Experimental Investigation of B_4C/Al Metal Matrix Composite for Enhanced Mechanical Properties

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Abstract— The objective of this study is to investigate the tribological and mechanical behavior of boron carbide reinforced aluminum matrix (AA 7010) composite. The aim of this study is to investigate the mechanical and tribological behavior of AA 7010 / Boron Carbide (B_4C) composites under dry sliding conditions. Aluminum 7010 alloy is chosen as matrix alloy, in which zinc is the main alloying element. Response surface methodology provides the predicting equation and it shows the optimal dry sliding condition for the optimum hybrid composition. Aluminum has a combination of properties that makes it one of the most versatile of all engineering materials. It can be alloyed with other elements to get a customized set of mechanical properties. Aluminum alloy AA 7010 is one such combination which provides medium to high strength, good formability and good corrosion resistance along with low density. Boron carbide is third hardest of all materials with a density of 2.54 g/cm3. The Boron carbide reinforced aluminum metal matrix composite was prepared through liquid casting technique. Various Volume % of B_4C is added with AA 7010. There is a possibility of increasing the hardness and other mechanical properties of aluminum or aluminum alloys without affecting the overall weight of the component by developing aluminum matrix composites. In the present study boron carbide particles were dispersed in AA 7010 matrix forming a new aluminum matrix composite. For improving wettability, the K2TiF6 flux was added. The cast composites were undergone T6 heat treatment. The heat treated AA 7010 / B_4C composites will be further processed Mechanical tests.

Key words: Boron Carbide, Aluminum, Mechanical Properties, Metal Matrix Composite

I. INTRODUCTION

A. Mathematical Analysis

Taguchi method is a scientifically disciplined mechanism for evaluating and implementing improvements in products, processes, materials, equipment, and facilities. These improvements are aimed at improving the desired characteristics and simultaneously reducing the number of defects by studying the key variables controlling the process and optimizing the procedures or design to yield the best results.

The method is applicable over a wide range of engineering fields that include processes that manufacture raw materials, sub systems, products for professional and consumer markets. In fact, the method can be applied to any process be it engineering fabrication, computer-aided design, banking and service sectors etc. Taguchi method is useful for 'tuning' a given process for 'best' results.

B. Response Surface Methodology

RSM is a collection of statistical and mathematical techniques useful for the development, improvement and optimization of processes and / product. The first step is to find a suitable approximation for the true functional relationship between responses of interest „y" and a set of controllable variables(x_1, x_2, x_n). Usually when the response function is not known or non-linear, a second-order model is utilized.

C. Tribology

Tribology is the science and engineering of interacting surfaces in relative motion. It includes the study and application of the principles of friction, lubrication and wear. Tribology is a branch of mechanical engineering and materials science.

1) Applications

The study of tribology is commonly applied in bearing design but extends into almost all other aspects of modern technology, even to such unlikely areas as hair conditioners and cosmetics such as lipstick, powders and lip gloss.

Any product where one material slides or rubs over another is affected by complex tribological interactions, whether lubricated like hip implants and other artificial prostheses, or un lubricated as in high temperature sliding wear in which conventional lubricants cannot be used but in which the formation of compacted oxide layer glazes have been observed to protect against wear. Tribology plays an important role in manufacturing. In frequent tool replacement, loss of tolerance as tool dimensions shift, and greater forces required to shape a piece. The use of lubricants which minimize direct surface contact reduces tool wear and power requirements metal-forming operations, friction increases tool wear and the power required to work a piece. This results in increased costs due to more.

D. Wear Behavior

Wear is related to interactions between surfaces and more specifically the removal and deformation of material on a surface as a result of mechanical action of the opposite surface .The need for relative motion between two surfaces and initial mechanical contact between asperities is an important distinction between mechanical wear compared to other processes with similar outcomes.

1) Types of Wear

The study of the processes of wear is part of the discipline of tribology. The complex nature of wear has delayed its investigations and resulted in isolated studies towards specific wear mechanisms or processes. Some commonly referred to wear mechanisms are listed below.

- Adhesive wear
- Abrasive wear
- Surface fatigue

- Fretting wear
- Erosive wear

E. Aluminum

The aim involved in designing metal matrix composite material is to combine the desirable attributes of metals and ceramics. The addition of high strengths, high modulus refractory particles to a ductile metal matrix produce a material whose tribological properties and mechanical properties are intermediate between the matrix alloy and the ceramic reinforcement.

Aluminum is the most abundant metal in the Earth's crust and the third most abundant element after oxygen and silicon. It makes up about 8% by weight of Earth's solid surface.

1) Atomic Structure of Aluminum

The chemical symbol of aluminum is Al, the atomic number 13. This shows aluminum atom is composed of 13 electrons, each having a unit negative electrical charge, arranged in three orbits around a highly concentrated nucleus having a positive charge of 13. The three electrons in the outer orbit give the aluminum atom a valence or chemical combining power of +3.

2) Crystal Structure

When metals change from the molten to the solid state, they assume crystalline structures. The atoms arrange themselves in definite ordered symmetrical patterns which are "lattice" structures. Aluminum has face-centered-cubic arrangement of atoms, so it has ductile nature. This means that the atoms form the corners of a cube, with one atom in the center of each face. The length of the sides of the cube for high purity aluminum has been determined as 4.049 x 10-8 cm; the shortest distance between two atoms in the aluminum structure is 2. Divided by 2 x 4.049. The face centered cubic structure is one of the arrangements assumed by close packed spheres, in this case with a diameter of 4.049 x 10-8 cm, the corners of the cube being at the center of each sphere.

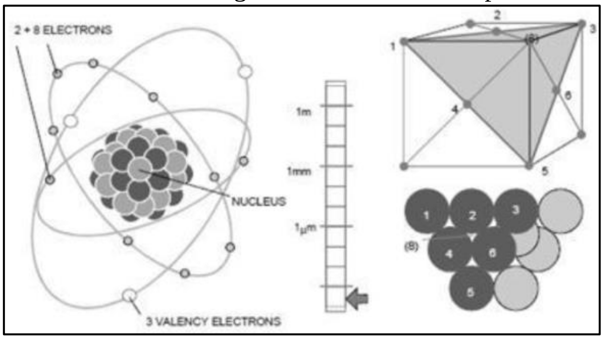

Fig. 1: Atomic Structure of Aluminum

3) Aluminum Alloys

Aluminum alloys are alloys in which Aluminum is the predominant metal. The typical alloying elements are copper, magnesium, manganese, silicon and zinc. There are two principal classifications, namely casting alloys and wrought alloys, both of which are further subdivided into the categories heat-treatable and non-heat treatable. About 85% of aluminum is used for wrought products, for example rolled plate, foils and extrusions.

Cast aluminum alloy yields cost effective products due to its low melting point, although they are generally have lower tensile strength than wrought alloys. The most important cast aluminum alloy system is Al-Si, where the high levels of silicon (4.0%-13%) contribute to give good casting characteristics.

Aluminum alloys are widely used in engineering structures and components where light weight or corrosion resistance is required.

Wrought aluminum alloys are used in the shaping processes, rolling, forging, extrusion, pressing, stamping. Cast aluminum alloys are comes after sand casting, permanent mold casting, die casting, investment casting, centrifugal casting, squeeze casting and continuous casting.

F. Composite Materials

Composites are materials in which two phases are combined, usually with strong interfaces between them. They usually consist of continuous phase called the matrix and discontinuous phase in the form of fibers, whiskers or particles called the reinforcement.

Composite materials are gaining wide spread acceptance due to their characteristics of behavior with their high strength to weight ratio. The interest in metal matrix composites (MMCs) is due to the relation of structure to properties such as specific stiffness or specific strength. Like all composites, aluminum matrix composites are not a single material but a family of materials whose stiffness, density, thermal and electrical properties can be tailored. Composite materials are high stiffness and high strength, low density, high temperature stability, high electrical and thermal conductivity, adjustable coefficient of thermal expansion, corrosion resistance, improved wear resistance, etc., The matrix holds the reinforcement to form the desired shape while the reinforcement improves the overall mechanical properties of the matrix. When designed properly, the new combined material exhibits better strength than would each individual material.

1) Classification of Composites based on Phases

Composite material is a material composed of two or more distinct phases (matrix phase and dispersed phase) and having bulk properties significantly different from those of any of the constituents.

a) Matrix Phase

The primary phase, having a continuous character, is called matrix. Matrix is usually more ductile and less hard phase. It holds the dispersed phase and shares a load with it.

b) Dispersed (Reinforcing) Phase

The second phase (or phases) is embedded in the matrix in a discontinuous form. This secondary phase is called dispersed phase. Dispersed phase is usually stronger than the matrix, therefore it is sometimes called reinforcing phase.

Many of common materials (metal alloys, doped Ceramics and Polymers mixed with additives) also have a small amount of dispersed phases in their structures, however they are not considered as composite materials since their properties are similar to those of their base constituents.

2) Classification of Composites based on Matrix Material

There are two classification systems of composite materials. One of them is based on the matrix material (metal, ceramic, and polymer) and the second is based on the material structure.

a) Metal Matrix Composites (MMC)

Metal Matrix Composites are composed of a metallic matrix (aluminum, magnesium, iron, cobalt, copper) and a dispersed ceramic (oxides, carbides) or metallic (lead, tungsten, molybdenum) phase.

3) Classification of Composite Materials based on Reinforcement Material Structure

– Particulate Composites
– Laminated Composites

G. Introduction to Reinforcement

The reinforcement material is embedded in to a matrix. The reinforcement does not always serve a purely structural task (reinforcing the compound), but is also used to change physical properties such as Wear resistance, friction coefficient or thermal conductivity. The reinforcement can be either continuous or discontinuous. Discontinuous MMCs can be isotropic and can be worked with standard metal working techniques such as extrusions, forging or rolling.

In addition they may be machined using conventional techniques but commonly would need the use of poly crystalline diamond tooling (PCD); continuous reinforcement uses monofilament wires or fibers such as carbon fiber or silicon carbide. Because the fibers are embedded into the matrix in a certain direction, the result is an anisotropic structure in which the alignment of the material affects its strength. One of the first MMCs used boron filament as reinforcement. The most common reinforcing material in this category is alumina and silicon carbide.

Non-Metallic	Metallic
Alumina	Beryllium
Boron	Niobium
Silicon Carbide	Stainless steel

Table 1: Reinforcement of Aluminum Alloy

H. Processing of MMCs

Accordingly to the temperature of the metallic matrix during processing of fabrication of MMCs can be classified into three categories.

– Liquid phase processes
– Solid state processes
– Two phase processes

I. Micro Structural Analysis

Microstructure is defined as the structure of a prepared surface or thin foil of material as revealed by a microscope above 25X magnification. The microstructure of the material which can be broadly classified into metallic, polymeric, ceramic and composite can strongly influence the physical properties of such as strength , toughness, ductility, hardness, corrosion resistance, high/low temperature behavior, wear resistance, and so on, which in turn govern the application of these materials in industrial practice.

J. Scanning Electron Microscope

SEM stands for scanning electron microscope. The SEM is a microscope that uses electrons instead of lights to form an image. Since, their developments in the early 1950"s scanning electron microscope have developed new areas of study in the medical and physical science communities. The SEM has allowed researchers to examine a much bigger variety of specimens.

The scanning electron microscope has many advantages over traditional microscopes. The SEM has a large depth of field, which allows more of a specimen to be in focus at one time. The SEM also has much higher resolution, so closely spaced specimens can be magnified at much higher levels. Because the SEM uses electromagnets rather than lenses, the researcher has much more control in the degree of magnification. All of these advantages, as well as the actual strikingly clear images, makes the scanning electron microscope is one of the most useful instruments in research today.

II. METHODOLOGY

A. Introduction

This chapter presents the materials used for wear testing under different testing conditions and with various chemical compositions. The different specimens used for wear test are listed below,

1) AA6061alloy
2) AA6061-2 wt. % Al2O3 – 5 wt. % graphite
3) AA6061-4 wt. % Al2O3 – 5 wt. % graphite
4) AA6061-6 wt. % Al2O3 – 5 wt. % graphite
5) AA6061-8 wt. % Al2O3 – 5 wt. % graphite

– Chemical composition

The materials used for testing the mechanical and wear properties are of various compositions. The base materials used are aluminum 6061.

These materials mainly constitute of Magnesium (Mg) and Silicon (Si). And other elements are Zinc (Zn), Copper (Cu), Manganese (Mn), Iron (Fe), Chromium (Cr), Titanium (Ti).

In wear test, counter body used is Oil Hardened Nickel Steel or Oil Hardened Non-Shrinking Steel (OHNS). The chemical composition of OHNS stainless steel also described in table 2 and 3 respectively.

Elements	Weight Percentage AA6061
Zinc	0.11
Copper	0.21
Manganese	0.04
Magnesium	0.89
Iron	0.25
Chromium	0.25
Titanium	0.1
Silicon	0.6
Aluminum	Remaining

Table 2: Chemical Composition of AA6061 & AA7075

Elements	Weight Percentage AA6061
Carbon	0.95
Manganese	1.15
Chromium	0.5
Tungsten	0.5
Vanadium	0.2
Iron	Remaining

Table 2: Chemical Composition of OHNS Steel

B. Specimen Preparation

1) Casting Method

For composite preparation the route used to cast is Stir Casting method. This is a liquid state method of composite materials fabrication, in which a dispersed phase (ceramic particles, short fibers) is mixed with a molten matrix metal by means of mechanical stirring.

Stir Casting is the simplest and the most cost effective method of liquid state fabrication. The liquid composite material is then cast by conventional casting methods and may also be processed by conventional Metal forming technologies.

Here the base metal aluminum alloy is transferred to molten state and the preheated reinforcement materials also in molten form are mixed. To obtain the uniform distribution of reinforced material over metal matrix the continuous stirred till they completely mix to form MMCs.

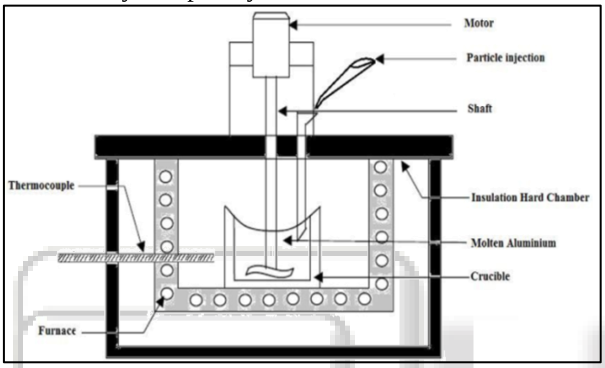

Fig. 2: Layout of Stir Casting

Then, the molten composite is poured on a metal mold and allow it solidify. The various composites were prepared using stir casting method are explained below,

2) AA6061- Al2O3-Graphite Composites

The 6061 aluminum alloy is used in this experiment as the matrix material. The conventional casting technique was used for this composite material preparation.

Aluminum alloy of 1.5Kg is melted in a graphite crucible furnace and the preheated graphite particles are introduced into the stirred molten aluminum alloy which is maintained at approximately 150ºC above the liquid us temperature. The stirring of the liquid metal ensured a uniform distribution of the SiC particles over the molten aluminum. After the complete addition of the SiC particles, the graphite preheated particles are added. The stirring was stopped and the metal is degassed and poured into the permanent steel mold and solidified.

The composite material casting are made with SiC particles at 2, 8, 6 and 8 Wt %. The prepared the matrix alloy specimens are heat treated to T6 condition. And the specimens are prepared as per the requirements of testing methods.

3) OHNS Stainless Steel

The OHNS stainless steel disc also prepared to act as counter body in wear test. To obtain the standard results the standard counter body is used. And it has the density of 8670Kg/m3. The hardness of OHNS steel is 62 HRc.

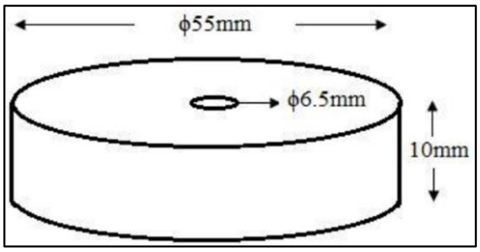

Fig. 3: Dimension of OHNS Disc

C. Testing Methods

1) Wear Test

A pin on disc apparatus is used to investigate the dry sliding wear characteristics of the aluminum alloy and the composites. Wear specimens are of 10 mm diameter and 15 mm height were cut from as cast samples and machined and polished metallographic ally for wear test. Wear tests are conducted at room temperature (29°C) and humidity of 65% - 70% with an applied load of 10N, 20 and 40N and with sliding speed of 0.6, 0.8 and 1.0 m/s with the sliding distance of 500m, 1000m, 1500m and 2000m and under no lubricated condition with a wear track diameter of 30 mm.. The initial disc of hardness 62 HRc under loaded condition. The frictional traction encounter by the pin in sliding is measured by a PC based data logging system. On completion of the running through the required sliding distance the specimen pins are cleaned with acetone, dried and the weight is again determined for ascertaining the weight loss.

Before each test, the disc surface was polished with grade 220 SiC paper to a Central line average (CLA) value of 2 µm. Digital weighing balance with a precision of ± 0.1 mg is used for determining the weight of the pins before and after the wear test. Weight of the specimen was determined in a digital balance with a precision of ± 0.1 mg. The pin was kept pressed against a rotating OHNS.

2) SEM Experiment

The scanning electron microscope (SEM) is a type of electron microscope that images the sample surface by scanning it with a high energy beam of electron in a raster scan pattern. The electrons interact with the atoms that make up the sample producing signals that contain information about the sample's surface topography, composition and other properties such as electrical conductivity.

The types of signals produced by an SEM include secondary electron, back scattered electron (BSE), characteristic X-rays, Light specimen current and transmitted electrons. These types of signal all require specialized detectors. The signal results from interactions of the electron beam with atoms at or near the surface of the sample.

In the most common or standard detection mode, secondary electron imaging (SEI), the SEM can produce very high resolution images of a sample surface, revealing details about 1ηm to 5ηm in size. Due to the way these images are created, SEM micrographs have a very large depth of field yielding a characteristic three dimensional appearance useful for understanding the surface structure of a sample.

Metallographic samples were prepared from the T6 heat treated composites by using grinders. The worn surfaces were analyzed by using HITACHI –S3400 Scanning electron microscope.

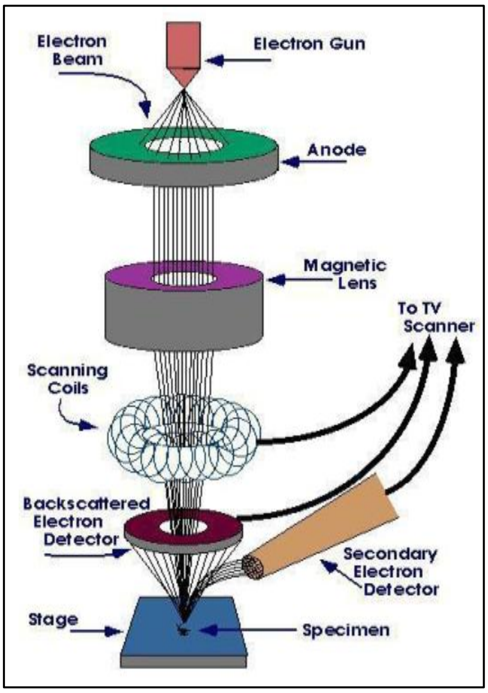

Fig. 4: SEM Working

3) Tensile Strength

The tensile strength test was conducted in UTM and results were listed in the table and graphically represented. From these results, it shows that the addition of Al2O3 content with graphite to base alloy increases the tensile strength because of the hard ceramic nature of Al2O3.

Fig. 5: Tensile Strength for Hybrid Composites

D. *Experimental Procedure*

First of all, 1000 gm of commercially pure aluminum was melted in a resistance heated muffle furnace and casted in a graphite crucible. For this the melt temperature was raised to 800°C and it was degassed by purging hexachloro ethane tablets. Then the aluminium-B4C composite was prepared by stir casting route. For this we took 1000 gm of commercially pure aluminum and 5,10,15,20 Vol % of B4C. The B4C particles were preheated to 373K for two hours to remove the moisture.

Commercially pure aluminum was melted by raising its temperature to 800°C and it was degassed by purging hexachloro ethane tablets. Then the melt was stirred using a mild steel stirrer. B4C particles were added to the melt at the time of formation of vortex in the melt due to stirring.

The melt temperature was maintained at 800- 850 °C during the addition of the particles. Then the melt was casted in a steel mold. The hardness testing and density measurement will be carried out for both commercially pure Al and Al-B4C composite. The hardness of the samples will be determined by Brinell hardness testing machine with 500 kg load and 10 mm diameter steel ball indenter.

The wear characteristics of commercially pure Al and Al-B4C composite will be evaluated using wear testing machine. For this, cylindrical specimens of 6mm diameter and 10 mm length will be prepared from the cast aluminum and Al-B4C composite. The SEM and EDS analysis will be done for all the samples.

III. RESULTS & DISCUSSION

A. *Hardness*

The hardness test was conducted as per the standards. The results of hardness test were shows the addition of Al2O3 with graphite to the base alloy AA6061 increases the hardness to the maximum of 125BHN because of the hard layer of Al2O3 on the composite, which about 1.2 times higher than base alloy.

B. *Tensile Strength*

The tensile strength test was conducted in UTM and results were it shows that the addition of Al2O3 content with graphite to base alloy increases the tensile strength because of the hard ceramic nature of Al2O3.

C. *Wear Behavior*

The wear test taken from the pin-on-disc apparatus and the results of wear test, it was noticed that the AA6061/ 4 wt. % Al2O3/ 5 wt. % graphite composite as high wear resistance as compared to base alloy.

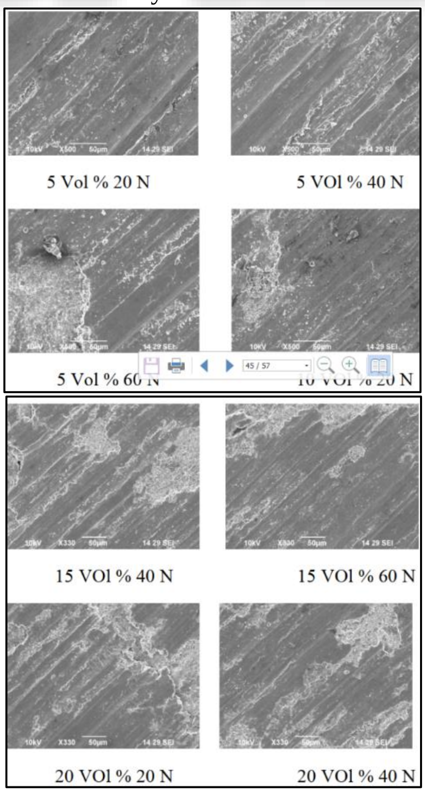

Fig. 6: Wear behavior of Different Composition

D. Response Surface methodology

The response surface methodology is used to find the optimum composite which provides minimum wear at any dry sliding condition. The constant variance for the residuals is explained by the residual versus fitted value plot while the non-correlation of the residuals to each other is explained by the residual versus the order of the data plot. The residual plots and normal probability plot explains the goodness of model fit to the observed experimental response and randomly scattered nature of the residuals.

E. SEM

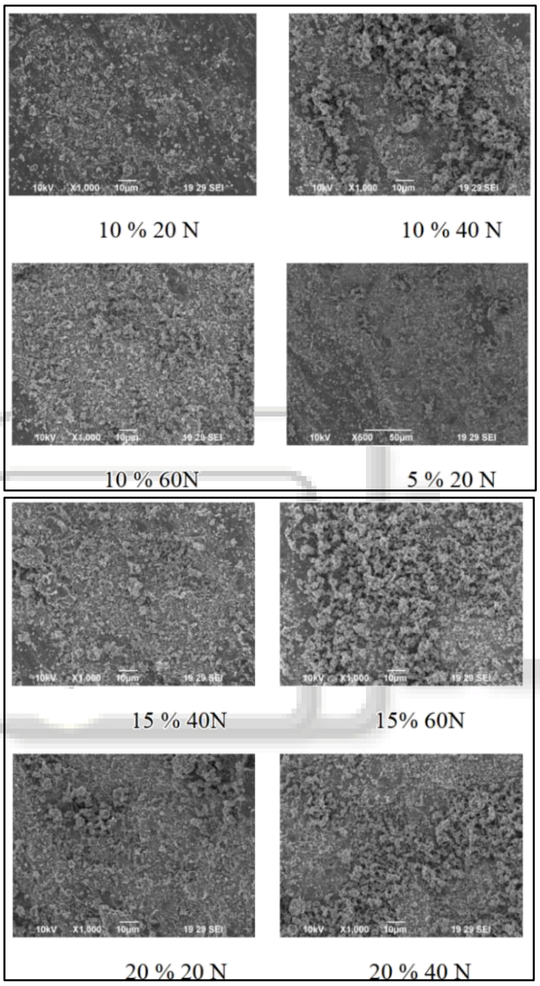

Fig. 7: SEM Structures for Different Composition

IV. CONCLUSION

Response surface methodology provides the predicting equation and it shows the optimal dry sliding condition for the optimum hybrid composition. The result will yield a better aluminum metal matrix composite with enhanced mechanical properties.

- Density and hardness measurement will be carried out for both commercially pure Al sample and Al-B4C composite sample.
- The wear characteristics of both commercially pure Al-B4C composite will be evaluated and compared.
- SEM analysis will be done for both the samples.
- EDS microanalysis will be done for all the samples.

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