Mechanical Characteristics of Coated Aluminium Matrix Composites - A Review

Karthik B M[a], Jayashree P K[b], Gowri Shankar M C[c], Sathyashankara Sharma[d]*, Abhishek Nayak[e]

[a]Assistant Professor, [b]Assistant Professor-Selection Grade, [c]Associate Professor, [d]Professor, [e]PG Student M.Tech Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal - 576104, Karnataka, India

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Abstract— Metal matrix composites are the most vital product used as engineering materials. This product has extensive applications in automotive, aerospace, and supplementary uses. Among the different metal matrix composites, aluminium matrix composites (AMMCs) are considered as one of the most useful materials for various applications in engineering. Different categories of reinforcement have been added into the matrix of aluminium in order to increase hardness, wear resistance, stiffness, toughness, thermal stability, fatigue properties and electrical properties. The nature of reinforcement materials, processing parameters and interface bonding has great influence on the characteristics of AMMCs. A number of approaches have been adopted to expand the interfacial properties of metal matrix composites. Out of which surface treatments and coating of the reinforcement are the main techniques by which the interfacial properties can be enriched. In the current study of aluminium MMCs, various mechanical and morphological characteristics of coated aluminium alloy matrix composites have been analysed and studied.

Keywords- Metal matrix composites, Stir casting, Nickel coating, Al7075, Al2024.

1. INTRODUCTION

Conventional nonferrous alloys have limitations to achieve desired strength, stiffness and density targets combinations. In order to achieve beneficial blend of properties, metal matrix composites have been fabricated. The MMC has two macro constituents namely matrix and reinforcement. The matrix preferred is commonly a light weight material (such as aluminium, magnesium and titanium alloys) with good strength to weight ratio. The reinforcement for these materials is generally ceramics because they give good combination of stiffness, strength and lubricating properties. The reinforcement materials are generally Al_2O_3, TiC, SiC, TiB_2, B_4C, graphite etc.

Aluminium and its alloys have a wide range of competency and applications which make the material for the number of products in the market due to specific yield strength. The 7xxx series is one among them can be heat treated and has high strength and toughness. Al7075 has good machinability, specific strength and corrosion resistance than other members. The 2xxx series aluminium alloys are heat treatable, high performance and high strength metals that uses copper as principle alloying agent. They are employed in aircraft and aerospace applications because of their exceptional strength over a wide range of temperatures.

A. Metal matrix composites (MMCs)

Material matrix composites are characterized as a mixture of two or more different materials, one being a metal while the other being a dissimilar metal, such as ceramic or any other organic compound. MMCs mainly consists of either discontinuous or continuous-fibres, whiskers or particulates which can result in higher specific modulus and specific strength. The important highlighting features of metal matrix composites are:

- Enhancement of tensile strength and yield strength at working temperature while retaining minimum ductility or durability at all levels of temperature.
- Improvement of creep resistance as compared with orthodox alloys at higher temperatures.
- Enhancement of fatigue strength both at room and higher temperatures.
- Increase in thermal shock resistance.
- Enhancement of corrosion resistance.
- Higher Young's modulus.
- Reducing the thermal deformation.

B. Aluminium matrix composites (AMCs)

Composites of aluminium alloy are usually hardened by reinforcing ceramic refractory particles into the base matrix materials. They are usually inherent in nature. Because of this, nucleation sites are produced in the matrix material that increases the matrix material's tensile-related properties. Powder reinforced composites undergo characterization by cost-effective fabrication methods with better-quality grains. The choice of the different varieties of reinforcement depends on the improvement of the property and on the budgetary investment. MMCs reinforced with continuous-fiber exhibit unidirectional properties in the fiber direction, but are expensive. Chopped fibers produces substantial increase in the two-dimensional (x and y) property at moderate cost in the direction of their orientation [1].

C. Coating

Reinforcement surfaces can be coated with non-metallic or metallic compounds to improve wettability adhesion, mechanical properties and to avoid an undesirable chemical reaction between the matrix and reinforcement at elevated temperature. There are different methods of coatings such as Chemical Vapour Deposition (CVD), Physical Vapour Deposition (PVD), Electro-less Nickel Plating (EN), etc.

PVD is a method which makes the samples go from a condensed phase to the vapour phase, then comes back to a very thin film condensed phase. Evaporation and Sputtering are some of the most common PVD processes [2].

In CVD, one or more volatile precursors are introduced to the substrate, which reacts with it and decomposes on the exterior of the substrate to generate the desired deposit. Products that are often volatile are also produced which are extracted through the reaction chamber by gas flow [3].

Electro-less nickel plating is an autocatalytic reaction which deposits an even layer of Ni-boron or Ni-phosphorus alloy on the surface of a solid material or metal or plastic substrate. The process involves dipping the substrate into a coating solution bath, where the reducing agents like hydrated sodium hypo-phosphite reacts with the material ions to deposit the nickel alloy [4].

In general coating of the reinforcement offers some advantages such as protection of the fiber from the reaction with the matrix acting as a diffusion barrier which increases the bonding and wetting between fiber and matrix and also increases the mechanical properties of the MMCs. Generally reinforcements are coated with copper, magnesium, nickel, borax etc. In the current study of aluminium MMCs nickel is coated on Al2024 using electroless nickel plating technique. The effects of introducing nickel coated aluminium alloy 2024 to a composite system with microstructural and mechanical properties are effectively assessed by conducting Scanning Electron Microscopy (SEM) and mechanical tests.

D. Al7075 and Al2024 alloy

Al7075 is an alloy from Al-Zn-Mg which is one of the most widely used alloy matrix in aerospace industry. Al7075 alloy has improved properties including higher durability, variable hardness and strength. Al-Zn-Mg alloys are used for casting and age hardening. Al2024 also has got good machining characterstics, fatigue resistance and higher strength than both Al2014 and Al2017 alloy. It is widely used in aircraft structures and used in reciprocating and rotating parts such as drive shafts, piston, brake motors and in other structural parts which requires light weight and high strength materials [5].

II. LITERATURE REVIEW

Sanchez et al. [4], fabricated the aluminium composites by reinforcing it with carbon fibers and by coating it with nickel by a centrifugal infiltration process and lost wax casting technique and the results revealed that nickel coating enhances the wetting of the preforms which allows them to totally infiltrate at very low temperatures. The composites manufactured with nickel coated fibers had higher hardness than that of composites with uncoated reinforcements.

Baik [6], studied the behaviour of composite materials manufactured with Al2024 and annealed Co-coated Al_2O_3 fibres at 300, 500, 700 and 1000 °C by a squeeze infiltration technique and it was observed that the ductility (50%) and tensile strength (30%) of the aluminum composite with the Co-coated Al_2O_3 improved significantly as the annealing temperature of fiber was increased.

Mithun et al. [7], studied mechanical properties and microstructure of copper coated Al_2O_3 powder reinforced Al6061 MMCs using compo-casting method and it was found that there was a improvement in hardness, ductility and ultimate tensile strength of composites prepared with copper coated Al_2O_3 when compared to non coated composite containing un-coated Al_2O_3.

Jaimon et al. [8], prepared Al7075 reinforced with nickel coated carbon fiber matrix composites by stir casting method. Autocatalytic reduction principle was used to coat reinforcements with nickel to improve wetttability. The existence of nickel coating on the surface of fibers was examined thoroughly using X-ray diffraction and scanning electron microscope. The results revealed that the Ni-coated fiber reinforced composites showed a maximum improvement of 10.47, 15.38 and 10.38% in the compressive strength, hardness and elasticity respectively.

Mandal et al. [9], performed electroless deposition techniques to coat copper (2 μm) and nickel (1.64 μm) on the plain steel fiber. It was found that there was a considerable influence of coating on the surface hardness and corrosion behaviour of steel and aluminium fiber reinforced composites. Coating of copper on the fiber increased the corrosion rate whereas nickel coating on fiber showed minimum corrosion.

Jothi et al. [10], studied fine nickel-phosphorous coating on Al7075 artificially peak aged and step heated at 200 and 400 °C/1h. This coating on Al7075 substrate improved hardness, wear resistance and frictional characteristics by altering the process parameters as well as pre-treatments. These properties were further improved by age hardening.

Mohandas et al. [11], performed a centrifugal casting method to fabricate aluminium ($AlSi_6Cu$)/ nickel coated SiC metal matrix composite. The microstructure and hardness were analysed from outer periphery taken in the radial direction. The microstructure shows the presence of reinforcement particles more in the case. Hardness and tensile properties were improved at the outer region compared to inner regions.

Deepa et al. [12], studied electroless Ni-B and Cu coated B_4C powder reinforced powder metallurgy processed aluminum composites and concentrated on the phase structure and electrochemical properties. It was found that metallic coating improves compatibility, wettability and minimizes the reaction between the reinforcement particles and matrix. It was found that the coating had better hardness and reduced porosity as compared to uncoated particles.

Jerin et al. [13], determined variation in structural and mechanical properties of coatings on aluminium alloy substrate by the combined action of magnetic stirring and ultrasonication techniques. Al356 aluminium strip was coated with Ni-B alloy and Ni-B-CeO_2 by electroless coating. Ultrasonication had better efficiency of coating with 99% of Ni and an insignificant quantity of aluminium on the surface in Ni-B coating. Electroless composite and alloy coatings formed by ultrasonication shows decrease in surface roughness and wear property.

Shirin et al. [14], investigated the influence of metallic coating of reinforcements on the mechanical characteristics and microstructure of aluminium-aluminium oxide nanocomposites. Al356 alloy was reinforced by coated aluminium oxide nanoparticles by a stir casting method. Alumina nanoparticles of particle size 50 nm were coated with Co, Cu, and Ni using electroless deposition method. There was an extensive enhancement in the mechanical properties of the nanocomposites when coated nanocomposites were used as reinforcements. Ni-coating on Al-Al_2O_3 nanocomposites had better hardness, tensile strength, compressive strength, and yield strength compared to Cu, Co coating and uncoated Al-Al_2O_3 nanocomposites.

J. Ye et al. [15], studied the mechanical properties of an aluminium-coated boron carbide-aluminium- particulate composite. The boron carbide particulates were cryomilled with an Al5083 powder to manufacture the composite powder. The unmilled coarse-grained Al5083 was reinforced with milled composite powder and consolidated using cold isostatic pressing and extrusion to form an MMC. This Al5083 coated boron carbide (5083/coated B_4C_p) composite shows improvement in strength and stiffness when compared with other uncoated composites such as Al6092/B_4C_p, Al6061/SiC_p, and Al5083/SiC_p.

Taherzadeh et al. [16], observed mechanical behaviour of metallic coatings on SiC reinforced in a pure aluminium matrix. The Al-SiC composites were manufactured by a stir casting method. The particles of SiC with a particle size 80 μm were coated with nickel (1.02 μm) and cobalt (1.83 μm) metallic layers by an electroless deposition method. The hardness, yield strength and UTS of samples were better in nickel coated SiC particles as compared to uncoated and cobalt coated SiC particles.

Zheng et al. [17], studied the metallography of laser-deposited Ti_6Al_4V composites using nickel coated powder. Gas atomised Ti_6Al_4V powder was reinforced with different quantities (10 & 20 wt. %) of nickel-coated TiC carbide particles using the LENS (Laser Engineered Net Shaping) process. The compressive YS (yield strength) of Ti_6Al_4V + TiC/Ni was later compared with unreinforced composite. The substantial upswing in the strength is due to the formation of titanium-nickel intermetallic compound, having higher strength.

Rams et al. [18], examined the mechanical properties of carbon fibre reinforced Al6061 fabricated by stir casting method. It was coated with nickel 0.92 ± 0.14 μm. Results revealed that coating of nickel decreased the hardness of the matrix which is closer to the fibers and produced a very high dispersion in the values of stiffness due to the precipitation of aluminium-nickel intermetallics especially in the own interface and at distances of 5 μm above the fibers.

Tzeng et al. [19], reported role of electroless nickel-phosphorous coating in graphitization of polyacrylonitrile based carbon fibers. Polyacrylonitrile based carbon fibers without and with electroless nickel-phosphorous coatings were subjected to heat treatment. Raman spectroscopy and X-ray diffraction were used to observe the structural changes and both indicated that the graphitization of polyacrylonitrile based carbon fibers was improved in the presence of the coating. The Electroless Ni–P coated polyacrylonitrile based fibers which were heat treated at temperature of 1400 °C showed better graphitization when compared with uncoated fibers heat treated at temperature of 2400 °C.

Ziyuan et al. [20], coated nickel on graphite fibres by the method of electroless deposition technique and studied the influence of chemical composition of the coating bath on deposition of nickel. It was found that electroless deposition technique had a vital role on coating a continuous and uniform nickel layer on surface of graphite fiber. It was observed that the tensile strength of coated fibers were less when compared with uncoated fibres. In addition, by pressure infiltration route the nickel coated graphite fibers were successively constituted into the matrix of aluminum and the microstructural results showed that the composites had a coated fibers that was uniformly distributed without any considerable interfacial reactions occurring between aluminium matrix and fibre.

Fang et al. [21], studied surface strengthening by TiC-TiB_2 composite coating on aluminium alloy. To obtain TiC-TiB_2 strengthening coating on ZL205A aluminium an integration technology system was employed, i.e., a blend of Vacuum Expendable Pattern Casting (VEPC) and Self-propagating High-temperature Synthesis (SHS). The dense and homogeneous microstructure was found with the addition of TiB_2 and TiC as reinforcements. The result shows extraordinary hardness and wear resistance.

Chang et al. [22], investigated the slight difference in condition of electrical resistivity of electroless Ni-coated carbon fibers that was subjected to heat treatement at different temperatures. Single fiber technique was used to measure the electrical resistivity. Measurement results indicated that as the heat treatment temperature was increased, the resistivity went on decreasing upto a temperature of 300 °C. When heat treatment temperature was further increased up to 450 °C, electrical resistivity was increased. X-ray diffraction was used to carry out structural study which showed that a larger proportion of Ni-P was formed only for temperature greater than 300 °C which was reason for improvement of resistivity. Also it was observed that the increase of resistivity was more at lower temperatures for specimens with higher content of phosphorous.

Susan et al. [23], coated nickel to the carbon fibres uniformly and continuously by the method of electroless, cementation or electroplating method. The thickness of coating was between 0.2 and 0.6 μm for all the three coating methods. Thickness of coating less than 0.2 μm indicated discontinuous coating of the nickel over the surface of fibre and coating beyond 0.6 μm thickness of nickel resulted in the formation of dendrite over the continuous coating. It was also observed that for fibres coated continuously, electroless coated fibres had the ultimate tensile properties nearer to uncoated carbon fibres which suggested for adherent and defect free coating.

Kulkarni et al. [24], investigated mechanical properties of different metallic coatings on carbon fibers. The different grades of carbon fibers (Polyacrylonitrile (PAN) supplied by USA, PAN, Courtalds Grafil 'A' type and Morganite Modmor) were coated with nickel and copper by the cementation process. The tensile strength and modulus of nickel coated samples were higher compared to uncoated and copper coated samples.

Kim et al. [25], investigated thermal and mechanical characteristics of nickel-coated (0.3 μm thickness) single-walled carbon nanotube (SWNT) reinforced copper matrix composites. The copper matrix composites were manufactured by powder metallurgy method followed by hot pressing. The properties of Ni-coated SWNT reinforced Cu MMCs notably enhanced when compared with pure copper and copper-nickel samples.

Ashassi et al. [26] investigated the influence of coating duration and thermal treatment on mechanical properties of electroless Ni–P alloy coated mild steel. As the coating duration increased, the percentage of phosphorous content decreased and the thickness of coating increased. The hardness of electroless nickel plating, in as-deposit condition, seems to improve with a decrease in phosphorous content. There was a 32% increase in hardness of coated samples heat treated at 400 °C for 1 h as compared with untreated specimens.

Ruiz et al. [27], observed enhancement of the interface bond strength of a powder metallurgy Al2014–$(Ti_5Si_3)_p$ composite by the Cu coated reinforcement. Composite materials were fabricated by homogenizing and mixing a pre-alloyed Al2014 powder, alloyed Ti_5Si_3–Cu and Ti_5Si_3 as the reinforcements. The bending strength and hardness of mechanically copper coated reinforced composites had higher values compared to uncoated composites.

Kretz et al. [28], studied the coating layer properties by subjecting it to different conditions of deposition. In this work SiC powder was coated with nickel by electroless method. SiC powder of three different grades 8, 14, and 70 mm were chosen in terms of average particle size. The growth conditions controlled the microstructure, morphology and thickness of the layers by using SEM and digital image analyzing methods. Since nickel coated SiC powders were used as reinforcement for Al matrix composites, their compatibility when compared with the uncoated SiC powders was also controlled by metallography.

Pallavi et al. [29], analysed the microstructural properties of aluminium-based MMC reinforced with copper coated silica particles. Composite materials were prepared by reinforcing Cu coated SiO_2 particles in pure Al-xMg master alloy. The metallic coating of copper on SiO_2 improves interfacial bonding between matrix and reinforcement and influences overall mechanical properties. Hence the yield strength and UTS of Cu coated SiO_2 reinforced composites were higher when compared with uncoated composites.

Dileep et al. [30], investigated whether there is any improvement in fracture toughness and hardness of aluminium 7075 alloy when coated with zinc. Time dependent electro-plating method was used to fabricate zinc coated Al7075 alloy. It was found that with coating there was substantial enhancement in hardness, but as thickness of coating increased the hardness remained constant. The results indicated that the yield stress of zinc coated aluminium alloy increased when compared with uncoated aluminium alloy, but there was increase in brittleness. Optical microscopy analysis showed a very good bonding of zinc coating on aluminium.

III. SUMMARY

- Aluminium composites are termed as advanced materials due to their enhanced mechanical, electrical, thermal properties and cost effectiveness as compared to other engineering materials.
- The application of coatings to the reinforcement during fabrication of metal matrix composites was found to be an important step which had promising effects on the interfacial, mechanical and physical properties of the composites.
- Compared to other Al alloys, if strength is the most important consideration, then it was found that Al7075 is the better choice. Also if both workability and high strength is required then Al2024 is considered as good choice.
- Ultimate tensile strength, shear strength, fatigue strength, yield strength and hardness of Al7075 is better compared to Al2024.
- Stir casting method of fabricating Al7075-Ni coated or Al2024-Ni coated MMCs was found to be advantageous over other methods when compared in terms of lower cost and ease of production.
- Among various coating such as nickel, cobalt and copper, coating of nickel on aluminium alloy was found to have most wettability and it showed there was efficient distribution of a different powder particle in the matrix of composite with very low porosity and interfacial reaction products.
- Relatively the density of the composites was observed to be increasing with coating. The improvement in density attributes to the closure of pores.
- The significant reduction in the pores resulted in better matrix-reinforcement interfacial bonding and improved mechanical properties of the composite such as hardness, tensile strength, compressive strength etc.

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