Tribological and Mechanical Behaviours of Nanostructured Aluminium Alloys and Nanocomposites at Elevated Temperatures: A Short Review

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Abstract- Aluminium alloys demonstrate exceptional properties such as high strength-weight ratio and corrosion resistance are used for general engineering applications, automobile, automotive and in aerospace industries. However, they suffer some limitations as wear and creep at high temperatures. With the trend in the development of nanometallurgy, diverse nano-structures have been reported in the public domains. This paper reviews some of the vast literature on the enhancement of nanostructured aluminium alloys and reinforced aluminium nanocomposites. Importance is laid on the tribological and mechanical behaviour of the fabricated composites and nano-composites with respect to their production methods and applications at elevated (high) and cryogenic (low) temperatures.

Keywords- Tribology, mechanical behaviours, nanostructure, aluminium alloys, nano-composites, elevated temperatures

1 INTRODUCTION

There have been steady increases in the number of studies carried out on enumerating the tribological behaviours of diverse engineering materials in their environments of applications with the aim of extending their services lifespan and dependability; more challenging issue is studying this at elevated temperatures. Some of the production methods (Magibalan et al., 2019) of these aluminium base alloys, nano-particle reinforced aluminium composites and nanocomposites such as the liquid (Shanmughasundaram et al., 2013) and semi liquid routes; the prospects and the limitations of the properties of the developed composites (Prasad and Ramachandra, 2018; Peddavarapu and Jayendra, 2018) have been widely published.

The effects of processing techniques (casting, heat treatment, sintering, etc) on the mechanical properties (strength, ductility, hardness, toughness, stiffness, etc) and tribological (friction behaviour (Dwivedi, 2010), wear morphology (Alhawarti et al., 2015), fracture mode, fatigue) properties of the composites under dry (Vashegani et al., 2014), and lubricating conditions; the thermal responses of the composites to creep, stiffness and wear at extreme temperatures (Su et al., 2019); and the physical (nano/microstructure) i.e. intermetallic reactions between aluminium and the reinforcing nanocompounds have also been reported in the public domains. A concise historical summary of alloys and processing technology is presented in (Sanders, 2001).

There are many types of aluminium alloys from which varieties of engineering components are made. These are alloys having aluminium as the prime base metal and contain other basic alloying elements like Mn, Si, Cu, Mg, Sn and Zn. They are principally categorised as cast and wrought aluminium alloys; by ANSI number classification or by major alloying components according to DIN and ISO; under the heat-treatable and non-heat-treatable categories.

For their exceptional properties displayed such as high strength, light weight, and corrosion resistance, aluminium alloys are designed for general engineering applications, automobile, automotive and in aerospace industries; formed products and aluminium foils. The Al-Mg–Si series form complex profiles by extrusion for their Cast aluminium are of low fusion point and usually lessens tensile strength than wrought alloys of which Al–Si, (4.0–13%) is the most prominent. Al-Mg alloy, being lighter than most Al alloys is found very useful in aerospace industry (Hombерgsmeier, 2007). Conversely, pure aluminium is too soft but lacks high tensile strength needed for most structural applications. Aluminium alloys are extensively applied in automotive engines cylinder blocks, brake systems (Ajibola et al., 2014a, b; Ajibola and Oloruntoba, 2015a,b) and crankcases because of the low weight and high strength combination. The paper is a short review added to few reports on nanotechnological enhancement of aluminium alloys and composites; and their suitability for tribological applications at extreme temperatures.

2 SYNTHESIS AND PROCESSING METHODS FOR NAOCOMPOSITE ALUMINIUM ALLOYS AND NANOALLOYS

There have been different methods and approaches to the manufacture of nanostructured aluminium alloys and composites. Severe plastic deformation (SPD) was reported (Thama, et al., 2007) and reviewed (Vishnu, et al., 2019) as efficient way for making bulk ultra-fine grained or nanostructured very high strain components. Ultra-fine grained (UFG) and nanocrystalline substances are better wear resistant and harder than coarse grained counterparts (Joshi et al., 2014).

Some other production methods of UFG Al microstructure like high pressure torsion (HPT), equal channel angular pressing (ECAP), asymmetric rolling (AR), cryo-rolling (CR) and accumulative roll bonding (ARB) have also been reported (Valiev and Langdon, 2006; Edalati and Horita, 2016; Zhilyaev and Langdon, 2008). Aluminium alloy grain refinement has been attained by other popular techniques (Vishnu, et al., 2019; Yu et al., 2015) and developed over the past two decades of which twist extrusion, ARB and hydrostatic extrusion (HE) are prominent. Various microstructural growth

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through ECAP processing of Al–Cu–Li, Al–Mg–Cu, Al–0.2Sc, Al–Mg–Sc, AA2219, Al–Mg–Mn–Zr, Al–7%Si, Al–Mg–Si, AA7475, Al–Mg alloys are readily reported in the literature (Thama, et al., 2007; Vishnu, et al., 2019; Prangnell et al., 2004; Garcia-Infanta et al., 2009).

Clay et al., (2012) reported the galvanic production of bi-modal nanostructures by means of Al nanoparticle pattern wherein about 120 nm diameter size Al nanoparticle pattern, was substituted by metals like Pt, Ni, Cu, Au, In, Pd, Co, Pb, Ag and Fe due to its very low redox potential. The substitution with In, Ni, Co and Fe formed scattered permeable nano particles of singular or several pores. Unbroken, permeable nanostructures of bigger micron size agglomerates were produced by substituting Ag, Pd, Au and Pb; and globular porous constituents via exchanging with Pt and Cu. It was hypothesized that growth kinetics has significant function in the development of the nanostructures with porous nature and thus proposed mechanisms of growth as the explanation to the making of bi-modal nanostructures that are porous.

Djebbari et al., (2010) used high energy planetary ball mill to fabricate Fe50Co50 and (Fe50Co50)80Al20 nanopowders through mechanical alloying under argon atmosphere. Milled Fe50Co50 combination formed heterogeneous solid solution having two bcc phases of almost close lattice parameter but diverse superfine factors, microstrains, percentages and crystallite sizes. Al atoms that dissolved into the bcc α-Fe(Co) solid solution yielded non-homogeneous combination of two bcc α-Fe(Co, Al) of disordered structures after 6 h milling and ordered B2 AlCo nanosize of CsCl phase after 48 h of milling.

Another way to production of Fe/Al alloy and aluminium doped iron oxide nanostructured material was reported by Bamdad and Ghotbi, 2012. A pioneer nanozone particle was fabricated via co-precipitation technique. Studies on fabrication of bi-modal Al alloys with microstructures possessing 1–3 μm micro size grains, and ultra-fine or nano grains with grain size of 0.1–0.3 nm and less have also been reported (Clay et al., 2012; Djebbari et al., 2010). Diverse industrial and medical practices (Chen et al., 2011; Biswas et al., 2010) have engaged iron oxide based nano materials because of their fascinating electric, magnetic, and optoelectronic properties as in water purification, functional materials, thermoelastic devices, magnetic resonance imaging, sensors and biosensors, tissue targeting, and magnetic refrigeration, etc. Aluminium reinforced with nanostructured iron oxide material with hematite phase was made by co-precipitation via the heat-treatment process of an amorphous precursor in air atmosphere obtaining intermetallic Fe3Al alloy nanoparticle sizes about 200 nm (Chen et al., 2011; Biswas et al., 2010; Bamdad and Ghotbi, 2012).

A gradient structured layer was produced by Xu et al., (2019) on 7850-77751 aluminium alloy via ultrasonic surface rolling process (USRP) where with a 425 μm thick gradient structure of 700 μm profound compressive residual stress field were created with ~ 67 nm fine grain aluminium.

The production of aluminium alloys by casting and Rheo-processing of semi-solid are also popular, studied and reported. Characteristics of nanostructured aluminium A413.1 fabricated by melt spinning at a cooling rate of 107 K/s, were studied by Salehi and Dehghani, (2008) via some microscopy and X-ray diffraction (XRD) methods, showing better solid-solubility of Si in the Al matrix, with spherical Si nano-crystals of 60–70 nm size, increased hardness having homogenous and ultra-fine dendritic structure.

Accordingly, the increased use of aluminium and magnesium alloys has resulted in the production of more fuel-efficient vehicles by the automotive and aircraft manufacturing industries. At present, the large automotive industry’s needs are met in liquid metal high-pressure die-casting (HPDC), increased interests in semi-solid forming processes as a result of the inherent problems linked with liquid metal-HPDC (Ivanchev et al., 2006).

Flores-Campos et al., (2012) produced 7075 aluminium alloy and carbon coated silver nanostructured composites by the combination of mechanical milling and indirect hot extrusion via high energy SPEX ball mill, and consolidated by uniaxial loading and pressure-less sintering in argon atmosphere.

The fabrication of different Al–Mg–Si matrix hybrid composites made by double stir casting process reported by Alaneme et al., (2013); Alaneme and Aluko, (2012a, b) were reinforced by addition of borax pre-mixed SiC, rice husk ash–alumina and silicon carbide. The authors inferred and reported enhanced microstructures with mechanical behaviours (fracture toughness (Kc) and tensile properties), corrosion and wear behaviours of the composites when compared with as-cast and age-hardened A6063 alloys (Alaneme et al., 2013; Alaneme and Aluko, 2012a, b).

The consequences of pouring temperature and particle permeability on the mechanical, metallurgical and microstructural properties of aluminium alloy component made by sand casting was investigated by Mahipal et al., (2019); the fine grain structures of casting formed and hardness increased while impact strength decreased, as the pouring temperature increased; while high moulding sand permeability produced high hardness value with low impact strength in fine grain of cast structures. The results aligned with the report on application of cooling combined with the reinforcing carbon fibres to get superior control over the microstructure of aluminium cast metal-matrix composites (Gupta et al., 2019).

Accordingly, Gruzeski and Closset (1990) evidenced that mechanical properties (hardness, strength, etc) and metallurgical properties (microstructure, phases etc) could be enhanced by different casting processes and proper management of other different controlling factors.
as the moulding sand size mixing ratio, superheating pouring temperatures and composition, the charge and alloying additive compositions. Reports by Ajibola et al., (2014a, b); Ajibola and Oluronotoba, (2015a, b) inferred that addition of magnesium ferrosilicon used at pouring temperature initiated nucleation in collaboration with other factors controlling casting processes that affect the ultimate cast grain size.

3 SURFACE TREATMENTS AND MECHANICAL BEHAVIOURS OF ALUMINIUM ALLOYS AND NANO-COMPOSITES

The problems arising from wear and corrosion could be eliminated or alleviated by means of materials and process design, surface treatment and deposition methods. (Hamid and Elkhair, 2002). Surface treatment includes the cleaning processes, (used for eradicating soils and impurities), classification and selection of cleaning media. Understanding the technicalities of the cleaning action for particular processes often guide the selection of a suitable method such as emulsion cleaning, solvent cleaning, alkaline cleaning, saponification, electrolytic cleaning, abrasive cleaning, acid cleaning, phosphoric acid etching, molten salt bath cleaning, ultrasonic cleaning, substrate considerations etc.

There are many renowned surface deposition methods that enhance the surface properties of materials subjected to chemical, tribological and mechanical stresses at different applied temperatures. These include: metal coating or plating processes such as anodising, hot dipping, electroless-plating, electroplating, cladding, parkerizing and galvanising. Electroless-deposition is a reduction of chemicals without the electrolysis; but rather based on the auto-catalysis of metal ions (with reducing chemical) in water base solution and the subsequent deposition of the metal (Ajibola et al., 2015; Sahoo and Das, 2011).

Different surface coating methods widely used on diverse aluminium alloys have also been reported in some literature (Estrada-Cabrera et al., 2019; Chen et al., 2007). Chen et al, (2007) reported the characterization of high %Al content (Al, Cr)N and (Al, Ti)N PVD coatings using different microscopy methods (scanning electron microscopy (SEM), electron probe microanalysis (EPMA), transmission electron microscopy (TEM) and X-ray diffraction (XRD)) to study the microstructures and crystal structures.

Masiha et al., (2014) coated AA1230 aluminium alloy samples devoid of and with surface mechanical attrition treatment (SMAT) using electrolytes containing silicate and phosphate; and adding SiNi nanoparticles) via plasma electrolytic oxidation (PEO). Coating tribological characteristics were compared whereas; the tests show that the average CoF of the coatings reduced to about 83% as compared to unSMATed species because of rise in reactivity of their matrix. The effect of stick/slip mechanism is smaller for the coated species (9 h SMAT); showing the evidence that increased SMAT time yields more nanoparticles in the layer that takes more active function in reducing stick or slip occurrence (Masiha et al., 2014).

Aluminium alloys have about 70 GPa modulus of elasticity; much lower than most kinds of steel and other alloys steel; even though some Al alloys have greater tensile strengths than the generally variety of steels in use. Precipitations and size of grains have effects on the ductility and mechanical strength of ultrafine-grained materials (Wen et al., 2013). Yu et al., (2016) established that asymmetric cryo-rolling and ageing when combined together; results in considerable enhancement of ductility and the strength of the ARB-fabricated 6061 aluminium alloy sheets. The enhancement of ductility of aluminium alloy was achieved by Xu et al., (2017) through age-hardening using a gradient nanostructured structure. The study revealed the difference in mechanical response between pure and Al7075 alloy with a gradient layer. The introduction of nano second phase particles (nano-precipitates), Zn addition into nanostructured Al alloy matrix were reported as viable methods of enhancing the ductility of nanostructured Al alloys.

Plastic deformation (including Severe plastic deformation (SPD) techniques (Thama et al., 2019) are recently reported as effective processing methods for nanostructured aluminium alloys placing special emphasis on the correlation among chemical behaviour, microstructural features, physical and mechanical properties. Much progress has been made in the synthesis and investigations on nanostructured Al alloys for advanced practical application and structural services via manufacture of massive nanostructured species by severe plastic deformation (SPD) method leading to enhanced properties (Sabirov et al., 2013). The fundamentals of producing nanostructures via SPD processing were founded in other reports by Estrin et al., (2008).

Microstructure and deformation behaviour of about 100 nm grain size commercial nanostructured aluminium-based Al-Zn–Mg–Cu–Zr alloy was made successfully and were studied under high pressure torsion (HPT). The result yielded 800 MPa (tensile strength) and 20% ductility at most favourable temperature-strain rate situations (Islamgaliyev et al., 2001). Super-plasticity is a mechanical property of nanostructured metallic materials briefed by Kumar et al., (2019). Plastic deformation occurs in the nano-structured Al alloys as high strain rate super plasticity (HSPS) and/or low temperature super plasticity (LTS) base on experimental accounts and shown in diverse AI alloys (Islamgaliyev et al., 2001).

4 TRIBOLOGICAL BEHAVIOURS OF ALUMINIUM ALLOYS & NANO-COMPOSITES AT ELEVATED TEMPERATURES

Tribology is the study of the friction, wear and lubrication. Friction considers the resistance to sliding or rubbing of two material surfaces in contact. Wear is a mechanical material weakening process occurring on impacting or rubbing surfaces appreciably influenced by factors such as lubricants, sliding speed, applied load, rubbing (ball, pin, block or ring) materials. Lubrication processes are of different forms; involves introducing
solid and fluid (gas, liquid) as lubricant between two sliding solids boundary in order to lessen wear and friction, and to eradicate heat and drive away fragments generated during the sliding contact. Usual liquid lubricants are often less effective at extreme or elevated temperatures above 500 °C or vacuum environments for their tendency to oxidize fast or crumble at elevated temperatures, vaporize or creep away from applied surfaces under high vacuum; thus, use of solid lubricants has grown steadily. Solid lubricants are solid-state materials or layered lattice compounds applied to a surface by a burnishing operation or deposited by plating or sputtering for applications in components such as compressor blades, uniball bearings, and bearing seal rings for gas turbine engines (McDaniel et al., 1980) and gears for spacecraft mechanism actuators (Rowntree, 1985).

Tribological study of light materials pivots around the comprehending and enhancing the friction and wear resistance of the lightweight materials, (aluminium, magnesium, their alloys and composites); and producing new protective films against wear. In addition to experimental studies, researches are carried out theoretically using computational simulation analysis and mathematical modelling to understand tribological occurrence at the atomic and the microscopic levels. Kumar et al., (2019) reviewed few reports of research studies on processing of aluminium alloys by friction stir technique; and inferred that the various aluminium alloys characteristics and properties can be enhanced through the various processes. However, the enhancements have varied effects in areas of manufacturing, aerospace and automotive industries.

The effects of microstructures, friction and lubrication on wear resistance of pure aluminium and cast aluminium alloys have been broadly studied on macro and micro scales by different people. Early reports (Rohatgi and Pai (1974, 1980); Gibson et al., 1984) studied seizure resistance of cast graphite-aluminium composite; consequences of graphite additions on pin-on-disc wear behaviours of cast Al-Si alloys produced via compocasting and squeeze casting. Recently, Menezes et al., (2012) reviewed the tribology of aluminium-graphite composites. Radhika and Subramaniam, (2013) reported the performance of aluminium-alka-graphite hybrid composites subjected to wear; and in another case, Nuruzzaman and Chowdhury, (2013) studied the friction of aluminium and copper using a pin-on-disc tribo-apparatus at diverse sliding velocities and normal load conditions. Other early works that attracted research interests were those reported by Chowdhury et al., (2011); Nuruzzaman and Chowdhury, (2012); Prasad et al., (2013); Venkataraman and Sundararajan, (2000); Sharma, (2001); Rosenberger et al., (2005); Ghaizali et al., (2007); Sudarshan and Surappa, (2008).

The results of pin-on-disc sliding experiment show that the resistance to wear for Al–Cu (AbdElAal et al., 2010) and AA6060 (Ortiz-Cuellar et al., 2011) improved with rising amount of ECAP passes due to enhanced hardness of Al alloys at all compositions. Whereas, the mechanical mill and hot-press nanostructuring of the AA2024 failed the wear rate test (Jafari et al., 2010) with no clarity in correlation linking microstructure and wear behaviours relative to the experimental results. Meanwhile some authors investigated the reasons for amplification in wear with speed which propelled the normal system of delamination of wear during dry sliding conditions (Peddavarapu et al., 2018).

5083 and 6082 Aluminium alloys were deposited by (Su et al., 2019) via friction surfaces (FS) subject to similar processing setting via solid-solution strengthened-AA5083 and precipitation hardened-AA6082. The AA6082 alloy has greater deposition volumes attainable at greater speeds, exhibits a higher torque but lower shear stress than AA 5083. The maximum temperatures of 430-465 °C and 450-480 °C for AA 5083 and AA 6082 respectively were attained on the shear zone which changed with diverse factors however within thin band. The higher % Mg in AA5083 caused the lower thermal softening rate as temperature increased.

Lightweight aluminium alloys are important in lightweight automobile, maritime and aerospace manufacturing industries. For these industries, the anti-icing ability is very fundamental to guarantee their protection for the fact that ice build-up can alter the aerodynamics behaviours and result to loss in control of automobile, ship, hovercraft in the maritime and even crash of airplane in the aerospace such as in the heavy snow, frozen rain, fog icing and in-cloud icing (Xing et al., 2019).

There are wide reports (Li et al., 2016; Gao et al., 2017; Parent and Ilinca, 2011; Li et al., 2017) on the production, effective processing, behaviour and testing of nanostructured substrates and coatings to resist the surface wetting effect on different alloys including aluminium in ice environments as well as anti/de-icing methods are known for more than ten years. Of recent, Xing et al., 2019 reported the cryogenic temperature application test on 5052 aluminium alloy sheets; the surrounding temperature measured with digital machine, declined from 0 °C at 3°C/min rate making use of recycled water temperature controller to about -23 °C freezing temperature with excellent anti-icing properties. The careful observation of the enlarged section of reveals hundreds of nano-structures on the cauliflower-like projections forming micro-nano structures on the 5052 Al alloy coupon used in the study.

Creep is a thermo-mechanical property of material demonstrating its limitation to loading at high temperature. Despite the much engineering benefits derived from the use of aluminium and its alloys, however it suffers creeping at elevated temperatures. Applications and testing of aluminium nano-composites at high temperatures revealed that the creep properties and creep behaviour can significantly be affected by grain refinement (Sklenicka, et al., 2004; Chauhan et al., 2005; Sklenicka et al., 2005; Kim, 2010; Kawasaki et al., 2010; Xu, 2005; Kawasaki et al., 2008). ECAP processing improves
creep resistance of 99.99% Al (Sklenicka, et al., 2004; Kawasaki, et al., 2008).

**5 Conclusion**
In conclusion, aluminium metal matrices have been widely produced by liquid and semi liquid routes. Different plastic deformation methods adopted for the grain refinement and nanostructure enhancement yielding better mechanical properties such as the ductility, strain rate and wear resistance. The productions of aluminium matrix composites enhanced mechanical characteristics and lessen the wear rates in some composites produced. The aluminium alloy using stir casting method produced more favourable results. In all cases, high and low temperatures studied did not exceed 600°C and -23°C respectively.

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