

Properties and Characterization of Al-Al₂O₃ Composites Processed by Casting and Powder Metallurgy Routes (Review)

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Abstract - Aluminium matrix composites with Al₂O₃ reinforcements give superior mechanical & physical properties. Their applications in several demanding fields like automobile, aerospace, defence, sports, electronics, bio-medical and other industrial purposes are becoming essential for the last several decades. Various manufacturing processes e.g. stir casting, ultra-sonic assisted casting, compo-casting, powder metallurgy, liquid infiltration are being utilized for the production of the aluminium matrix composites. These composite materials possess improved physical and mechanical properties e.g. lower density, low coefficient of thermal expansion, good corrosion resistance, high tensile strength, high stiffness, high hardness and wear resistance. This paper reviews the characterization of mechanical properties with production routes of powder metallurgy and castings for aluminium matrix- Al₂O₃ composites. Reinforcing aluminium matrix with much smaller particles, submicron or nano-sized range is one of the key factors in producing high-performance composites, which yields improved mechanical properties. A uniform distribution of the Al₂O₃ reinforcement phase in the Al matrix can be obtained by high-energy ball milling of Al-Al₂O₃ blends. Nearly 92% increase in the hardness and 57% increase in the tensile strength were obtained in the nano-composites as compared to the commercially pure aluminium. Ultrasonic assisted casting and powder metallurgy methods are becoming more common for the production of Al-Al₂O₃ composites. Agglomeration of the reinforcing particles along with the increasing volume percentage is still a challenging task in composites materials manufacturing.

KEYWORDS: Al matrix-Al₂O₃ composites, Mechanical properties, Powder Metallurgy, Stir casting, Ultrasonic assisted casting.

I. INTRODUCTION

Light metal matrix composite materials with ceramic particles as reinforcements have received widespread studies during the past decades because of their superior mechanical properties. Among them, the Al₂O₃ particulate reinforced aluminium composites (Al-Al₂O₃) are the most successful type of MMCs. The Al₂O₃ reinforced aluminium alloys matrix composites have been progressively more used in the automotive or aircraft industry and aerospace because of their high strength-to-weight ratio, good castability and better tribological properties over the unreinforced alloys [4]. A strong interface between aluminium alloy matrix and reinforcement phase crucially determines failure behaviour of the composites. Fabrication of Al/Al₂O₃ composite via powder metallurgy method from the mixture of Al and Al₂O₃ powders usually results in weak bonding at interface due to the poor wettability between the two phases [3]. Metal-matrix composites are most promising in achieving enhanced mechanical properties such as: hardness, strength, wear resistance and fatigue resistance etc. Aluminium-matrix composites (AMCs) reinforced with particles and whiskers are widely used for high performance applications such as in automotive, military, aerospace and electricity industries because of their improved physical and mechanical properties [22].

Reinforcement of Al matrix materials with nano size alumina particles yields the superior properties which are very important for today's requirement. Nano-structures have the ability to generate new features and perform

new functions that are more efficient than or cannot be performed by larger structures and machines. Due to small dimensions of nano-materials, their physical/chemical properties (e.g. stability, hardness, conductivity, reactivity, optical sensitivity, melting point, etc. can be altered [1, 6].

A. COMPOSITES

Composite material is a mixture of two or more materials or phases of the same material, insoluble in one another possessing properties which are superior to any of the component materials. Nano-composites are defined here as a class of materials that contain at least one phase with constituents in the nanometre range ($1 \text{ nm} = 10^{-9} \text{ m}$) [3, 4, 8]. The amount, size and distribution of reinforcing particles in the metal matrix play an important and critical role in enhancing or limiting the overall properties of the composite material. Reinforcing aluminium matrix with much smaller particles, submicron or nano-sized range, is one of the key factor in producing high-performance composites, which yields improved mechanical properties [13]. There are certain size effects which govern the property of these materials:

B. TYPES OF NANOCOMPOSITES

- a) Ceramic Matrix Nanocomposites (CMNC)
- b) Metal Matrix Nanocomposites (MMNC)
- c) Polymer Matrix Nanocomposites (PMNC)

a) *CERAMIC MATRIX NANOCOMPOSITES (CMNC)*: In this group of composites the main part of the volume is occupied by a ceramic, i.e. a chemical compound from the group of oxides, nitrides, borides, silicides etc. In most cases, ceramic-matrix nanocomposites encompass a metal as the second component. Ideally both components, the metallic one and the ceramic one, are finely dispersed in each other in order to elicit the particular nanoscopic properties. Nanocomposites from these combinations were demonstrated in improving their optical, electrical and magnetic properties as well as tribological, corrosion-resistance and other protective properties. Ceramic Matrix Nanocomposites include $\text{Al}_2\text{O}_3/\text{SiO}_2$, SiO_2/Ni , $\text{Al}_2\text{O}_3/\text{TiO}_2$, $\text{Al}_2\text{O}_3/\text{SiC}$, $\text{Al}_2\text{O}_3/\text{CNT}$ etc.

b) *METAL MATRIX NANOCOMPOSITES (MMNC)*: Metal matrix nanocomposites (MMNC) refer to materials consisting of a ductile metal or alloy matrix in which some nanosized reinforcement material is implanted. These materials combine metal and ceramic features, i.e., ductility and toughness with high strength and modulus. Thus, metal matrix nano-composites are suitable for production of materials with high strength in shear/compression processes and high service temperature capabilities. They show an extraordinary potential for application in many areas, such as aerospace, automotive industries and other Metal Matrix Nanocomposites include $\text{Al}/\text{Al}_2\text{O}_3$, Al/SiC , $\text{Fe-Cr}/\text{Al}_2\text{O}_3$, $\text{Ni}/\text{Al}_2\text{O}_3$, Co/Cr , Fe/MgO , Al/CNT , Mg/CNT etc.

c) *POLYMER MATRIX NANOCOMPOSITES (PMNC)*: In the simplest case, appropriately adding nano-particulates to a polymer matrix can enhance its performance, often in very dramatic degree, by simply capitalizing on the nature and properties of the nanoscale filler (these materials are better described by the term nanofilled polymer composites). This strategy is particularly effective in yielding high performance composites, when good dispersion of the filler is achieved and the properties of the nanoscale filler are substantially different or better than those of the matrix, for example, reinforcing a polymer matrix by much stiffer nanoparticles of ceramics, clays, or carbon nano-tubes. Polymer Matrix Nano-composites include thermoplastic/thermoset polymer/layered silicates, polyester/ TiO_2 , polymer/ CNT , polymer/layered double hydroxides.

C. $\text{Al}/\text{Al}_2\text{O}_3$ NANOCOMPOSITES

Due to their light weight and high specific strength, particulate reinforced aluminium composites are attractive structural materials for various domains such as automotive and aerospace applications. An optimum combination of high strength and ductility gives Aluminium metal matrix nano-composites (AMNC) a wide range of advanced applications [15]. If compared with pure Al, 2.0 vol% nano- Al_2O_3 additions improves yield strength of around 66%, hardness of around 50% and tensile strength of around 80% [7, 22]. In another study, ultrasonic assisted casting method was used to disperse 2.0 wt% nano- Al_2O_3 (10 nm) in aluminium matrix. Compared with pure Al cast by the same method, composite hardness was increased by 92% and the yield strength by 56% [17]. Owing to low density, low melting point, high specific strength and thermal conductivity of aluminium, a wide variety of reinforcement particulates such as Al_2O_3 , SiC, B_4C , AlN, Si_3N_4 , TiC, TiO_2 , TiB_2 and graphite have been reinforced into it. Among these particulates, Al_2O_3 , SiC, B_4C , TiB_2 additions improved the wear behaviour of aluminium matrix composites [19].

II. FABRICATION OF Al/Al₂O₃ COMPOSITES

Aluminum matrix composites (AMCs) are manufactured using various techniques. These techniques could be classified as (a) liquid-state (casting) processes e.g. stir casting, squeeze casting, ultrasonic-assisted casting, vacuum infiltration, pressureless infiltration and dispersion methods; (b) solid state processes e.g. powder metallurgy (PM) techniques with variations in the processing steps, that is, use of hot iso-static pressing, cold iso-static pressing, hot die pressing, dynamic compaction and (c) liquid-solid processing e.g. compo-casting, semisolid forming. The limitations of the first and third groups arise from difficulties in mixing the two phases thoroughly, difficult determination of critical temperature for infiltration, problems due to fluidity and/or wettability at matrix-reinforcement interface, as well as harmful reactions at the interface [7].

A. POWDER METALLURGY

The basic process of powder metallurgy consists of three major stages. First, the primary material is physically powdered into many small individual particles. Then, the different powders of metals and /or ceramics are mixed in required proportions. Ball milling may be performed to achieve mechanical alloying of powder mixtures for better mechanical properties. Next, the powder is injected into a mold or die and compacted on a press to produce a weakly cohesive structure close to the dimensions of the object ultimately to be manufactured. Finally, the product is formed by applying high temperature, pressure, long setting times, or any combination thereof. Afterwards, secondary operations like extrusion, heat treatment or machining etc. may be done.

A.A. Mazen and A.Y. Ahmed [7] mixed pre-weighed pure alumina powder (Al₂O₃) with pure aluminium (Al) powder with the use of a mechanical mixer and four different compositions, Al-0wt%Al₂O₃, Al-2.5wt%Al₂O₃, Al-5wt%Al₂O₃, & Al-10wt%Al₂O₃ were prepared. The Al-Al₂O₃ powder mixture was then hot pressed at 723 K for 4 h using the hot-pressing setup shown in Fig. 1, using a compaction pressure of 74 MPa on the 24 mm diameter billets.

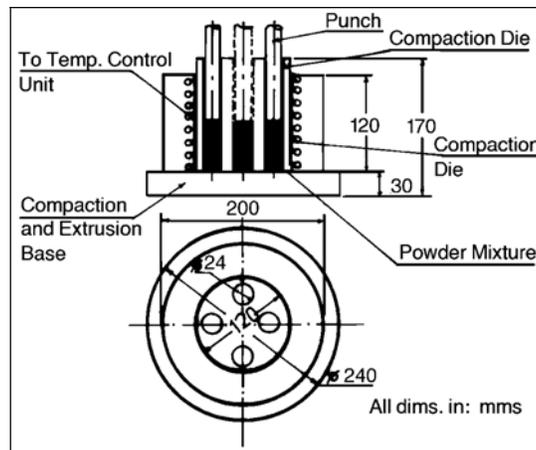


Fig. 1 Hot pressing and extrusion setup [7]

The hot-pressed billets were then hot extruded at 723 K with an extrusion ratio of 5. From the extruded rod after machining it, specimens were prepared for tests. However, these techniques add limitations to the size and geometry of the produced billet. SEM revealed the presence of porosity, particle-rich areas in the matrix and debonding of some alumina particles under fractographic examination due to weak bond strength and large difference between the melting points of Al and Al₂O₃.

Yung-Chang Kang and Sammy Lap-Ip Chan [8] took commercial pure aluminium powder containing 38 ppm Cu, 20 ppm Si, 38 ppm Mg, 18 ppm Mn, and 1200 ppm Fe. The mean particle size of this gas-atomized powder was about 28 μm. Nanometric spherical Al₂O₃ powder with a purity of 98.5% as the reinforcement with mean particle size of about 50 nm. The aluminium powder was mixed with different volume fraction (1–7 vol.%) of Al₂O₃ powder in pure ethanol slurry. Mixed powders were dried at 150°C and then compacted by CIP. For the comparison of mechanical properties between nano-metric & micrometric particle-reinforced aluminium

composites, a 10 vol.% SiC_p (13 μm)/Al composite was fabricated following the same route. All compacted billets were sintered in vacuum at 620°C for 2 h, extruded at 420°C to form bars of 15mm in diameter and annealed at 350°C for 2 h. It was found that the nanometric particulates improve the mechanical properties in the monolithic system because of Orowan strength mechanism. However, as nano-particle content in the composites exceeds 4 vol.%, the agglomerations of nano particles reduce the amount of 'effective' nano-particulates available, and the particle strengthening effect diminishes.

B. MECHANICAL MILLING

Mechanical milling is a process concerning repeated deformation, welding and fracture. Many parameters such as miller type, ball to powder weight ratio, characteristics of the balls and speed of ball milling, milling atmosphere, temperature, and process control agent influence the stages of milling. Upon milling of composite powders, the volume fraction, the particle size and the type of the reinforcement also affect the process.

Z. Razavi Hesabi et. al. [9] produced aluminium powder of mean diameter 48μm by nitrogen gas atomization process. Two grades of α-Al₂O₃ powders with average particle size of 35 nm (*n*-Al₂O₃) and 1μm (Al₂O₃) were used with stearic acid as the PCA. The Al powder was blended with 5 vol% Al₂O₃ and 1.5 wt% PCA in a Turbula T2C mixer for 20 min. The powder mixtures were then milled in a planetary ball mill under argon atmosphere up to 24 h with the rotational speeds of 250 rpm and ball to powder weight ratio of 10:1. Aluminum powder without alumina addition was also processed at the same condition. It was found that when hard alumina particles are added to aluminium powder, the fracture occurs earlier, and thus the steady-state condition is achieved in shorter milling time. The bulk density of composite powders was found to be higher than that of unreinforced Al and shorter milling time for Al–Al₂O₃ micro-composite compared to the nano-composite.

Z. Razavi Hesabi et. al. [10] utilized nitrogen gas atomized Al powder with mean particle diameter of 49 μm. Al₂O₃ nano-particles with average size of 35 nm, and 1.5 wt.% stearic acid (PCA). Al–5.0 vol.% Al₂O₃ composite powder was prepared by mechanical blending of the starting powders in a Turbula T2C mixer for 20 min. Steel balls with diameter of 10mm and the ball to powder charge ratio of 1:2 (wt.%) were used. This mixture was milled for 72k seconds in a planetary ball mill under a high purity argon atmosphere with the rotational speed of 250 rpm and the ball to powder charge ratio (wt.%) of 10:1. Monolithic aluminum powder was also processed at the same condition for comparison of compressibility behaviour. The compressibility of Al and 5 vol.% *n*-Al₂O₃ powders during uniaxial compaction was investigated and observed that the addition of hard nano particles to aluminium powder improves the densification capacity at Stage I due to disintegration of the clusters and agglomerates under the applied load and filling the voids between the matrix particles. The powder also exhibited lower plastic deformation capacity, owing to the load partitioning effect.

Kee Do Woo and Hyun Bom Lee [11] used pure Al, Mg, Cu, Si and SiO₂ powder (average particle size 70, 30, 20, 50 and 40μm, respectively) in their experiments. The compositions of the powder mixture were Al–0.4 wt.% Mg–14 wt.% SiO₂ and Al–3 wt.% Cu–3 wt.% Si–9 wt.% SiO₂ powder, respectively. Ball milling was done under an argon atmosphere to prevent powder oxidation, with ball to powder (weight) ratio of 4:1. Milling of the mixed powders was conducted for 1–8 h using an SPEX 8000 Mixer/Mill. The green sample was sintered at 650°C and 750°C for 2 h in a tube furnace under vacuum. SEM results indicates that Nano- and/or subsive-size Al₂O₃ particles were homogeneously distributed in the Al matrix. The flexural strength of the sintered specimen (1.2 GPa) using Al–0.4% Mg–14% SiO₂ powder milled for 8 h was about four times that of as the sintered specimen (300MPa) using as-mixed powder.

T.G. Durai et al. [12] used aluminium powders (99.7% purity, <20 μm size), ZnO and CuO powders (99.5% purity, <10μm size). Powders mixtures have been subjected to a high-energy ball milling using tungsten balls with a diameter of 10 mm for up to 60 h using a ball to powder weight ratio of 10:1 and rotational speed of 300 rpm using a toluene medium. Mechanically milled powders have been cold pressed under a pressure of 650MPa to form green compacts of 10mm diameter and 4mm length, followed by heating at a given temperature to initiate the reaction in argon atmosphere. The results demonstrate that an improvement in wear resistance is a strong function of Al₂O₃ content and size of Al₂O₃ particles as well as crystallite size of the matrix alloy. Mechanical milling causes a uniform distribution of the particle with small inter-particle distance resulting in an improved wear resistance. Hardness of the milled composites is higher than the unmilled composites. The wear rate increases linearly with the applied load irrespective of the material and decreases with the increasing sliding distance.

Ismail Ozdemir et. al.[13] manufactured the chemical composition of aluminium alloy powder EN AW-2017 by gas atomization process is 3.9Cu, 0.6Mn, 0.7Mg, bal. Al (wt.%). Gas atomized aluminum alloy powders with a

mesh size of $\sim 100\mu\text{m}$ was supplied as the starting matrix material. The matrix powder was mixed with volume fractions of 5 and 15% commercially available SiC and Al_2O_3 powders with a particle size of $-55+15$ and $-22+5\mu\text{m}$, respectively. The high-energy milling was performed in argon atmosphere with various rotation speeds (ranging from 600 to 800 rpm) in a stainless steel chamber using stainless steel balls and a powder to ball weight ratio of 1:10. The milling time was varied from 10 min to 8h in case of Al_2O_3 and from 10 min to 6h in case of SiC to investigate its influence on the milled products. HEM process decreased the crystallite size of the aluminium matrix to about 45 nm. No matter how small (fine Al_2O_3) or how much volume fraction were being utilized (5 or 15 vol.%), no significant effect on further decrease in crystallite size was detected.

H. Mahboob et al.[14] used commercial aluminium powders with particle size smaller than $63\mu\text{m}$ and nano-sized α -alumina powder with %99.5 purity and average size of about 27-43 nm have been provided. Figures 1(a) and (b) show micrographs of the α -alumina and aluminium powders taken by TEM and SEM, respectively. It was found that the- alumina particles are almost spherical and aluminium particles are irregular in shape.

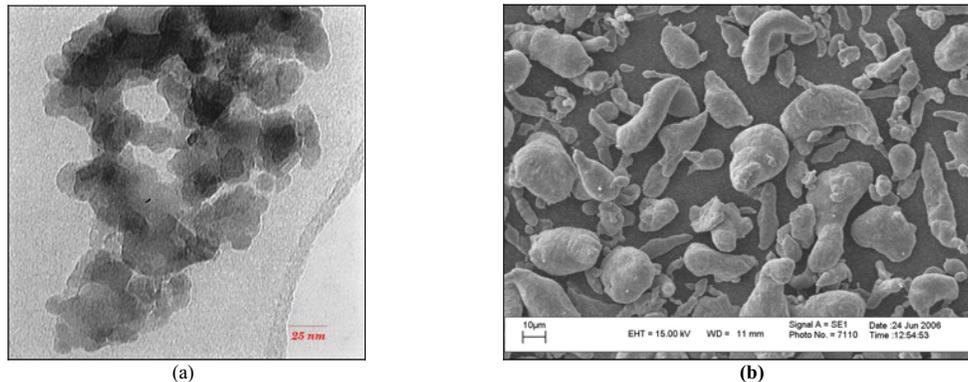


Fig.2. Initial used powders: (a) α -alumina, (b) aluminium [14]

SEM results shown that the distribution of the alumina particles in the Al matrix reaches a full homogeneity after steady state. The effect of the nanostructured Al matrix, the presence of submicron alumina particles and nanometric particles caused by decomposition of PCA increase the hardness of powder up to 180 HV.

M. Tavoosi et al. [15] took a mixture of commercial aluminium (99.7% purity and particle size of $50-70\mu\text{m}$) and 15.8 wt% ZnO powders (99.9% purity and particle size of 250 nm) was milled in planetary ball mill in order to produce Al-13.8 wt%Zn/5 vol% Al_2O_3 nanocomposite. The MA was executed in a planetary ball mill with a rotation speed of 600rpm and a ball-powder mass ratio of 15:1 for predetermined hours without interruption. It was found after 60 h milling and hot pressing at 500°C under 400MPa pressure that the relative density of the hot pressed samples increased (from 95% to 99.6%) as the temperature increased (from 400 to 500°C). The hardness value for Al-13.8 wt%Zn/5 vol% Al_2O_3 nanocomposite (relative density about 99.6% and crystallite size about 40 nm) was about 180HV and for Al-13.8 wt%Zn (relative density 99.8% and crystallite size of about 40 nm) was about 150 HV which shows that the produced nanocomposite had a good thermal stability at temperatures below 400°C .

Dominique Poirier et al. [16] used three different sizes of Al_2O_3 powders. Spherical Al_2O_3 of 4 nm nominal size was bought from Aldrich, spherical Al_2O_3 of 80nm average particle size was produced by combustion synthesis. Al powder was first milled alone for 5 h under argon atmosphere in a high energy Spex 8000 mill with a rpm of 1200 with 2.0 wt% stearic acid. Tungsten carbide balls (11mm) and container with a 10:1 ball-to powder ratio were used. It was found that the Al_2O_3 composites resulting from milling display a uniform dispersion of the second phase with few agglomerates of around 1 micron in size. The $\text{Al}_2\text{O}_3/\text{Al}$ nanocomposite powders hardness is near five times higher than pure unmilled Al. A decrease in the Al_2O_3 particle size from 400 to 4 nm has increased the nanocomposite powder hardness of 11%. Compression tests performed on the hot pressed compacts have shown similar trends with a final yield stress and compression strength of 661 and 723MPa respectively for the 10 vol% Al_2O_3 (4 nm) composite which is associated to grain refinement and dispersoid formation.

M. Tabandeh Khorshid et al. [17] used air atomized commercial pure aluminium powder with a mean particle size of $45\mu\text{m}$ and spherical pure alpha- Al_2O_3 powders with average particle sizes of 35 nm and $0.3\mu\text{m}$. The P/M process was used to produce the composite materials using hardened steel balls of 5 mm diameter with he rotational speed of 480 rpm and the ball-to-powder ratio (BPR) of 15:1 (wt. %) for 8 h milling time. The

composite powders were dried at 150°C for 90 minutes and compacted at 140 MPa pressure to prepare billets followed by hot forward extrusion process at 600°C. Different ratios of the nanometric Al₂O₃ powder to the sub-micrometric Al₂O₃ powder were tested, including 2:8, 3:7, 4:6, 5:5, and 6:4 in weight percent. It was found that by increasing the ratio of the nano- to submicron-sized particulates, the relative density first increases and then decreases. The amount of the micro-hardness and strengths of the composites first increases and then decreases by increasing the nanoparticles content. For the samples having the nanoparticles more than 4 wt.%, a decrease in the strengths was observed, attributed to the agglomeration of the nanoparticles and the formation of a continuous brittle phase along grain boundaries.

S.S. Razavi-Tousi et. al. [18] utilized a high purity aluminum powder (particle size: 1mm) was separately mixed with 1, 3 and 7 v% of alumina (D50 ≈500 nm) and alumina nano-powder. The mixtures were wet milled in a P5 planetary mill for 22 h using stainless steel cup and balls in Toluene media. The ball to powder ratio was 20:1 and the mill speed was maintained at 300 RPM. The produced powders were dried at 100°C. In order to obtain green samples, the powders were pressed by an iso-static press at 1 GPa in the air atmosphere, the green samples were sintered at 640°C for 30, 60, 120, 240 and 480 min in the Ar atmosphere using a tube furnace. Weight of the samples was measured in dry, wet and soaked condition for obtaining the densities. This study shows that pressability of nanocomposite powders decreases as the particle size of reinforcement phase decreases or its volume fraction increases. This effect has been explained by the effect of reinforcement phase on the strength of composite powders. Moreover, the inhibited grain growth of Al matrix profoundly decelerated neck growth or coarsening mechanisms, which resulted in stabilization of initial pores.

B. CASTING

Casting is a manufacturing process which is used for metal matrix nanocomposites in which the matrix material in liquid form is poured into a mold, which contains a hollow cavity of the desired shape; reinforcement particles are added to it and then allowed to solidify. Various parameters are used to control the mixing and uniform distribution of nano reinforcement particles in the metal matrix. The following are the advantages of casting method:

1. Uniform distribution of nano particles
2. Better matrix particles bonding
3. Easier control of matrix structure
4. Simplicity in operation
5. Nearer net shape dimensions

A. STIR CASTING

In a normal practice of stir casting technique, cast metal matrix composites (MMC) is produced by melting the matrix material in a vessel, then the molten metal is stirred thoroughly to form a vortex and the reinforcement particles are introduced through the side of the vortex formed. From some point of view this approach has disadvantages, mainly arising from the particle addition and the stirring methods. During particle addition there is undoubtedly local solidification of the melt induced by the particles, and this increase the viscosity of the slurry.

Ali Mazahery and Mohsen Ostadshabani [19] selected aluminum 356 alloy ((wt%): 7.5 Si, 0.38 Mg, 0.02 Zn, 0.001 Cu, 0.106 Fe, and Al (balance)) as the matrix and a mixture of nano- Al₂O₃ ((wt.%): 93 a-Alumina, 0.8 Fe₂O₃, 1.8 TiO₂, 1.1 CaO, and 0.2 other magnetic materials) and aluminium particles with average particle sizes of 50nm and 16 μm, respectively, was used as the reinforcement. The powders were mixed in the ratio of Al/Al₂O₃=1.67 and they were ball milled in isopropyl alcohol for 20 min using WC/Co balls followed by drying in a rotary vacuum. The powder mixtures were cold-pressed under 200 MPa into samples having 60x60x60 mm³ dimension and then crushed. Microstructural observations revealed a reasonably uniform distribution of Al₂O₃ nanoparticles in the Al matrix. These particles refined the grain structure of the cast materials. There are also a few agglomerated particles through the matrix. The addition of nanoparticles resulted in significant improvements in both compressive and tensile flow stress, for which the highest values were obtained at 2.5 and 1.5 vol.% of Al₂O₃ nanoparticles, respectively. The presence of nanoparticles primarily improves the ductility of composite at 800°C. However, the elongation remains rather constant with the addition of nanoparticles at 900°C. Porosity level increased slightly with increasing particulate content at both casting temperatures. Fractography of the samples displayed lot of dispersed dimples with varying sizes in the matrix, confirming the high ductility observed in the tensile studies.

B. ULTRASONIC ASSISTED CASTING

Ultrasonic assisted casting is a casting method used casting for fabrication of metal matrix nanocomposites. In addition to normal casting method, an ultrasonic probe is used which is generating ultrasonic waves transmitted to the molten metal for uniform distribution and better mixing of reinforcement particles.

S. Mula et. al.[20] ball milled a micron sized (average size $\mu 75$ mm) Al_2O_3 powder for 22 h to produce nano-sized (average size ~ 10 nm) Al_2O_3 dispersoids in a high energy ball mill with WC grinding media, rotational speed of 300 rpm and toluene as the PCA. The ball to powder weight ratio was maintained at 10:1. The particle size of the milled Al_2O_3 powder was examined by TEM. Commercially pure Al (cp-Al) having a nominal composition of Al-0.96% Fe-0.43% Mg-0.26% Si was reinforced with this nano-sized Al_2O_3 by the non-contact ultrasonic casting method to prepare the cast ingots of Al-2% Al_2O_3 nanocomposite of 205 g weight. Fig.3. schematically illustrates the experimental set-up for this casting method.

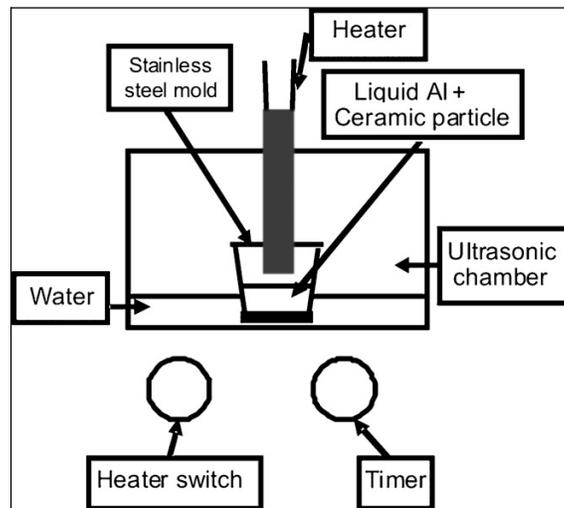


Fig.3. Experimental set-up for non-contact ultrasonic casting of Al- Al_2O_3 nanocomposite [20]

It consists of an ultrasonic chamber which can vibrate at a frequency of 35 kHz, a stainless steel mold and a hanging heater. The base of the mold was tightly fitted to the ultrasonic chamber, which was partially filled with water, so that the ultrasonic waves are effectively transmitted to the molten metal. The mold was preheated by the heater to delay the solidification process. After preheating the mold, the heater was withdrawn, and the mold was subjected to vibration at a frequency of 35 kHz. Then the liquid Al and nano-sized Al_2O_3 particles (2 wt.%) were simultaneously poured into the vibrating mold. The heater was immediately brought close to the liquid metal in order to delay the solidification process. The vibration continued for 5 minutes to ensure completion of the solidification. The ultrasonic waves in the molten metal were expected to generate transient cavitations and acoustic streaming to cause uniform mixing of the nano-sized dispersoids.

Investigations on Al-2% Al_2O_3 nanocomposite using optical, scanning and transmission electron microscopes revealed that the nanocomposite was a 'super-composite' of nearly continuous nano-alumina dispersed zones (NDZs) enveloping the Al_2O_3 depleted zones (ADZs). The NDZs were 200–300 nm wide and situated mostly near the grain boundaries. The NDZs had a dense dispersion of nano-sized (~ 10 nm) Al_2O_3 particles with an average inter particle spacing of ~ 24 nm. Nearly 92% increase in the hardness and $\sim 57\%$ increase in the tensile yield strength were obtained in the present nanocomposite, as compared to those of the commercially pure (cp) Al, cast by the non-contact ultrasonic casting method. [20]

Ali Mazahery and Mohsen Ostadshabani [21] selected aluminum 356 alloy ((wt%): 7.5 Si, 0.38 Mg, 0.02 Zn, 0.001 Cu, 0.106 Fe, and Al (balance)) as the matrix and a mixture of nano- Al_2O_3 ((wt%): 93 a-Alumina, 0.8 Fe_2O_3 , 1.8 TiO_2 , 1.1 CaO, and 0.2 other magnetic materials) and aluminum particles with average particle sizes of 50nm and 16 mm, respectively, was used as the reinforcement. The powders were mixed in the ratio of $Al/Al_2O_3=1.67$ and they were ball milled in isopropyl alcohol for 20 min using WC/Co balls. The mixture was then dried in a rotary vacuum evaporator and passed through a 60-mesh screen. The powder mixtures were cold-pressed under 200MPa into samples having $60 \times 60 \times 60 mm^3$ dimension. The compacted samples were crushed and then passed through 60-mesh screen. The required amount of Al_2O_3 was calculated according to the ratio of Al/Al_2O_3 . Microstructural observations revealed a reasonably uniform distribution of Al_2O_3 nanoparticles in the

Al matrix. These particles refined the grain structure of the cast materials. The presence of nanoparticles primarily improves the ductility of composite at 800°C. However, the elongation remains rather constant with the addition of nanoparticles at 900°C. Porosity level increased slightly with increasing particulate content at both casting temperatures. These results can be attributed to the increased surface area of the nano-Al₂O₃ particles which can in turn increase the porosity levels. Fractography of the samples displayed lot of dispersed dimples with varying sizes in the matrix, confirming the high ductility observed in the tensile studies.

IV. COMPARISON OF PROCESSING TECHNIQUES

S. No.	Process	Advantages	Limitations
1.	Powder metallurgy	<p>1. Homogeneity of mixture is better controlled, component is produced in near net shape dimension, good ductility, b. low ball to powder charge ratio provides a better blend homogeneity</p> <p>2. The gas atomized aluminium particles exhibit a spherical shape with broad size distribution while small satellite particles attached to the large ones</p> <p>3. the most economical method for manufacturing aluminium MMCs, one can avoid the segregation and agglomeration of the reinforcement particles</p> <p>4. The high-energy ball milling offers grain size refinement, making the crystals less susceptible to fracture, and hence nano crystallization process of aluminium MMCs has been the subject of intensive research in recent years.</p>	<p>1. In processing of Aluminium, the oxide and hydroxide films coating the powder,</p> <p>2. Metal powders do not act as perfect liquids under pressure and a difference in pressure is established both parallel and perpendicular to the direction of pressing.</p>
2.	Casting	Better matrix–particle bonding, easier control of matrix structure, simplicity, low cost of processing, and nearer net shape	Extremely difficult for the mechanical stirring method to distribute and disperse nano-scale particles uniformly in metal melts due to their large surface-to-volume ratio and their low wettability in metal melts,

V. COMPARISON OF VARIOUS PROPERTIES

S. No.	Process	Process parameters	Properties
1.	Powder metal-urgy	<p>1. Compaction stress of 74-157 MPa & compaction temp. of 723-873K applied for 4 h-3h, followed by hot extrusion</p> <p>2. Al powder was mixed with volume fraction (1–7 vol.%) of Al₂O₃ powder and sintering was done at 620°C for 2 hours.</p> <p>3. The Al powder was blended with 5 vol% Al₂O₃ and 1.5 wt% PCA (Stearic acid powder) in a Turbula T2C mixer</p> <p>4. Nitrogen gas atomized Al powder with mean particle diameter of 49 µm, α-Al₂O₃ nanoparticles with average size of 35 nm, and stearic acid.</p> <p>5. To prevent powder oxidation, the powders were sealed in stainless steel vial under an argon atmosphere during ball milling. The weight ratio of ball to powder was 4:1. Milling</p>	<p>1. Strength improvement of 64 to 100% compared to the matrix material, considerable ductility, main fracture mechanism in Al-Al₂O₃ MMC is the ductile mode of void initiation, growth, and coalescence,</p> <p>2. The strengths of composites increased with the 4% volume fraction of particulate.</p> <p>3. The bulk density of composite powders was found to be higher than that of unreinforced Al, longer milling time was found necessary to achieve steady-state condition compared to microcomposite powder.</p> <p>4. The compressibility of the lended and milled aluminum/nanometric alumina particles exhibits the same features, The addition of hard nanoparticles to aluminum powder by mixing improves the densification capacity</p>

	<p>of the mixed powders was conducted for 1–8 h.</p> <p>6. Milling has been carried out at 300 rpm using a toluene medium in order to avoid oxidation or sticking of powders on the wall of the vial.</p> <p>7. Gas atomized aluminum alloy powders with a mesh size of $-100\mu\text{m}$ was mixed with volume fractions of 5, and 15% commercially available SiC and Al_2O_3 powders. The milling time was varied from 10 min to 6 or 8 h.</p> <p>8. Commercial aluminum powders with particle size smaller than $63\mu\text{m}$ and nano-sized α-alumina powder with 99.5% purity and average size of about 27–43 nm.</p> <p>9. Commercial purity Al powder as a monolithic system and a mixture of Al–20 wt.% alumina powder were separately milled in a P5 planetary mill for various periods of time up to 25 h.</p> <p>10. A mixture of commercial aluminum (99.7% purity and particle dia. of $50\text{--}70\mu\text{m}$) and 15.8 wt% ZnO powders (99.9% purity and particle size of 250 nm) was milled in planetary ball mill in order to produce Al–13.8 wt%Zn/5 vol% Al_2O_3 nanocomposite.</p> <p>12. Air atomized commercial pure aluminum powder with a mean particle size of $45\mu\text{m}$ and spherical pure alpha- Al_2O_3 powders with average particle sizes of 35 nm and $0.3\mu\text{m}$.</p> <p>13. The base material used is Aluminium 6063 (Al 6063), whose nominal chemical composition (wt.%), purity and mesh size of the pure elemental powders</p> <p>14. A high purity aluminum powder (Aldrich, no.: 518573, flakes, particle size: 1mm) was separately mixed with 1, 3 and 7 vF% of MR70 alumina ($D_{50} \approx 500\text{ nm}$) and alumina nano-powder.</p> <p>15. Air atomized Al powder of technical purity (99.8%) with nominal diameters $d_{10} = 0.66\mu\text{m}$, $d_{50} = 1.31\mu\text{m}$, and $d_{90} = 2.51\mu\text{m}$ were determined by Sympatec HELOS laser diffraction method.</p>	<p>5. The flexural strength of the sintered specimen (1.2 GPa) using 8 h milled powder was about four times as the sintered specimen (300MPa) using as-mixed powder.</p> <p>6. An addition of the ceramic reinforcement such as Al_2O_3 particles improves the wear resistance of the composite</p> <p>7. Higher hardness is obtained when the size of the reinforcement is small and its volume fraction is high. HEM process decreased the crystallite size of the aluminium matrix to about 45 nm.</p> <p>8. Strength and hardness were increased by increasing of milling time but the elongation was almost constant, the uniform distribution of ultra-fine alumina particles inhibits stress concentration and crack growth.</p> <p>9. The effect of the nanostructured Al matrix, the presence of submicron alumina particles and nanometric particles caused by decomposition of PCA increase the hardness of powder up to 180 HV.</p> <p>10. The produced nanocomposite had a good thermal stability at temperatures below 400°C.</p> <p>11. The $\text{Al}_2\text{O}_3/\text{Al}$ nanocomposite powders hardness is near five times higher than pure unmilled Al. A decrease in the Al_2O_3 particle size from 400 to 4 nm has increased the nanocomposite powder hardness of 11%.</p> <p>12. For the samples having the nanoparticles more than 4 wt.%, a decrease in the strengths was observed, attributed to the agglomeration of the nanoparticles and the formation of a continuous brittle phase along grain boundaries.</p> <p>13. Addition of ceramic nano particles into the aluminium matrix sustains the crystallite size reduction and better particle size distribution</p> <p>14. Pressability of nanocomposite powders decreases as the particle size of reinforcement phase decreases or its volume fraction increases.</p> <p>15. On top of it, continuous Al_2O_3 skeleton within Al matrix led to superior mechanical properties and creep performance of forged compacts at elevated temp. up to 400°C.</p>
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2.	Casting	<p>1. In this study, A356 aluminium alloy {(wt.%): 7.5 Si, 0.38 Mg, 0.02 Zn, 0.001 Cu, 0.106 Fe and Al (balance)} was used as the matrix material(16μm) while nano- Al₂O₃ (alumina) particles with average particle size of 50nm was used as the reinforcements, Al/ Al₂O₃ = 1.67, the crucible temperature upto 800 °C</p> <p>2. Micron sized (average size ~75 mm) Al₂O₃ powder was ball milled for 22 h to produce nano-sized (average size~10 nm) Al₂O₃ dispersoids in a high energy Fritsch Pulverisette- 5 planetary ball mill withWC grinding media.</p> <p>3. Aluminum 356 alloy ((wt%): 7.5 Si, 0.38 Mg, 0.02 Zn, 0.001 Cu, 0.106 Fe, and Al (balance)) was selected as the matrix and a mixture of nano- Al₂O₃ ((wt.%): 93 a-Alumina, 0.8 Fe₂O₃, 1.8 TiO₂, 1.1 CaO, and 0.2 other magnetic materials) and aluminum particles with average particle sizes of 50nm and 16 mm, respectively, as the reinforcements.</p>	<p>1. Porosity level increased slightly with increasing particulate content, The yield strength, UTS and ductility of nano-Al₂O₃ reinforced aluminum composites improved with the increase in volume fraction of nanoparticles, The maximum hardness was observed in composite including 2.5 vol.% Al₂O₃ and cast at 800°C.</p> <p>2. Nearly 92% increase in the hardness and ~57% increase in the tensile yield strength as compared to those of the commercially pure (cp) Al, cast by the non-contact ultrasonic casting method with 1.4% Al₂O₃ dispersoids</p> <p>3. The addition of nanoparticles resulted in significant improvements in both compressive and tensile flow stress, at 2.5 and 1.5 vol.% of Al₂O₃ nanoparticles, respectively, Porosity level increased slightly with increasing particulate content at both casting temperatures (800 & 900°C)</p>
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VI. FUTURE SCOPE

Metal matrix composites with micron-size reinforcements have been used with outstanding success in the automotive, aerospace, defence, sports and industries, as well as in small engines and electronic packaging applications. In case of metal matrix nanocomposites, incorporation of as little as one volume percentage of nano size ceramic particles has lead to a much greater increase in the strength of aluminium. Such potential improvements have great implications for the automotive, aerospace, and, in particular, defense industries due to the drastic weight savings and exceptional properties that can be achieved. Potential aerospace applications may include ventral fins for aircrafts, as well as fan exit guide vanes for commercial airline jet engines. Both components require high stiffness and strength, low weight as well as resistance to erosion from rain, airborne particulates and hail. Components used in the automotive industry where bulk nanocomposites would find potential application include brake system components, which require high wear resistance and thermal conductivity, intake and exhaust valves, which require high creep resistance and resistance to sliding wear, as well as piston liners, which require high wear resistance, good thermal conductivity and low coefficient of thermal expansion. Metal matrix nano-composites can be designed to exhibit high thermal conductivity, low density, and matching coefficient of thermal expansion with ceramic substrates and semiconductors, making them ideal candidates for such applications.

VII. CONCLUSIONS

There are exciting opportunities for producing exceptionally strong, light weight, wear resistant metal matrix composites with acceptable ductility by solidification processing and powder metallurgy. A fundamental understanding, however, must be gained of the mechanism that provides these improvements in properties, if such materials are to find wider commercial applications. In addition, processing methods must be developed to synthesize these materials in bulk, at lower cost, with little or no voids or defects, and with improved ductility, possibly as a result of bimodal and tri-modal microstructures. Metal matrix nanocomposites can lead to significant savings in materials and energy and reduce pollution through the use of ultra-strong materials that exhibit low friction coefficients, high wear resistance, low coefficient of thermal expansion and light weight. The following points are concluded:

- 1) A detail study of the work done so far has been done in this paper on powder metallurgy and casting techniques and characterization of Al nano Al₂O₃ composites.
- 2) A comparison of properties has also been done for the materials fabricated by these techniques to select a composite material required for a particular application.

- 3) From the various processes discussed in this paper, the ultrasonic-assisted casting is a method which provides better matrix–particle bonding, easier control of matrix structure, simplicity and low cost of processing.
- 4) Mechanical stirring method, it is extremely difficult to distribute and disperse nano-scale particles uniformly in metal melts due to their large surface-to-volume ratio and their low wettability in metal melts.
- 5) It is reported that mechanical properties of Aluminium alloy can be improved by reinforcement of nano Alumina particles up to the 4.0 vol.% and beyond that strengthening effect is levelled off because of clustering of nano Al_2O_3 particles which requires further research in this area.
- 6) Further research is warranted to develop better processing techniques which could control and retain properties and microstructures of nanocomposites.

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