Chapter

Introductory Chapter: Structural Aluminum Alloys and Composites

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1. General background

Aluminum is a metal of great importance because of its excellent corrosion resistance, high electrical and thermal conductivity, good reflectivity and very good recycling characteristics. Aluminum atoms are arranged in a face-centered cubic (FCC) structure with a melting point of 660°C. There are nine different series of aluminum, which will be discussed later in this section, four of which are referred to as heat-treatable aluminum alloys, and these alloys are so-called because of the potential to increase the mechanical properties by precipitation strengthening [1, 2].

The properties of heat treatable Al-alloys can be further enhanced by the inclusion of a reinforcing phase that increases the mechanical properties of the overall composite. Metal matrix composites (MMC) are usually manmade materials that consist of two or more distinct phases; a continuous metallic phase (the matrix) and a secondary reinforcing phase. The secondary phase may take the form of continuous or discontinuous reinforcement as particles or fibers. When this phase is introduced into the matrix the overall impact is an improvement of the mechanical properties of the material [3]. The properties of MMCs are comparatively superior to those of the unreinforced alloys [4, 5].

The properties of discontinuously reinforced aluminum MMCs containing particles or short fibers are modest compared to the continuous fiber reinforced MMCs, however, these materials are less expensive to fabricate and have more flexibility in production making them more cost-effective [6–8]. The reinforcements used in fabricating the composites are dependent on the desired material properties, ease of processing, and part fabrication.

The stability of the reinforcement/metal matrix interface and the differences in properties such as the coefficient of thermal expansion and thermal conductivity are limiting factors that affect the compatibility of the materials used to make the composite. The quality of the bond is dependent on adequate interaction between the reinforcement and the matrix.

Over the last two decade, the application of nano and micro-sized ceramics such as alumina (Al_2O_3), MgO nanoparticle [9], boron carbide [10] and silicon carbide (SiC) [11] to aluminum metal matrix composites have become popular reinforcing phases, since these hard phases can lead to an increase in flow stress from the matrix by load transfer across a strong interface from the matrix to the reinforcement [12]. An example of the typical microstructure of a particle reinforced aluminum metal matrix composite is presented in **Figure 1** and shows an Al_2O_3 particulate reinforced Al-6061 MMC. The properties of these reinforcements include high strength, high modulus of elasticity and high thermal and electrical resistance. The constraint imposed by the ceramic reinforcements on the plastic deformation of the matrix is large tensile hydrostatic stresses.

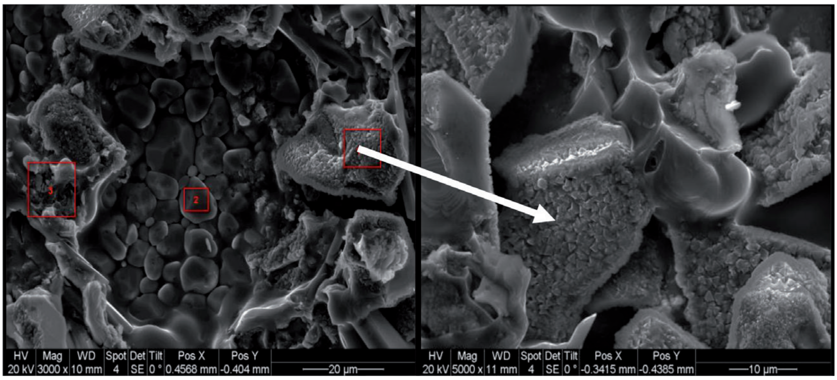

Figure 1.
SEM micrographs of Al-6061 MMC showing Al_2O_3 particulate reinforcements.

Recently, researchers have explored the use of graphene as a reinforcing phase within an aluminum metal matrix as a method of improving the mechanical properties of the composite [13]. The results of the study showed that the hardness, tensile strength, and ductility of the aluminum-graphene composite were approximately 2–3 times higher than the properties of the unreinforced aluminum alloys. The authors also demonstrated that the enhancements of the mechanical properties of the aluminum-graphene composite were proportional to the concentration of graphene added. Similar findings were published by Kumar et al. [14] and Jauhari et al. [15] who produced Al 6061 MMC reinforced with graphene by ultrasonic liquid processing and microwave sintering respectively.

Metal matrix composites (MMCs) find application extensively in the design and construction of engineering components that require a lightweight material with superior mechanical properties such as high tensile strength, high Young's modulus, good wear resistance [16], and good elevated temperature properties. Al-MMCs are used extensively in industries such as aerospace, automotive, sports goods, and marine.

Numerous processes have been investigated for producing aluminum MMC. These include various casting techniques [17] and powder metallurgy approaches [18]. Currently, several additive manufacturing techniques are used to develop rapidly deposit aluminum alloys and composites [19, 20]. From the list available additive manufacturing techniques; selective laser melting (SLM), and wire arc additive manufacturing have shown the greatest promise for producing aluminum alloys and composites [19, 21].

1.1 Nomenclature and crystal structures

Aluminum is a nonferrous and relatively low-cost material with a high strength to weight ratio. These characteristics make aluminum alloys and composites very attractive and competitive structural materials in several industries. For applications requiring greater mechanical strength, aluminum is alloyed with metals such as copper, zinc, magnesium, and manganese. The alloying components determine the series assigned to the aluminum alloy. The possible series categories range from 1xxx to 9xxx. Aluminum alloys can be further divided into two categories: heat-treatable and non-heat-treatable alloys. Heat-treatable alloys are those in which strength is developed by precipitation hardening [22].

These alloys are found in the 2xxx (aluminum-copper), 6xxx (aluminum-magnesium-silicon), and 7xxx (aluminum-zinc-magnesium) series [23]. In non-heat-treatable alloys, strength is developed mainly by solid solution strengthening and strain hardening. The non-heat treatable alloys are found in the 1xxx (Al), 3xxx (Al-Mn), 4xxx (Al-Si) and 5xxx (Al-Mg) aluminum series. The Gibbs free energy curves recorded at a 700°C for Al-Mn, Al-Mg, Al-Cu, and Al-Zn are shown in **Figure 2** and suggest the formation of various intermetallic compounds having a hexagonal close pack (HCP) crystal structure within the aluminum matrix having a face-centered cubic structure (FCC). The 2xxx series which consists of Al-Cu is a heat-treatable alloy that strengthens due to the precipitation of copper aluminides within the aluminum matrix [23].

Ternary systems of Al-Mg-Si and Al-Mg-Zn which are found in the 6xxx or 7xxx series respectively are other heat treatable aluminum alloys that are used in many applications within the aerospace and automobile industries. The high strength-to-weight ratio and corrosion resistance of heat-treatable aluminum alloys make them a very attractive class of materials. The phase diagrams presented in **Figure 3** show the relationship between temperature and composition for the 6xxx series.

1.2 Development strategy and key applications

The research on aluminum alloys and composites has seen substantial development in several new methods of fabricating components using aluminum as the

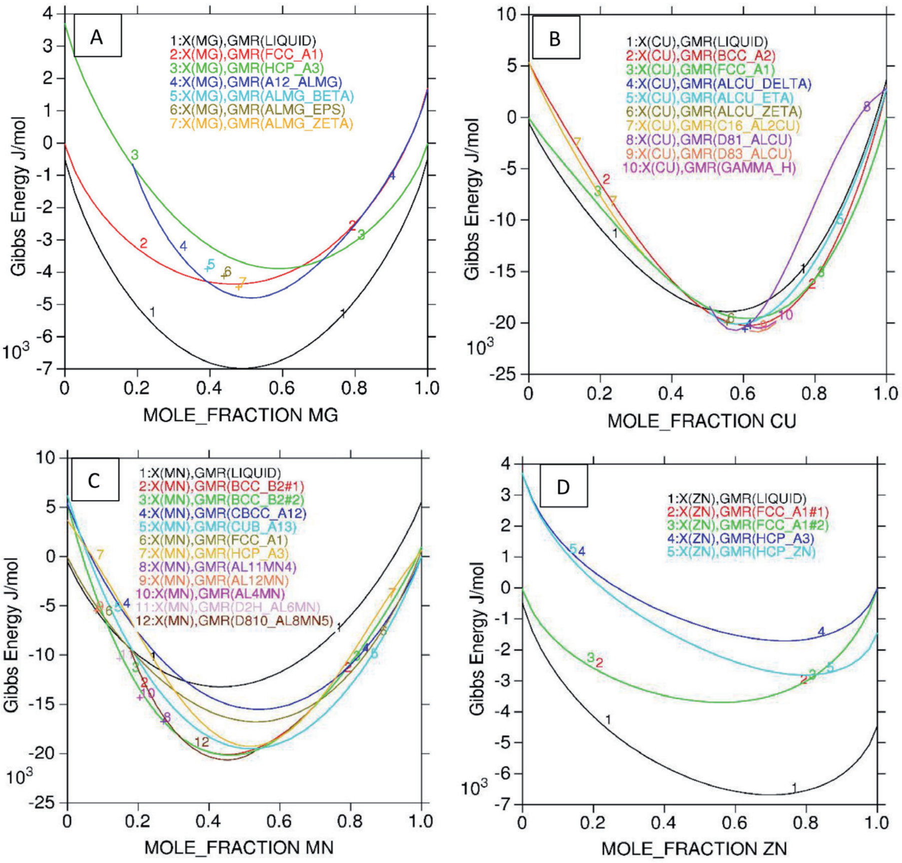

Figure 2.
Gibbs free energy curve plotted at a temperature of 700°C for (A) Al-Mg, (B) Al-Cu, (C) Al-Mn, (D) Al-Zn alloys.

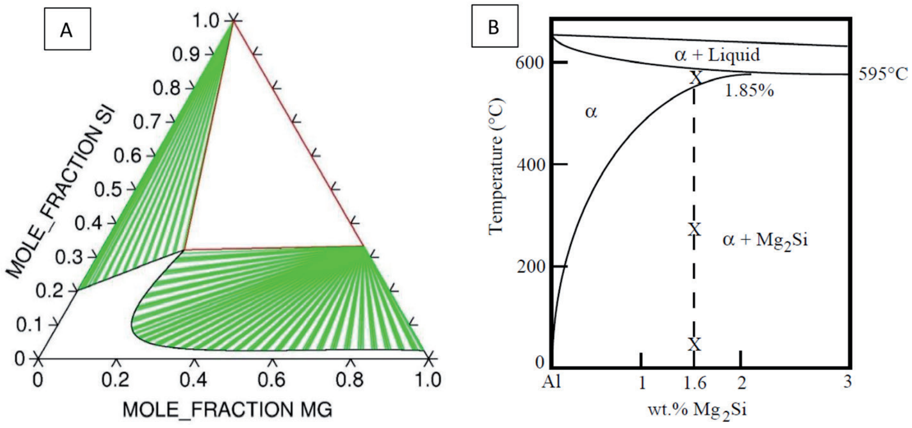

Figure 3.
(A) Isothermal section of the Al-Mg-Si ternary phase diagram at 700°C and (B) pseudo-binary phase diagram of Al-6061.

Alloy	YS (MPa)	UTS (MPa)	Elongation (%)	E (GPa)
6061 (T6)	275	310	20	69
2014 (T6)	476	524	13	73
2124 (T6)	325	470	12	72
2618 (T6)	370	470	9	74
7075 (T6)	505	570	10	72
8090 (T6)	415	485	7	80
A356 (T6)	205	280	6	76

Table 1.
Typical properties of some heat treatable aluminum alloys [5].

base metal and combining the metal with new forms of reinforcements for various new applications. In a recent study, it was demonstrated that a 3D self-assembly of aluminum nanoparticle can be used for plasmon-enhanced solar desalination and [24]. **Table 1** shows a summary of the properties of various heat treatable aluminum alloys. These properties justify the pervasive use of aluminum in automotive, aerospace and explosive mixtures for underwater propulsion. Among the available aluminum alloys, the 2xxx series, 6xxx series, and 7xxx series are used frequently in the aerospace and defense sectors, transportation, automotive, medical appliances, dental implants, sports, mobile phones, etc. [1, 2, 11, 25, 26].

Given the low melting point (660°C) and density (2.7 g/cm^3) aluminum is now a key material used in metal additive manufacturing processes such as selective laser melting (SLM), these processes are largely termed layered manufacturing process in which the subject material is deposited in layers and build up to the required dimension [20]. Given the high strength-to-weight ratio and low melting temperature of aluminum, this material is used to fabricate various near-net-shape complex structures by additive manufacturing. Though additive manufacturing has seen extensive development over the last 5 years, there are several areas of the technology that will require significant research investment and investigation [20]. As the technology matures for depositing aluminum alloys will focus on process optimization to remove weaknesses such as oxide film formation on the surface of the metal powder, improve thermodynamic stability of the aluminum oxide and reduce the difficulty of finding low melting point binders to be used with aluminum powders [27–29].

Wire arc additive manufacturing (WAAM) using gas metal arc welding (GTAW) has been used successfully to deposit AA5183 aluminum alloy [21]. The technique demonstrated the potential of rapidly depositing large metal structures [30]; however, there is still the need for further development to optimized materials properties, surface texture and internal defects within the components produced.

The development of new aluminum alloys and composites is expected to continue to lower production costs and increasing the strength-weight ratio. These improvements in the properties of MMCs have made these materials important alternatives to traditional materials for high-temperature applications. Increasingly, aluminum MMCs containing SiC are used in engines (engine block and pistons), drive shafts and disc brakes (including rail type). It has been reported in the scientific literature that when MMCs are used to make drive-shafts the increase in stiffness, increases the maximum attainable rotation. The application of aluminum MMCs to the construction of pistons is one of the most significant developments in the automotive industry. In the electronics industry, the new generation of advanced integrated circuits generates more heat than previous types given the increase processing power. Therefore, the dissipation of heat has become a major concern. Thermal fatigue may also occur due to a small mismatch of the coefficient of thermal expansion between the silicon substrate and the heat sink. These problems can be solved by using MMCs with matching coefficients (e.g., Al with boron [10] or graphite fibers and Al with SiC particles [11]).

In addition, Al-based MMCs can be used in situations in which an "adjustable" coefficient of thermal expansion is required. This is possible because the coefficient of thermal expansion is dependent upon the volume fraction of the fibers or particles added. Components produced using Al-MMCs are not only significantly lighter than those produced from aluminum metal alloys, but they provide significant cost savings through net-shape manufacturing [31].

1.3 Future challenges

The research shows that the primary challenges affecting aluminum alloys and composite are directly linked to the properties of the material. An example can be seen in additive manufacturing where the growth in the application of aluminum in additive manufacturing has been driven by several important factors which include; low melting point, corrosion resistance, good strength-to-weight ratio. On the other hand, an important hurdle is finding suitable binders with the appropriate melting point to be used with powdered aluminum metals. The technology is also constrained by several other factors such as the need for a better understanding of the material properties, poor reproducibility, the need for additional material, lack of training and education of users and finally the unavailability of standards and certification.

Most manufacturers are cautious about using additive manufacturing as a viable manufacturing process due to the lack of repeatability and consistency of the manufactured parts. Manufacturers are also skeptical of the structural integrity of the finished products as compared to conventional manufacturing processes [12]. The primary challenge, however, is that materials produced using these processes contain numerous defects that limit the application.

The verification and validation of the relationships between the process parameters and the finished product have been hampered by the lack of available data, poor understanding of the causes of internal defects, and uncertainty in detecting the critical flaw. These gaps in the existing knowledge limit the wide-scale application of additive manufacturing technology. Research into this area will aim to bridge the gap by quantifying the relationship between the process parameters, surface quality and defects present within the finished products.

Aluminum alloys and composites (Al-MMCs) are of interest to the automotive and aerospace industries, because of comparably high strength-to-weight ratio, formability, and corrosion resistance. However, despite the unique properties of these materials, the lack of a reliable joining method has limited their use to engineering applications where joining is unnecessary. This can be seen as another major hurdle affecting the proliferation of aluminum alloys as an important material in achieving lightweighting objectives [34, 35].

Over the last two decades, numerous joining techniques have been extensive studied to identify a process that can be successfully used for dissimilar joining of aluminum alloys and composites by minimizing undesirable interfacial reactions between the materials being joined. Some of the processes that have been studied include fusion welding [36], brazing [37], friction stir welding [38], solid-state diffusion bonding [39] and transient liquid-phase (TLP) bonding [35, 40]. The key findings have shown that the inclusion of nanoparticles within the joint regions has the capability of significant increases in joint strength while minimizing unwanted interfacial reactions. The procedure has been applied to the diffusion bonding of aluminum alloys to magnesium as showing in see **Figure 4** and diffusion bonding of Al-MMCs as shown in **Figure 5**. Application of the concept to resistance spot welding also proved successful as shown in **Figure 6** which demonstrates that Al and Mg can be successfully welded together without the formation of undesirable compounds.

1.4 Chapter plan

This introductory chapter presents a brief overview of the state of science and the application of aluminum alloys and composites. Particular attention is paid to the application of new/novel methods of producing aluminum alloys while highlighting the future direction of the technology and some of the key challenges that affect the use of these materials. The book contains seven chapters that have been divided into two sections.

The first section of the text is focused on evaluating the types and properties of advanced aluminum alloys and composites. The chapters in this section provide a comprehensive overview of the processing, processing, formability, chemical composition of advance aluminum alloys and composites and the development of new types of alloys.

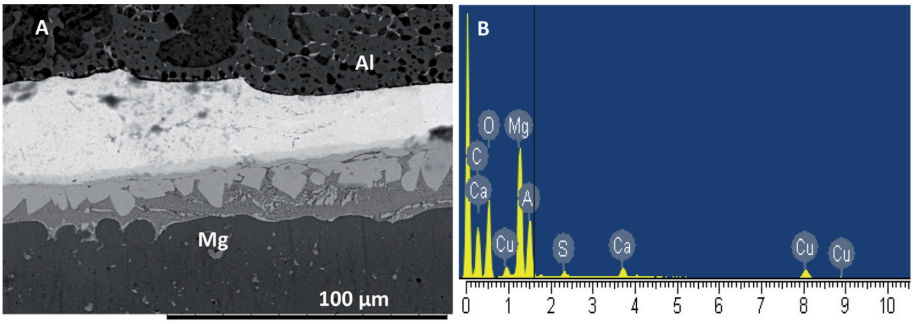

Figure 4.
Eutectic microstructure formed at the joint interface during TLP bonding: (A) eutectic microstructure formed using Cu/Al$_2$O$_3$ interlayer; and (B) EDS spectrum of region-2 [32, 33].

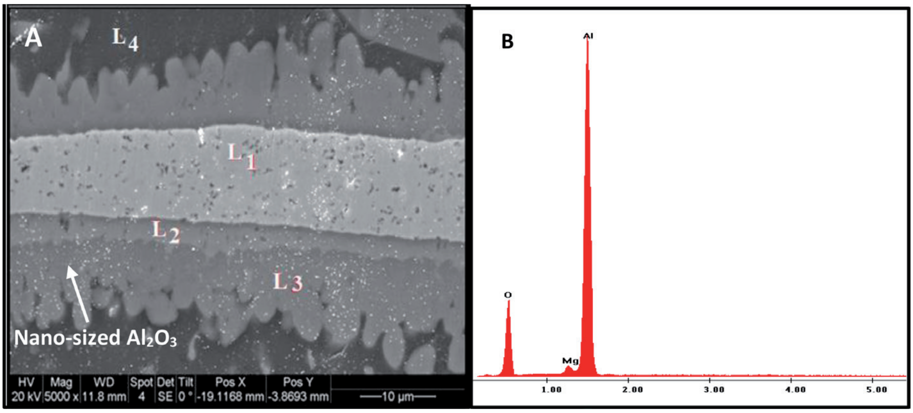

Figure 5.
(a) SEM micrograph of joint bonded with a 15 µm Ni-Al_2O_3 coating for 1 min. (b) DS analysis of nano-Al_2O_3 particle.

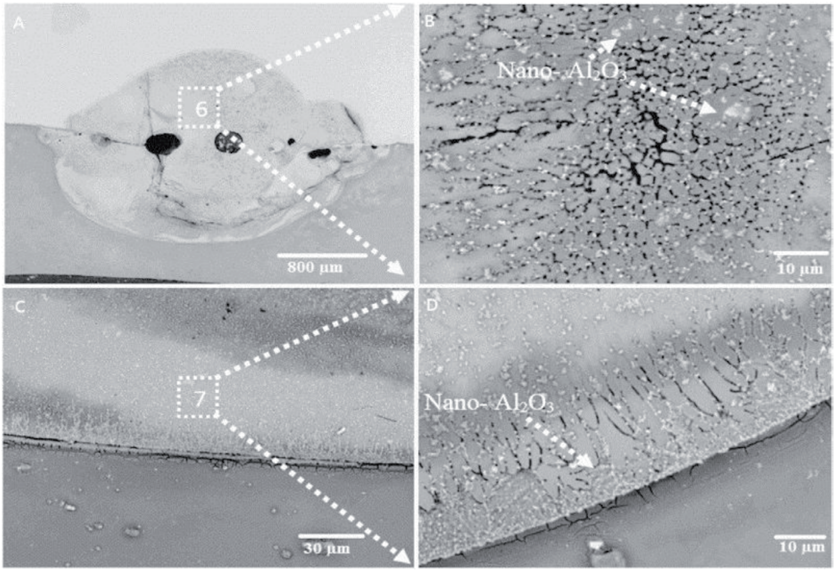

Figure 6.
SEM micrograph showing: (A) Al/Ni-Al_2O_3/Mg spot weld; (B) microstructure of point-6; (C) weld nugget/Al interface; and (D) microstructure of point-7 [41, 42].

The second section of the text contains chapters that are focused on exploring processing, characterization, and testing of aluminum alloys and composites such as wear testing. The advantage of this text is that it provides a detailed review of major advances that have occurred in the development and application of aluminum alloys and composites while outlining a development strategy for these materials.

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