:

Dry sliding wear experiments are conducted on the AZ91D and its composites AZ91D+3%B4C and AZ91D+3%B4C+2% ZrO2 samples as per ASTM-G99 standard, using a computerized pin-on-disc friction and wear test rig (Make: Magnum) shown in Figure . The technical specifications of wear test machine are given in Table. The wear pin samples are machined from the AZ91D and its composites AZ91D+B4C, and AZ91D+B4C+ZrO2. Wear tests are conducted on 6×6 mm pin and 100 mm height square specimen as shown in Figure against a rotating (high carbon EN-32 steel) disc having a hardness of HRC62 and diameter of 220 mm. Wear pin sample contact surfaces are polished by polishing machine to make sure about 100% of contact between wear pin and rotating disc surfaces. After every test, the rotating disc (counter face) is cleaned by using acetone to remove the debris. Before and after every test, the pin masses are calculated by using an electronic weighing scale with an accuracy of 0.0001g. From the literature, the wear test parameters like applied load, sliding distance and sliding velocity are identified and presented in Table . In every wear test,
the speed, linear wear and frictional force is recorded from display.

7. COMPARISION OF EXPREIMENTAL VS FEA RESULTS:

Specimen	Yield strength (MPa)		% Of error	tensile strength (MPa)		% Of error	% of elongation		% Of error
	Experimental	FEA Result		Experimental	FEA Result		Experimental	FEA Result	
AZ91D	71	72.9	2.61	81	85	4.71	3.9	4	2.50
AZ91D+3%B4C	75	76.78	2.32	109	115	5.22	3.2	3.4	5.88
AZ91D+3%B4C+2%ZR02	78.64	78.64	0	195	200	2.50	2.7	2.9	6.90



8. CONCLUSION:

Effect Of Reinforcement On Hardness:

The reinforced composites had higher hardness compared to the base material. While AZ91D had an average hardness of 92.38 HV, the 3% B4C showed an average hardness of 98.15 HV, the 3% B4C+ 2% ZrO2 composite showed the highest value of hardness with 123.5 HV. It is known that ceramic particles in reinforced composite materials played a role in increased hardness.

Effect Of Reinforcement On Tensile:

Strength The tensile tests were conducted under similar environment conditions. While the AZ91D material displayed the lowest tensile resistance with 8.10×107 N/m2, the 3% B4C composite had the value at 10.9×107 N/m2, the 3% B4C+2% ZrO2 composite had the highest value at 19.5×107 N/m2. This study thus demonstrated that in B4C and ZrO2 composites, tensile strength tends to increase with increasing B4C and ZrO2 reinforcement ratio.

Effect Of Reinforcement On Wear:

When compared to the base alloy, the addition of B4C decreased the wear from 0.026 to 0.016 micron/min. A 38% decline in wear is observed, this proves B4C is a good reinforcement that works against the wear. The addition of ZrO2 further decreased the wear to 0008 micron/min. A 50% decline in wear relative to the second test and 69.2% decline in wear relative to the test performed on base alloy is observed. The more rapid decrease in wear by the addition of ZrO2 may be attributed due to grain refinement provided by the Zirconium particles making it much more wear resistant.

Effect Of Reinforcement On Coefficient Of Friction:

The coefficient of friction remained constant (i.e. Independent of reinforcement) because it depends on frictional force and frictional power alone whose ratio nullifies the effect of frictional force. Hence, it only depends on RPM of the disk and the Radius.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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