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Review Article

MECHANICAL AND TRIBOLOGICAL BEHAVIOUR OF ALUMINIUM METAL MATRIX COMPOSITES USING POWDER METALLURGY TECHNIQUE—A REVIEW

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Aluminium metal matrix composites are widely used in engineering applications, specially automobile, aerospace, marine and mineral processing industries owing to their improved wear properties compared to conventional monolithic aluminium alloys. Presently hybrid composites plays vital role in engineering application. The researchers who developed composites, were subjected to many characterisations, specifically wear behaviour of these composites were explored to a maximum extent by number of researchers for the past 25 years. In this review an attempt has been made to consolidate some of the aspects of mechanical and wear behaviour of Al-MMCs and the prediction of the Mechanical and Tribological properties of Aluminium MMCs fabricated using Powder Metallurgy Technique.

Keywords: Al-MMCs, Density, Hardness, Mechanical properties, Wear, Powder metallurgy

INTRODUCTION

Composite materials are materials made from two or more constituent materials with significantly different physical or chemical properties, that when combined, produce a material with characteristics different from the individual components (Rajesh *et al.*, 2012). The individual components remain separate and distinct within the finished structure. The new material may be preferred for many reasons such as strength, light weight and less expensive when compared to traditional materials (Izadi *et al.*, 2013).

Aluminium alloys are the most widely used nonferrous materials in engineering applications owing to their attractive properties such as high strength to weight ratio, good ductility, excellent corrosion resistance,

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availability and low cost (Chinawad Dhadsanadhep *et al.*, 2008). Aluminium alloy-based Metal Matrix Composites (AMMCs) have been by now established themselves as a suitable wear resistant material especially for sliding wear applications. However, in actual practice engineering components usually encounter combination of different types of wear.

Aluminium Metal Matrix Composites (MMCs) have enhanced properties such as elastic modulus, hardness, tensile strength at room and elevated temperatures and significant weight savings over unreinforced alloys (Zulkoffli *et al.*, 2009; and Ravichandran *et al.*, 2014).

Hybrid Composites are relatively new and obtained by using two or more different kinds of reinforcement materials in a common matrix (Ramesh, 2014). Hybrids have a better all-around combination of properties than composites containing only a single reinforcement phase (Dinesh Kumar Koli *et al.*, 2013).

Powder metallurgy is the process of blending fine powdered materials, pressing them into a desired shape or form (compacting), and then heating the compressed material in a controlled atmosphere to bond the material (sintering) .The powder metallurgy process generally consists of four basic steps: powder manufacture, powder blending, compacting, and sintering. Compacting is generally performed at room temperature and at elevated-temperature, the process of sintering is usually conducted at atmospheric pressure (Saidatulakmar Shamsuddin *et al.*, 2011; and Yao Guini and Sun Kewei, 2011).

Rajesh Purohit *et al.* (2012) their work on "Fabrication of Al-SiCp composites through Powder Metallurgy Process evolved its Properties". Al-SiCp composites with 5 to 30 weight % of SiCp were fabricated using powder metallurgy process. Sintering of Al-SiCp composite parts was more energy efficient than for most other PM materials due to the relatively low sintering temperatures.

Mechanical alloying of aluminum and silicon carbide powders for 12 hours of milling results in fine homogeneous equiaxed composite powder structure. SEM studies of ball milled powders at intermediate stages reveal that due to impact of steel balls, the repeated cold welding, fracturing and re-welding of powder particles takes place and SiC particulates get embedded in the aluminum matrix.

Cold isostatic compaction at 600 MPa followed by vacuum sintering at 600 °C has been successfully used to produce Al-SiCp composites. Rockwell hardness, Density, porosity, compressive strength and tensile strength of powder metal Al-SiCp composites increases with increase in reinforcement content from 5 to 30 weight percent of SiCp. Sintering of Al-SiCp composites result in de-densification due to higher compaction pressure used in the green stage and also due to the removal of volatile materials during sintering and thus improving the properties.

Mechanical alloying of powders result in improvement in hardness, compressive strength and indirect tensile strength of Al-SiCp composites with 5 to 30 weight percent of SiC particulates.

Izadi *et al.* (2013) their work on "Friction stir processing of Al/SiC composites fabricated by powder metallurgy". Friction Stir Processing (FSP) was applied to modify the microstructure of sintered Al–SiC composites with particle concentrations ranging from 4 to 16 vol%. Two SiC particle sizes (490 N and 800 grades) were examined. The use of FSP has been shown to improve the micro hardness of Al-SiC composites produced by traditional powder metallurgy and sintering methods. However, when samples with 16 vol% SiC were processed there were residual pores and lack of consolidation. This was likely due to the initial low density (81.5-83.8% of theoretical) in the compacted materials, which could be attributed to the larger surface area of the fine particles used.

An increase in hardness of all samples was observed after friction stir processing which was attributed to the improvement in particle distribution and elimination of porosity. Some refinement of the initial SiC particles appeared to occur and it was shown that the influence of reducing the initial SiC particle size on hardness values of the friction stir processed samples was negligible. The increase in hardness with SiC concentration in the friction stir processed samples appeared to be related to the mean inter-particle spacing. In this regard, a possible quantitative linear correlation has been proposed.

Figure 1: Microstructure of the Sintered and Friction Stir Processed Alumix 431D Alloy, with a Comparison of (b) The as-Sintered and, (c) Friction Stir Processed Microstructure

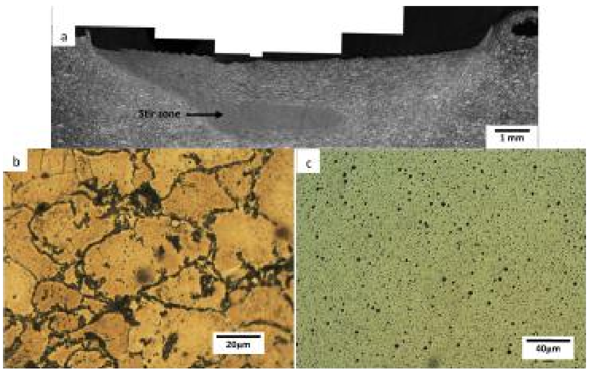
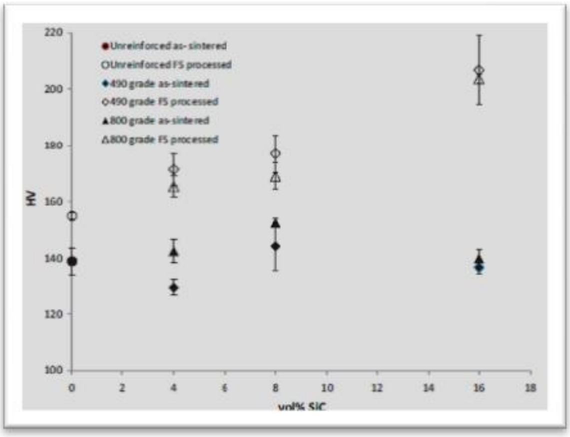
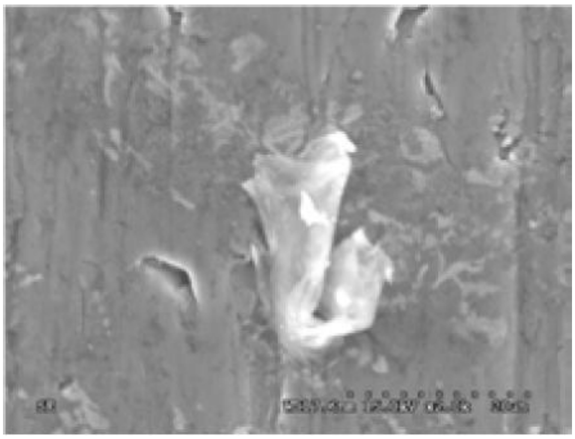


Figure 2: Microhardness Values of the Sintered Al-SiC Composites Modified by FSP



Chinawad Dhadsanadhep *et al.* (2008), "Fabrication of Al/Al2O3 Composite by Powder Metallurgy Method from Aluminium and Rice Husk, and Ash rich in alumina". Their work on Fabrication of Al-4wt.%Cu/Alumina composite was reported. The method of fabrication was powder metallurgy by in-situ reaction to form alumina during fabrication. Starting materials were mixture of aluminum, copper, and silica powders. Silica is in form of rice husk ash. The mixture was cold compacted, and sintered at 650 °C for 1 h. Hot forging was carried out to further consolidate the sintered billet, followed by 10-h heat treatment at temperatures between 590 to 650 °C. This work suggests Sintering of powder mixture was carried out at 650 °C for 1 h, followed by hot forging at 600 °C, and finally heat treatment at 590 °C for 10 hrs. They observed that Chemical reaction

Figure 3: SEM Image of Remaining Silica Shown as Bright Irregular Particle Surrounded by Reacted Area (Al-4wt%Cu /15vol%Silica: Sintering 650 °C -1 h + Hot Forging 600 °C + Heat Treating 650 °C -10 hrs)

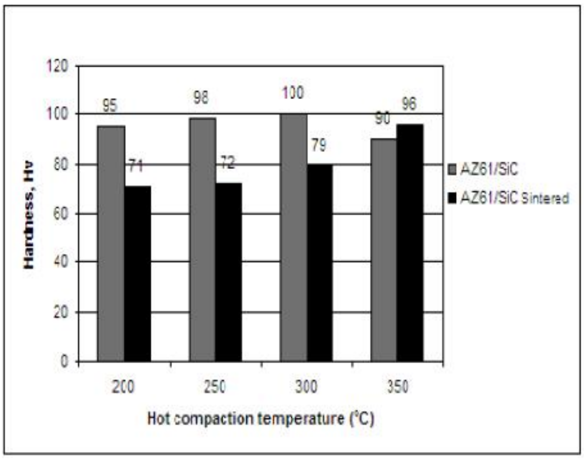


between silica and aluminum powder took place during long time heating at temperature above 590 °C.

The investigation of microstructure showed reacted areas, consisting of gamma-alumina and silicon. In some areas, silica powder remained amid the products of the reaction. Copper was found distributed in all areas, in form of Al2Cu compound.

Zulkoffli *et al.* (2009), "Fabrication OF AZ61/ SIC Composites by Powder metallurgy process". Mg-based Metal Matrix Composites (MMCs) with addition of SiC reinforcement was fabricated by using a pre-alloyed AZ61 powder compressed without binder agent under compaction pressure of 200 MPa for 20 minutes at different temperature intervals of 200 °C, 250°C, 300 °C and 350 °C. Metal matrix composite of AZ61 magnesium alloy reinforced by SiC particles was fabricated from pre-alloyed powder using a hot compaction and sintering techniques at

Figure 4: Hardness Comparison Between as-Hot Compacted and Sintered AZ61 Magnesium Alloy



different temperature intervals, i.e., 200 °C, 250 °C, 300 °C and 350 °C.

The microstructures and hardness of the as-hot compacted and sintered samples were investigated. The as-hot compacted samples show the compaction at 350 °C allowed diffusion element from SiC into the AZ61 matrix. The sintering process allow recovery of defects and releasing of internal stresses of compacted samples, and lead to the softening of the material, but for sample AZ61/ SiC 350 °C sintered sample show increasing of hardness value owing to alloy elements diffusion and the growing of lamellar precipitates on the sample during sintering.

Ravichandran *et al.* (2014), "Synthesised aluminium-based hybrid powder metallurgic composites". Aluminium-based metal matrix composites were synthesized from Al-TiO2-Gr powder mixtures using the powder metallurgy technique and their forming characteristics were studied during cold upsetting. Green cylindrical compacts of pure Al, Al-5wt%TiO2, Al-5wt%TiO2-2wt%Gr, and Al-5wt%TiO2-

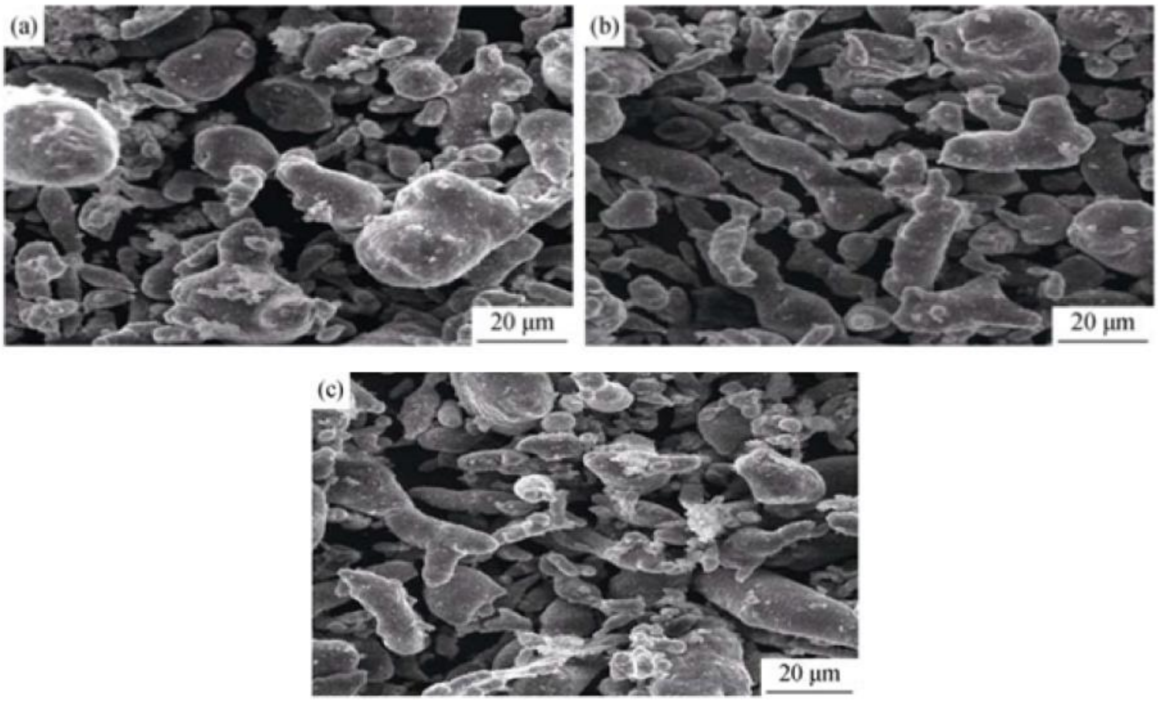
4wt%Gr were made using a 400-kN hydraulic press equipped with suitable punch and die and by sintering at (590 ± 10) °C for 3 h. Concluded that the apparent density, tap density and theoretical density increase with the addition of TiO2 and Gr reinforcements to the pure Al matrix. The reason for the density increase is the filling with fine powders of TiO2 and Gr of the pores formed in the matrix by large irregular Al particles. The XRD patterns of the composite powders confirm the presence of the matrix (Al) and reinforcements (TiO2 and Gr) phases, but no other intermetallic phases are found.

According to the SEM images, after 20 h of ball milling, the distribution of the reinforcement within the matrix material is homogeneous and the addition of reinforcements (TiO2 and Gr) to the soft material influences the morphological characteristics of the MMCs.

The maximum value of true axial stress (±*z*), true hoop stress (±¯) and true hydrostatic stress (±*m*) were obtained for Al-5wt%TiO2 composites having 4wt%Gr. The addition of TiO2 and Gr with the Al matrix increases the strength coefficient (*K*) and strain hardening index (*n)* of the composite. Addition of TiO2 and Gr reinforcements to pure Al reduces the densification and deformation characteristics because of matrix work-hardening.

Wong Wai Leong Eugene and Manoj Gupta (2010), "*Journal of Microwave Power and Electromagnetic Energy*", Characteristics of Aluminum and Magnesium Based Nanocomposites Processed Using Hybrid Microwave Sintering. The sintering usually takes a few hours to realize density in excess of 90%.

Figure 5: SEM Images of as-Milled Al-5wt%TiO2 (a), Al-5wt%TiO2-2wt%Gr (b), and Al-5wt%TiO2-4wt%Gr (c) Composite Powders



The present study highlights the use of energy efficient and environment friendly microwave sintering route to synthesize pure aluminum, magnesium and magnesium based nanocomposites. Three reinforcements were targeted: a) silicon carbide, a microwave susceptor, b) alumina, a microwave transparent material and c) copper, a conducting material.

Composites were prepared using blend – compact – microwave sintering – extrusion method. Process evaluation revealed that microwave assisted sintering can lead to a reduction of 86% in sintering time and energy savings of 96% when compared to conventional sintering.

Moreover, microwave assisted sintering of metal compacts in this study was carried out in air, in the absence of any protective atmosphere, without compromising the mechanical properties of the materials. Results revealed that Compared to conventional sintering, hybrid microwave assisted rapid sintering can lead to reduction in processing time up to 85% and energy savings of 96%.

Figure 6: SEM Micrograph Showing Distribution of Al_2O_3 in Mg / 1.0Al_2O_3

Cost savings can also be achieved with the elimination of inert atmosphere during microwave sintering.

Micro structural characterization revealed finer microstructure for microwave sintered magnesium when compared to conventionally sintered magnesium. For monolithic magnesium and aluminum samples, an improvement in hardness, 0.2%YS, UTS and work of fracture was observed, when compared with hybrid microwave sintered samples with conventionally sintered samples. In magnesium composite formulations, nano-size reinforcements formed a continuous network along with the grain boundaries of the matrix. Mechanical characterization revealed an increase in hardness, 0.2%YS and UTS of magnesium with the addition of nano-size reinforcements.

Asif *et al.* (2011), "Development of Aluminium Based Hybrid Metal Matrix Composites for Heavy Duty Applications". Their study deals with the investigation of dry sliding wear behaviour of aluminium alloy based composites, reinforced with silicon carbide particles and solid lubricants such as graphite/antimony tri sulphide (Sb2S3). The first one of the composites (binary) consists of Al with 20% Silicon Carbide particles (SiCp). The other composite has SiCp and solid lubricants namely Graphite + Sb2S3 (hybrid composite). Both composites are fabricated through P/M route using "Hot powder pre forms forging technology".

The density and hardness are measured by usual methods. The pin-on-disc dry wear tests to measure the tribological properties were conducted for one hour at different parameters namely loads: 30 N, 50 N and 80N and speed:

Figure 7: Effect of Load on Coefficient of Friction at Different Speeds: 5, 7 and 9 m/s

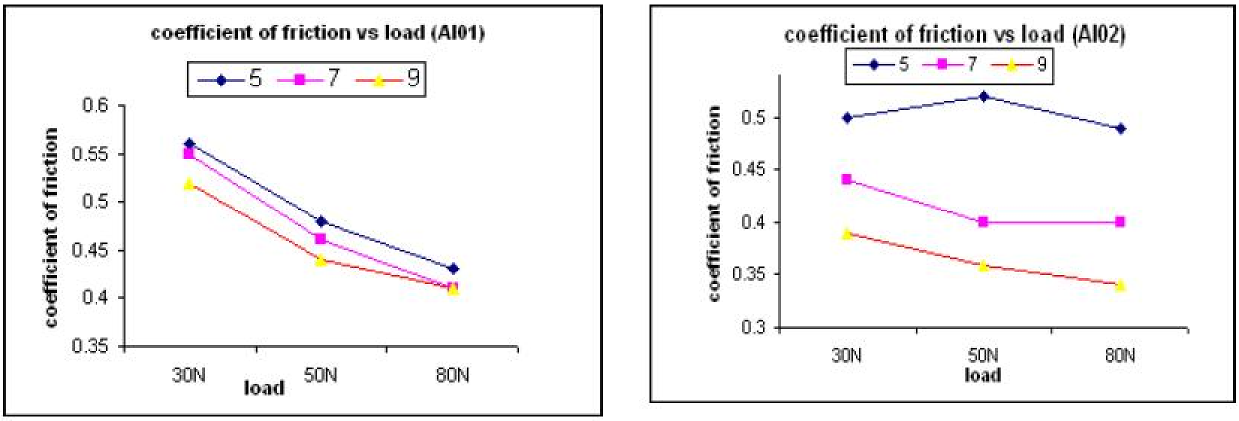
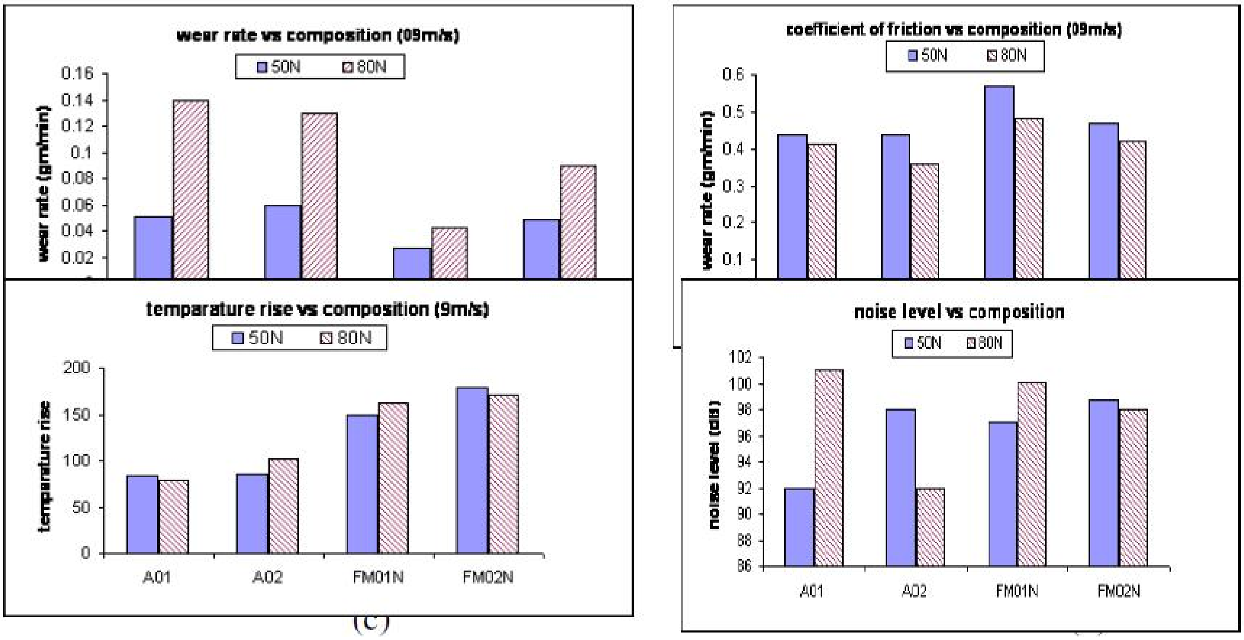


Figure 8: Comparison of Proposed Al Based Composites with Corresponding Values of Fe-Based Composites at Loads: 50 and 80 N for Sliding Speed: 9 m/s



5, 7 and 9m/s. Conclusions from this work was drawn that by Incorporation of graphite particles in the aluminium matrix as a second reinforcement decreases the wear rates of the composite compared to SiCp reinforced composite. Coefficient of friction is stabilized with incorporation of solid lubricants in composite at solid state for various sliding speeds and applied loads. Temperature rise for hybrid composite was more than that of temperature rise for binary composite but it is significantly lower than iron based composites.

Incorporating solid ingredients in aluminium powder play an important role in reducing the noise level. Wear rate decreases as the sliding speed increases up to transition speed and load, due to work hardening of the surface, formation of Iron oxide, crushing of the SiC particles and smearing of Graphite. Seizure occurred for wrought aluminium based alloys, but no seizure occurred for Al/SiCp and Graphitic powder composites. Combination of abrasion, delamination and adhesive nature of wear was observed. Proposed aluminium based composites with lower wear resistance have better tribological characteristics than iron based composites.

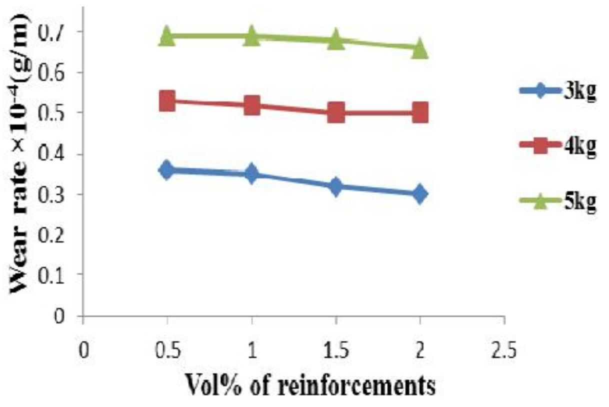
Ramesh (2014),"Characterization of Al Based Nano composites Using Powder Metallurgy Technique" by taking aluminium as the matix and nano-materials such as carbon nanotube, graphene and nano-diamond as reinforcement to get the nanocomposites.

Uniform dispersion of the fine reinforcements and a fine-grained matrix improved the mechanical properties of the composite. His work concludes that the carbon nanotubes reinforced aluminum matrix composite had been successfully developed through powder metallurgy.

The density values of AL + CNT + GR + ND composition were very near to the density value of base metal. The density values of AL + CNT + GR composition were less compared to the density values of AL + CNT + GR + ND composites. The hardness values were high for AL + CNT + GR + ND composition than the AL + CNT + GR composition.

The wear resistance increases with the amount of reinforcements. It is evident from the experiments that for AL+CNT+GR and AL+CNT+GR+ND composition composites, wear resistance was higher. Remarkable change in compression strength values were

Figure 9: Volume % of Reinforcement v/s Wear Rate



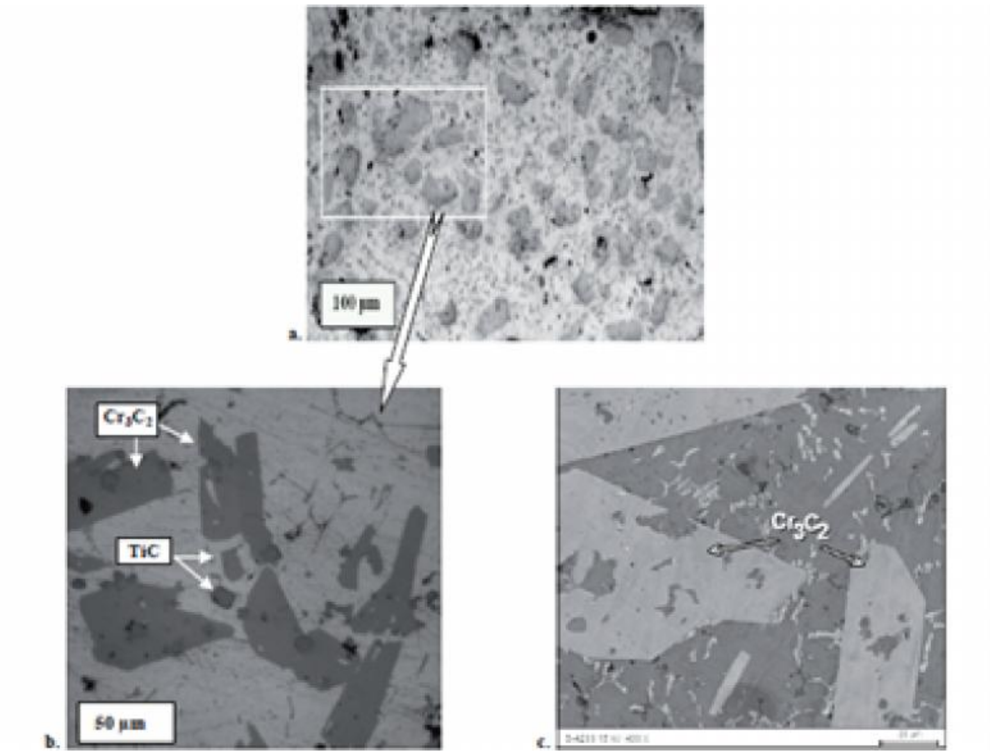
observed, which decreases with increasing percentage of reinforcements.

Dolata-Grosz and Wieczorek (2007) their work on "Tribological properties of hybrid composites containing two carbide phases". The aim of the research conducted was to examine the tribological properties, i.e., the friction coefficient and wear, of hybrid composites containing chromium and titanium carbides, shaped in the process of centrifugal casting, as well as to assess the wear of the element cooperating with it.

The scope of the research encompassed— the production of a composite with an aluminium matrix and carbides, examination of the structure and phase composition of a composite formed by mechanical stirring, the use of a composite suspension in centrifugal casting and production of a sleeve with layered arrangement of reinforcing phases, examination of the tribological properties, friction coefficient and wear of the friction couple: cast iron-composite, examination of hardness.

The decreased wear of the composite with a lower fraction of reinforcing phases in the

Figure 10: The Structure of Aluminium Cast Composite with Hybrid Reinforcement Phases a) Structure of Outside Layer, OM; b) Microstructure of Outside Layer, SEM



friction region results from the fact of occurrence, during its work, of two mechanisms of wear: adhesive and abrasive.

The combination of these mechanisms clearly intensifies the degree of wear, thus resulting in its almost triple growth compared to the material with a larger fraction of hetro phase reinforcement. An increase in the reinforcing phase fraction allowed the elimination of the phenomena connected with adhesion wear. An increase in the reinforcing phase percentage fraction did not result in increase in wear of the cast iron.

Therefore, it can be affirmed that a 10% fraction of a carbide reinforcing phase ensures a uniform wear mechanism and has a beneficial influence on the operation of the tribological couple: cast iron – hetro phase composite, during which no negative effects of increased wear of the cooperating material were observed.

RESULTS AND DISCUSSION

A small number of scientists were engaged in research of tribological and mechanical characteristics of Hybrid Aluminium composites using Powder Metallurgy Technique. The research review is given below.

Sintering of Al-SiCp composite parts was more energy efficient than for most other PM materials due to the relatively low sintering temperatures. During isostatic compaction of powders, the quality of final product depends upon the quality of initial manual compaction Sintering of Al-SiCp composites result in de-

densification due to higher compaction pressure used in the green stage and also due to the removal of volatile materials during sintering and thus improving retention properties.

Friction Stir Processing (FSP) was applied to modify the microstructure of sintered Al-SiC composites. The use of FSP has been shown to improve the microhardness of Al-SiC composites produced by traditional powder metallurgy and sintering methods. The material flow in the stir zone during FSP was successful in uniformly distributing the SiC particles. The increase in hardness with SiC concentration in the friction stir processed samples appeared to be related to the mean inter-particle spacing.

Starting materials were mixture of aluminum, copper, and silica powders. Silica was in form of rice husk ash. The mixture was cold compacted, and sintered at 650 °C for 1 h. Chemical reaction between silica and aluminum powder took place during long time heating at temperature above 590 °C. The investigation of microstructure showed reacted areas, consisting of gamma-alumina and silicon. In some areas, silica powder remained amid the products of the reaction.

SiC reinforcement was fabricated by using a pre-alloyed AZ61 powder compressed without binder agent under compaction pressure of 200 MPa for 20 minutes at different temperature intervals of 200 °C, 250°C, 300 °C and 350 °C. The sintering process allow recovery of defects and releasing of internal stresses of compacted samples, and lead to the softening of the material, but for sample AZ61/SiC 350 °C sintered sample show increasing of hardness value owing to alloy element diffusions and the growing of lamellar precipitates on the sample during sintering.

Al-TiO2-Gr powder mixtures using the powder metallurgy technique and their forming characteristics were studied during cold upsetting. Green cylindrical compacts of pure Al, Al-5wt%TiO2, Al-5wt%TiO2-2wt%Gr, and Al-5wt%TiO2-4wt%Gr were made using a 400-kN hydraulic press equipped with suitable punch and die and by sintering at (590 ± 10) °C for 3 h. The reason for the density increase is the filling with fine powders of TiO2 and Gr of the pores formed in the matrix by large irregular Al particles. The distribution of the reinforcement within the matrix material is homogeneous and the addition of reinforcements (TiO2 and Gr) to the soft material influences the morphological characteristics of the MMCs. Addition of TiO2 and Gr reinforcements to pure Al reduces the densification and deformation characteristics because of matrix work-hardening.

Aluminum and Magnesium Based Nanocomposites Processed Using Hybrid Microwave Sintering. The sintering usually takes a few hours to realize density in excess of 90%. The present study highlights the use of energy efficient and environment friendly microwave sintering route to synthesize pure aluminum, magnesium and magnesium based nanocomposites. Compared to conventional sintering, hybrid microwave assisted rapid sintering can lead to reduction in processing time up to 85% and energy savings of 96%.

Cost savings can also be achieved with the elimination of inert atmosphere during microwave sintering. Microstructural characterization revealed finer microstructure for microwave sintered magnesium when compared to conventionally sintered magnesium.

In the investigation of dry sliding wear behaviour of aluminium alloy based composites, reinforced with silicon carbide particles and solid lubricants such as graphite/ antimony tri sulphide (Sb2S3). The first one of the composites (binary) consists of Al with 20% Silicon Carbide particles (SiCp). The pin-on-disc dry wear tests to measure the tribological properties were conducted for one hour at different parameters namely loads: 30, 50 and 80N and speed: 5, 7 and 9 m/s. Incorporation of graphite particles in the aluminium matrix as a second reinforcement decreases the wear rates of the composite compared to SiCp reinforced composite. Coefficient of friction was stabilized with incorporation of solid lubricants in composition of composite at solid state for various sliding speeds and applied loads. Combination of abrasion, delamination and adhesive nature of wear was observed. Proposed aluminium based composites with lower wear resistance have better tribologocal characteristics than iron based composites.

Aluminum as the matix and nanomaterials such as carbon nanotube, graphene and nano-diamond as reinforcement were used to form nano composites, using powder metallurgy technique. The density values of AL + CNT + GR + ND composition were very near to the density value of base metal. The density values of AL + CNT + GR composition were less compared to the density values of AL + CNT + GR + ND composition composites. It is evident from the experiments that for AL + CNT + GR and AL + CNT + GR + ND composition wear resistance high for 2%. Less wear loss was observed.

CONCLUSION

Sintering of Al composites is more energy efficient than for most other PM materials due to the relatively low sintering temperatures. Cold isostatic compaction at 600 MPa followed by vacuum sintering at 600 °C has been successfully used to produce Al composites. Energy efficient and environment friendly microwave sintering route to synthesize pure aluminum composites can be used. Uniform dispersion of the fine reinforcements and a fine-grained matrix improve the mechanical properties of the composites. An increase in hardness of all samples was observed after friction stir processing which was attributed to the improvement in particle distribution and elimination of porosity. The apparent density, tap density and theoretical density increase with the addition reinforcements to the pure Al matrix. The reason for the density increase was the filling with fine powders of reinforcements of the pores formed in the matrix by large irregular Al particles. Coefficient of friction was stabilized with incorporation of solid lubricants in composition of composite at solid state for various sliding speeds and applied loads. Incorporation of graphite particles in the aluminium matrix as a second reinforcement decreases the wear rates of the composite compared to SiCp reinforced composite.

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