RESEARCH ARTICLE

ALUMINUM BASED HYBRID NANO COMPOSITES: A REVIEW ON REINFORCEMENT, MECHANICAL AND TRIBOLOGICAL CHARACTERISTICS.

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Manuscript Info	*Abstract*

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Recent demands of advance engineering domains are satisfied by the new generation hybrid nano metal matrix composites (HNMMCs). The demands are reached due to their improved performance characteristics, reduced production cost and optimistic weight reduction factors. The behavior of these hybrid-nano metal matrix composites is depends on the mechano-chemical combination of different reinforcing particles with the metal matrix also the process parameters are associated while synthesis of these composites. This paper is an attempt to review the different combinations of hybrid nano metal matrix composites and also gives brief discussion about the major development techniques those of having control on mechanical and tribological characteristics. Further improvement on this research field is suggested.

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Introduction:-

In recent decades the modern in service performance demands the materials with broad bundle of properties, which are quite difficult to achieve using monolithic materials [1]. These demands can overcome by metal matrix composites (MMCs) offers such tailored properties like high specific strength, low coefficient of thermal expansion, good thermal resistance ,ultimate wear resistance, good damping capacity, improved corrosion resistance required by different engineering applications[1,2]

Many research efforts made to improve the properties and extend their availability in the advance field of automobile to defense, aerospace and Marian recreation industries [3].MMCs are metallic alloys reinforced with one or more ceramic materials. The particle size may vary from micro to nano depending upon applicability. Most common metallic alloy uses light metals (Al, Cu and Mg) other metallic materials like zinc (Zn) and Titanium (Ti) can be used in rare cases. Aluminum is most commonly used metallic alloy in major applications the reason is reported [4,5,6]. The property of a composite is mainly based on the reinforcement quantity, particle size and chemical reaction between matrix and reinforcement. Most challenging task is selecting right choice of reinforcing material. Considering the number of article published by the expert authors while preparing this review the importance of reinforcing material can be studied. To improve the properties of AMCs there are different parameters can be adopted they are finding alternative and cheaper reinforcement, optimizing the properties of reinforcement by

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reducing the size of particle from micro to nano scale approximately(<50μm to an average<100nm), developing composite using two or more reinforcing materials. This class is called hybrid composites.

Hybrid composites give the solution to improve the property optimization, reduced cost. Some authors reported the improved performance of hybrid composites over single reinforcement AMCs at same production cost [7]. This article is an attempt to review the studies on different combination of hybrid nano composites reinforced with different nano particles to reveal the overall performance of composites.

Different Reinforcing Materials:-

Selection of reinforcing material while developing AMCs lead to a major role. Selection is based on performance and applicability of AMCs. The final property of AMC is mainly depending on the matrix and hybrid reinforcement [8]. In major cases processing route can also affect the properties of AMCs and most of the parameters come into consideration while designing the AMCs they are shape of particle, grain size, type, young's modulus, density and hardness[9]. By the literature study on different authors publications, the combination of reinforcements used in synthesis of hybrid AMCs. The major constituent in hybrid composites is synthetic ceramic reinforcing material. To improve the performance and properties combinations synthetic with Agro waste reinforcement and also synthetic with industrial waste reinforcement were used as hybrid reinforcements [10].

AMCs with different hybrid synthetic ceramic reinforcements

Tungsten carbide (WC), Alumina (Al_2O_3),Boron carbide (B_4C), silicon carbide (SiC),Carbon nano tubes (CNT), Graphite (Gr), silicon Nitride(Si_3N_4),Zinc oxide (ZnO), Zirconia are some of the synthetic ceramic particulates that are studied[11,12-14]. Under this category the most of the research publications utilized Alumina and Silicon carbide as major constituents [15,16]. These synthetic ceramic particles expenses more and reveals good strength and stiffness against the monolithic alloys but less fracture toughness and less ductility [17-18] ceramics in application of high shock loads and different fluctuating load conditions. This overcomes by other improved synthetic ceramic particles those having required properties for different field of applications. To optimize the performance Tungsten carbide (WC), Boron carbide (B_4C), were used in other side [19]. This paper aims to reviewing importance of ceramic hybrid nano reinforcements on different engineering properties, structural properties and mechanical performance like tensile strength, compressive strength, hardness behavior and tribological properties like wear and frictional properties were studied. Under continuous evaluation of advance findings some of the literatures presented below.

T. Rajamohan et.al.,[20] Studied the synthesis of hybrid micro and nano composites reinforced aluminum matrix by sintering process. Atomized 99.5% pure aluminum powder is used as matrix alloy and micro silicon carbide (SiC 10wt %) particles and nano copper oxide (CuO 0-2wt%) particles used as a hybrid reinforcements. Characterization is done by fixed weight percentage of micro particle and by varying nano particles. Sintering is done in an electric muffler by cold pressing at typical pressure of 55 to 66 N/m². Table 1 shows the details of composition pressing and sintering data. Green compacts of blend are pressed at 1.0MN capacity punch press. These compacted surfaces coated by aluminum and dried for 7 hours. Microstructure and mechanical characterization of sintered specimen is done by Scanning Electron Microscope (SEM), X-ray Diffraction (XRD) analysis and Atomic Force Microscope (AFM) were observed. Finally they concluded that the inclusion of nano CuO particles in the AMC improves the structure and property of the composite material.

Table 1:- Sample Types, pressing and sintering data[20]

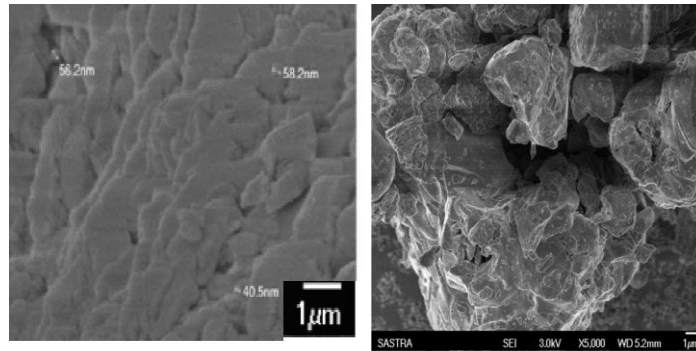| Sample type	Pressing data	Lubricant	Sintering parameters	
			Temperature in degree	Time in hours
Al+10%SiC	58.87	Kerosene	5.80	2.5
Al+10%SiC+1% nano CuO	68.71	Kerosene	5.90	3
Al+10%SiC+2% nano CuO	63.80	Kerosene	5.90	3

Figure 1:- SEM images of spherical shape copper oxide nano particles [20]

K.M Shorowordi et.al.,[21] Investigated that the interfacial characteristics between Aluminum metal matrix composites containing reinforcing particles of B_4C, SiC and Al_2O_3 (0 to 20vol %) were processed. The stir casting manufacturing route followed by hot extrusion was utilized. The study undergoes the interfacial reaction product between the Al-SiC, Al- B_4C and Al- Al_2O_3 were observed in resolution limit of SEM. By the result of this Al-SiC having clear interfacial reaction product or layer found at long processing time of >30min.The suggestion given by the author for fracture surface analysis, Al- B_4C composite seemed to exhibit a better interfacial bonding compared to Al- Al_2O_3 and Al-SiC composites.

Lakshmanan poovazhagan et.al.,[22] Worked on ultrasonic cavitation assisted casting process was used to fabricate the aluminum alloy-nano boron carbide (B_4C) metal matrix nano composites (MMNCs). The implosive effects generated by the high-intensity ultrasonic cavitations have the capacity to split the agglomerated nano particles and distributes these particles consistently in metal melts. Apart from uniformly dispersing the nanoparticles into liquid cast, the ultrasonic nonlinear effects also enhance the wettability between melt and nano reinforcements. Results shows the significant reduction in grain size was observed in A6061-2vol% B_4C.Acording to Hall-petch theory, the ability of the material increases as the grain size reduces, during the solidification the B_4C nano particles acted as Centre point for no homogeneous nucleation forms the less ductility and toughness of material. Yang, Yong et.al.[24] Investigated on same ultrasonic cavitations based manufacturing of bulk aluminum nano composites. A high power ultrasonic probe is used to disperse nano SiC particles into molten A356 aluminum alloy. Finally they concluded that the uniform particle dispersion in the matrix by ultrasonic cavitations results significantly improved mechanical properties.
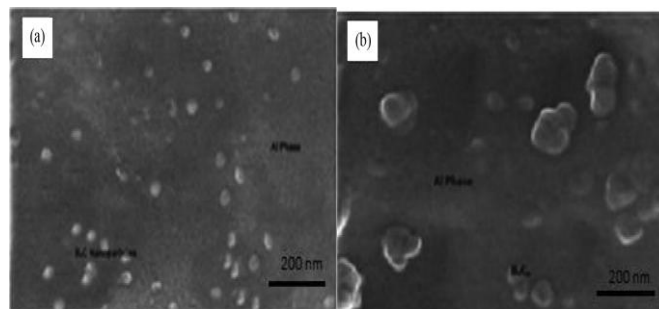

Figure 2:- (a) SEM images of Al6061-0.5vol% B4C nano particles (b) Al6061-2.5vol% B4C nano particles [22]

Pradeep L. Menezes et.al.,[24] Evaluated importance of powder metallurgy methods while synthesis of aluminum matrix nano composites reinforced graphene nano platelets. The author investigated tribological behavior of pure aluminum and graphene platelets by varying the percentage of reinforcement. The investigation results show that morphological changes in shape of Al-1wt%GNPs powder at 6 hours of milling. The shape changed from regular shape to flaky shape, as a result variation of coefficient of friction (COF) with normal load and Al-0.1wt%GNP and Al-1wt%GNP at constant sliding speed of 100rpm. The results shows that because of the insufficient solid lubricant available at the contact surface the COF does not change significantly by adding 0.1wt% of GNP to aluminum matrix. The variation in wear rate (weight loss) with normal load for pure aluminum, Al-0.1wt%GNP and Al-1wt%GNP at constant speed of 100rpm. Finally they concluded that the wear rate of Al-1wt% GNP is higher at

higher normal loads when compared to lower normal loads, and the COF of al-1wt%GNP is lower at higher normal load.
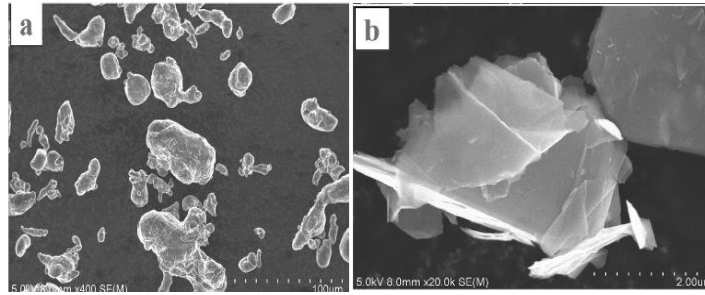

Figure 3:- SEM images of (a) as received pure aluminum powder (b) Graphene nano platelets [24]

P. Ashwath et.al.,[25] Investigated effect of ball milling and reinforcement on aluminum alloy metal matrix reinforced with SiC,Al_2O_3 and graphene particles. The average particle size of matrix is 10 microns and reinforcements are SiC,Al_2O_3 10 microns and Graphene of 10 nano microns. The matrix material used is AA2900 alloy alloyed with copper. The ball milling operation was done to mix the matrix with reinforcement to get the fine grains of uniform microstructure. The ball milling time was 20 min at a speed of 150rpm for all the reinforcements. Sintering was carried out for 550^0C for 15min in microwave sintering furnace at a rate of heating up to 10^0C per minute. The specimen after sintering time was allowed to cool up to 250^0C inside the furnace to avoid atmospheric contamination. The hardness measurement test was carried out for two different conditions, one was on the same day when the specimen was sintered other one was after 2 months. Author was observed that the hardness measurement was possible on the same day when it was sintered. The sample reinforced with SiC, Al_2O_3 were subjected to hardness test after 2 months were broke. The reason and conclusion was given by the researcher is reinforcing percentage, rate of heating in microwave furnace and aging.SEM and XRD results showed the carbide formation in the sample due to rate of heating factor. The suggestions were given by author is 2^0C heating factor which almost relevant to conventional type that over comes this issue. Graphene as a reinforcement range of 1% or less to get good and improved mechanical properties.

M. Ramachandra et.al.,[26] Studied the hardness and wear resistance of pure aluminum powder reinforced with nano ZrO_2. The process is used to synthesis the nano composites is powder metallurgy technique. First the ZrO_2 nano powder is synthesized by combustion synthesis process. Zirconyl nitrate of 5 gms with a weighed amount of fuel urea is mixed thoroughly with 25 ml of distilled water in a petri dish. By continuous stirring using mechanical stirrer of about 15 min a homogeneous solution is obtained. The crystalline dish containing the aqueous solution is placed in a preheated muffle furnace for boiling. Due to high exothermic process the boiling solution yields a aqueous solution and converts into a flaky type powder. This flaky powder is grounded to fine powder. The XRD analysis was carried out involves specimen preparation, specimen slide and activation of apparatus. Data obtained from XRD apparatus is plotted in graph with different diffraction angles $2\theta=30^0$, $2\theta=35^0$, $2\theta=50^0$ and $2\theta=60^0$. The tiny peaks which occur at certain angles corresponding impurities present in the sample powder and represents less impurities.
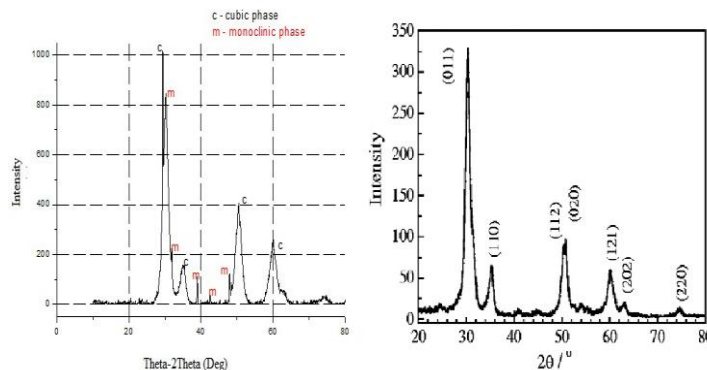

Figure 4:- (a) XRD pattern for nano-ZrO2 synthesized at 500^0C, (b) Standard nano-ZrO_2 [26].

After XRD process the nano composite was manufactured by using powder metallurgy, initially the mixture of Aluminum and nano zirconia was placed in die cavity, the load is applied of 75KN through UTM, and the compaction is carefully removed and sintered. Results show that the hardness of the n-composite is higher than that of the unreinforced aluminum. From figure it shows the decrease in wear rate of composites compared to unreinforced aluminum. Also the wear resistance increases with increase in percentage of n- ZrO_2particles. The improvement in the wear resistance that can be attributing to improve the hardness of the composites.

Amal E. Nassar et.al.,[27] Evaluated on properties of aluminum matrix nano composites synthesized by powder metallurgy process.Al-TiO_2 composites were used as matrix and reinforcement in their work. Pure aluminum powder with particle size of 15 μm and reinforcing material of 15nm were used. The volume fraction about 0.5, 1.5, 2.5, 3.5 and 4.5% mixed with matrix by ball milling. The powder mixture was compressed at room temperature at a pressure of $104N/cm^2$ for 6 min. Resultant compacts were sintered at 450^0C under argon gas. Microstructure study done by using SEM. Porosity was measured by using water displacement method by weighing in air, then in water. The porosity was calculated by Archimedes law [27].

$$V_c = W_A - W_L/\rho_w \hspace{3cm} (1)$$

Where Vc : Volume of the composite sample

$\quad$ WA: Weight of the sample in air

$\quad$ WL: Weight of the sample in liquid

ρ_w : Density of Liquid

The actual composite density ρ_c can be calculated by:

$$\rho_c = {W_A}/{V_C} \hspace{3cm} (2)$$

And theoretical density could be calculated by:

$$\rho_c = 1 \Big/ \left({W_{fp}}/{\rho_p} + {W_{fm}}/{\rho_m} \right) \hspace{2cm} (3)$$

Where W_{fm} and W_{fp} are weight fractions of the matrix and the particles respectively. ρ_m and ρ_p the density of the matrix and particles respectively.

The porosity can be estimated using the formula:

$$porosity = \rho_{th} - {\rho_c}/{\rho_{th}} \hspace{2cm} (4)$$

Tensile properties reveal the mechanical strength of the composites. The great enhancement in tensile strength was observed due to low degree of porosity and fine distribution of particles achieved by powder metallurgy route. This leads to the uniform distribution of TiO2 particles and lowest air gaps between grains. The multi-directional grain refinement and thermal stress also play a important role. The grain refinement strengthening effect of the TiO_2 particles due heterogeneous nucleation catalyst in matrix which improves by increase in volume fraction [shabani et.al. 2013]. The weakening factors in mechanical properties might be the reason for inclusion of porosity (Figure 5).
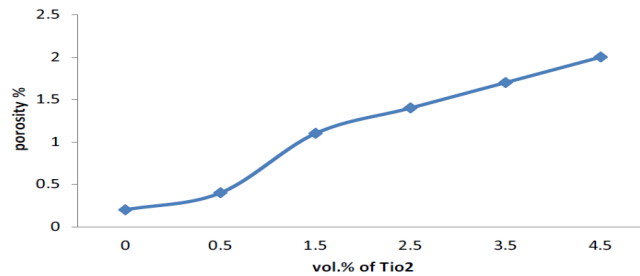

Figure 5:- variation of porosity to the volume % of Al-TiO_2 Nano composites.

Durai T. G. et.al.,[28] manufactured a powder of aluminum (99.7% purity) zinc oxide and copper oxide powder (99.5% purity, <10μm) using a high –energy ball milling (Figure 6) having tungsten balls with a diameter of 10 mm for a time period of 60 hours. A ball to powder weight ratio of 10:1 at a milling speed of 300rpm using toluene as a medium. Mechanically milled powders have been cold pressed under a pressure of 650MPa to form green compacts of 10mm diameter and 4 mm length, heating at basic temperature to initiate the reaction in argon atmosphere. The result yields improvement in wear resistance due to strong content of Al_2O_3 particles and size. Mechanical milling gives the uniform distribution of the particles. Inter- particle distance in the crystal range gives better wear resistance. Hardness of the composite drastically improved compared to the un milled composites. The wear rate linearly increases with the applied load irrespective of the material and decreases with the increasing sliding distance.
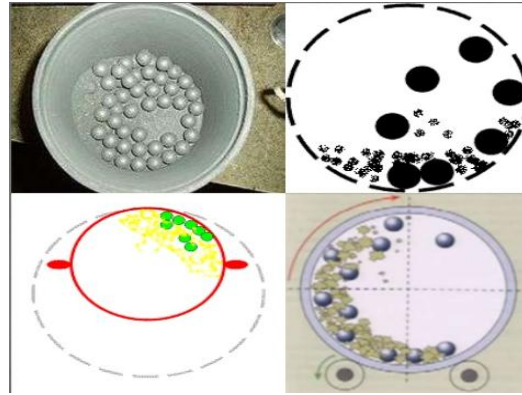

Figure 6:- High Energy ball milling to mill nano powder particles.

S. Mula et.al.,[29] Selected a micron sized Al_2O_3 powder of average size of 75μm. A commercial available pure aluminum(cp-Al) having a nominal composition of Al-0.96% Mg-0.26% Fe-0.45% was selected as a matrix material. Al_2O_3 nano powder is produced by high energy ball milling for 22 hours with a WC as a grinding media at rotation speed of 300 rpm and toluene as a PCA. Cast ingots were prepared by non- constant ultrasonic casting method (Figure 7) to cast Al-2% Al_2O_3 nano composites. Consist of a ultrasonic chamber which is having a vibrating frequency of 35kHz. A mold is partially filled with water and it is tightly fitted to ultrasonic chamber, the mold was preheated to avoid the solidification process. After preheated the mold was subjected to vibration at a frequency of 35 kHz. After that the liquid Al and nano Al_2O_3 particles (2wt %) were simultaneously poured into the vibrating mold. The vibration continued for 5 minutes to ensure completion of solidification. The ultrasonic waves in the molten metal were expected to generate a transient cavitations and acoustic streaming to cause uniform mixing of nano particles. The further Investigation was carried out to check the microstructures using optical, scanning and transmission electron microscopes. The microstructure revealed that continuous nano alumina dispersed zones(NDZs) covered the Alumina depleted zones (ADZs). The NDZs were nearly 200-300nm wide and situated near the grain boundaries. The NDZs had a dense dispersion of nano alumina particles with an average inter particle spacing of 24nm.Hardness and tensile yield strength were drastically increase in the synthesized nano composites by non-contact ultrasonic synthesis as compared with those of pure Al, as cast composites with other casting techniques.

A.R.I. Kheder et.al.,[30] explained the importance of hybrid metal matrix composites in their recent publication.
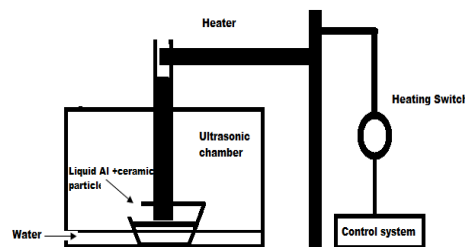

Figure 7:- Experimental set up of non-contact ultrasonic casting route for synthesis of nano composites.

Strengthening of pure aluminum alloy by reinforcing with ceramic additives like Al_2O_3, SiC and MgO particles with different compositions (Table 2). Liquid state mixing technique incorporated to evaluate properties of composites. The different combination of compositions were examined at different regions like upper middle and upper edge, middle then from the lower middle and lower edge of specimens in scanning electron microscope and high energy dispersive X-ray analysis. The strengthening properties of the each combination of composites were checked using different ASTM standard experiments. The addition of SiC, MgO and Al_2O_3 particulates into matrix alloy increased the yield strength, ultimate tensile strength and hardness, decreased elongation (Ductility) of the composites. SiC is the most effective strengthening particulate but it reduces the ductility and toughness.

Table 2:- Alloy with different compositions [30]

Melt number	Alloy with Different composition
1	Al-10wt%Si, 5wt % SiC
2	Al-10wt%Si, 7.5wt % SiC
3	Al-10wt%Si, 10wt % SiC
4	Al-10wt%Si, 15wt % SiC
5	Al-10wt%Si, 20wt % SiC
6	Al-5wt%MgO
7	Al-10wt%MgO
8	Al-15wt%MgO
9	Al-20wt%MgO
10	Al-10wt%Si, 5wt % Al_2O_3
11	Al-10wt%Si, 7.5wt % Al_2O_3
12	Al-10wt%Si, 10wt % Al_2O_3
13	Al-10wt%Si, 15wt % Al_2O_3
14	Al-10wt%Si, 20wt % Al_2O_3

Johny James S et.al.,[31] In their research the pure hybrid composite was examined for the machining and mechanical properties. Preparation of hybrid aluminum metal matrix composite was done by reinforcing with Silicon carbide (average 25 microns), Titanium di boride (average 10microns) were used for different compositions. Synthesis of composites is done by using gravity casting. The hardness test was carried out using vicker's hardness machine with 200gf for 10 seconds. To achieve reliability test minimum 10 readings were taken with standard distance of approximately 0.5mm for every indentation. The specimen of 10mm width and 30mm length polished to a surface roughness of less than one micron was used to check the tribological properties. Test was conducted at a load range of 50N and 70N respectively. Distance traveled by pin is around 720meters.Tensile property of the composite considerably reduced due to addition of TiB_2 particles. It is due to excess cluster formation which leads to porosity. The specimen exhibits ductility and considerable tensile property as it contains 10Wt%SiC and 0wt% TiB_2 graph shows that the specimen fractures at 3900N load with elongation of 0.75mm. Wear test results increase of wear properties due to addition of TiB_2 particles. Test is carried out for 60 minutes and the wear loss is calculated. Value yields the reduction in wear rate due to addition of TiB_2 particles in 10%SiC, but when addition of 5% of TiB_2 reduces the wear resistance property due to porosity cluster in that range of composition.
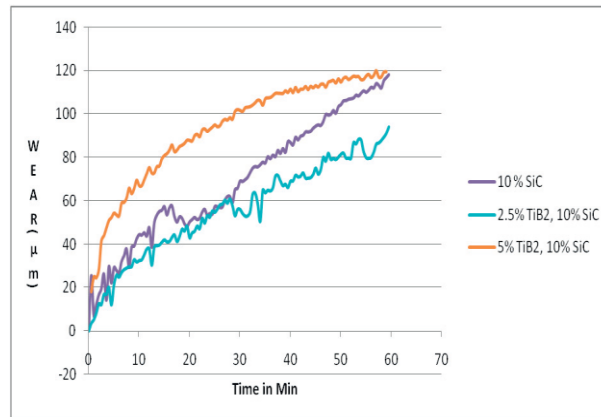

Figure 8:- Wear V/s Time [31]

Future scope:-

Metal matrix composites reinforced with different particle sizes (micro or nano) have been used in many industries, automotive, defense, aerospace sectors. Incorporation of hybrid metal matrix composites by changing ceramic additives can lead much greater increase in the strengthening properties. Further research leads to incorporation of hybrid nano metal matrix composites of as little as volume percentage drastic saves in weight and achieves exceptional properties. Great advantage for aerospace sector to incorporate the hybrid nano metal matrix composite technology in the application of aircrafts fin design as well as in guide vanes for commercial jet engines. Improved wear and erosion resistance of HNMMCs finds their application in automotive piston liners, intake and exhaust valves and in brake pads. MMNCs designed for good thermal conductivity and less coefficient of thermal expansion to match the ideal applications.

Conclusion:-

Fundamental understanding is achieved from the mechanism of synthesis evaluation and production of hybrid nano metal matrix composites with the existing opportunities and techniques that leads to gain superior mechanical and tribological properties. In addition, improved production techniques will lead to develop these materials in bulk at less cost.MMNCs exhibits material saving with high strength material properties with less weight.

Final conclusion of this article is a detailed study on the work done so far on casting techniques; production and synthesis of MMNCs were reported. From the different processing techniques discussed in this article, the ultrasonic assisted casting method is superior technique that provides better additive bonding with matrix, control on microstructure, controlled cluster formation. Mechanical stirring method that having some drawbacks in distribution of particles uniformly and there low wettability in metal melts. Nano reinforcements up to 4.0 vol % can sustain the good strengthening level after that due to clustering and porosity effect strength of composite drastically decreases. Further research is entertained to develop improved processing techniques which could retain properties and microstructures of the composites.

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